Quantum Communications and Networking:

A Challenge for Mathematics/CS/Physics/Engineering

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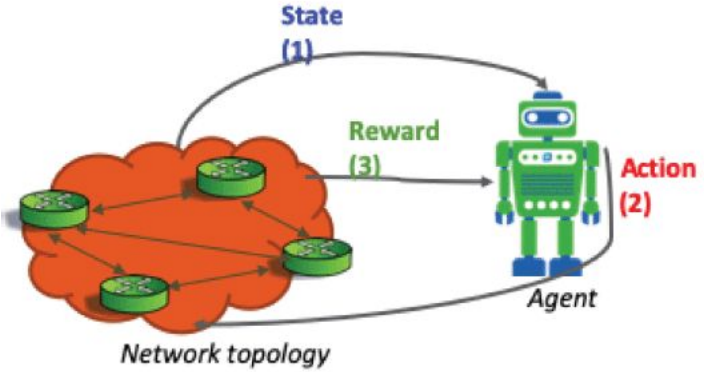
SIAM Quantum Intersections Convening Oct 2024

Outline

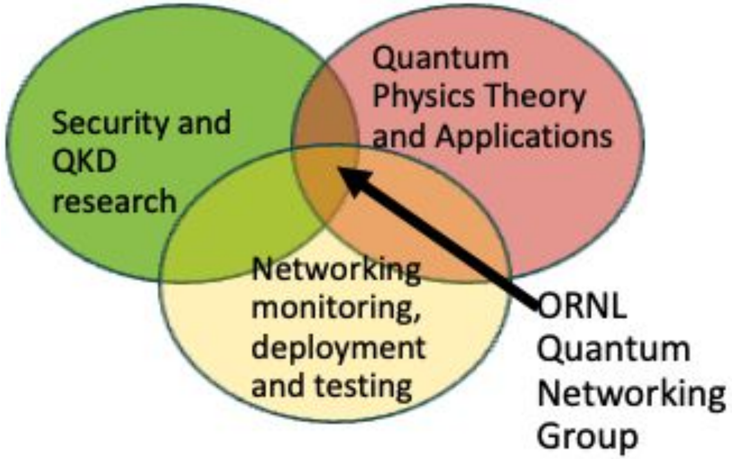
- Introduction
- DOE and Quantum Networking challenges
- Key Applications for Quantum Networks
- Other Examples for SIAM community engagement
- Takeaways

