Networks of the Future & Next-Generation Production

Rooms 203-204 (Level 2)

Sunday March 30, 2025 (13:00 - 15:30)

Organizers

Scotty Strachan (Lead), Nevada System of Higher Education, United States

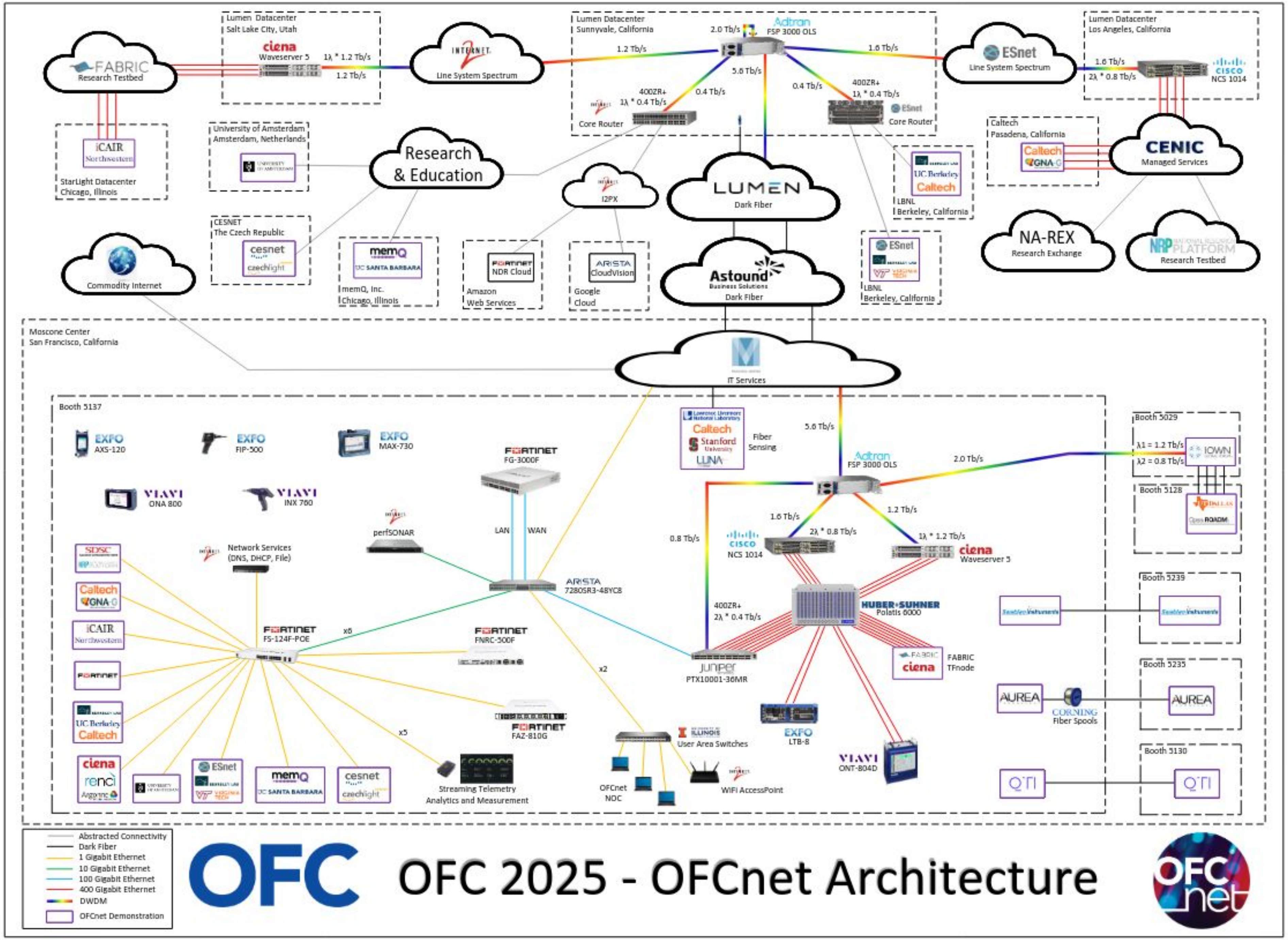
Sana Bellamine (Lead), CENIC MMBI, United States

Akbar Kara, Ciena, United States

James Stewart, Utah Education and Telehealth Network, United States

Chris Tracy, ESnet, United States

OFC 2025 - OFCnet Architecture



Welcome to OFCnet 2025!

Bridging Today's Innovations to Tomorrow's Networks

Thank you for joining us for a dynamic 2.5-hour panel-format workshop that connects the latest advancements from the OFC conference to the networks of the future.

Focus Areas

- Automation & Orchestration

  Evolving network ops teams for smarter, faster decision-making
- Trend Analysis & Failure Prediction

  Leveraging standardized data for machine learning-driven insights
- Quantum Networking Early Wins

  Real-world implementation updates and lessons learned
- Networks of the Future

  Bleeding-edge tech: What's coming next—and when?

Welcome Speakers!

James Deaton, Internet2, United States

Danial Ebling, Utah Education & Telehealth Network, United States

Lidia Galdino, Corning Optical Communications, United Kingdom

Mariam Kiran, Oak Ridge National Laboratory, United States

Hideki Nishizawa, NTT, Japan

Reza Rokui, Ciena, Canada

Dirk van den Borne, Juniper Networks, Germany

Wenji Wu, Energy Sciences Network, United States

John Wu, Energy Sciences Network, United States

Thank you to our facilitators!

(as well as their sponsoring organizations)

Sana Bellamine (Lead), CENIC MMBI, United States

Scotty Strachan (Lead), Nevada System of Higher Ed, United States

Akbar Kara, Ciena, United States

James Stewart, Utah Education and Telehealth Network, United States

Chris Tracy, Energy Sciences Network, United States

Workshop Structure

- 2.5 hour workshop divided into 4 sessions
  - 30 min: Automation and Orchestration
  - 30 min: Trend Analysis and Failure Prediction
  - 15 min break
  - 30 min: Quantum Networking Early Wins
  - 30 min: Networks of the Future
- Moderated Panel + Audience Q&A:
  - Dive into challenges, opportunities, & real-world applications
  - **Interactive!**

Automation and Orchestration:

Evolving the network operations team

Akbar Kara, Ciena, United States (Facilitator)

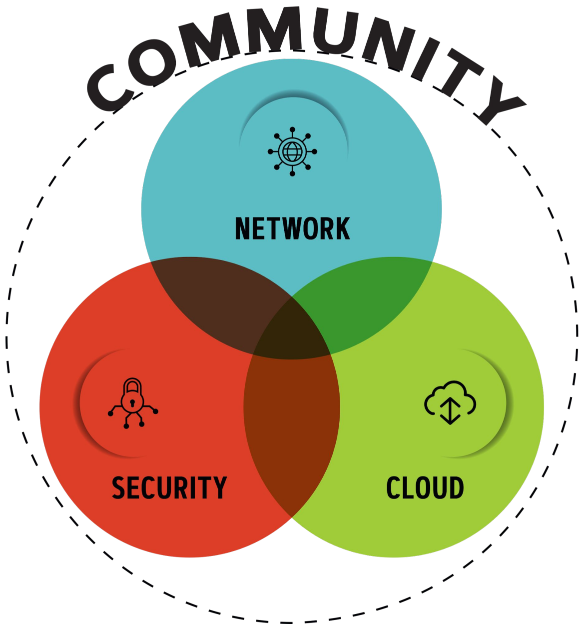
James Deaton, Internet2, United States

Hideki Nishizawa, NTT Japan

Questions:

- What is your vision for the path from CLI to an orchestrated network? How far are you in this journey?
- Are you developing network automation tools/workflows in-house, or are you deploying commercial solutions? How should organizations approach this decision?
- How are automation/orchestration tools changing your team’s makeup or subject-matter expertise?
- What tools/software have you tried or are currently working with for multi-vendor automation & orchestration? What are your likes and dislikes?

Internet2: A Member Consortium



COMMUNITY

Internet2 is a non-profit consortium providing research support, cloud solutions and custom services tailored for Research & Education.

A trusted, adaptable, secure network that empowers higher education, research institutions, government entities and cultural organizations.

BY THE NUMBERS

330+
HIGHER EDUCATION MEMBERS

100+
COUNTRIES & RESEARCH NETWORKS CONNECTIONS

80,000+
COMMUNITY ANCHOR INSTITUTIONS

500+
NET+ SUBSCRIBERS

50+
AFFILIATE & GOVERNMENT MEMBERS

800G+
WAVELENGTHS OF NETWORK CAPABILITY

1000+
INCOMMON PARTICIPANTS

50+
INDUSTRY MEMBERS

1100+
EDUROAM SUBSCRIBERS

50+
COMMUNITY GROUPS SHAPING PRIORITIES

50+
CLOUD SCORECARD PARTICIPANTS

750+
NET+ CLOUD CONTRACTS

46
REGIONAL & STATE NETWORKS

20+
NET+ SERVICE OFFERINGS

32Tbps
CAPACITY PER LINK

Internet2 Network Services

LAYER 1 SERVICE

Point-to-point 10, 100 & 400G links and flexible grid spectrum to support private network needs.

LAYER 2 SERVICE

Effective and efficient wide area 100 gigabit Ethernet technology.

LAYER 3 SERVICE

For IP network and peer exchange needs.

PEER EXCHANGE

Provides institutions with access to commercial peers across the national footprint.

RAPID PRIVATE INTERCONNECT

Allows Internet2 connectors to present themselves for private peering at selected national peering locations.

R&E

Provides institutions with access to each other across the national footprint.

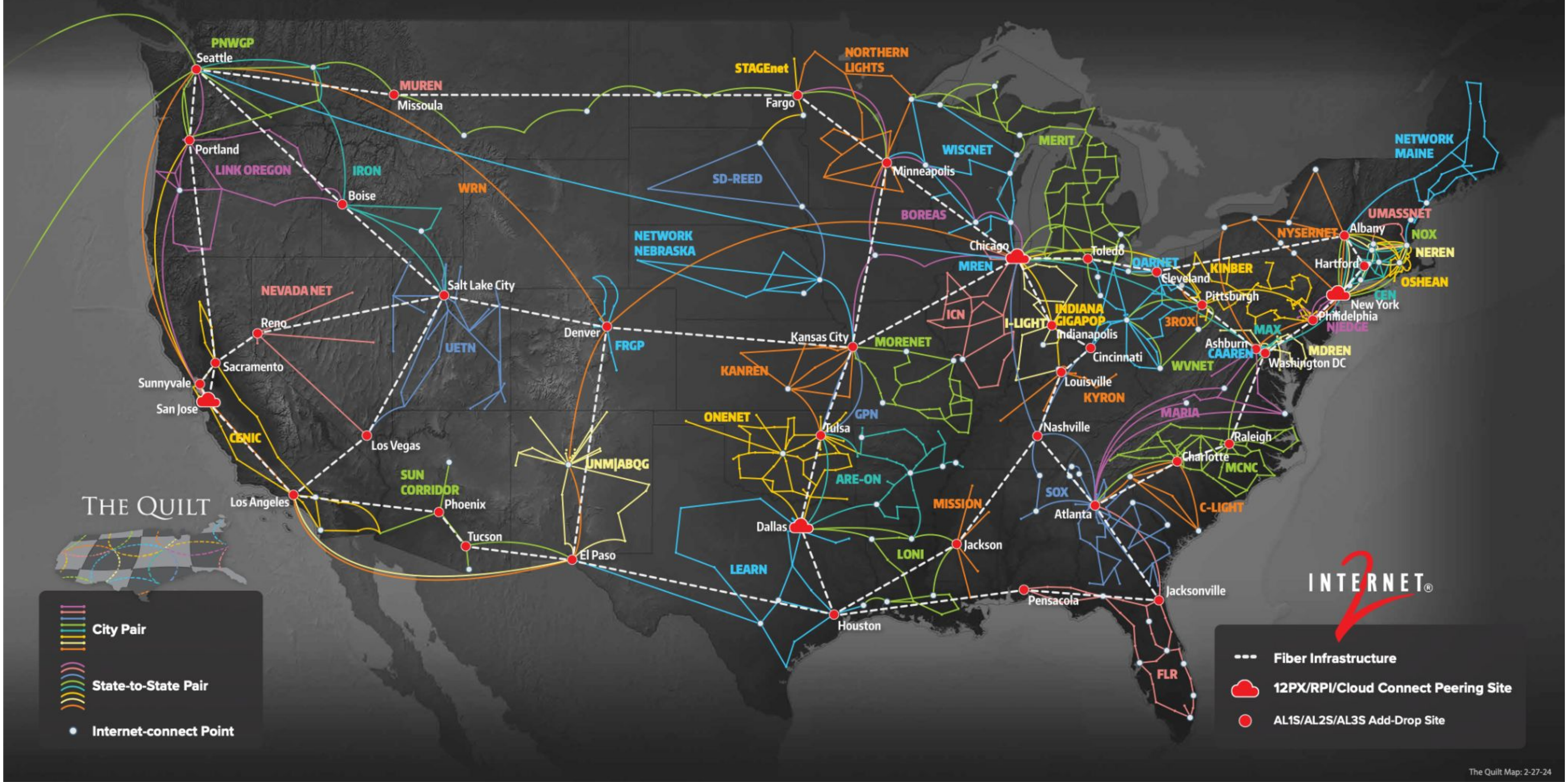
CLOUD CONNECT

Uses regional's infrastructure in conjunction with the Internet2 Network to reach cloud resources.

GLOBAL DDoS PROTECTION

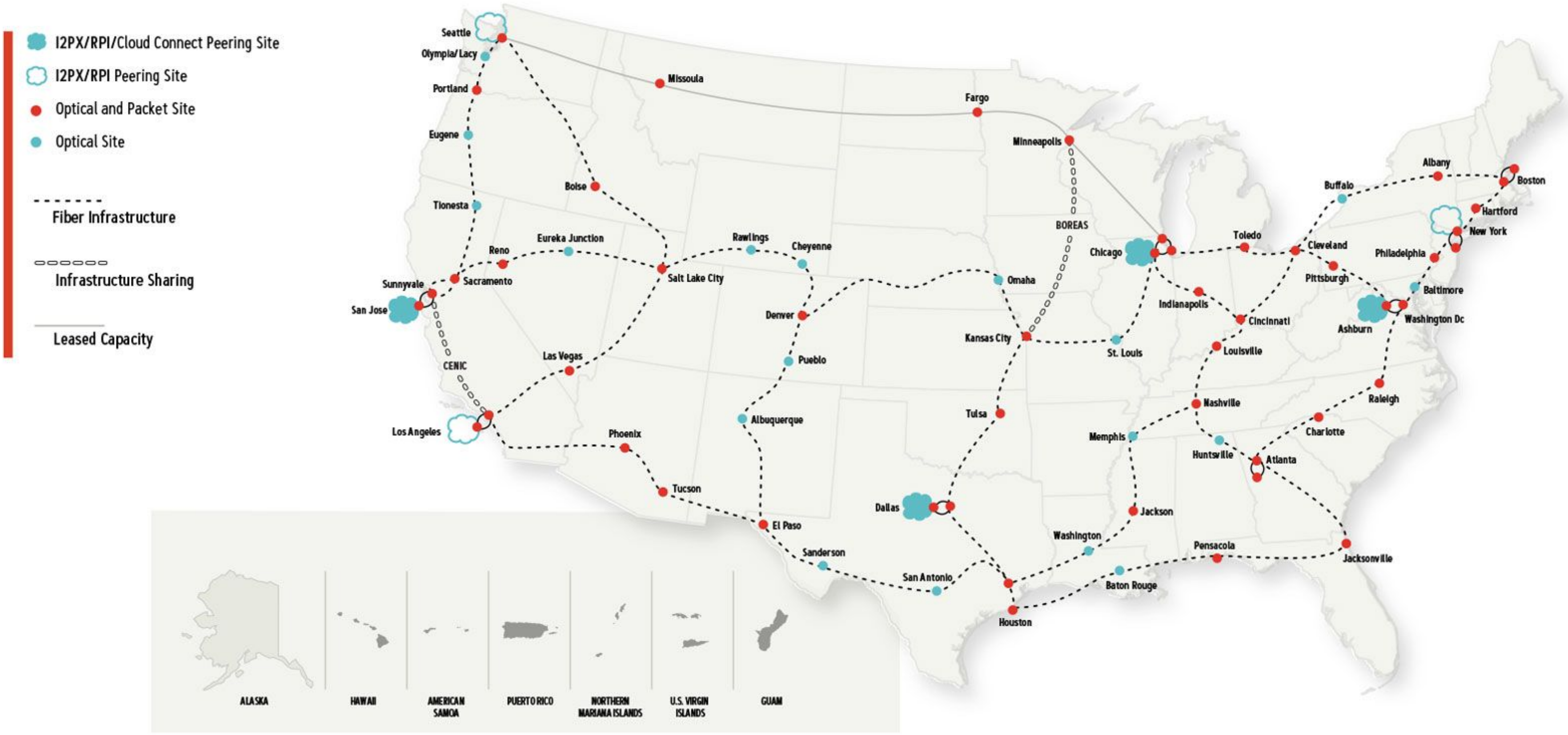
Our cloud-based, volumetric DDoS mitigation service was procured on behalf of the community.

Internet2 & Regional Research & Education Networks (REN) in the United States

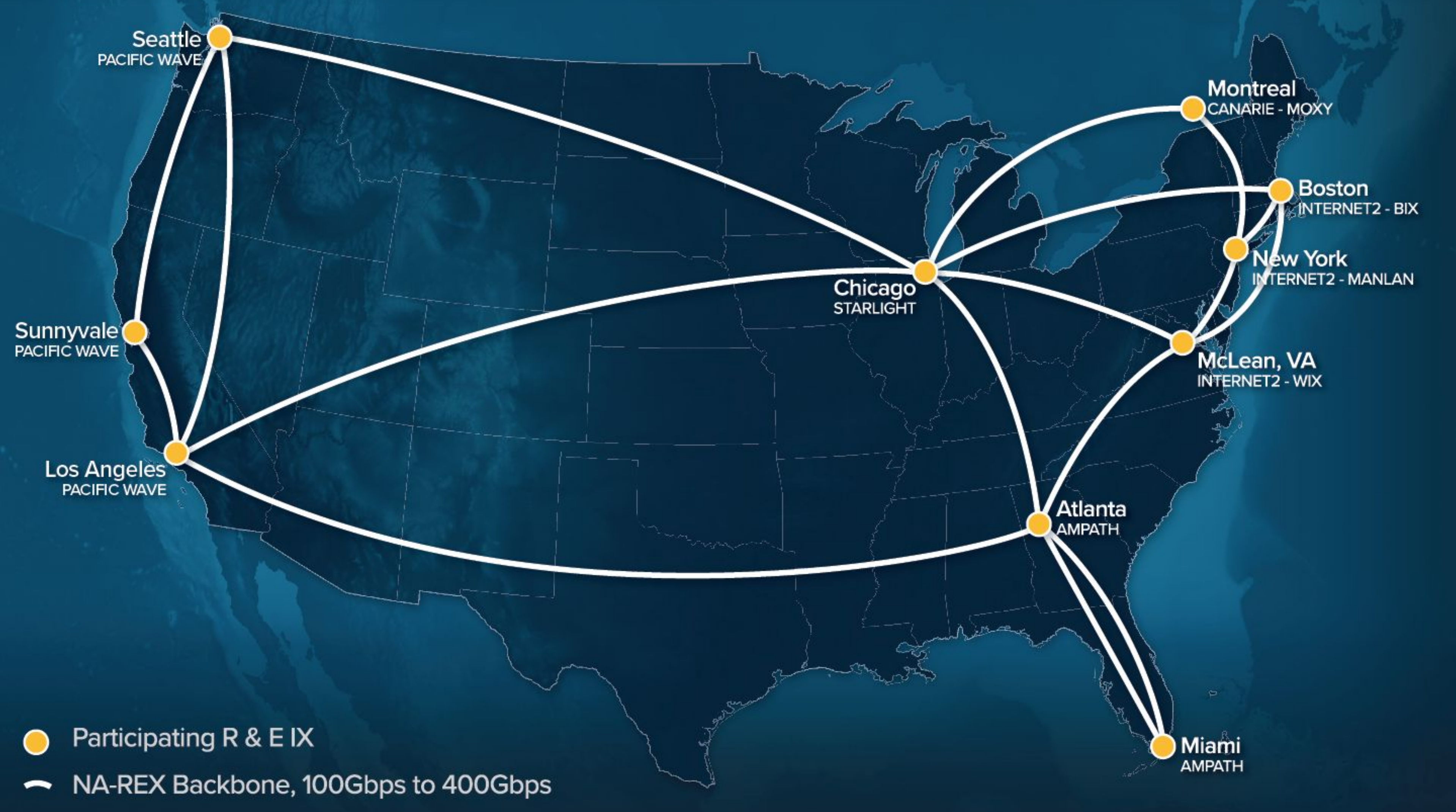


Network Infrastructure Topology | May 2024

This map represents all 50 states and five major territories of the U.S. The Internet2 network infrastructure extends across the contiguous U.S. and, through a global fabric of research and education networks and exchange points, interconnects with locations in Alaska, Hawaii, Guam, Puerto Rico, and 100+ countries worldwide.



NA-REX North America Research & Education Exchange Collaboration



AMPATH PATHWAY TO THE AMERICAS

canarie

ESnet ENERGY SCIENCES NETWORK

INTERNET2

International Networks at Indiana University

STARLIGHT The Optical STAR TAP

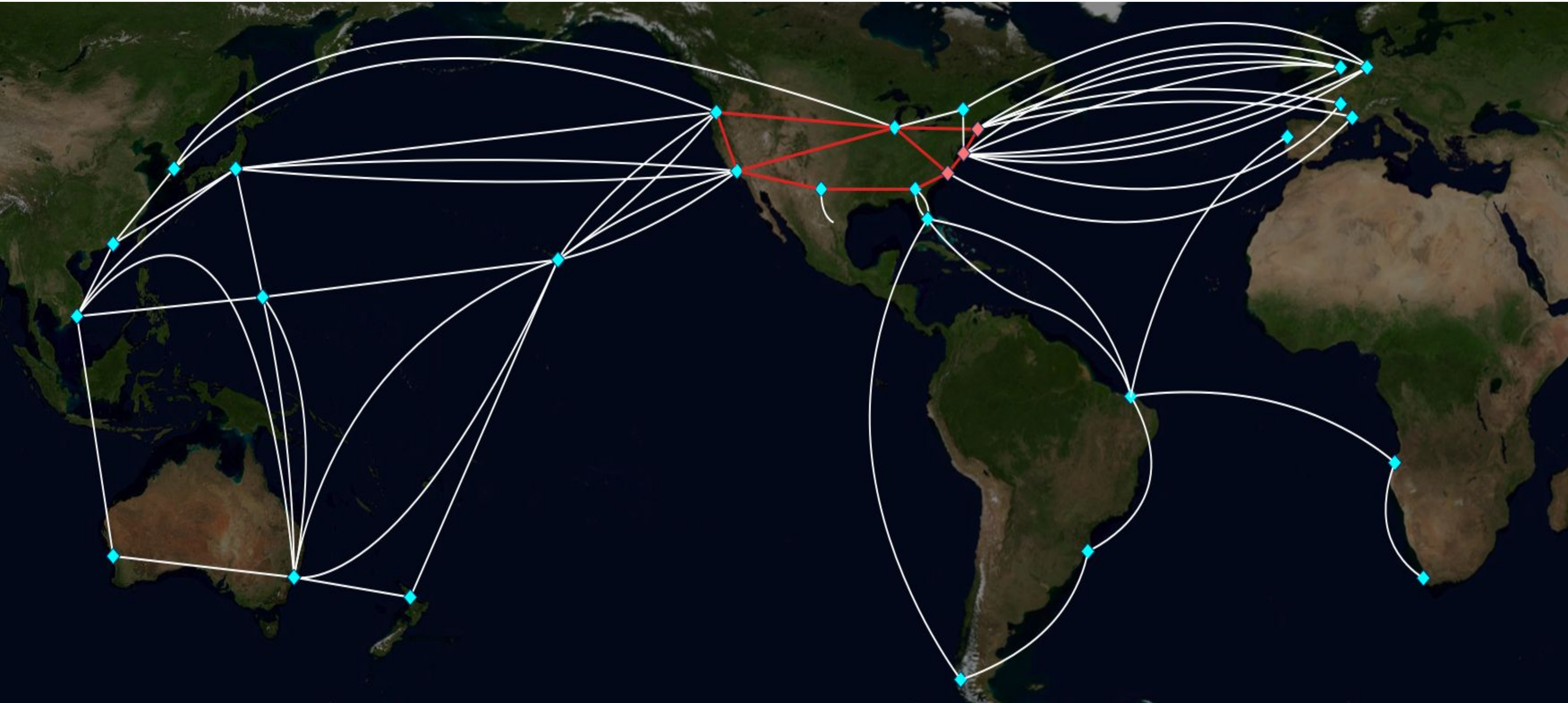
CENIC

PACIFIC NORTHWEST GIGAPOP

PACIFIC WAVE

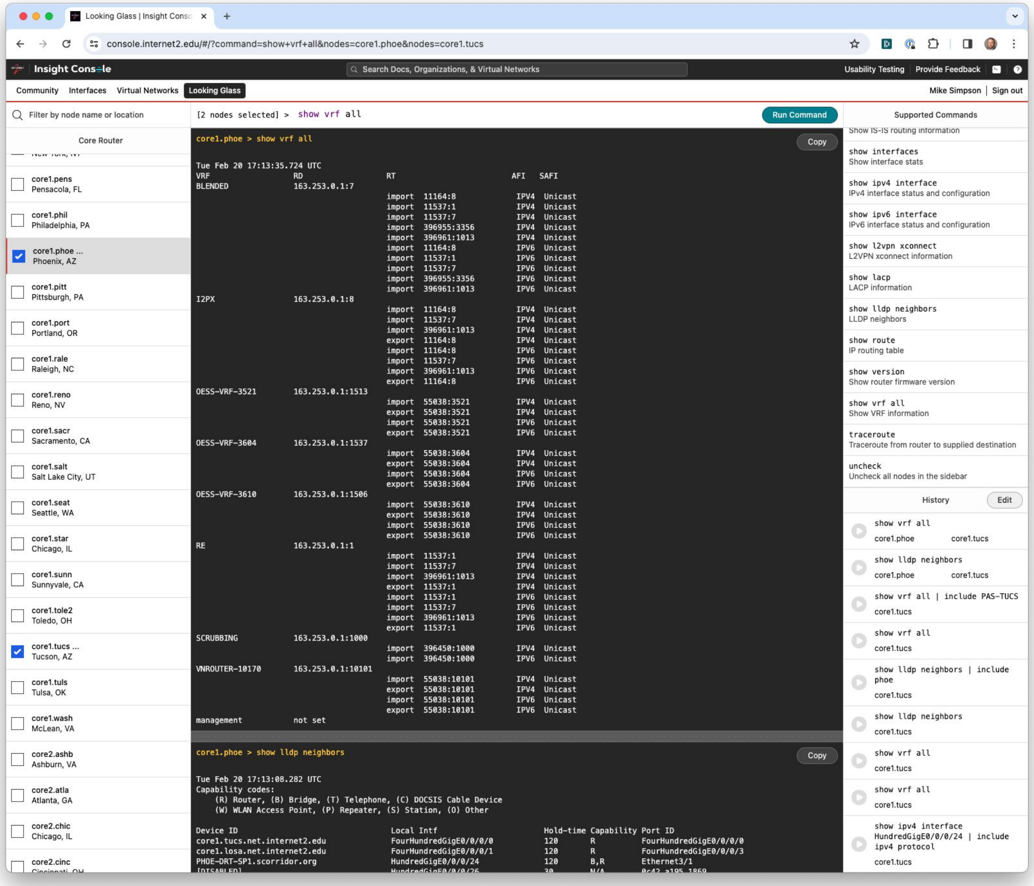
October 2024

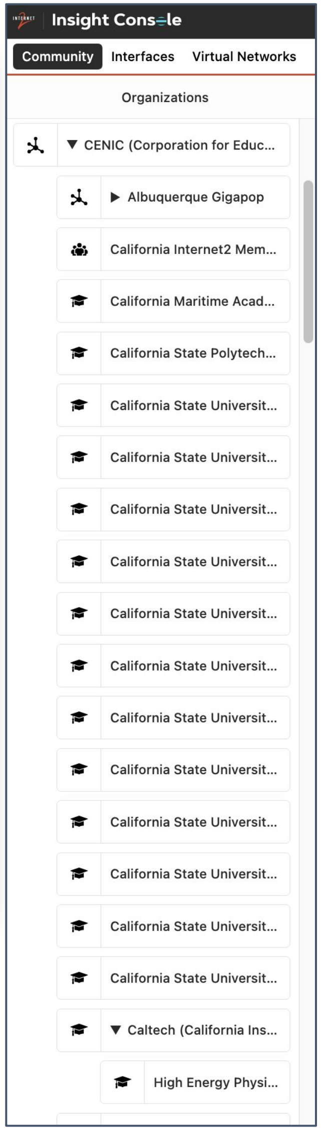
International Connectivity (NREN to NREN) via multiple partnerships and consortiums



Insight Console

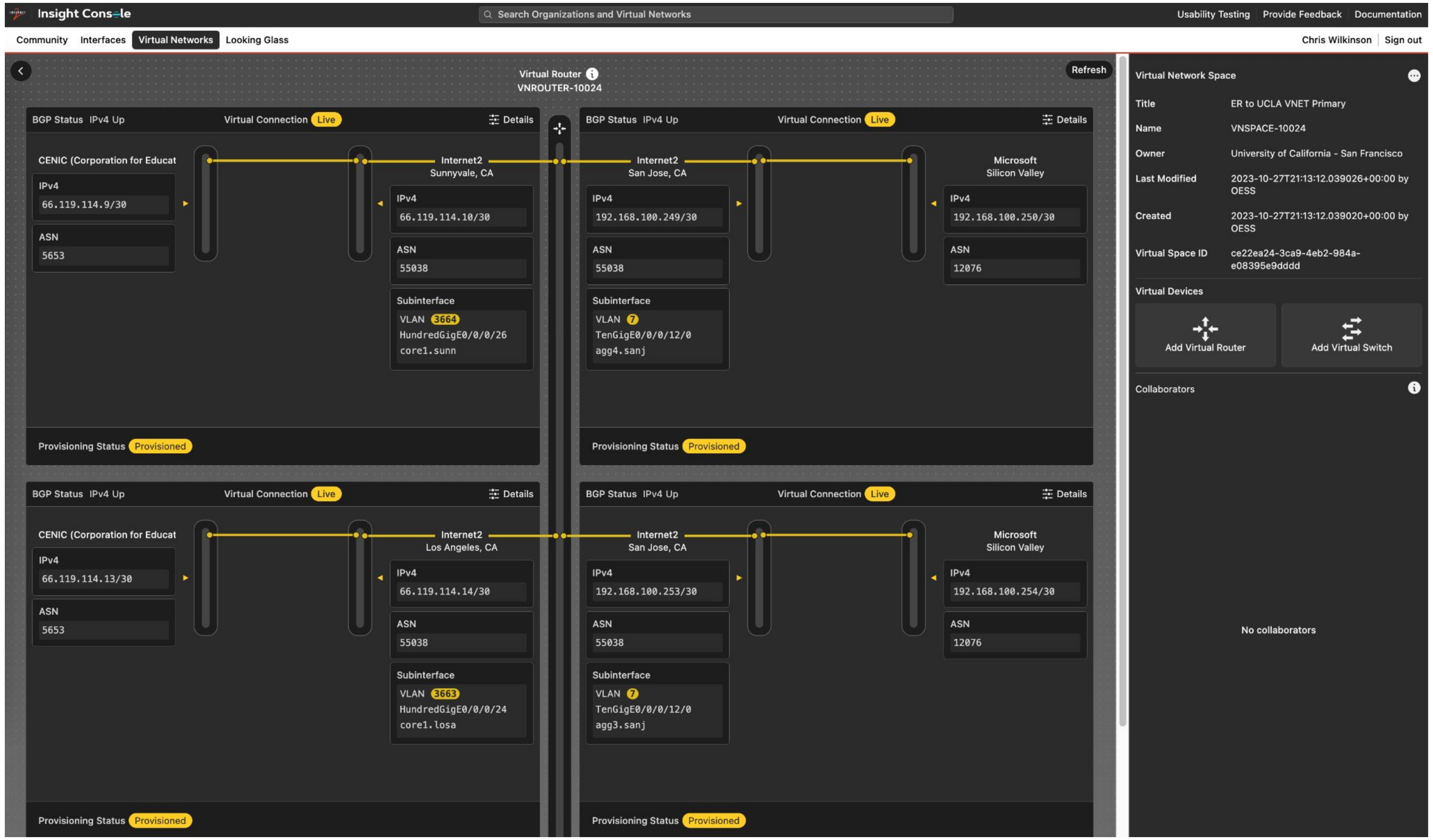
- A web-based tool for **visualizing**, **managing**, and **troubleshooting** all Internet2 **network services**.
- The most visible part of the **Insight** architecture.
- Authentication and authorization integrated with **Internet2 Identity Services** (a.k.a. “InCommon SSO”).
- Functions available:
    - **Looking Glass**: Run commands (in a safe and secure environment) against our production devices and get live results.
    - **Community**: Self-management of organizations, people, and roles.
    - **Interfaces**: Visualization of network ports and services.
    - **Virtual Networks**: Creation and management of L2 and L3 overlay networks, including CloudConnect.
    - **Routing Intentions**: Visualization and management of I2RE and I2PX routes and routing policy.





Virtual Networks

- **Visualization**, **management**, and **troubleshooting** for L2 and L3 **overlay networks**
- **Virtual spaces** provide a canvas within which different organizations can **collaborate** on building overlays.
- **Virtual devices** (switches and routers) can be added to spaces to **establish** L2 and L3 overlays.
- **Virtual connections** can be added to devices to **connect** the overlays to interesting places: other Internet2 members or downstream sponsored parties, government and industry partners, cloud partners (AWS, Azure, GCP, OCI), etc.
- Provisioning of the overlay networks on Internet2's production network is handled via **Insight API** calls, with backend automation provided through **NTC Nautobot**, **Cisco NSO,** and other supporting tools.



Internet2 Network Automation SIG: Community of Practice

Technology Stack

Top Tools & Technologies

- NetBox/Nautobot (Source of Truth)
- Ansible/NSO (Orchestration)
- Python/Go (Languages)
- Git/GitOps (Version Control)

SIG By Numbers

50+	Institutions
~20	Attendees/Session
24x	Meetings/Year

Evolution & Trends

2023

Basic tools, use cases, team structures

2024

Implementation strategies, technical deep-dives

2025

Adv topics: gNMI/gRPC, telemetry, GitOps

Emerging Trends

- Go for network automation
- GitOps deployment pipelines
- Event-driven automation
- Cross-team collaboration models
- AI integration possibilities

Organizational Transformation

Key Challenges

- Team structure & skill development
- Adoption resistance & CLI comfort
- Resource justification & ROI
- Balancing security with automation

Knowledge Sharing

Community Activities

- Show-and-Tell demos
- Code repositories & examples
- Workshop coordination
- Technical discussions & debates

OFC 50

Cloud-native platform and digital twin technology to accelerate open innovation

Hideki Nishizawa

NTT Network Innovation Laboratories

Co-lead of TIP OOPT Disaggregated Optical Systems

Coordinator of IOWN GF Open APN Task Force

IEEE ComSoc IEEE Communications Society

IEEE Photonics Society

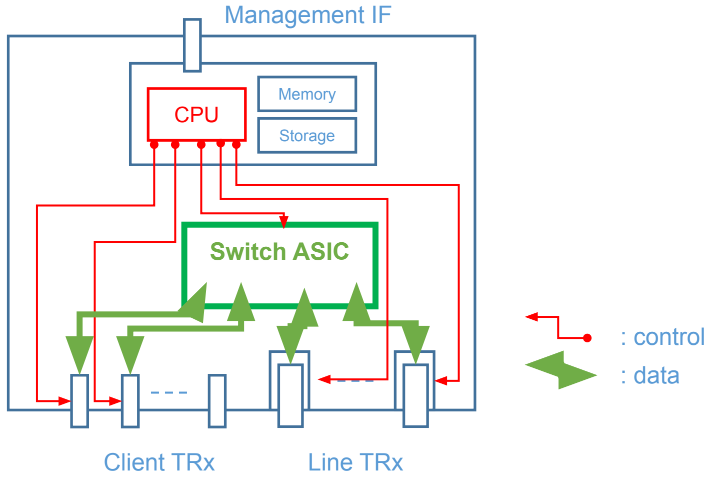
OPTICA

Cloud-Native Platform (Commercial Solutions)

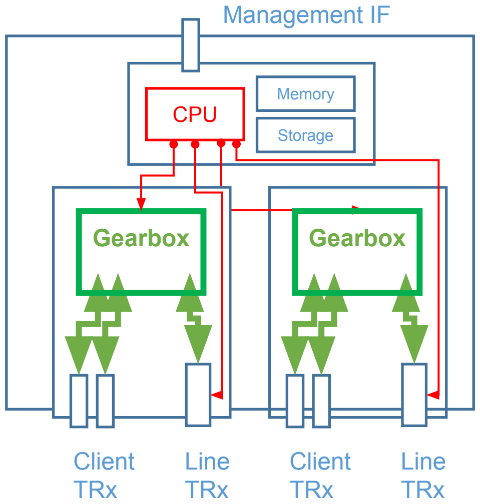
Enabled lower price solution with open hardware from server/switch industries.

The market has been cultivated, and commercial implementation is progressing.

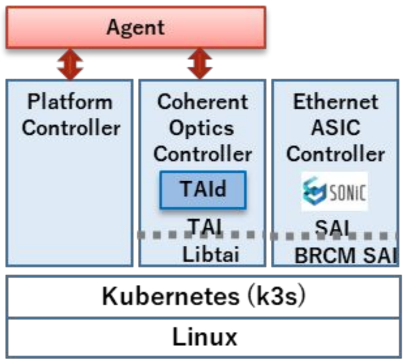
Switchponder H/W



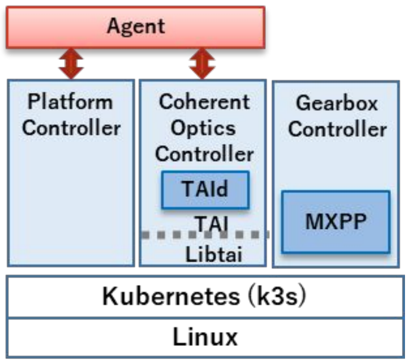
Muxponder H/W



Switchponder S/W



Muxponder S/W



Cassini
(Edgecore)

400G DCSG
(Ufispace)

TELECOM INFRA
PROJECT

Galileo Flex T
(Wistron)

Endeavor
(Pegatron)

NOS function split with container

-> Reducing S/W deploy time dramatically

Collaboration Across Open Forums

- **Although the targets, approaches and strengths of each organization differ, all three share a common goal.**
- **Work together to achieve their common goals by combining individual strengths.**

TELECOM INFRA PROJECT®

Collaboration with GNPy

OpenROADM

2016～
Optical + IP, Vertical disaggregation
Agile, implementation-driven
community approach such as GNPy

Multi-vendor
Disaggregation
Open Interface
SDN architecture

2016～
Horizontal disaggregation
Detailed optical interoperability standards
such as Open ROADM mode

TRx model + GNPy
Liaison in 2024

IOWN GLOBAL FORUM™

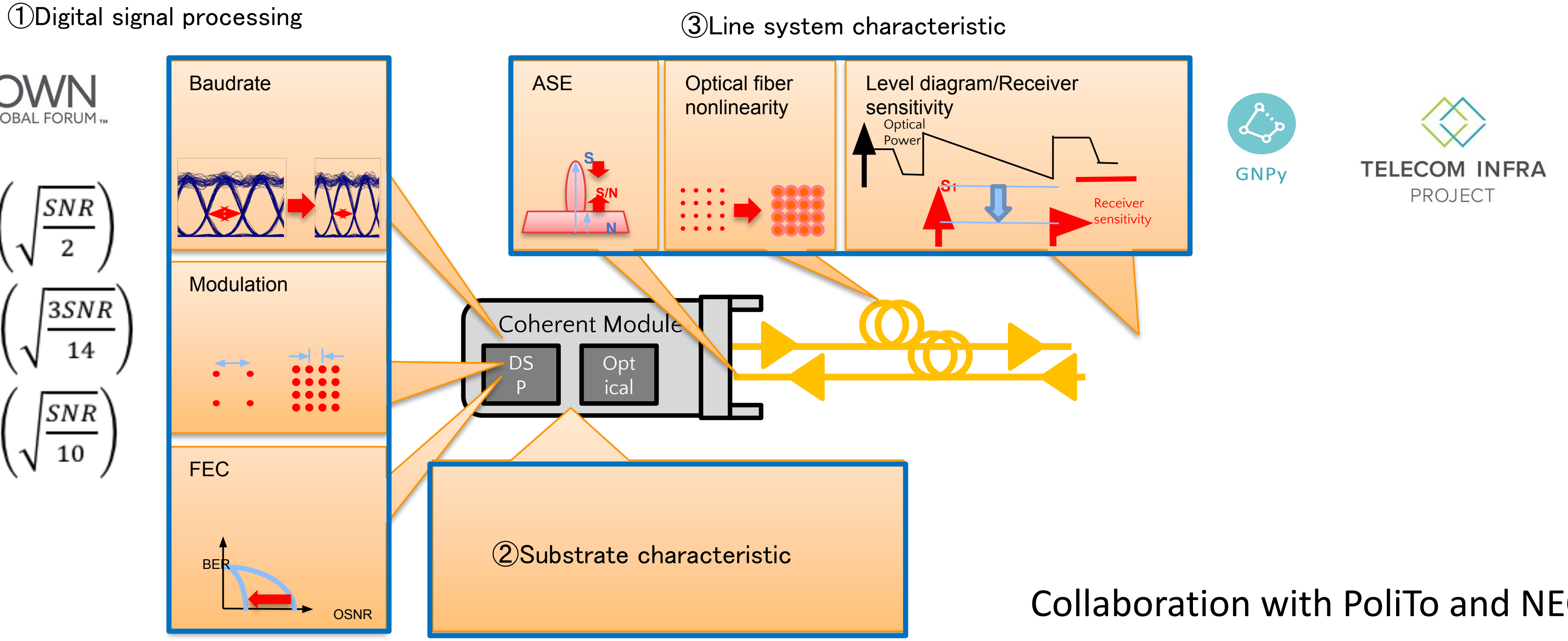
Liaison in 2021

2020～
Optical + Computing
Visionary APN architecture such as
Remote transponder, Data Center eXchange

Fast Provisioning with Gaussian Noise Model

To design an end-to-end (E2E) optical wavelength path, it is essential to identify the following basic characteristics.

$$BER = \begin{cases} \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{SNR}{2}}\right) \\ \frac{2}{3}\operatorname{erfc}\left(\sqrt{\frac{3SNR}{14}}\right) \\ \frac{3}{8}\operatorname{erfc}\left(\sqrt{\frac{SNR}{10}}\right) \end{cases}$$



Collaboration with PoliTo and NEC

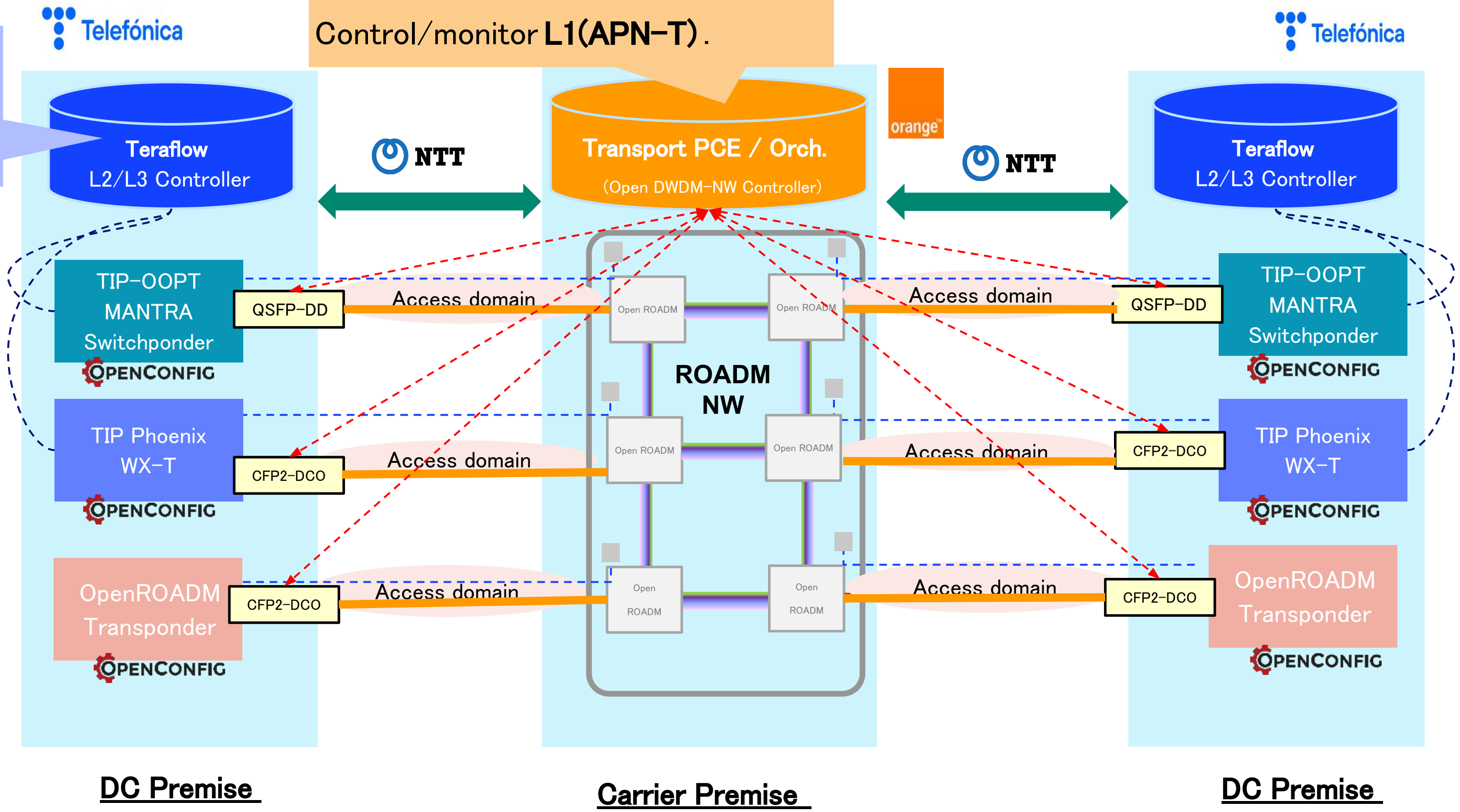
Demonstration at IOWN Networking Hub (#5029)

- **End-to-End optical path establishment between remote-transponders at user sites (e.g., DC premise)**.
  - Multi-vender remote-transponder (Switchponder/Muxponder) configurations.
    - TransportPCE/Orchestrator manage L1 (APN-T) and ROADM networks.
    - TeraflowSDN controller manages L2/L3 functions on Switchponder.

Manage **L2/L3 functions** .
Each component is realized by container.

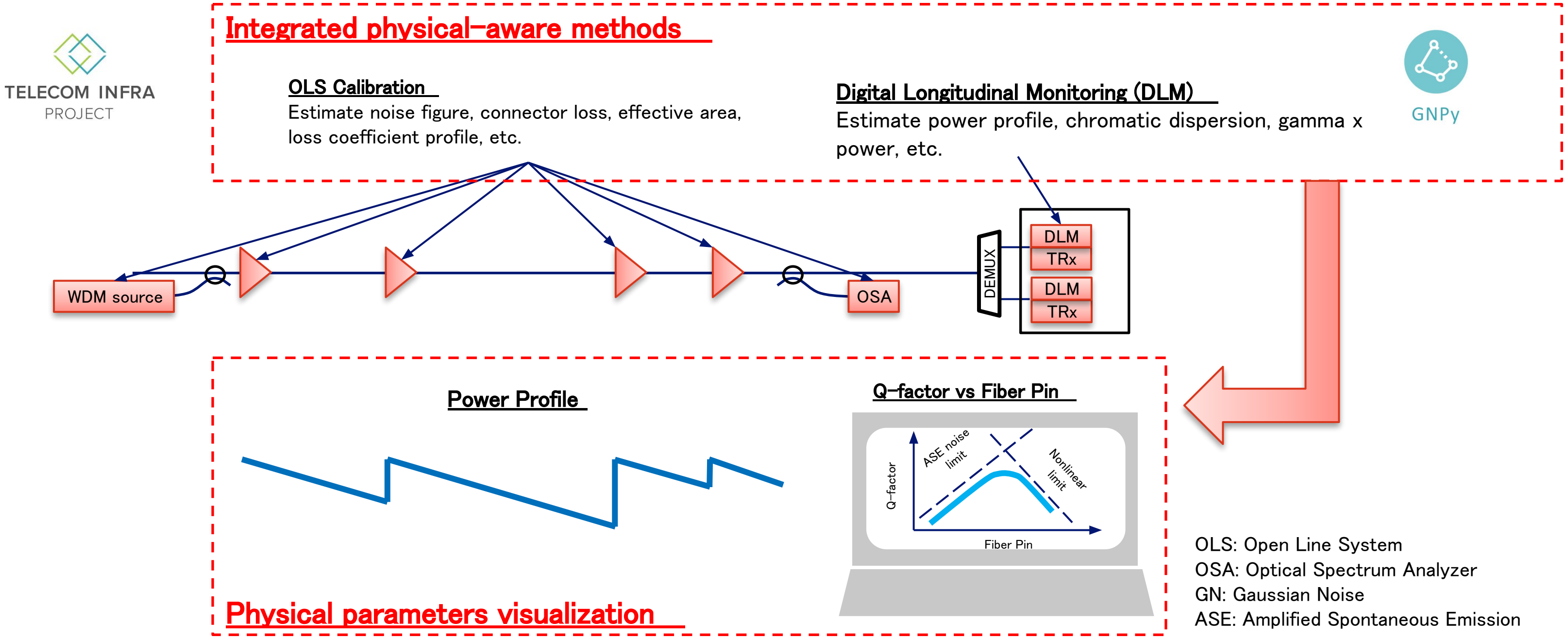
Feasibility of remote-transponder

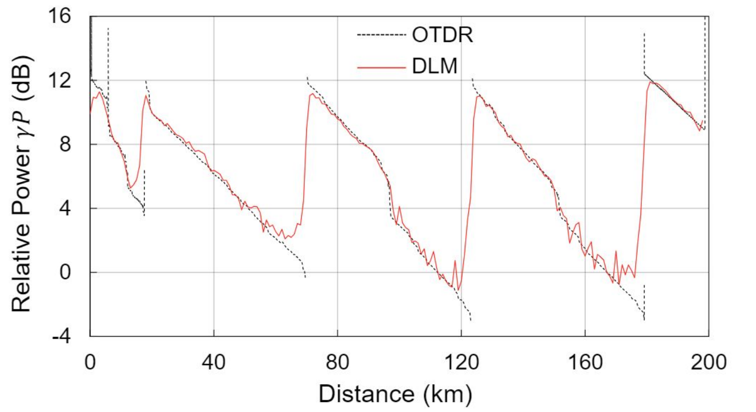
- Multi-vendor multi-type equipment configurations.
- L1 management by APN-C.
- L2/L3 management by L2/L3 controller.