Engineering Challenges

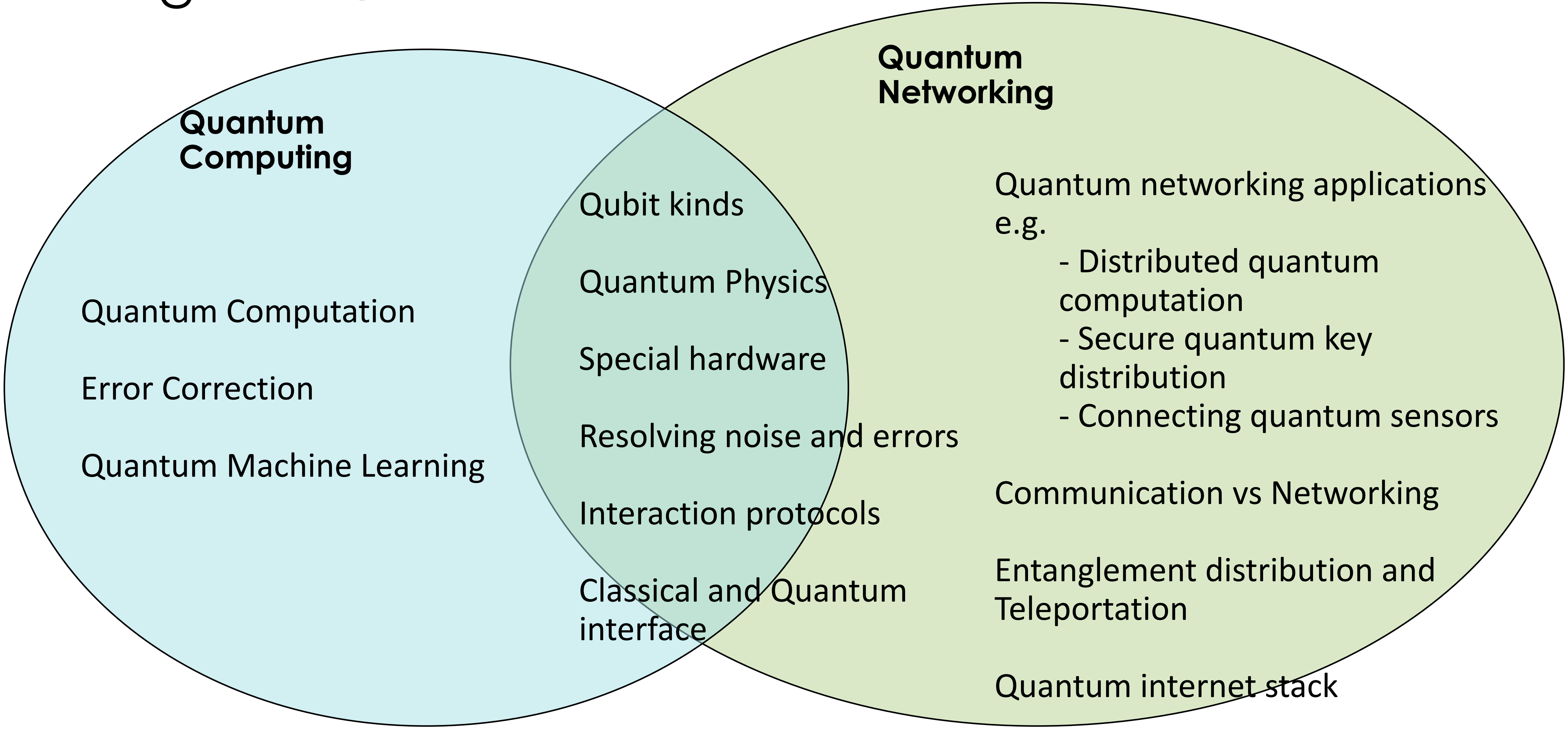
AI for Self-driving Networks – Wired, Wireless and (now) Quantum



- Deep Learning methods for Traffic prediction or Network optimization – Graph optimization problem
- Quantum Networks (QN) have both challenges – fundamental physics and engineering (and maths)
  - Critical physics – components to work
  - Engineering – fiber infrastructure, real-world deployment
- QN is not a replacement for current internet (classical) networks, but along side
- Game changing capabilities for science discovery
- Access to testbed or simulations to develop QN



Building the Quantum Internet



Quantum Computing

Quantum Computation

Error Correction

Quantum Machine Learning

Qubit kinds

Quantum Physics

Special hardware

Resolving noise and errors

Interaction protocols

Classical and Quantum interface

Quantum Networking

Quantum networking applications e.g.

- Distributed quantum computation
- Secure quantum key distribution
- Connecting quantum sensors

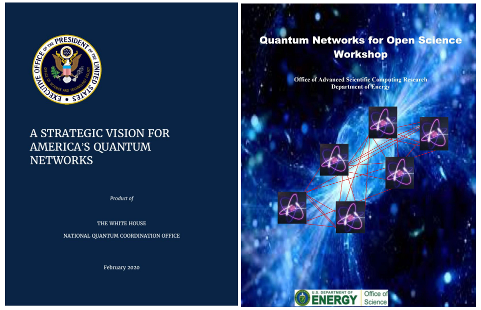
Communication vs Networking

Entanglement distribution and Teleportation

Quantum internet stack

Skills: Theory & Experimentalist Physics, Computer Science, Mathematicians, Hardware engineers, Software code

Quantum Networking at ORNL



A STRATEGIC VISION FOR AMERICA'S QUANTUM NETWORKS

Product of

THE WHITE HOUSE

NATIONAL QUANTUM COORDINATION OFFICE

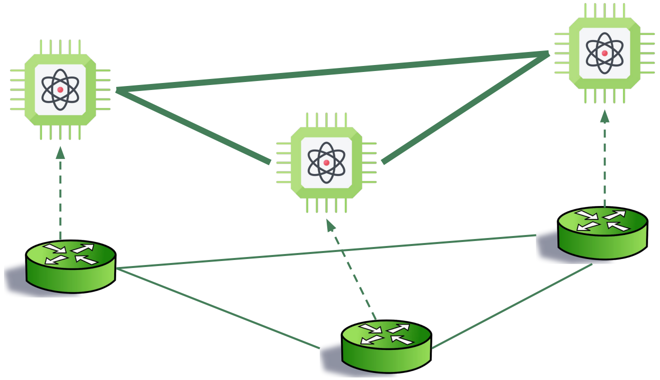
February 2020

Quantum Networks for Open Science Workshop

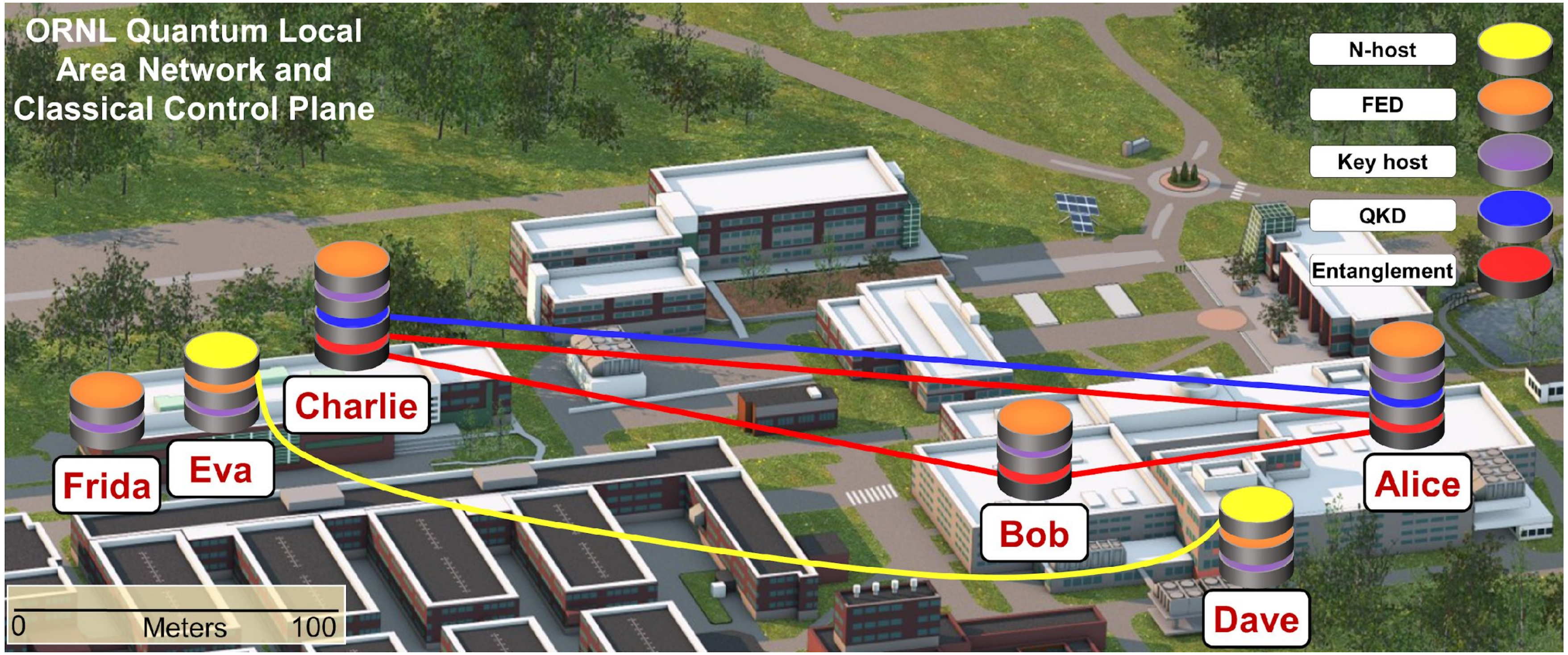
Office of Advanced Scientific Computing Research