Digital Twin Technology (Under Development)

Methods and an architecture to conduct measurements and optimize newly installed optical fiber line systems semi-automatically.





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

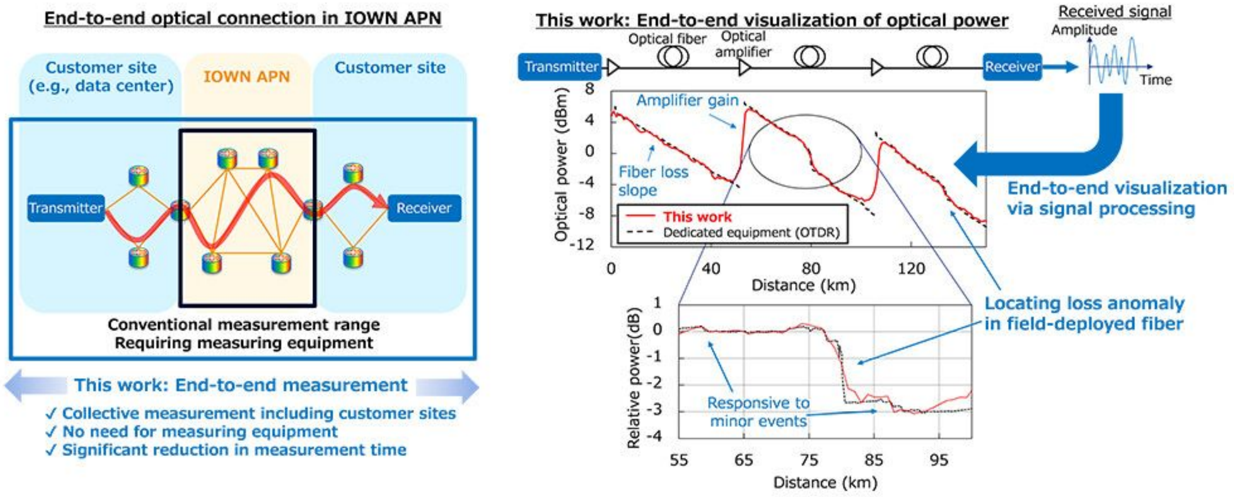
H. Nishizawa, G. Borraccini, T. Sasai, Y. K. Huang, T. Mano, K. Anazawa, M. Namiki, S. Usui, T. Matsumura, Y. Sone, Z. Wang, S. Okamoto, T. Inoue, E. Ip, A. D'Amico, T. Chen, V. Curri, T. Wang, K. Asahi, and K. Takasugi, "Semi-automatic line-system provisioning with an integrated physical-parameter-aware methodology: field verification and operational feasibility," Journal of Optical Communications and Networking, vol. 16, no. 9, pp. 894–904, Aug. 2024.

Collaboration with Duke, PoliTo and NEC

Field Trials at Duke Univ. and CONNECT testbed

- **We have validated end-to-end visualization of fiber-optic link at Duke Univ.**
- **Last year, we began large-scale experiments with TCD at CONNECT testbed.**

Duke University Testbed



World's first and most accurate field demonstration of end-to-end visualization of fiber-optic link without measuring equipment (NTT PR, OFC2024 PDP)

CONNECT SFI Research Centre for Future Networks

A World Leading SFI Research Centre

Science Foundation Ireland For what's next

HOST INSTITUTION

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

PARTNER INSTITUTIONS

Funding

National Institute of Information and Communications Technology (50201); National Science Foundation (CNS-2211944, CNS-2330333); Twilights (22/FFP-A/10598); Open Ireland (18/RI/5721); CONNECT (13/RC/2077 P2).

Questions:

- What is your vision for the path from CLI to an orchestrated network? How far are you in this journey?
- Are you developing network automation tools/workflows in-house, or are you deploying commercial solutions? How should organizations approach this decision?
- How are automation/orchestration tools changing your team's makeup or subject-matter expertise?
- What tools/software have you tried or are currently working with for multi-vendor automation & orchestration? What are your likes and dislikes?

Trend Analysis and Failure Prediction:

Standardized data collection for Machine Learning

Chris Tracy, ESnet, United States (Facilitator)

Danial Ebling, UETN, United States

Reza Rokui, Ciena, Canada

John Wu, ESnet, United States

Questions

- How do you see AI impacting network analytics in the next 5 years?
- How should network operations teams approach AI?
- What are some of the immediate challenges in implementing network assurance/troubleshooting, performance monitoring, failure prediction, and automation? How do you see AI/Gen-AI helping with these challenges?
- For extracting actionable insights from the performance metrics, which tools (commercial and/or open-source) would you suggest to network operators to evaluate?

Let's talk Data Collection

Danial Ebling
Utah Education Network

Why?

- Standardization!
- Reliability

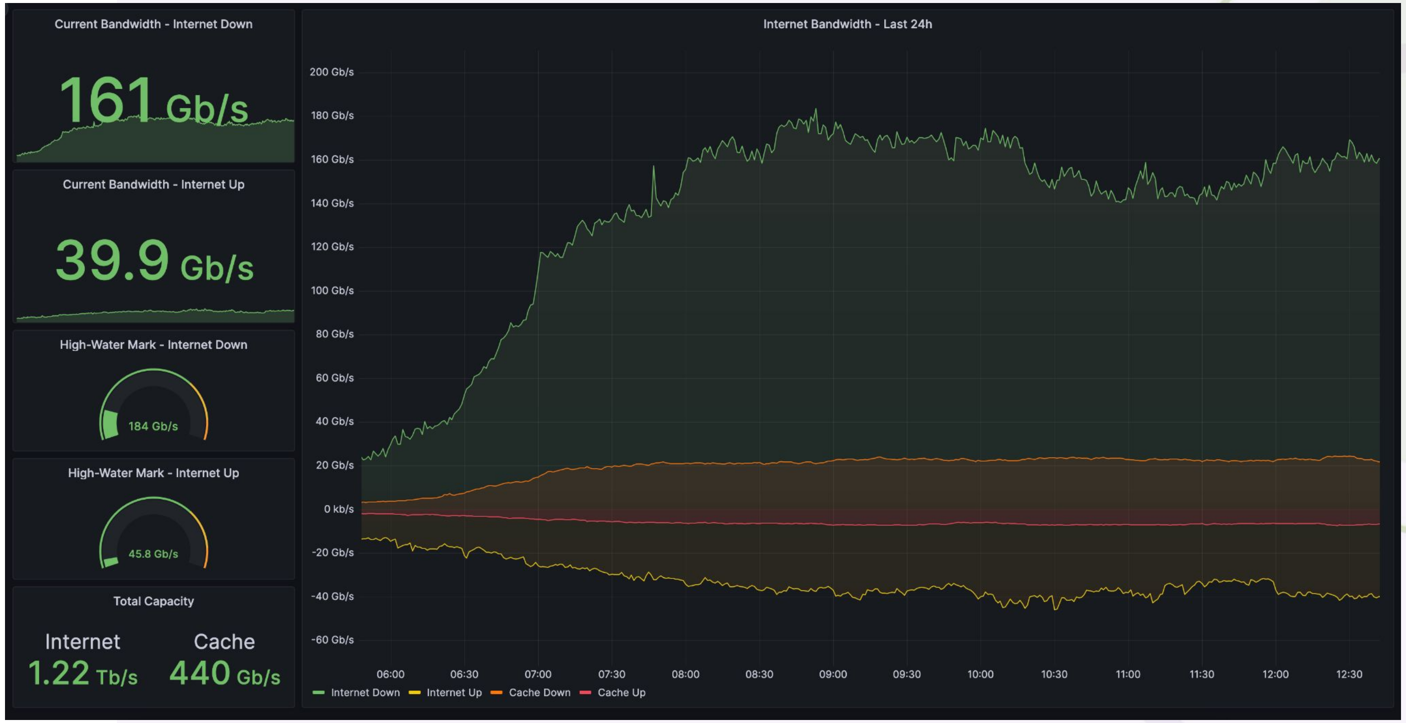
Options for network metrics

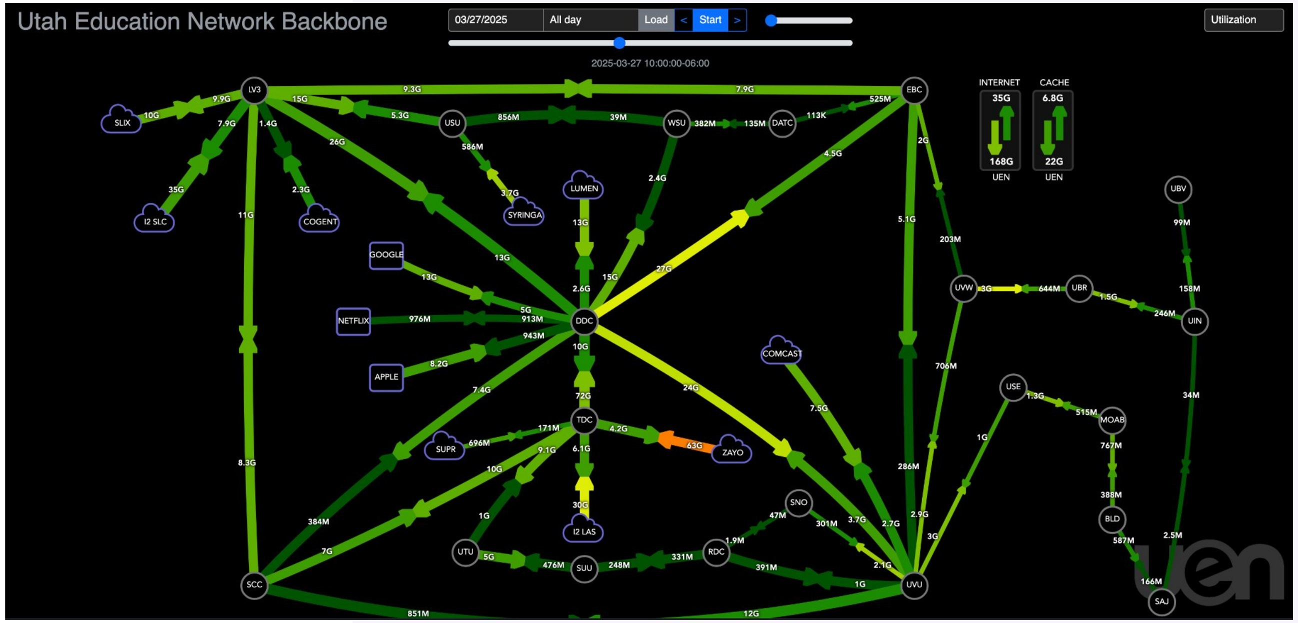
- SNMP
- OpenConfig
- Your favorite vendor flavor

UTAH EDUCATION NETWORK

Metrics collection at UEN

- Streaming telemetry
  - Vendor paths + OpenConfig
- 220 devices
  - 5 sec-1 min. intervals
- TIG stack
  - 100% open source





A few slides for Reza's position statement

Ciena AIOps
Empower Network Operations and Automation Using AI/ML/Gen-AI

Reza Rokui Senior Director, SDN Application Architect

March 30, 2025

OFC 2025
Networks of the Future and Next-Generation Production

See Details HERE

What problem are we solving?
How does AIOps relate to Operators?

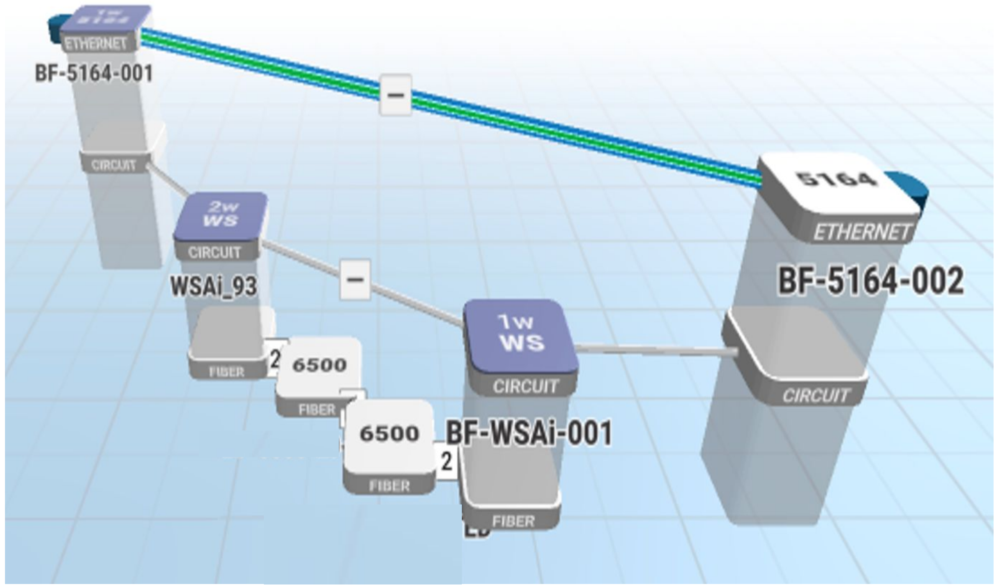
For multi-layer IP/Optical network, main objective of AIOps for operators

- Operational Efficiency
- CAPEX savings

Various aspects of Operational Efficiency:

- Assurance & Troubleshooting
- Optimization
- Automation

Multi-layer IP/Optical Network



<u>AIOps will have positive impact in your network Operation & CAPEX</u>

Why is AI/ML Gaining Renewed Interest in IP and Optical Networks?

AI/ML has been in networking for the past 10–15 years... **What is new?**

Key factors driving renewed interest

I. Proliferation of Generative AI:

- Advanced AI models improving decision-making, predictive analytics, and automation.
- Enhanced data-driven insights leading to better network performance.

II. Willingness of IP and Optical operators:

- Operators increasingly adopting AI/ML for enhanced network efficiency.
- Demand for automated network management and self-healing capabilities.

III. Lower cost of software and hardware:

- Declining costs of GPUs, TPUs, and AI-specific hardware.
- Availability of open-source AI/ML frameworks reducing software expenses.

Impact of AI for Operators
3 Areas to Consider

AI Ops

Network for AI	AI for Network	AI for Engineering
Addresses network architectures & network configurations	Addresses how network operation benefits from AI/ML/Gen-AI	Addresses the use of AI/ML/Gen-AI for Network Engineers

AIOps: Artificial Intelligence for Operations

AIOps
(term coined by Gartner)

Application of AI / ML / Gen-AI
Improve network operations

Big Data Driven

- Historical Data
- Real-time Streaming data (Time-series PM, alarm, topology & logs)

AIOps

AI / ML / Gen-AI / Rule-Based

Operational Insight

Decision

Action (Automation)

Various Operational Benefits in areas of:

- Network Assurance
- Network Optimization
- Network Automation

ciena

Ciena AIOps Multifaceted Operational Scenarios

Ciena AIOps

Using AI / ML / GenAI

Assurance

Optimization

Automation

Trend Analysis, Forecasting, Pro-active Monitoring and PM collection used in some of these Scenarios

ciena

Network Automation using GenAI Multi-Agent Dynamic Workflow

An Enabler for IP/Optical Automation

GenAI based Multi-layer IP/Optical Automation

Note:
- To demonstrate the idea, example is provided for **Reactive Network Assurance**
- However, this idea can be extended to all other AIOps scenarios

Problem Statement At-a-glance

1
Operator has an issue in their network and asks "Network Engineer" to find the issue and to fix it

2
Network Engineer investigates, and goes through loops of **"Reasoning & Acting"**

3
Network Engineer provides both the result of their investigation and remedial actions

Network Engineer

Problem Statement

- Mimic the Network Engineer's behaviour and create **Virtual Network Engineer**
- To achieve this, create dynamic workflow using **Gen-AI Multi-Agent Capability**

Thank You

U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

ESnet ENERGY SCIENCES NETWORK

ESnet Preparing for Predictive Operations

John Wu
JohnWu@ES.net

ESnet is taking a system approach, the following is my own personal observations.

Gathering Input with ESnet Data and AI Workshop

February 25 - 27, 2025, Berkeley:

- Organizing committee: Chin, Ed, John M., Chris T., John Wu
- 48 ESnet staff, plus special guests (center front in photo)
- A working group will write reports
- More to come by the end of May

Workshop Agenda and Overall Object

The objective of the Data and AI workshop was to identify challenges within ESnet that can be addressed through data-driven methods. This will help define ESnet's data analysis requirements and shape our AI strategy, guiding data stewardship efforts, and the direction of AI research and AIOps exploration for ESnet7.

The workshop had 5 sessions, each building on the output of the previous session.

Session 1: Understanding the questions / problems

Session 2: Understand our data

Session 3: Understanding AI

Session 4: Bringing it together, building work packages

Session 5: Where do we go from here, a cross-cut analysis.

Workshop Outcomes - 29 Work-packages

WP1	Alerting	WP2	Rule Correlation	WP3	Data Quality	WP4	Lifecycle
WP5	Data Catalog	WP6	Service Usage	WP7	Business Ops	WP8	Outage Notification Parsing
WP9	Ticket Resolution	WP10	Alarm Correlation	WP11	Hardware Failure Prediction	WP12	External Configuration Anomaly Detection
WP13	Capturing Configuration Intent	WP14	Fast Contract Lookup	WP15	Consistent Data Management	WP16	All Data Query
WP17	Automating Site Deployment	WP18	Automating Configuration	WP19	AI Sandbox	WP20	Generating RFP / Contracts
WP21	Unified Document Search	WP22	Ticket Summarization	WP23	Federated Authentication	WP24	Rewriting Legacy Perl Software
WP25	NLP Interface to Systems	WP26	Information Architecture	WP27	Requirement Management	WP28	Mission Support Management
WP29	Dataset Unified Query						

ESnet

Clustering Work-packages Based on AI/ML Tasks

I: Data Integration

- WP3 Data Quality
- WP4 Lifecycle
- WP5 Data Catalog
- WP14 Fast Contract Lookup
- WP15 Consistent Data Management
- WP16 All Data Query
- WP21 Unified Document Search
- WP26 Information Architecture
- WP29 Dataset Unified Query

- WP6 Service Usage
- WP7 Business Ops
- WP27 Requirement Management
- WP28 Mission Support Management

IV: Knowledge Management

- WP8 Outage Notification Parsing
- WP22 Ticket Summarization
- WP9 Ticket Resolution
- WP10 Alarm Correlation

V: AI Core

- WP25 NLP Interface to Systems
- WP19 AI Sandbox

- WP23 Federated Authentication

III: Predictive Maintenance

- WP1 Alerting
- WP11 Hardware Failure Prediction
- WP12 External Configuration Anomaly Detection

II: Process Automation

- WP2 Rule Correlation
- WP13 Capturing Configuration I
- WP17 Automating Deployment
- WP18 Automating Configuration
- WP20 Generating RFP / Contracts
- WP2 Rewriting Legacy Perl Software

ESnet

Introducing AI into ESnet Operations

1. **Establish a Robust Data Foundation**:
    - Invest in high-quality, data and ontology unification.
    - Ensure cross-system integration to enable AI-powered analytics.
2. **Leverage AI for Automation & Efficiency Gains**:
    - Prioritize anomaly detection and automated configuration to minimize manual interventions.
    - Develop AI-driven workflows for ticket summarization and document retrieval.
3. **Monitor Progress with Clear KPIs**:
    - Track false positive reduction rates for anomaly detection.
    - Measure efficiency gains in ticket handling and configuration automation.
    - Assess hardware failure prediction accuracy over time.
4. **Enable a Scalable AI/ML Ecosystem**:
    - Set up an AI sandbox (WP19) for experimentation and controlled testing.
    - Partner with industry and academic collaborators for AI innovation.
5. **Address Organizational Challenges & Skills Development**:
    - Provide training on AI/ML tools and methodologies to operational teams.
    - Ensure human oversight in all AI-driven decision-making.

Questions

- How do you see AI impacting network analytics in the next 5 years?
- How should network operations teams approach AI?
- What are some of the immediate challenges in implementing network assurance/troubleshooting, performance monitoring, failure prediction, and automation? How do you see AI/Gen-AI helping with these challenges?
- For extracting actionable insights from the performance metrics, which tools (commercial and/or open-source) would you suggest to network operators to evaluate?

15-minute break

Return at 14:20

Quantum Networking Early Wins:

Report-out on the state of implementation

Scotty Strachan, NevadaNet, United States (Facilitator)

Mariam Kiran, Oak Ridge National Laboratory, United States

Wenji Wu, ESnet, United States

Questions

- What do you see as crucial R&D projects in the quantum technology space today, and how do you see the results impacting production networks in the immediate (3-5 year) future?
- Could you unpack for us the extent to which current production network design drives or influences R&D progress in quantum technologies?
- What do you think the next step is in quantum R&D, i.e., what will we be talking about or see demonstrated at OFC2026?

Oak Ridge National Laboratory

March 2025, OFC

Networks of the Future and Next Generation Production

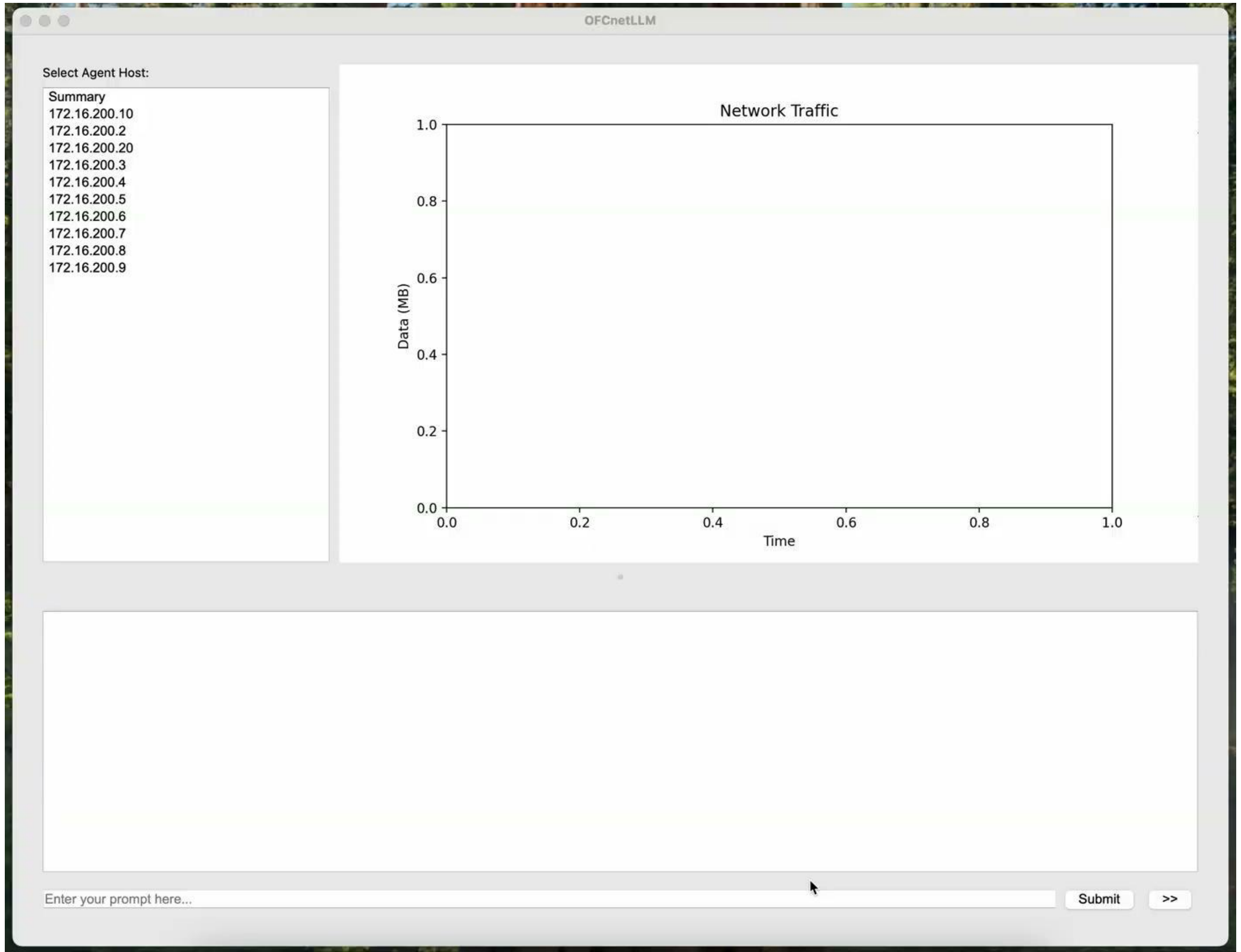
Mariam Kiran
Group Leader
Quantum Communications and Networking
ORNL

U.S. DEPARTMENT OF ENERGY

Use of AI in Networks

Deep Learning for studying traffic patterns - anomaly detection, optimizing infrastructure
Deep reinforcement learning for traffic engineering
LLMs for Networks – Learn over large datasets for unknown situations

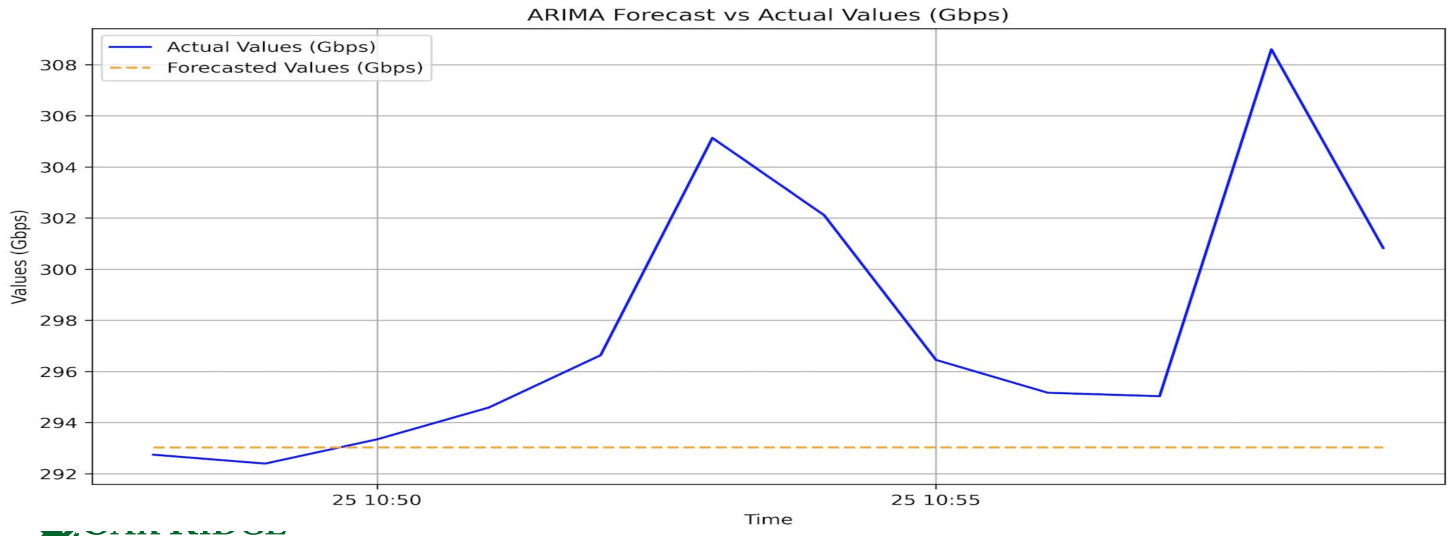
OFCnetLLM
LLM designed for OFC Network Monitoring



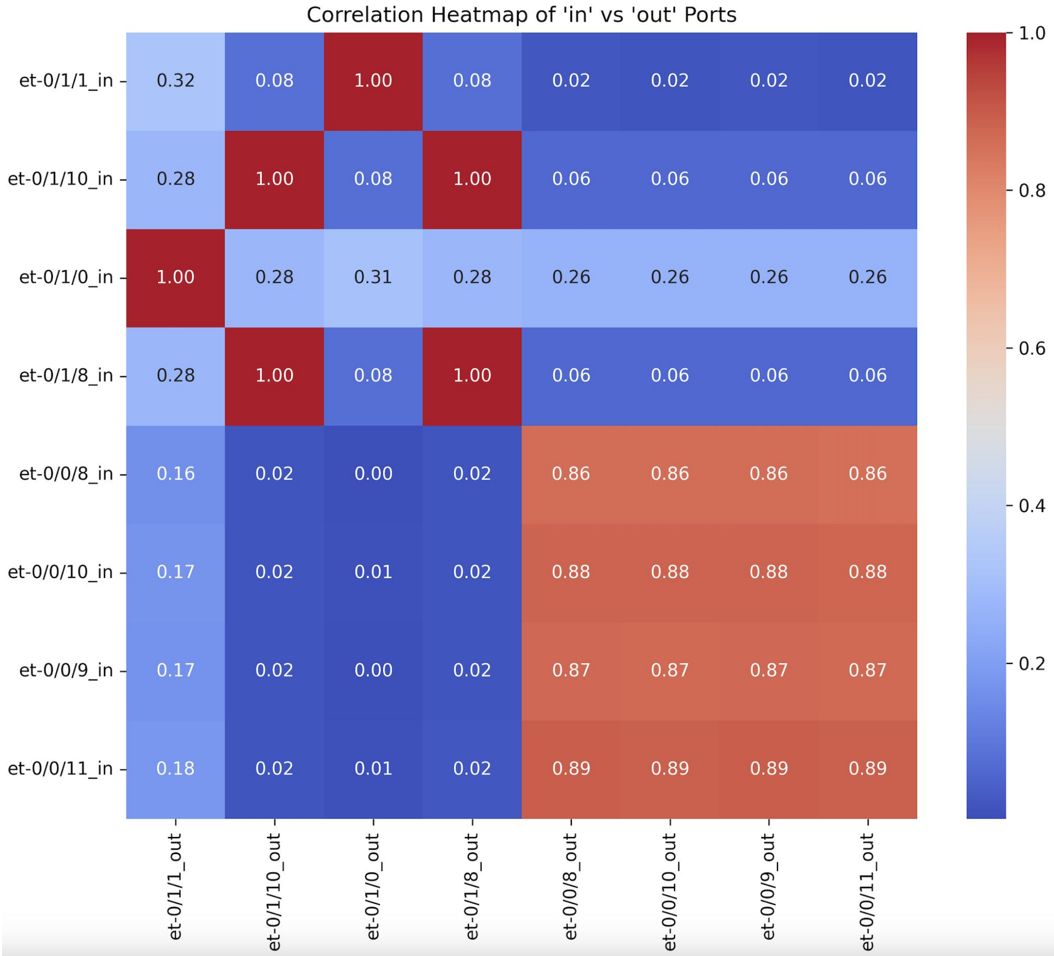
Key Considerations and Application of a DataLake:

- **Data Aggregation**: Must be able to aggregate and ingest data from various sources. PMs, logs, SNMP, gRPC, sFlow etc.
- **Data Types**: raw CLI, JSON, XML, log files etc.
- **Scalability**: Must be able to scale horizontally as more devices and platforms are added.
- **Analytics Integration**: Processed data must be made available and easy to integrate to BYO Analytics applications. This is valuable for future Data Analytics Challenges etc.
- **Security and Privacy**: Data must be accessed in a secure way
- **Effective Data Storage and Movement**: DAQ can turn into an expensive process if not processed correctly.

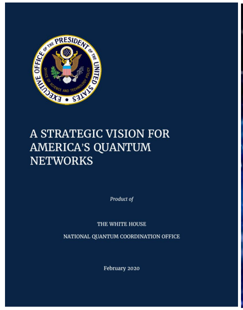
Network Parameter Forecasting

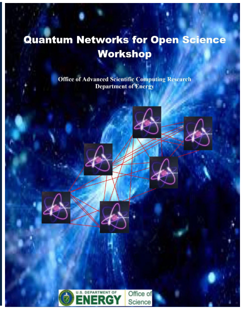


Statistical Topology Weaver

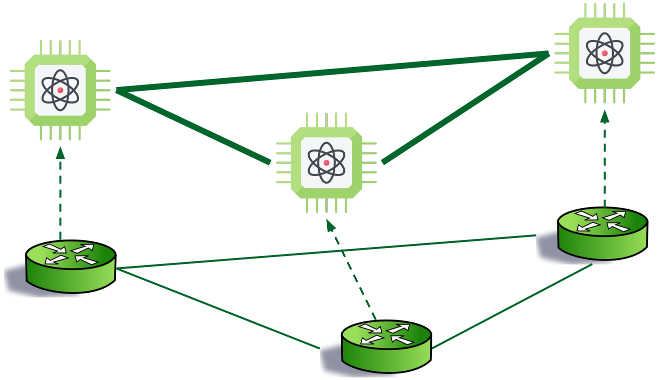


Quantum Networking at ORNL

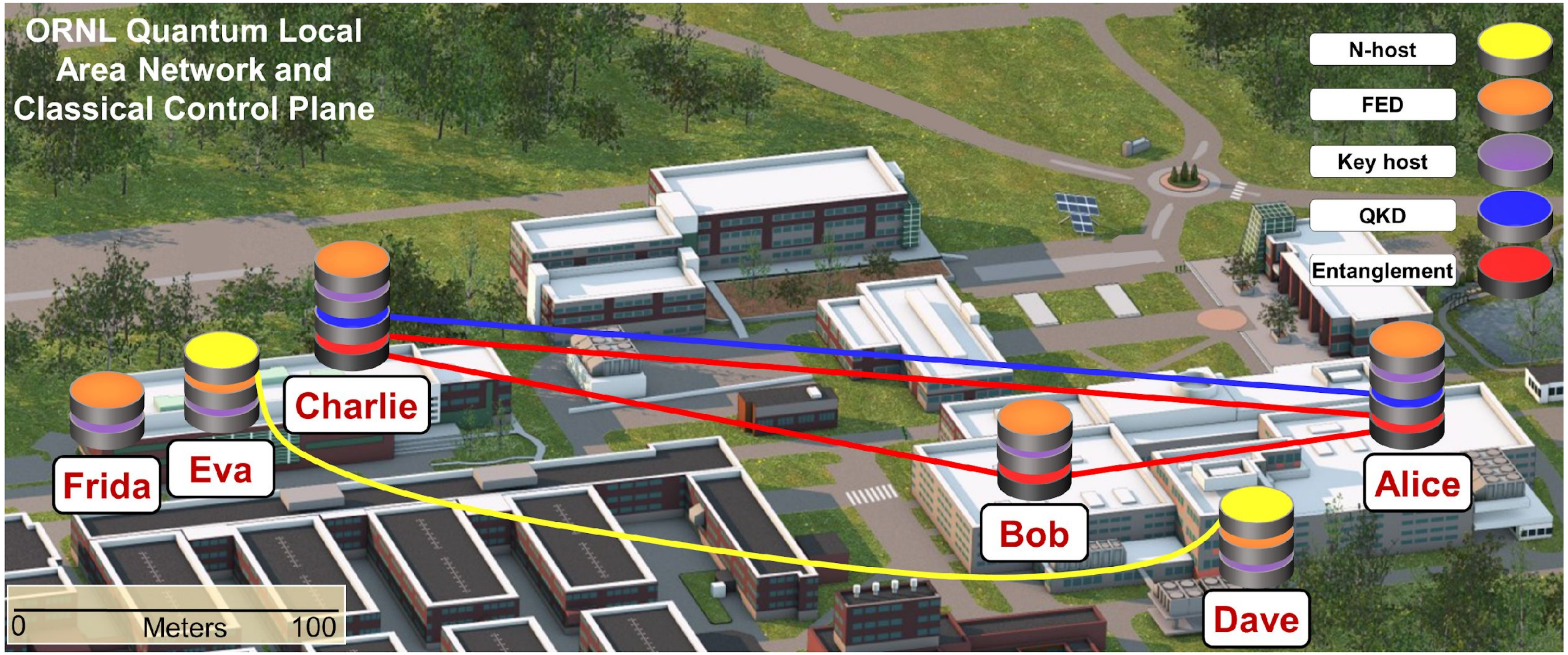


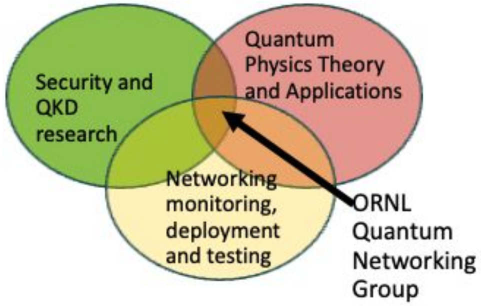


- DOE and Quantum
  - Upgraded Detectors with Quantum capabilities
  - Quantum Sensing: More precision measurements
  - Distributing quantum states through entanglement: Q Computers will need Q Networks to scale



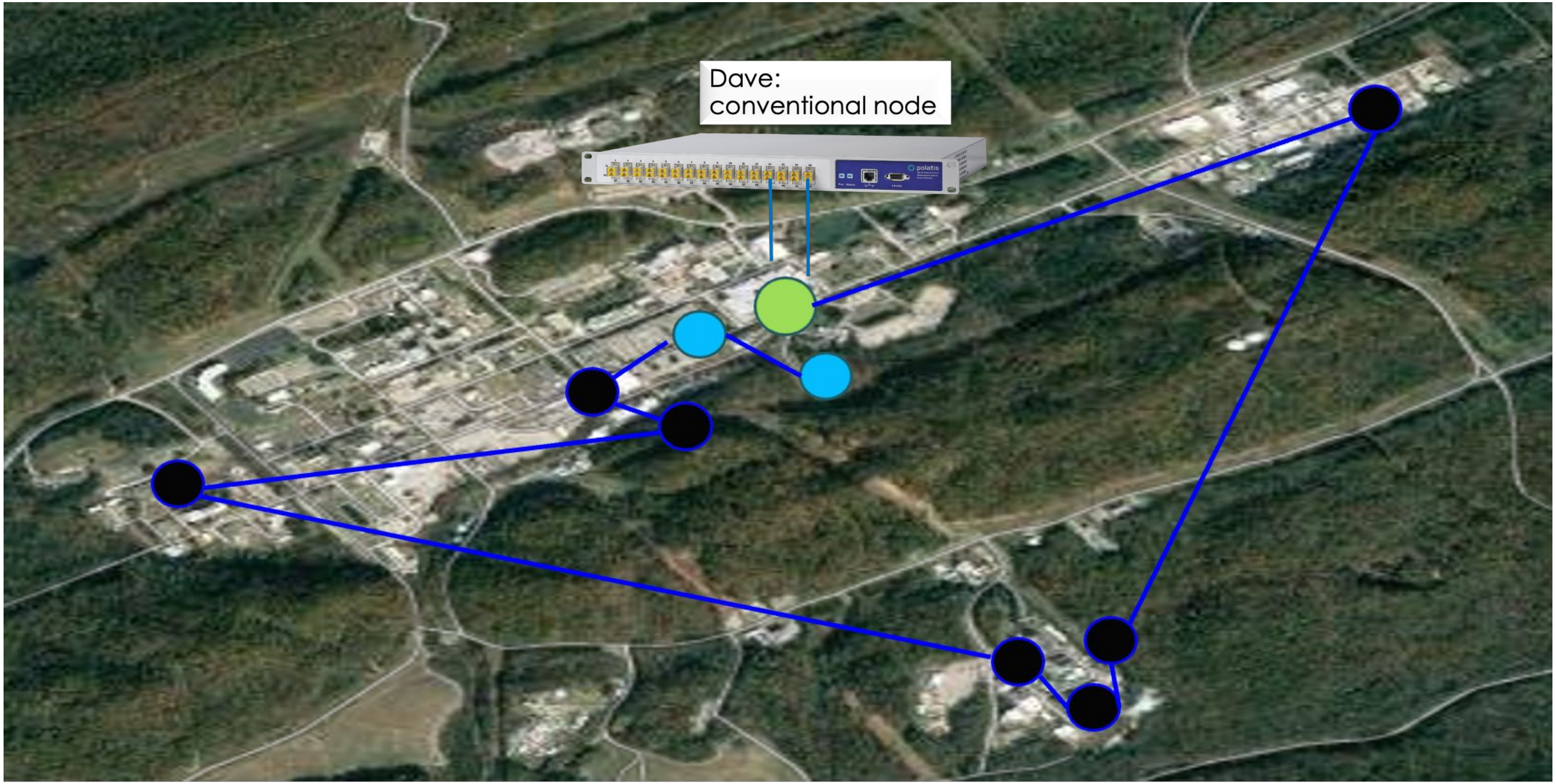
quantum/optic infrastructure (coexistence signals)



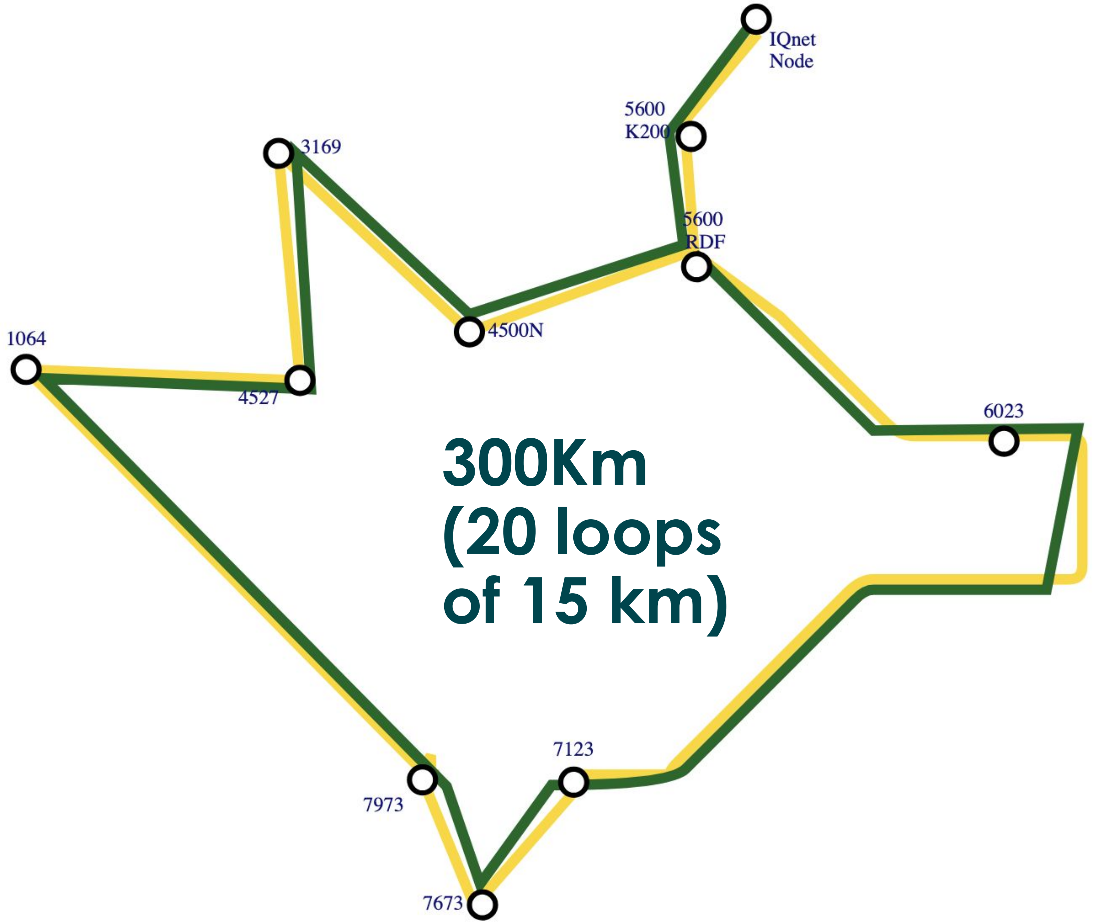


M. Alshowkan, et al., PRX Quantum 2 (4), 040304 (2021)

ORNL QLAN: the longest (300km) deployed dark fiber testbed in Lab Complex



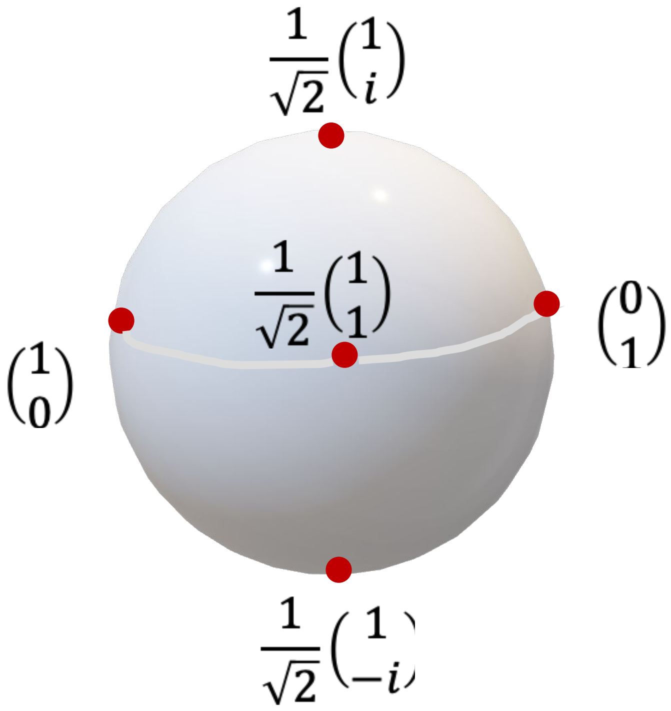
Developing a Quantum Network Testbed for Research

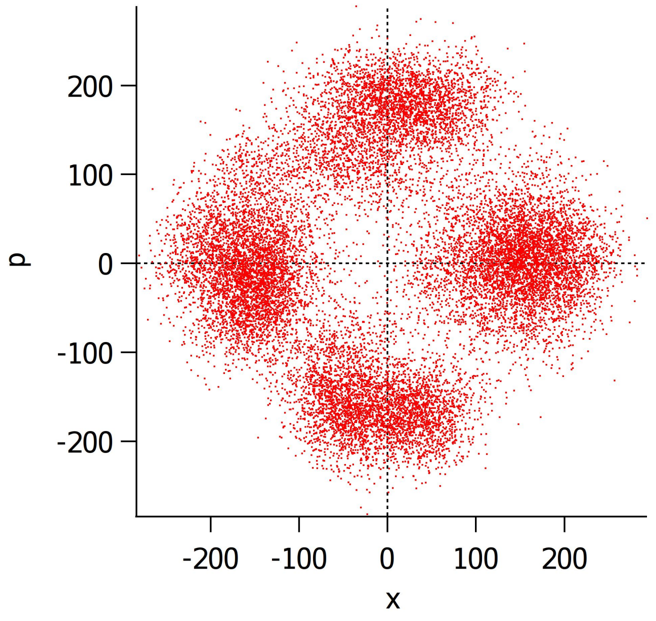


- Deployed 400Gb fiber
- Demonstrating Quantum Key Distribution (QKD) in smart grids, over fiber and free space
- In-house development for Alice/Bob pairs for secure exchange (e.g. FPGA engineers)
- Squeezing: showing coexistence of quantum and optic signals
- Advancing state of art for networking, control plane, frequency modulation, splicing over channels, network standards (e.g. Internet Research Task Force)

Discrete and Continuous Variables

From N. Peters





Poincare Sphere (qubit)

Discrete Variable (DV): qubit

Examples: polarization,
orbital angular momentum, time-bin

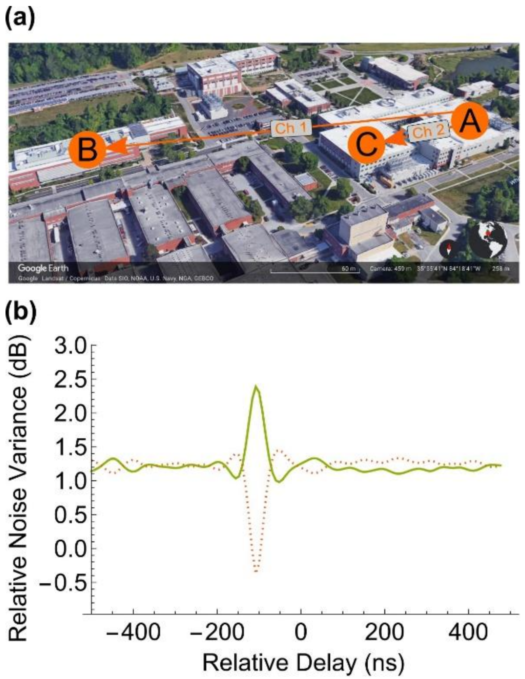
Continuous Variable (CV)

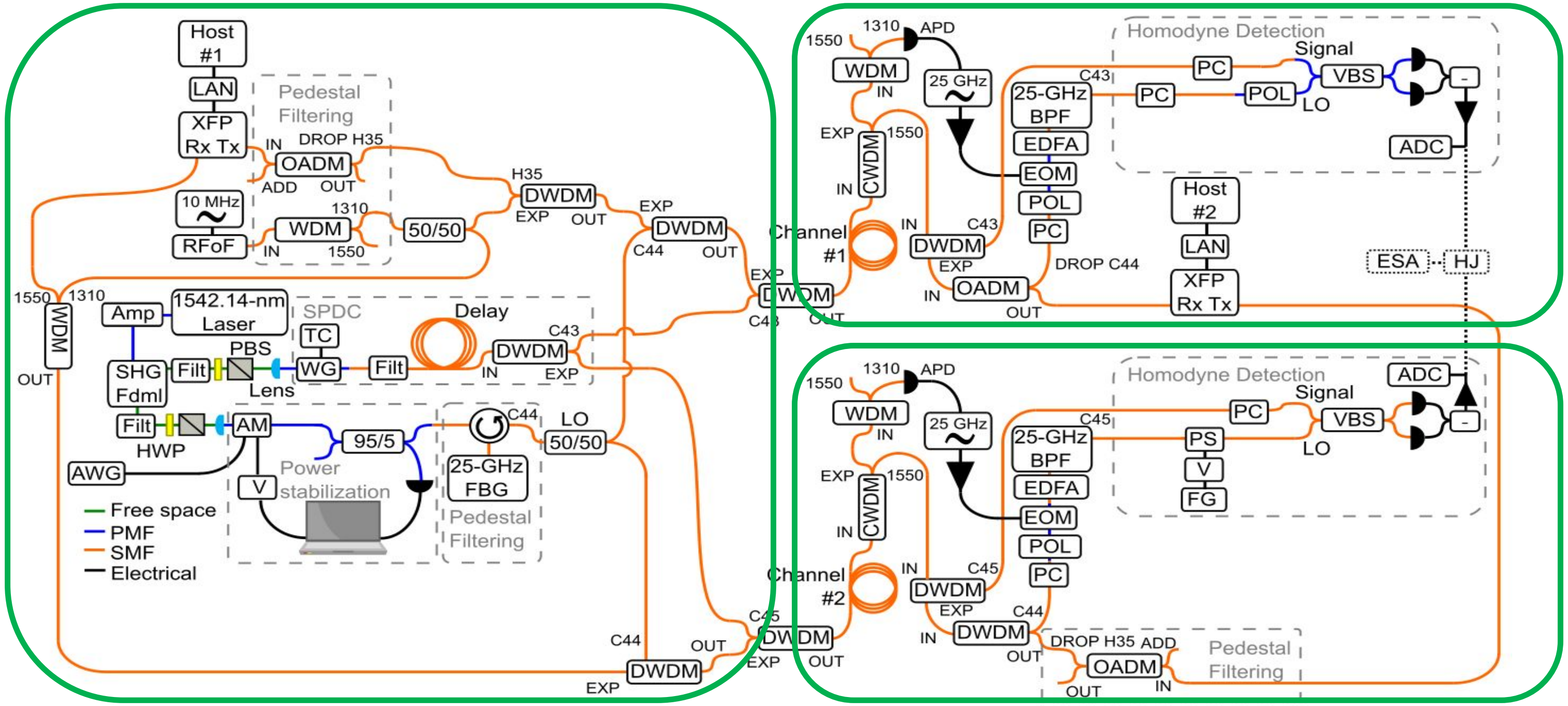
Examples:
position-momentum,
energy-time,
amplitude-phase

Experiments with DV and CV for various applications

Squeezing and Entanglement

- Squeezed light is a useful quantum resource with applications across QIS
- Squeezed light can coexist with classical networking signals without being corrupted by noise beyond some added insertion loss
- Distributed joint homodyne detection to enable measurements of two-mode squeezing across our campus network

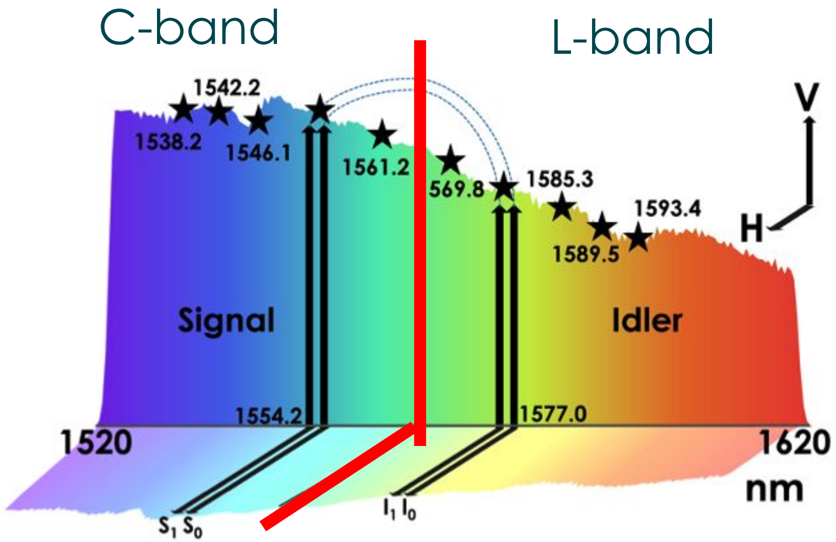


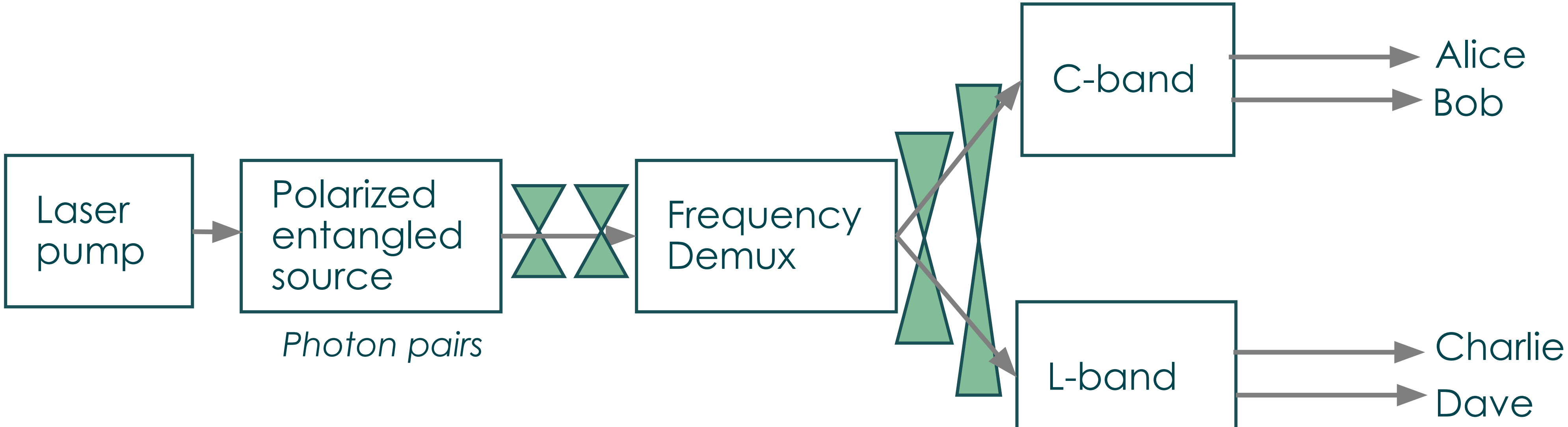


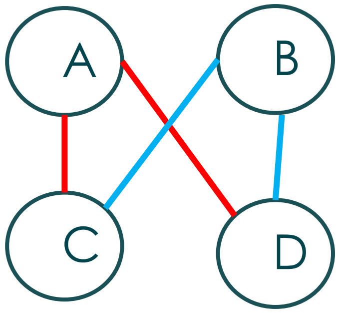
Chapman et al., “Two-Mode Squeezing Over Optical Fiber Coexisting with Conventional Communications .” Optics Express, (2023)

Distributing Entanglement across Distance

- Select frequency channels to select rooms
- Alice entangled with Charlie or Dave
- Bob entangled with Charlie or Dave





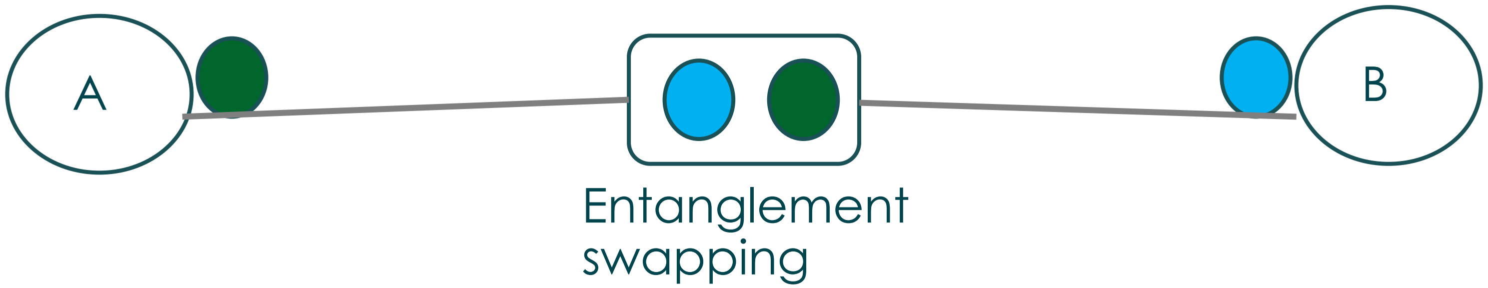


H Lu et al. Optics Letters (2023)

How Far can Entanglement Travel?

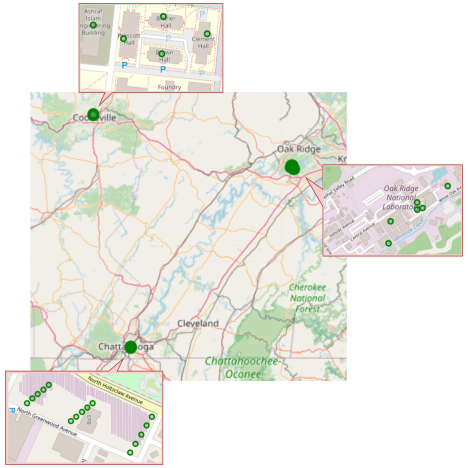
Examples	Distance
Entanglement using trapped ion (Hajdusek et al.) (2023)	50 km
LANL/NIST (2007) QKD	148.7 km
Teleportation Free space (Zeilenger et al.) (2012)	144 km
China (Wei Pan et al.) (2021) space	4600 km

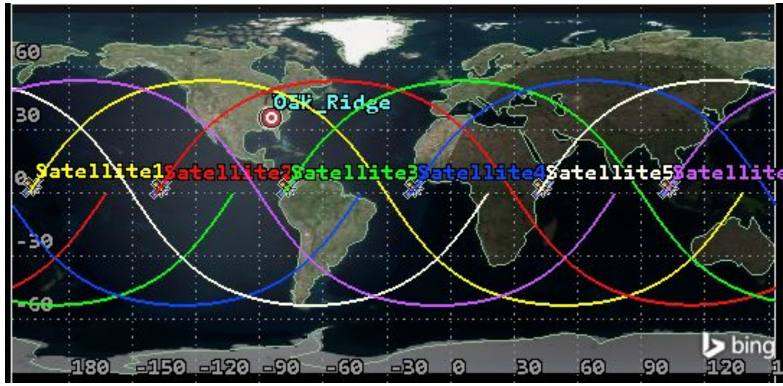
- Over long distance, photon loss increases
- Quantum repeaters use entanglement swapping for reliable transport over short distances

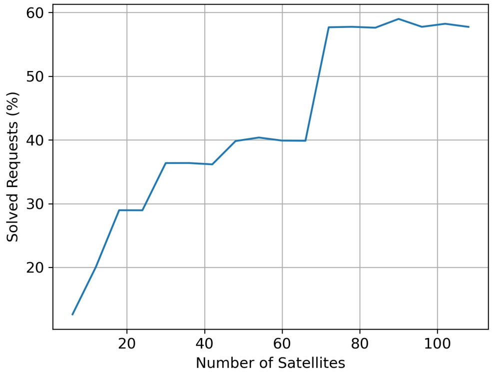


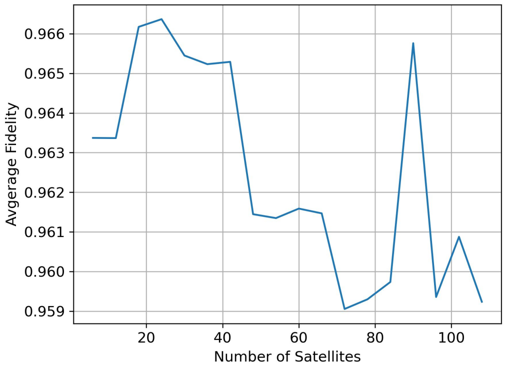
Investigating Satellite Communications

- New optimization algorithms in simulation; until we get satellite access
- Connecting (100 miles apart)
  - EPB Chattanooga
  - ORNL
  - Tennessee Tech
- Optimum number of satellites
  - 108 satellites provides 55.17% day coverage
  - 57.75% of entanglement distribution
  - Average fidelity of 0.96









M. Mohammed, et al., INDIS SC (2024)

Repeaters, Infrastructure, Protocols and more

- Impact of fiber quality, working with providers – Loss, fidelity
- Research needed:
  - Quantum memory
  - Splicing
  - Reducing loss (fiber)
  - New routing algorithms (graph problem)

U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

ESnet

Quantum networking early wins: report-out on the state of implementation

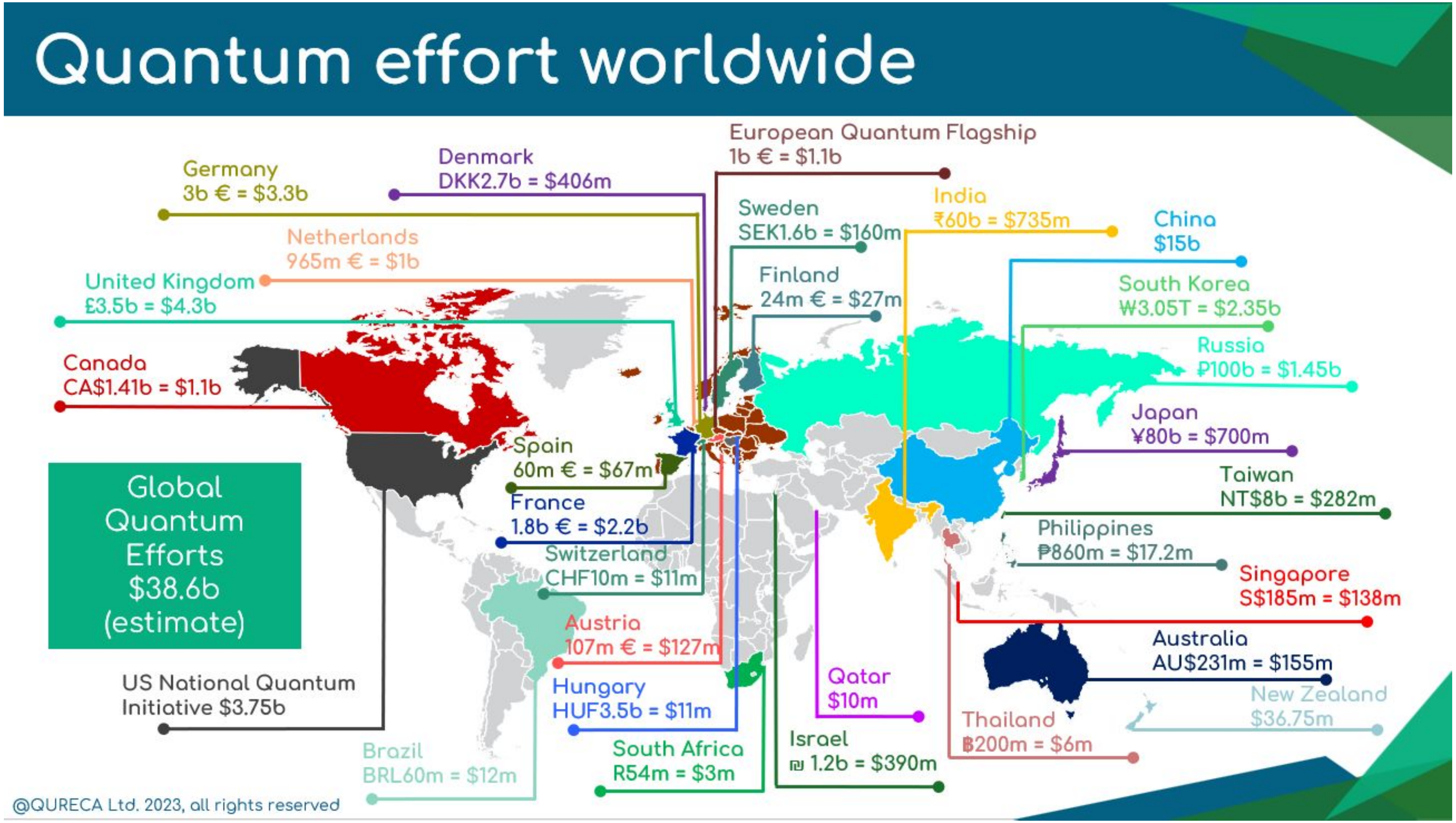
Wenji Wu
ESnet

OFCnet 2025 Workshop
San Francisco CA, USA
March 30, 2025

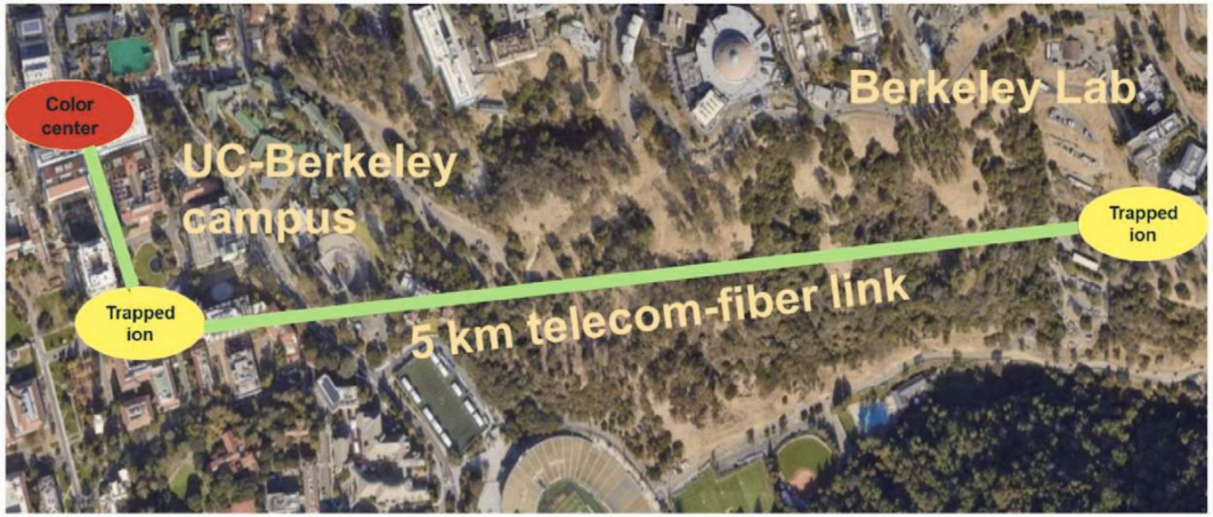
Agenda

- World-wide quantum network efforts
- Status for quantum network architecture and control
- Status for scalable quantum repeaters and networks
- System area, Local area, Wide area quantum networks

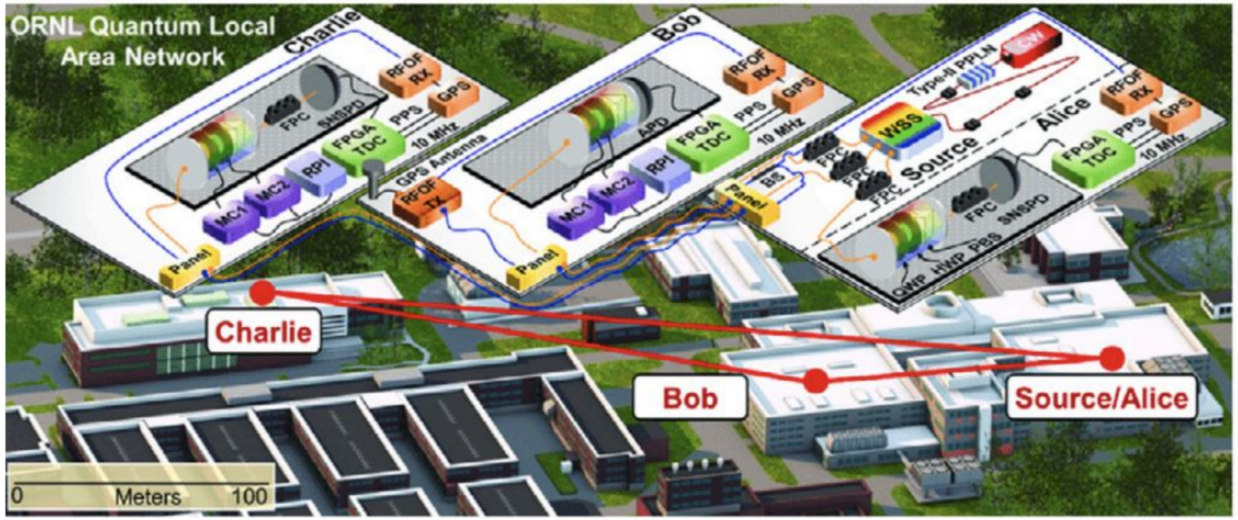
Quantum Computing and Networking is a Worldwide Initiative



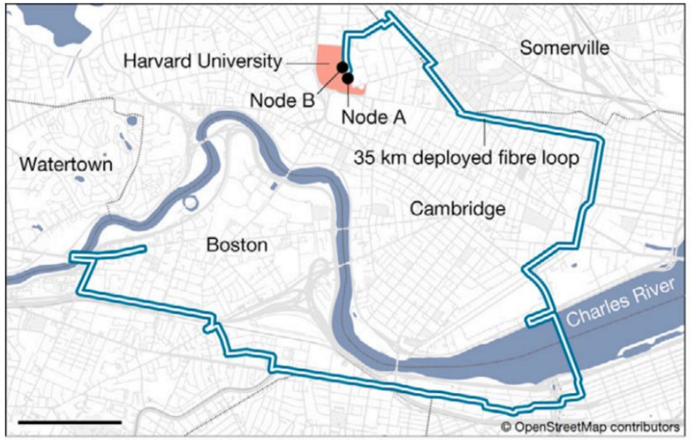
World-wide quantum network efforts - US

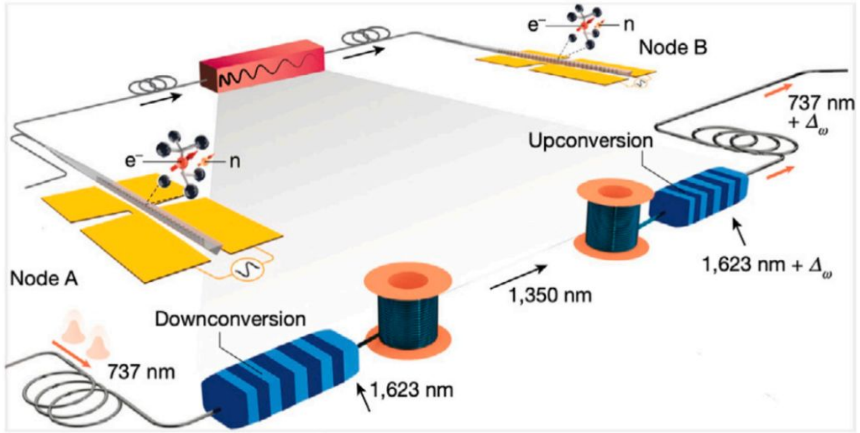


The QUANT-NET Testbed ($^{40}Ca^{+}$ ions)



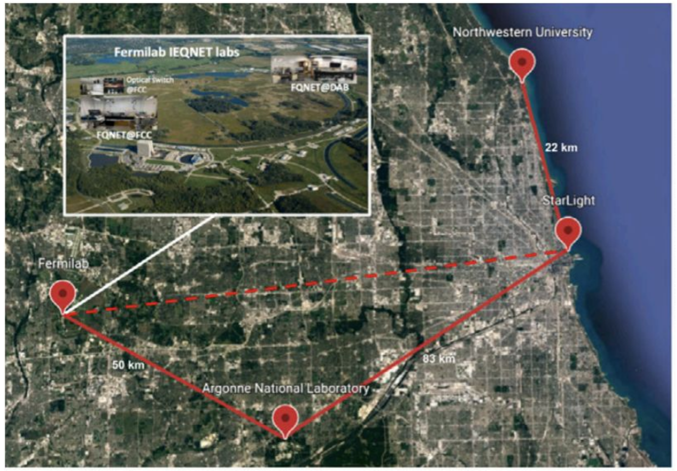
ORNL-QLAN Testbed





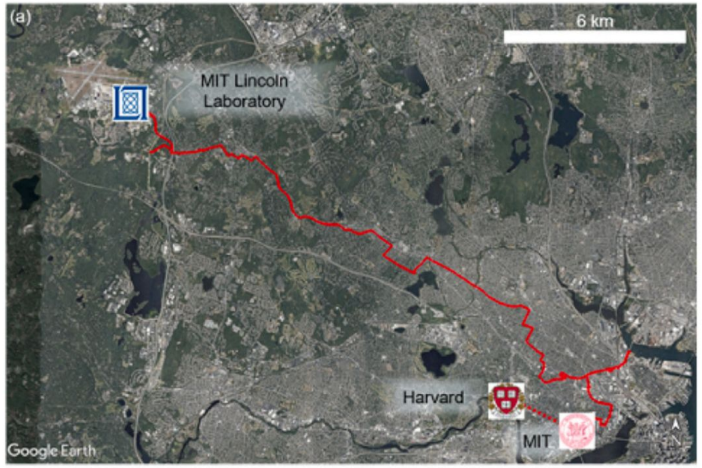
Amazon-Harvard quantum network testbed (^{29}Si nuclear spins)

World-wide quantum network efforts - US (cont.)

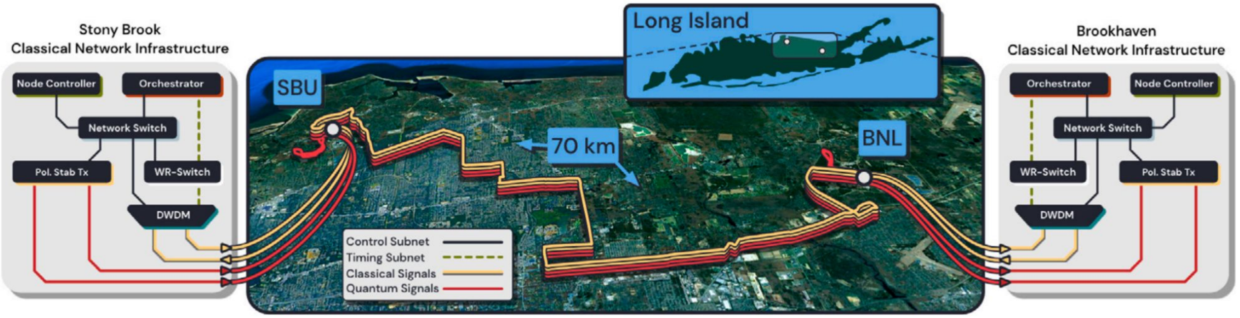


Illinois-Express Quantum Networks

The INQUIRE quantum network testbed

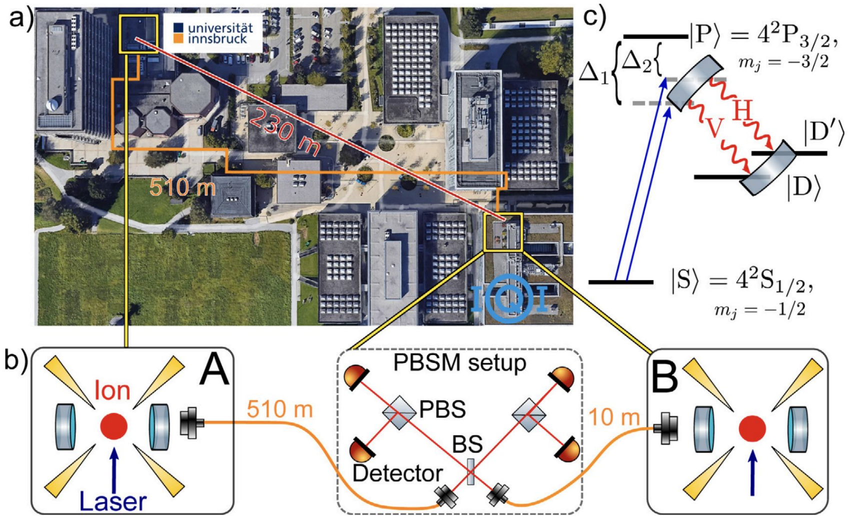


Boston-Area Quantum Network testbed

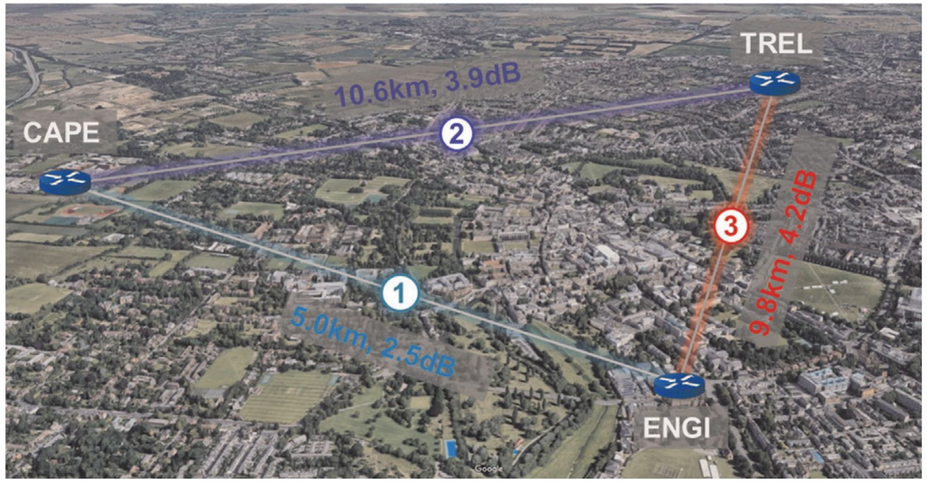


Long Island Quantum Information Distribution Network (LiQuIDNet)

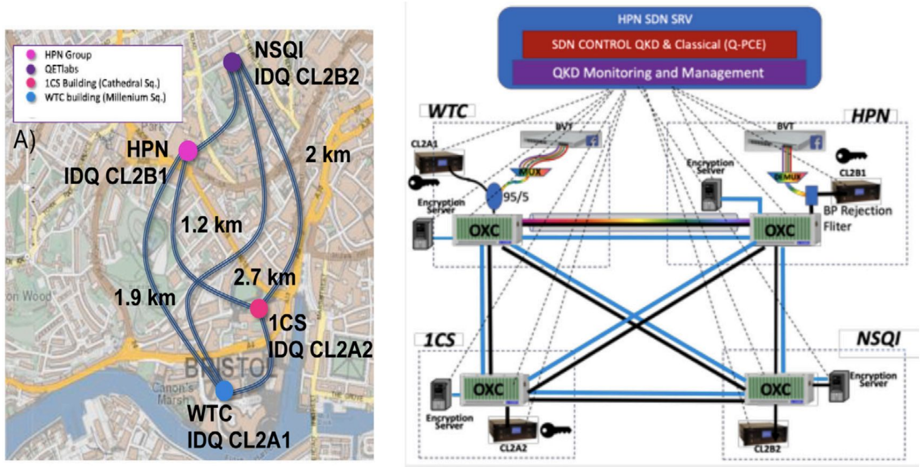
World-wide quantum network efforts - Europe



Innsbruck quantum network testbed



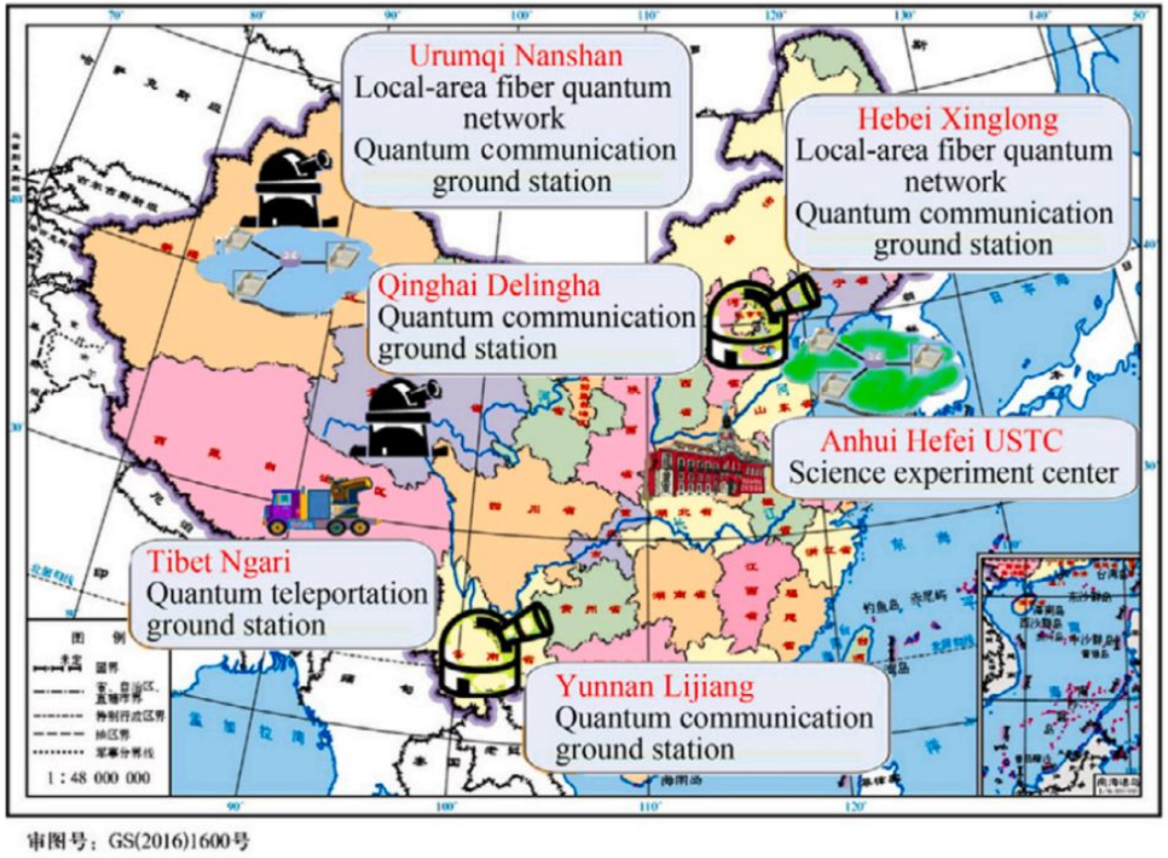
The Cambridge quantum network testbed

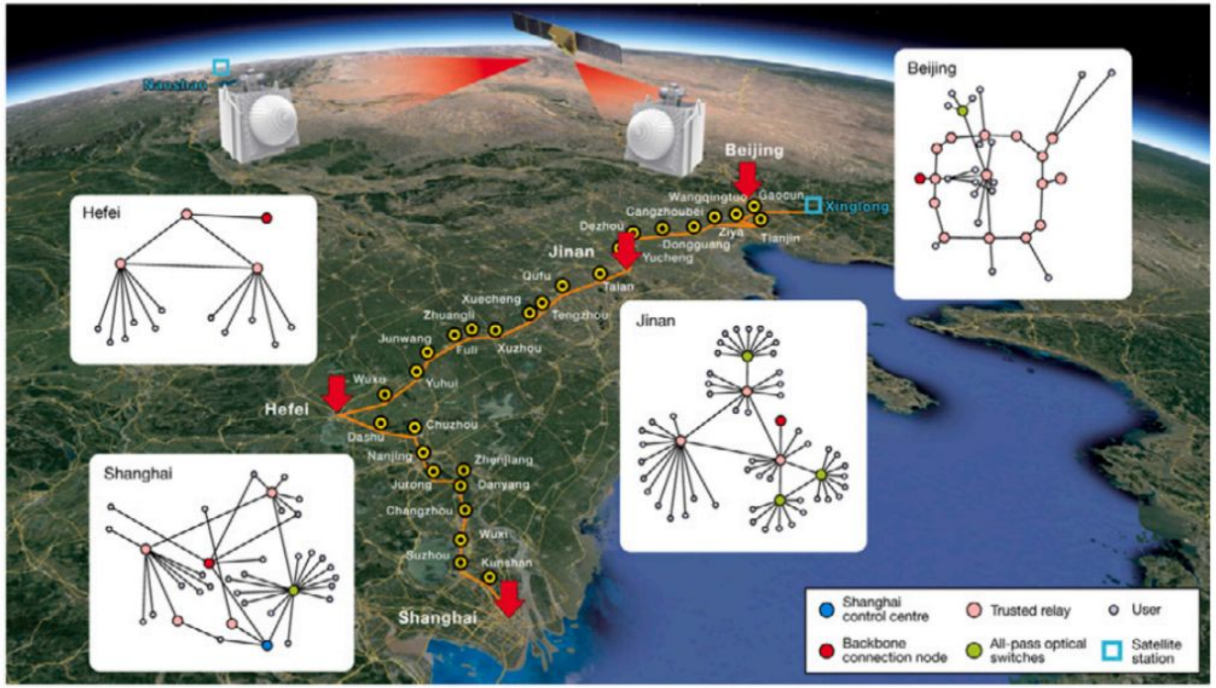


Bristol quantum network testbed

Swiss QKD network

World-wide quantum network efforts - China

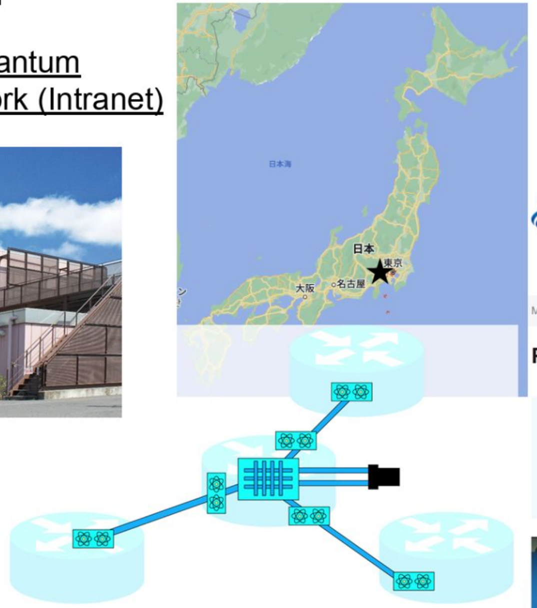




The Micius Project

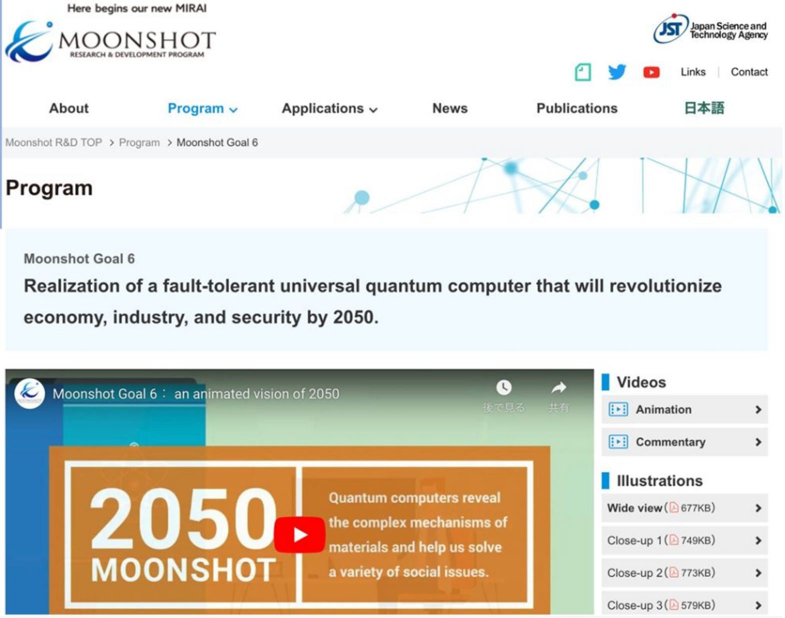
World-wide quantum network efforts - Japan

Short Range Quantum Computer Network (Intranet)



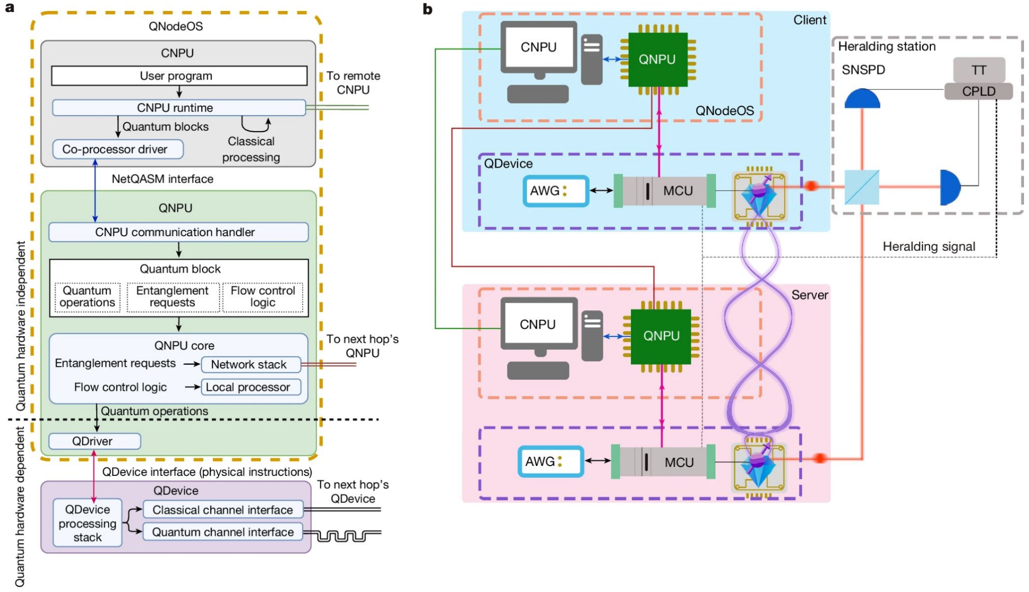
- A laboratory at Shinkawasaki-city (Tokyo-area)
  - construct a 4-node star network
  - Realize the entire network system, including routing, etc.

Demonstration of full system of quantum network by integrating various elemental technologies to be researched (Moonshot Goal6 Nagayama PJ)



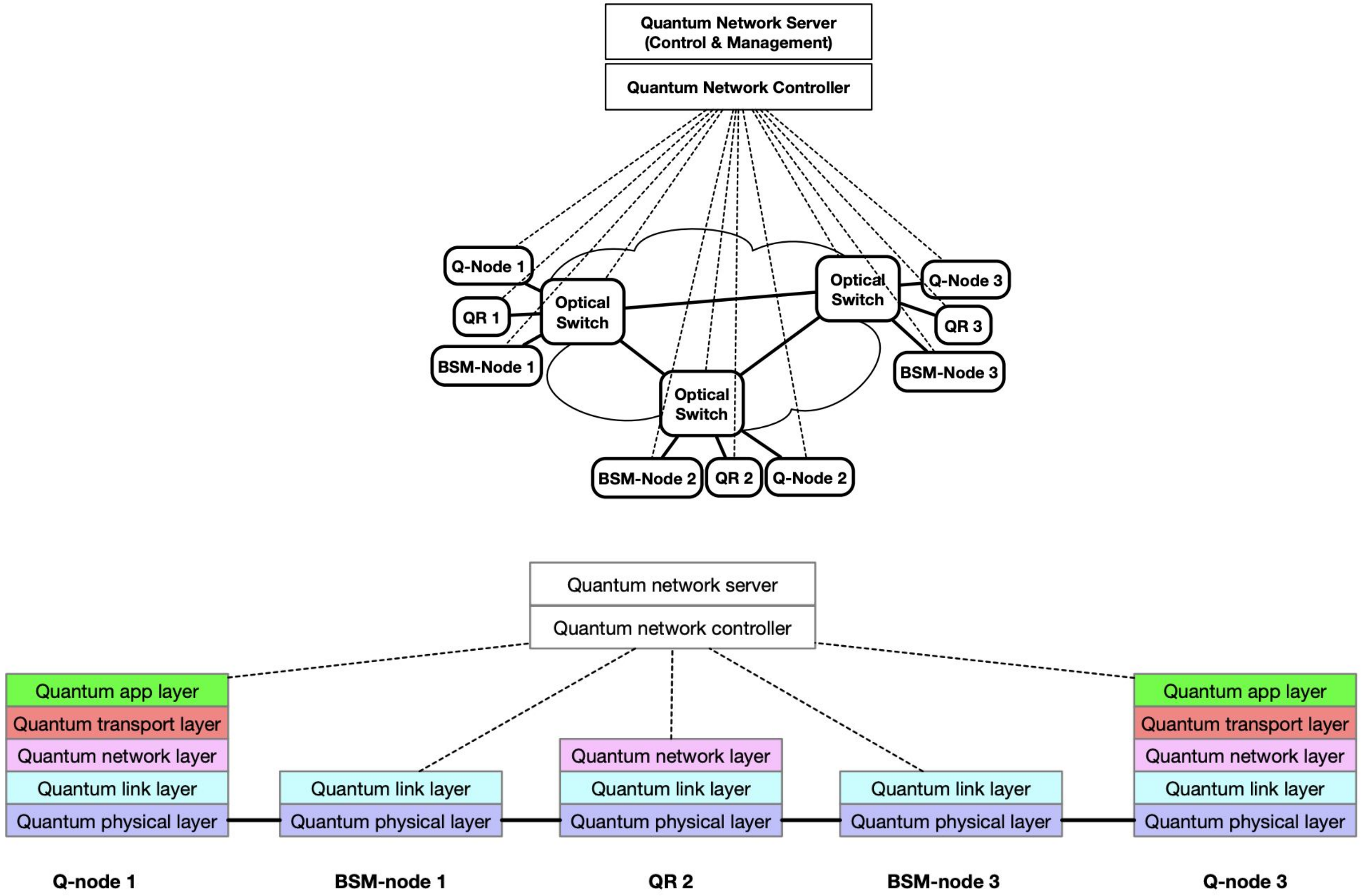
Moonshot quantum network testbed

Status for quantum network architecture & control



Quantum node control

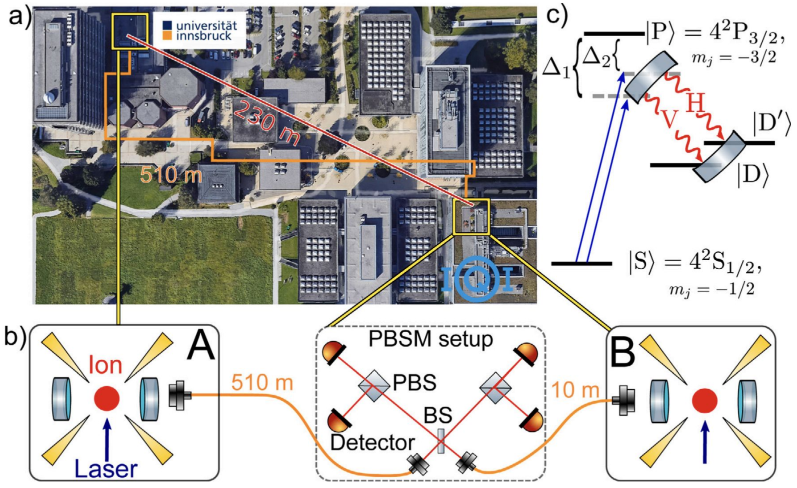
Delle Donne, C., Iuliano, M., van der Vecht, B. *et al.* An operating system for executing applications on quantum network nodes. *Nature* 639, 321–328 (2025).



Centralized quantum network control

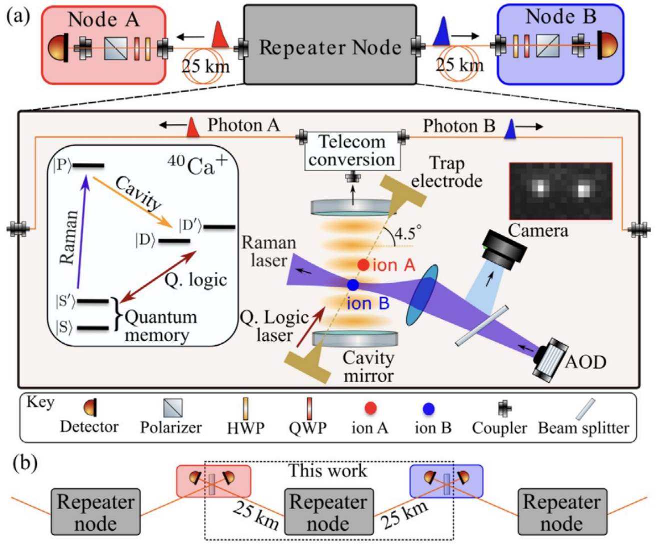
Monga, Inder, et al. "QUANT-NET: A testbed for quantum networking research over deployed fiber." *Proceedings of the 1st Workshop on Quantum Networks and Distributed Quantum Computing*. 2023.

Status for quantum repeaters and networks



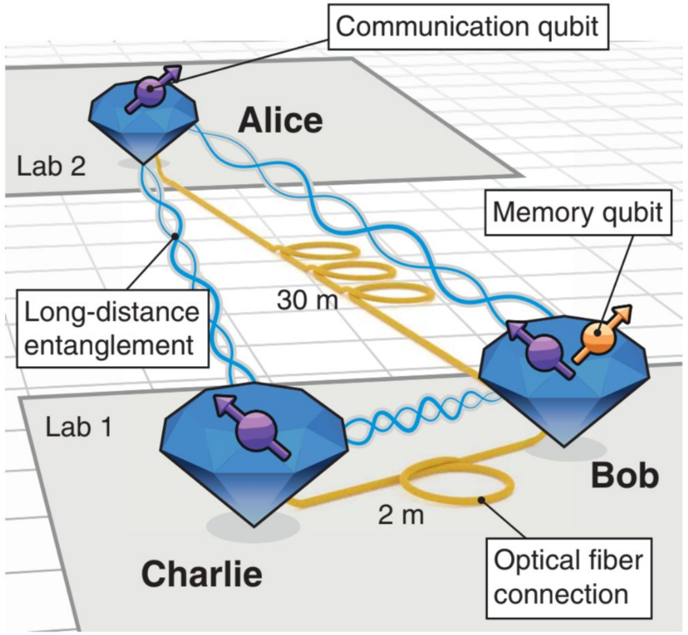
Entanglement of trapped-ion qubits separated by 230 meters

Krutyanskiy, V., et al. "Entanglement of trapped-ion qubits separated by 230 meters." *Physical Review Letters* 130.5 (2023): 050803.



Trapped ion quantum repeater node

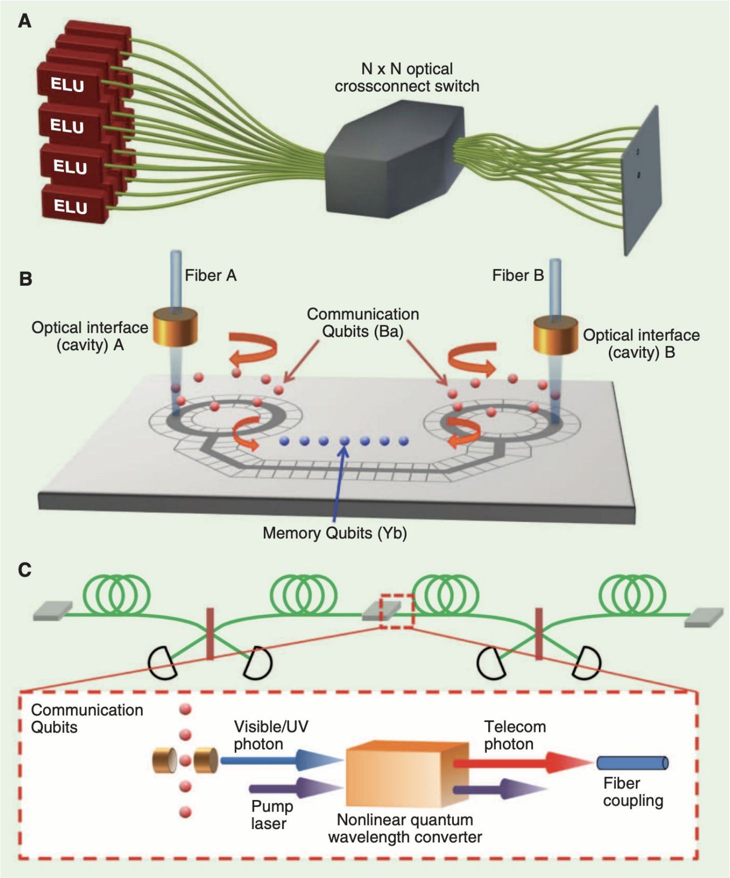
Krutyanskiy, Victor, et al. "Telecom-wavelength quantum repeater node based on a trapped-ion processor." *Physical Review Letters* 130.21 (2023): 213601.



Realization of a multinode quantum network of remote solid-state qubits

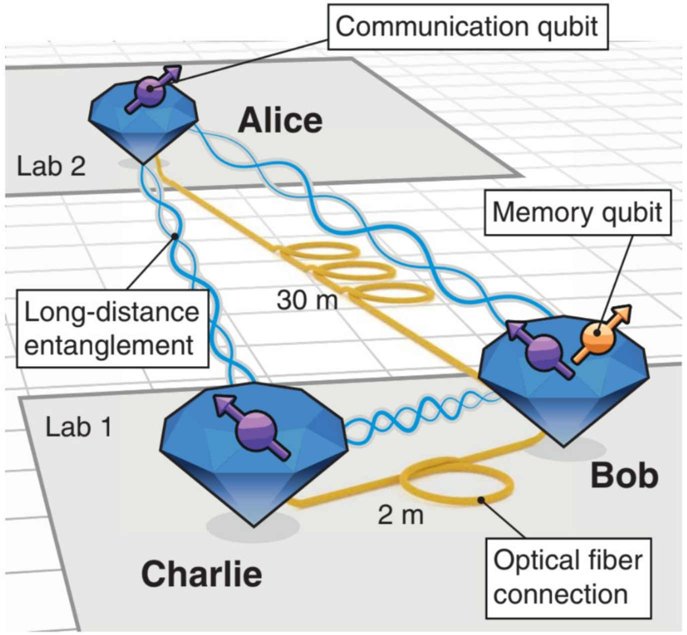
Pompili, Matteo, et al. "Realization of a multinode quantum network of remote solid-state qubits." *Science* 372.6539 (2021): 259-26

System area → Local area → Wide area (Quantum Internet)



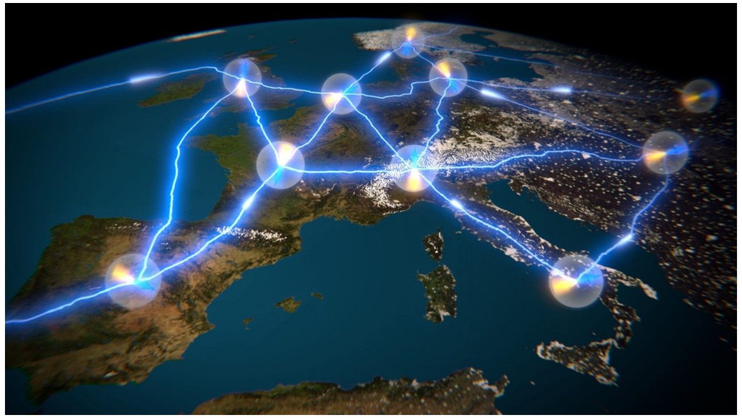
System area to scale up

Monroe, Christopher, and Jungsang Kim. "Scaling the ion trap quantum processor." *Science* 339.6124 (2013): 1164-1169.



Local area to scale out

Pompili, Matteo, et al. "Realization of a multinode quantum network of remote solid-state qubits." *Science* 372.6539 (2021): 259-26



Wide area to scale out

Wehner, Stephanie, David Elkouss, and Ronald Hanson. "Quantum internet: A vision for the road ahead." *Science* 362.6412 (2018): eaam9288.

ESnet's quantum activities at OFC'25

- Paper
  - Experimental Test of Bell-state Measurement for Narrow-band Ion-photon Interfaces in the Quant-net Testbed
    - Session Title: Quantum Entanglement and Computing, M4E
    - Session Time: March 31, 2025 from 4:30 PM to 6:45 PM Pacific Time (UTC-07:00)
    - Session Location: Room 208 (Level 2)
- Demos:
  - The QUANT-NET Project Demonstration
    - Location: Booth 5137
  - Modeling and simulation of quantum networks
    - Location: Booth 5137

Questions

- What do you see as crucial R&D projects in the quantum technology space today, and how do you see the results impacting production networks in the immediate (3-5 year) future?
- Could you unpack for us the extent to which current production network design drives or influences R&D progress in quantum technologies?
- What do you think the next step is in quantum R&D, i.e., what will we be talking about or see demonstrated at OFC2026?

Networks of the Future:

Bleeding-edge technologies and how soon will they be here?

Sana Bellamine, CENIC MMBI, United States (Facilitator)

Lidia Galdino, Corning Optical Communications, United Kingdom

Dirk van den Borne, Juniper Networks, Germany

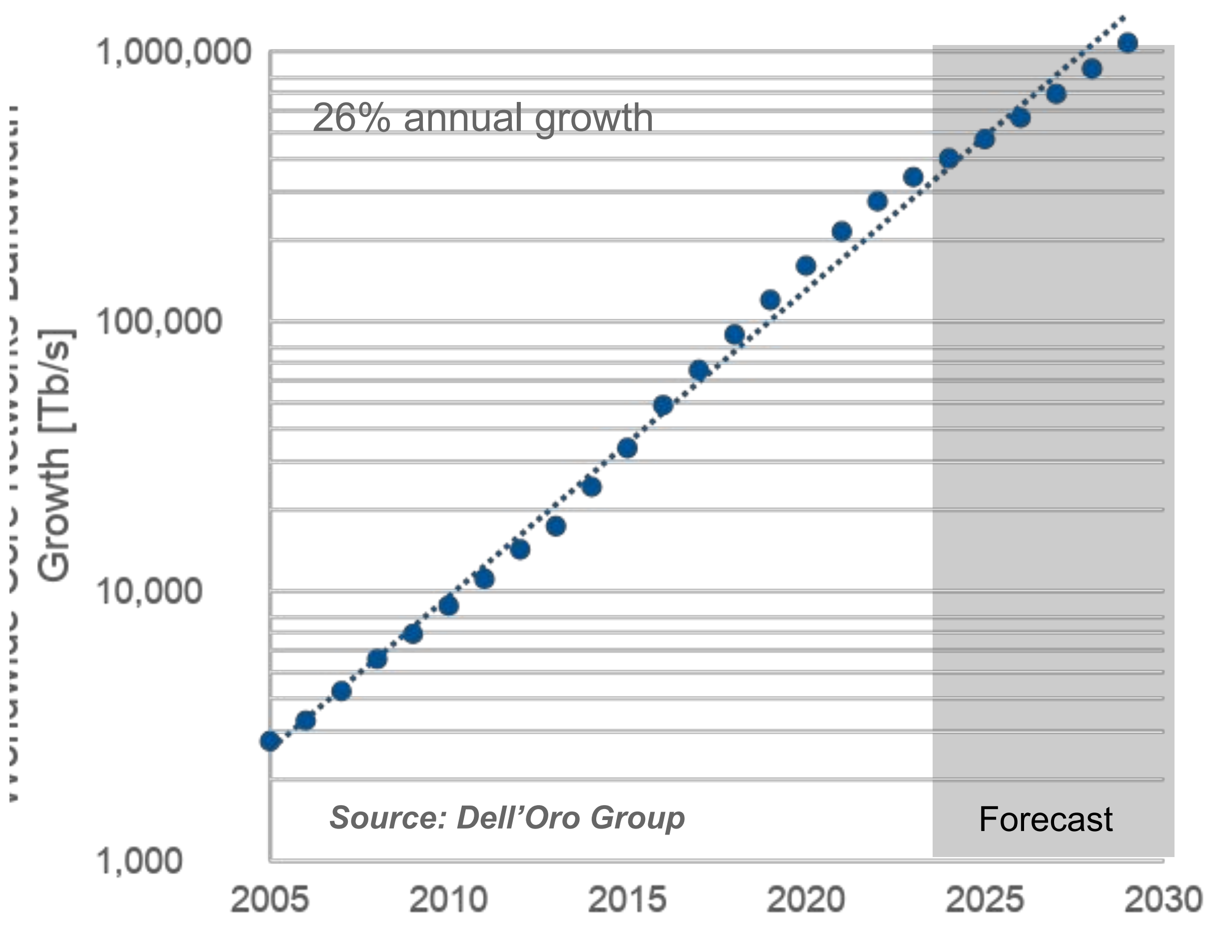
Questions

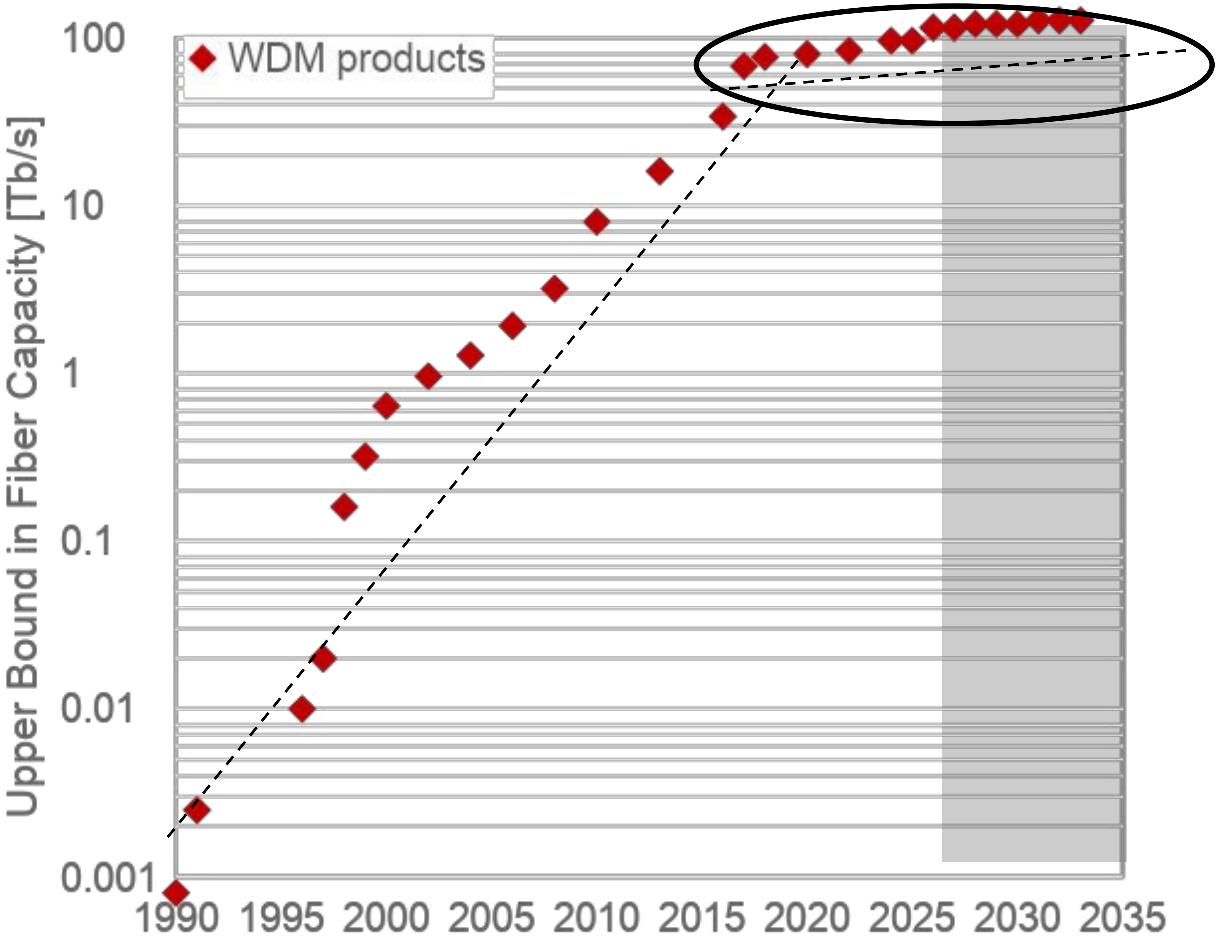
- How are AI advancements impacting inter-datacenter connection development, and which spatial scales are becoming most critical (1km, 10km, 100km, 1000km, 10000km)? Are we seeing new trends in deployed solutions?
- How does fiber selection impact the performance and capabilities of next generation networks? What advancements in fiber technology can benefit future production networks?
- How do you see advancements in wireless technologies impacting next-generation optical networking development?
- What is on the horizon that excites you in terms of hardware and/or protocol or advancements that will transform networking performance for hyperscalers or cloudy applications?

The Role of Parallelism in Driving Innovation in Fiber Optic and Cable Technology

Lidia Galdino
Corning Optical Communications

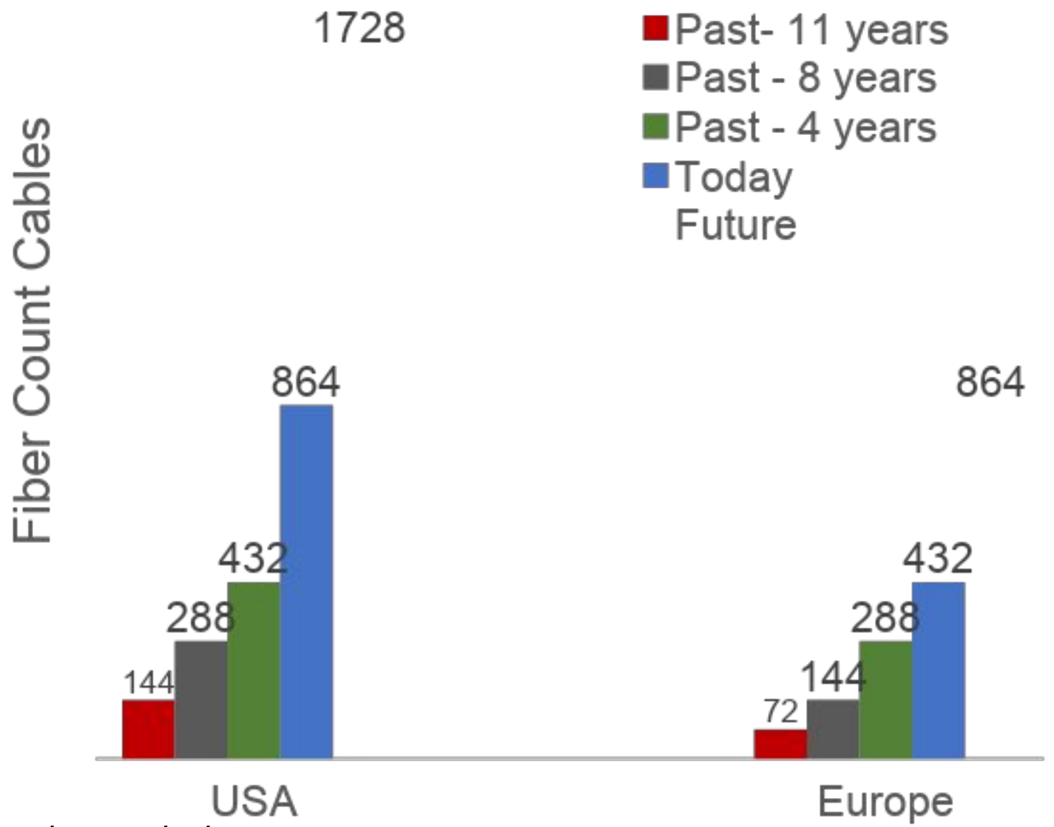
World-wide core networks bandwidth continues to grow while fiber capacity is saturating





CORNING

Exponentially bandwidth growth and saturation in fiber capacity led to fiber count cable growth, doubles every 4-years



Corning analysis

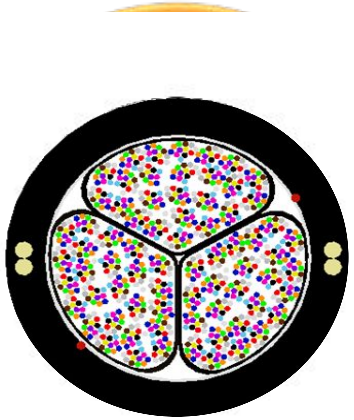
$$C = 2.\underline{M}.B.\log_2(1 + SNR)$$

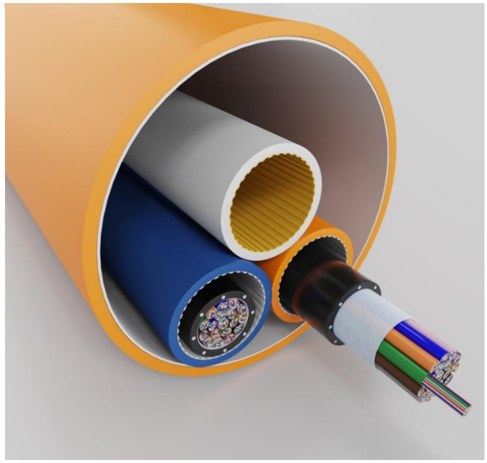
Capacity per path

spatial paths

Bandwidth

Noise

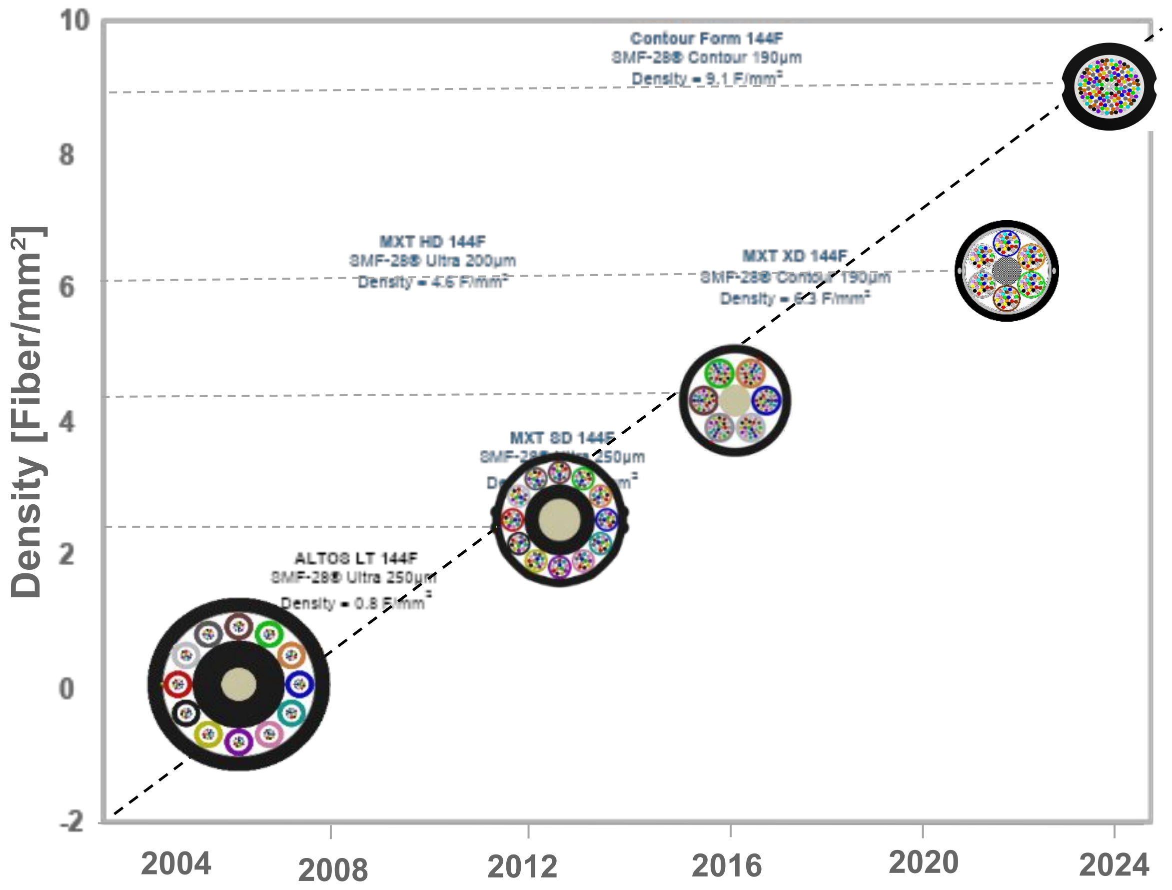




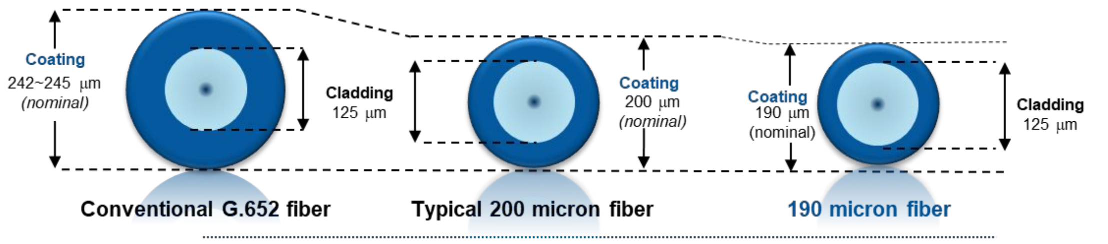
Higher core density (fibers/mm²) is required to fully utilize precious space in the installed ducts

CORNING

Innovative cable designs and smaller OD fibers enable a tenfold increase in fiber density over the last 20 years



~40% reduction in cross-sectional area (245 um to 190 um OD)



$$C = 2.M.B.\log_2(1 + SNR)$$

Capacity per path

Polarization

Bandwidth

Noise

spatial paths (f/mm²)

Innovation in fiber design is required to increase density without compromising optical performance and therefore spectral efficiency

CORNING

Aggressive high-density cables combined with lower OD fibers makes them more susceptible to microbending-induced loss

Mechanisms to mitigate microbend induced attenuation in high density cables

Cable Design

- Microbend stimuli along length
- Microband induced attenuation

Fiber Design

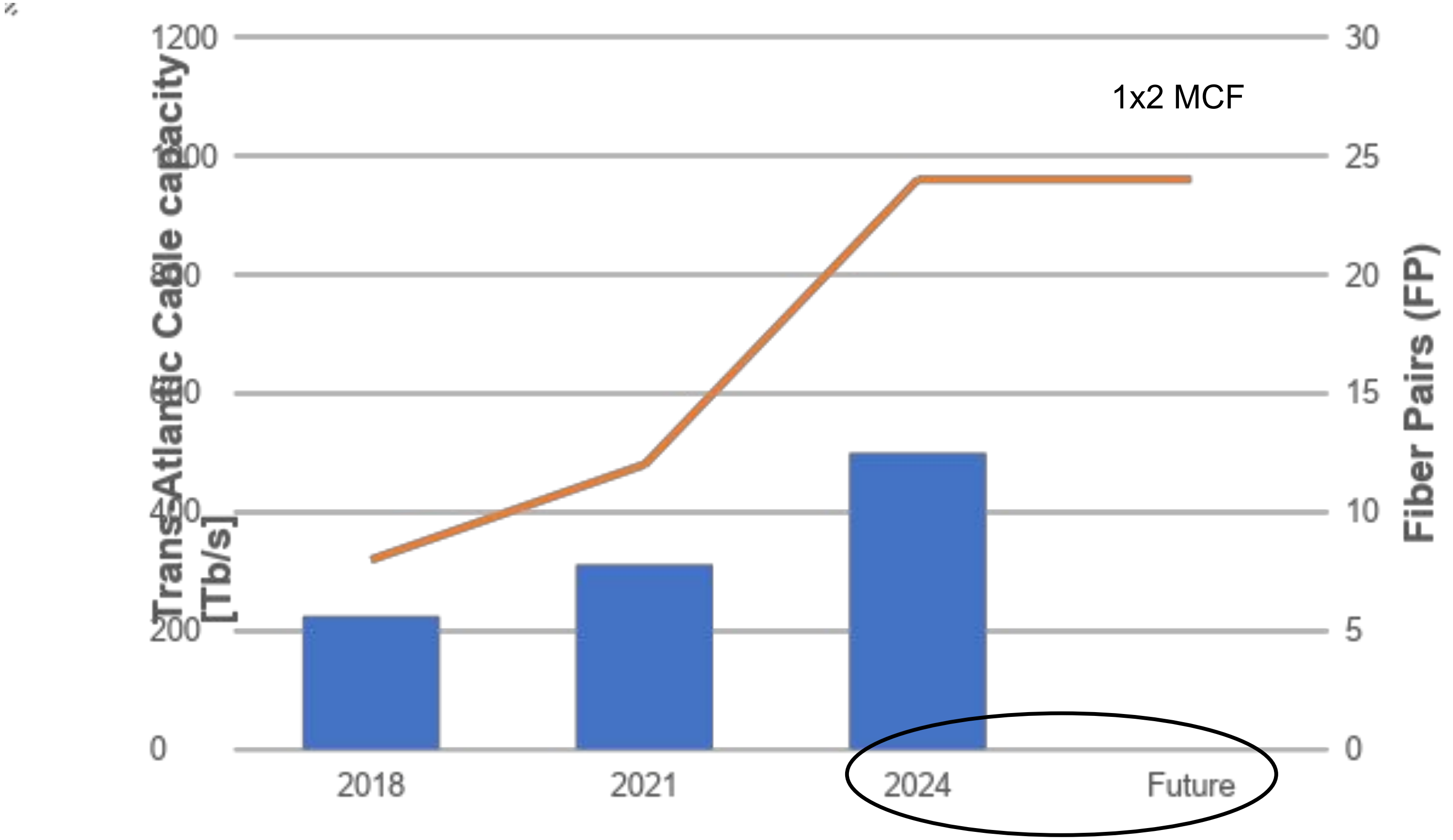
- Core radius (MFD)
- Refractive index/Optical
- Total fiber diameter (OD)

Coating Attributes

- Softer primary coating with lower modulus

Removing primary coating makes fiber more susceptible to microbending

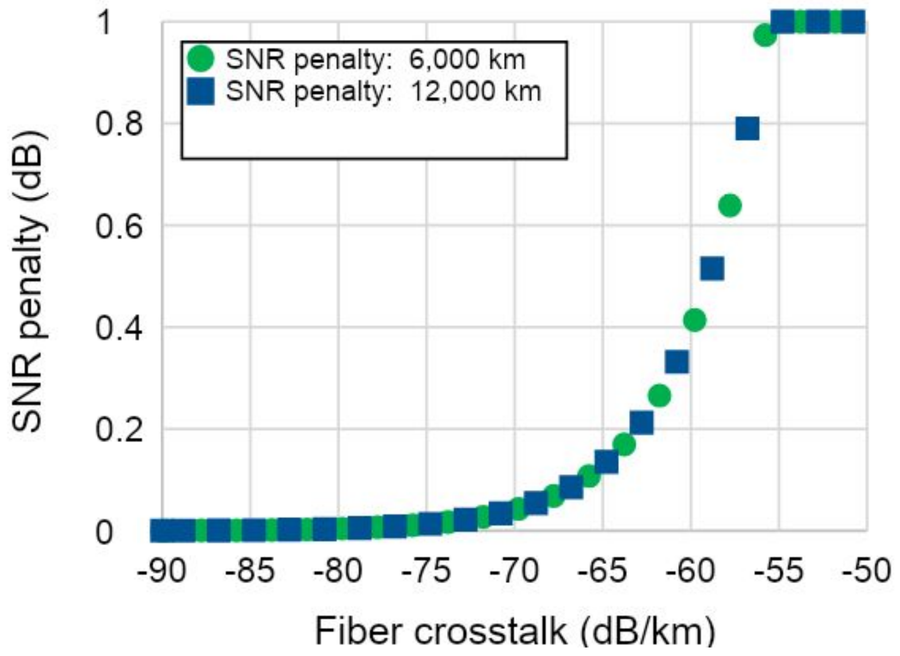
Doubling subsea cable capacity and density with 1x2 MCF

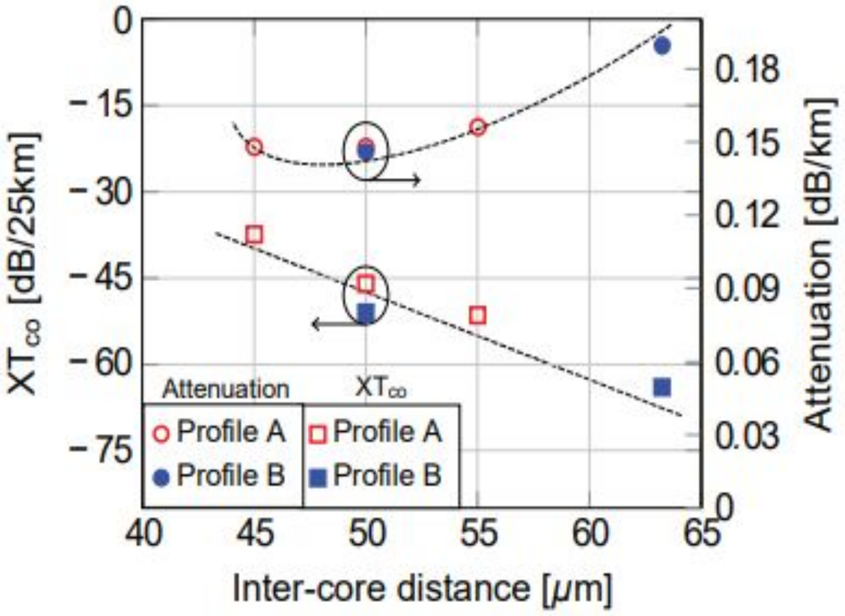


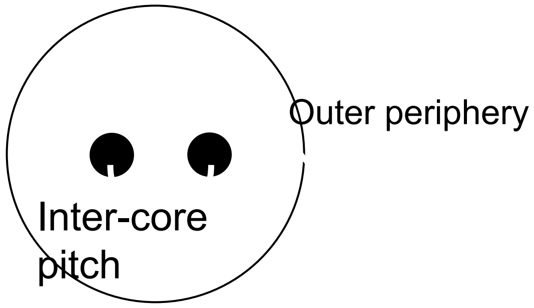
1x2 MCF

The 1x2 Multi-Core Fiber (MCF) doubles the capacity of the subsea cable while maintaining the same number of fiber pairs

Ultra-low attenuation and negligible cross-talk levels is paramount to not compromise spectral efficiency



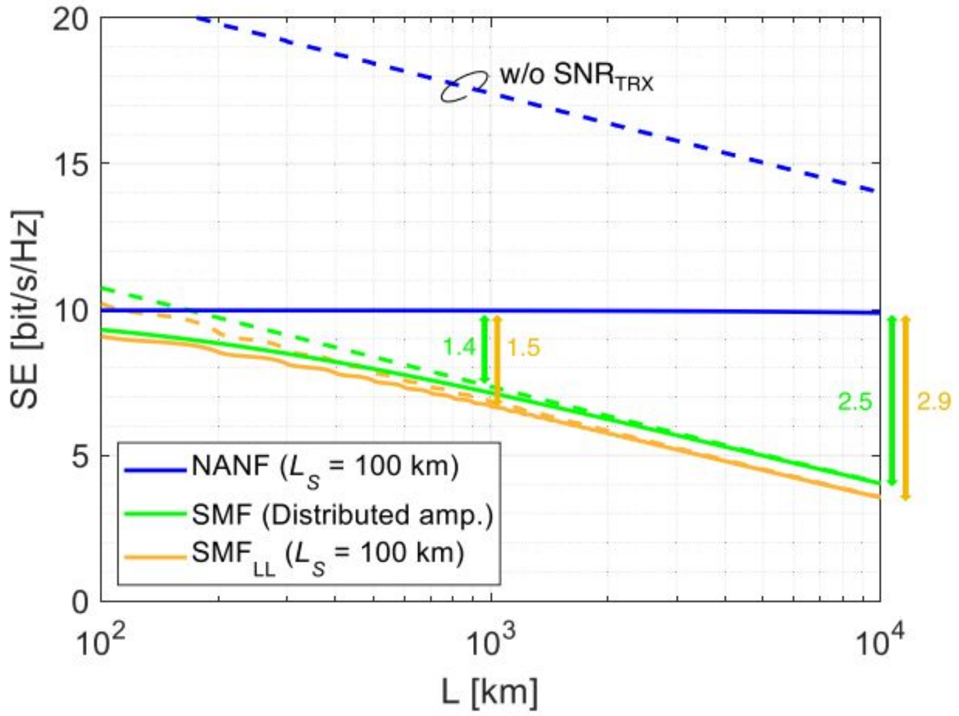




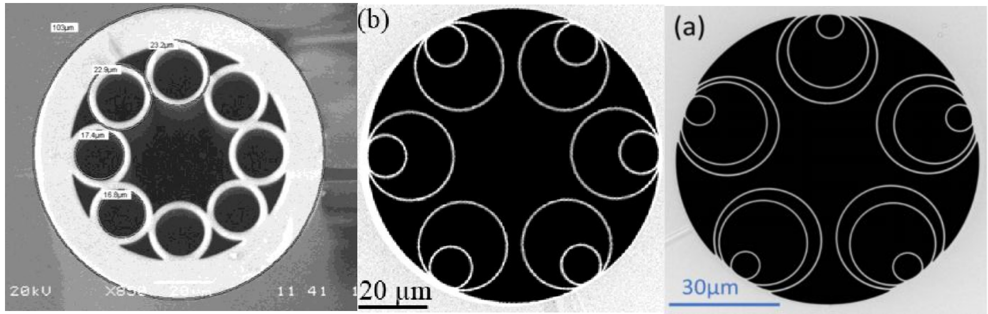
[1] P. Tandon, at. all. " Record Low Loss 0.144 dB/km 2-Core Optica Fiber for Submarine Transmission", Journal of Lightwave Technology, June 2024

In an uncoupled core MCF design, an increase in the inter-core distance improves the inter-core crosstalk, but also places the cores closer to the outer periphery of the fiber cladding, resulting in increased radiation

Can Hollow Core Fiber Solve the Scaling Challenge?



[1] SE vs. distance without (dashed lines) and with (solid lines) a transponder SNR limit of 30 dB



Source: Compilation of publicly available images (via Google image search)

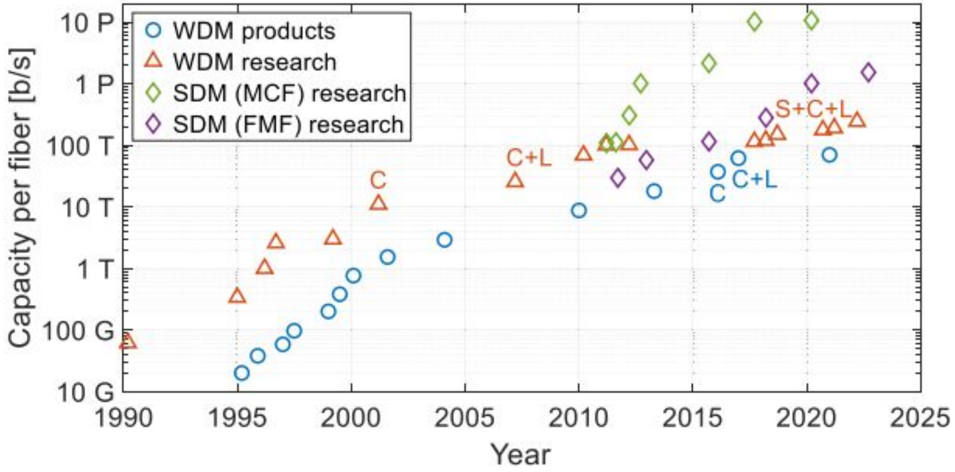
$$C = \underbrace{2}_{\text{Polarization}} . \underbrace{M}_{\text{spatial paths (f/mm²)}} . \underbrace{B}_{\text{Bandwidth}} . \log_2(1 + \underbrace{SNR}_{\text{Noise}})$$

Capacity per cable

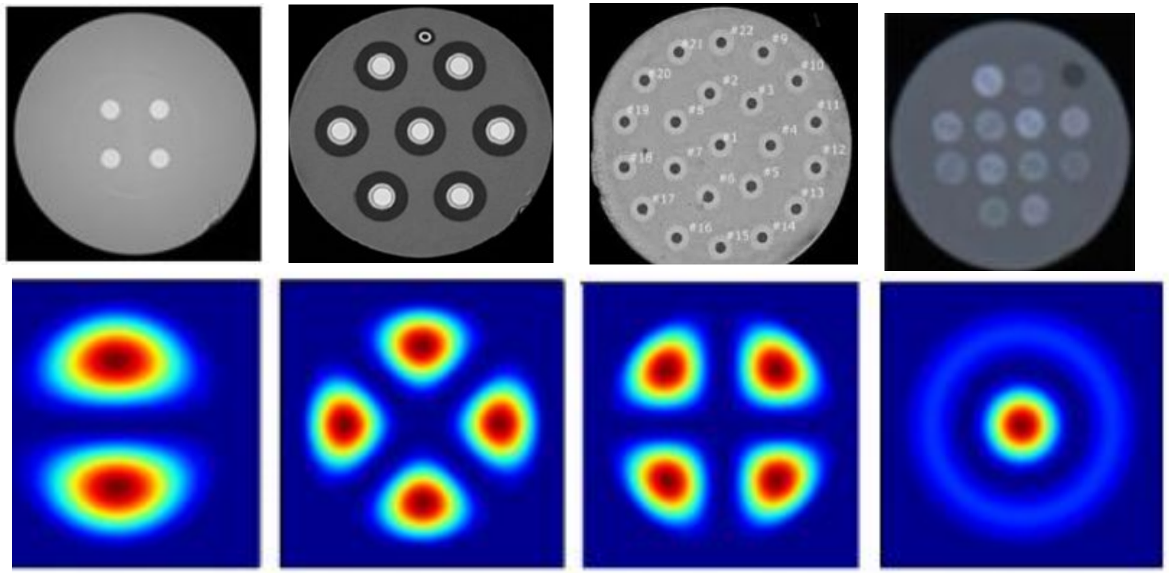
- Upper bond of SE is set by transporter technology
- HCF has the potential for a much wider ultra-low-loss spectral range compared to SMF
  - Will transponders (amplifiers if needed) deliver similar SNR as today's operating at the telecom window?
- Can HCF achieve the same cable density as SMF without compromising attenuation?

[1] Werner Klaus, "The Role of Parallelism in the Evolution of Optical Fiber Communication Systems," Proceedings of the IEEE, November 2022

Pathways to overcome scaling challenges with SDM Fibers



Werner Klaus, “The Role of Parallelism in the Evolution of Optical Fiber Communication Systems,” Proceedings of the IEEE, November 2022



$$C = 2.M.B.\log_2(1 + SNR)$$

Capacity per path

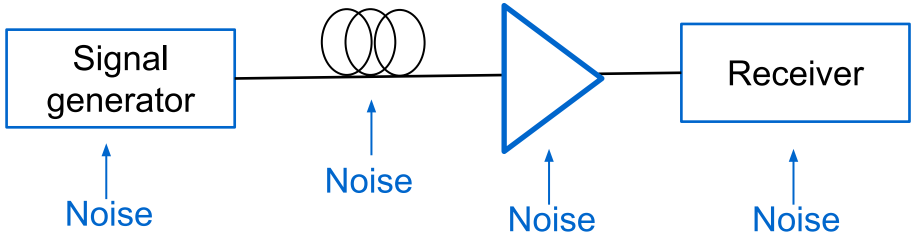
Polarization

spatial paths (core/mm²)

Bandwidth

Noise

Optical fiber properties that impact SNR include polarization dependency loss, crosstalk, mode dependency loss, intermode interference, microbend sensitivity, and attenuation.



Future optical line systems and transceiver technologies required to support these revolutionary fibers will also impact SNR.

CORNING Source: Compilation of publicly available images (via Google image search)

Networks of the future

bleeding-edge technologies and how soon will they be here?

Dirk van den Borne

30th March 2025, OFCnet workshop, OFC 2025, San Francisco

Driven by Experience™

A QUICK INTRODUCTION

Who am I?

Dirk van den Borne

- Director of Systems Engineering at Juniper Networks. Heading the Technology Solution Architecture organization for WAN/routing
- Originally from the Netherlands, now living in Munich, Germany
- OFC #20 this year 😱

THE BLEEDING EDGE TODAY

Example of a compact router platform

28.8T Packet Forwarding Engine ASIC	36 x 800GE with QSFP-DD800 ports	28.8T full-duplex throughput with 10B PPS	<30 W/Tbps power efficiency	800ZR/ZR+ supported on all 36 ports

Juniper PTX10002-36QDD

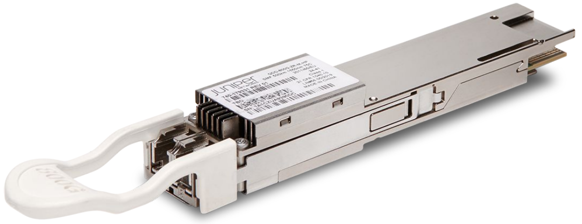
<850W

(typical & without optics)

First routing platform for which the optics can consume majority of the power consumption, more than the router itself!

WHAT'S NEXT

The most reliable way to predict the future is to create it



800ZR/ZR+
optics

1600ZR+	1.6T/λ for long-haul transport: how to build it in less than 40W?
1600ZR	1.6T/λ for DCI: parity with 800ZR, but scale beyond C+L band?
800G ZR+	800GE anywhere: can we extend into the (ultra)-long-haul?
400G ZR+	400GE into the metro-access: can we fit it in a QSFP112 or SFP-DD?

The most reliable way to predict the future is to create it

- Abraham Lincoln

Questions

- How are AI advancements impacting inter-datacenter connection development, and which spatial scales are becoming most critical (1km, 10km, 100km, 1000km, 10000km)? Are we seeing new trends in deployed solutions?
- How does fiber selection impact the performance and capabilities of next generation networks? What advancements in fiber technology can benefit future production networks?
- How do you see advancements in wireless technologies impacting next-generation optical networking development?
- What is on the horizon that excites you in terms of hardware and/or protocol or advancements that will transform networking performance for hyperscalers or cloudy applications?

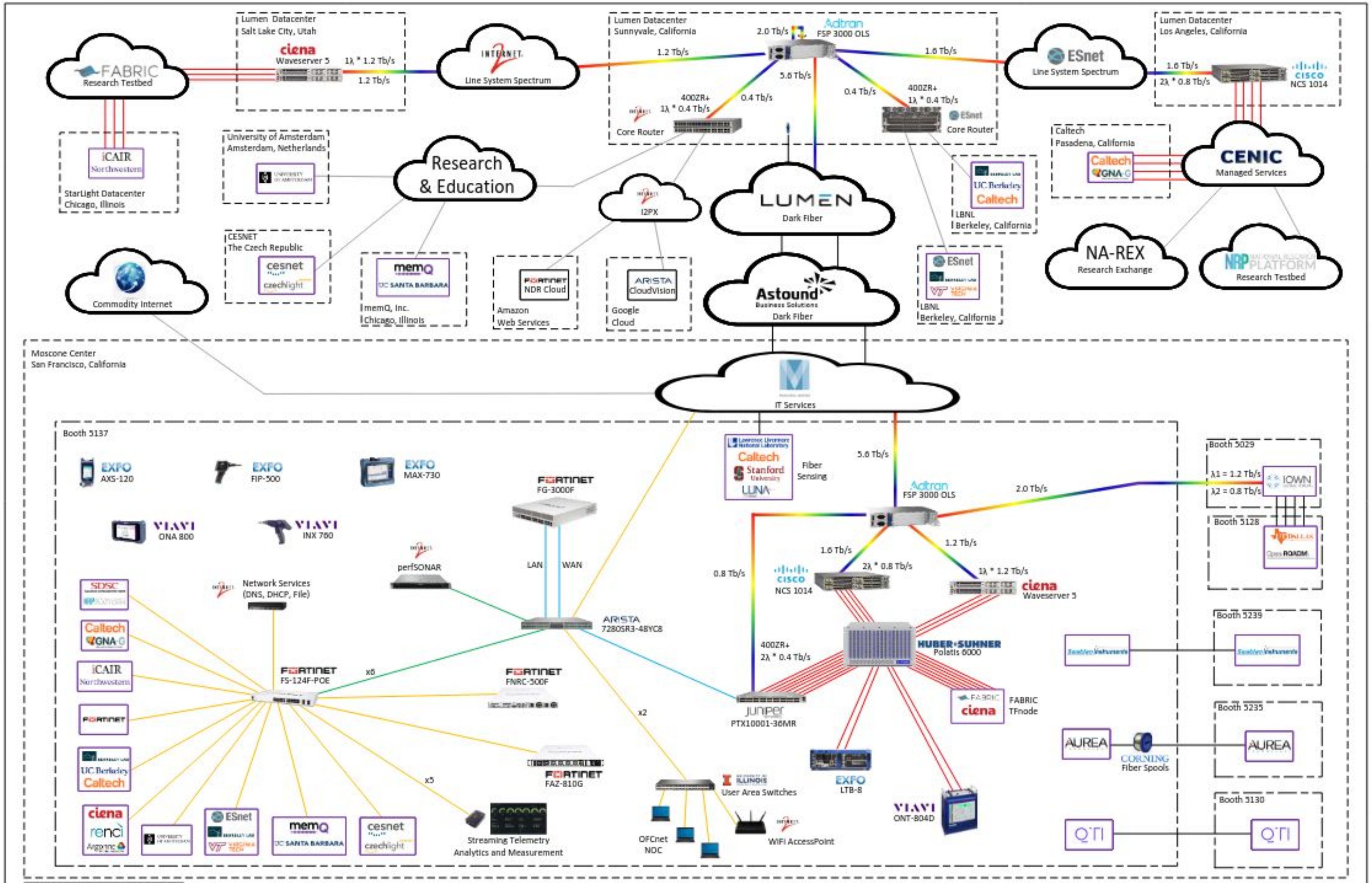
Concluding Remarks

Thank you to our speakers & audience for your participation and engagement!

Comments & Feedback? sstrachan@nshe.nevada.edu, sana.bellamine@goldenstatenet.org

Check out the OFCnet NOC and Demos - Booth 5137

https://www.ofcconference.org/en-us/home/exhibition-and-show-floor-programs/ofcnet/



Abstracted Connectivity
Dark Fiber
1 Gigabit Ethernet
10 Gigabit Ethernet
100 Gigabit Ethernet
400 Gigabit Ethernet
DWDM
OFCnet Demonstration

OFC

OFC 2025 - OFCnet Architecture