Department of Energy

- 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

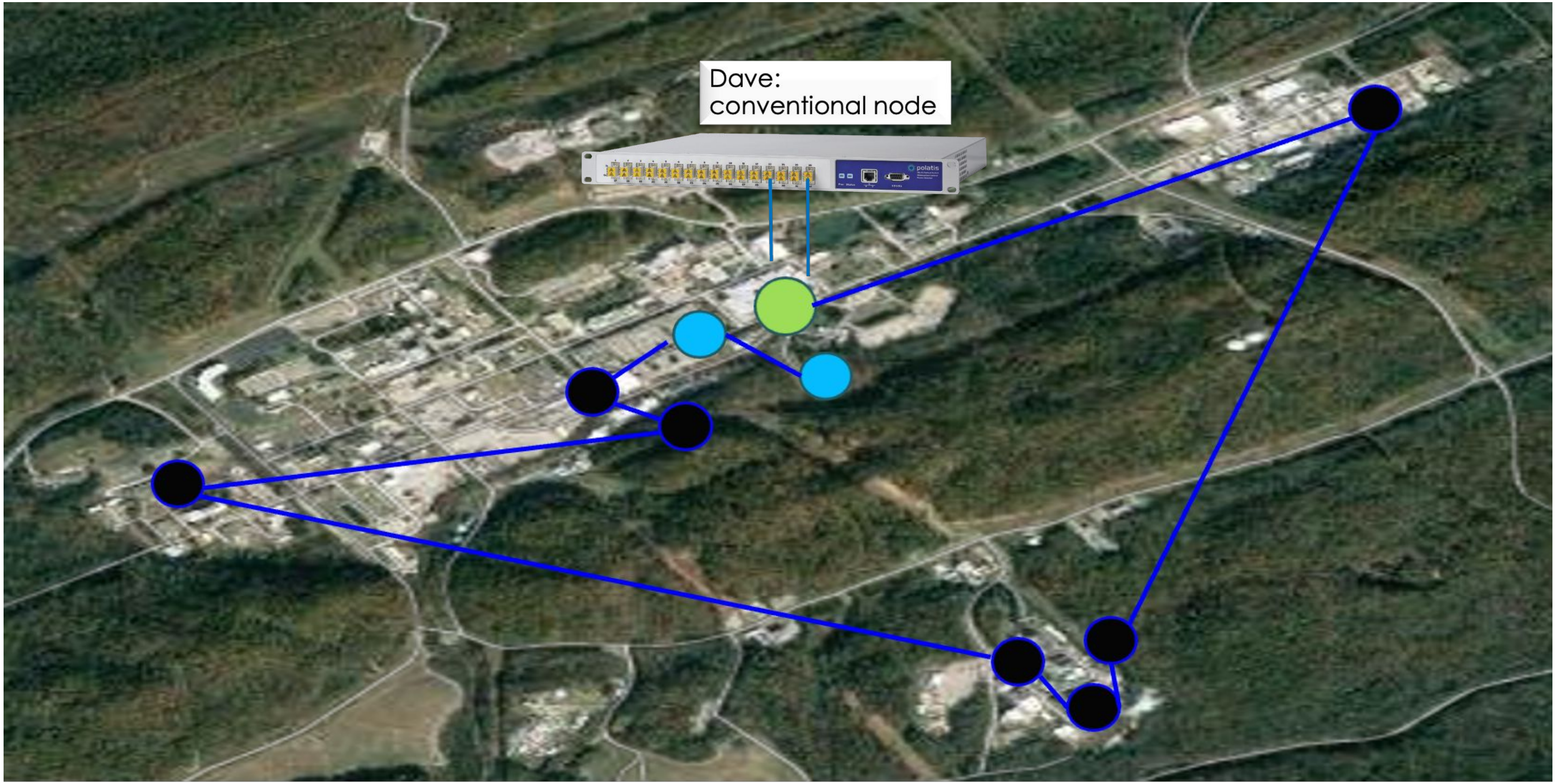


quantum/optic infrastructure (coexistence signals)

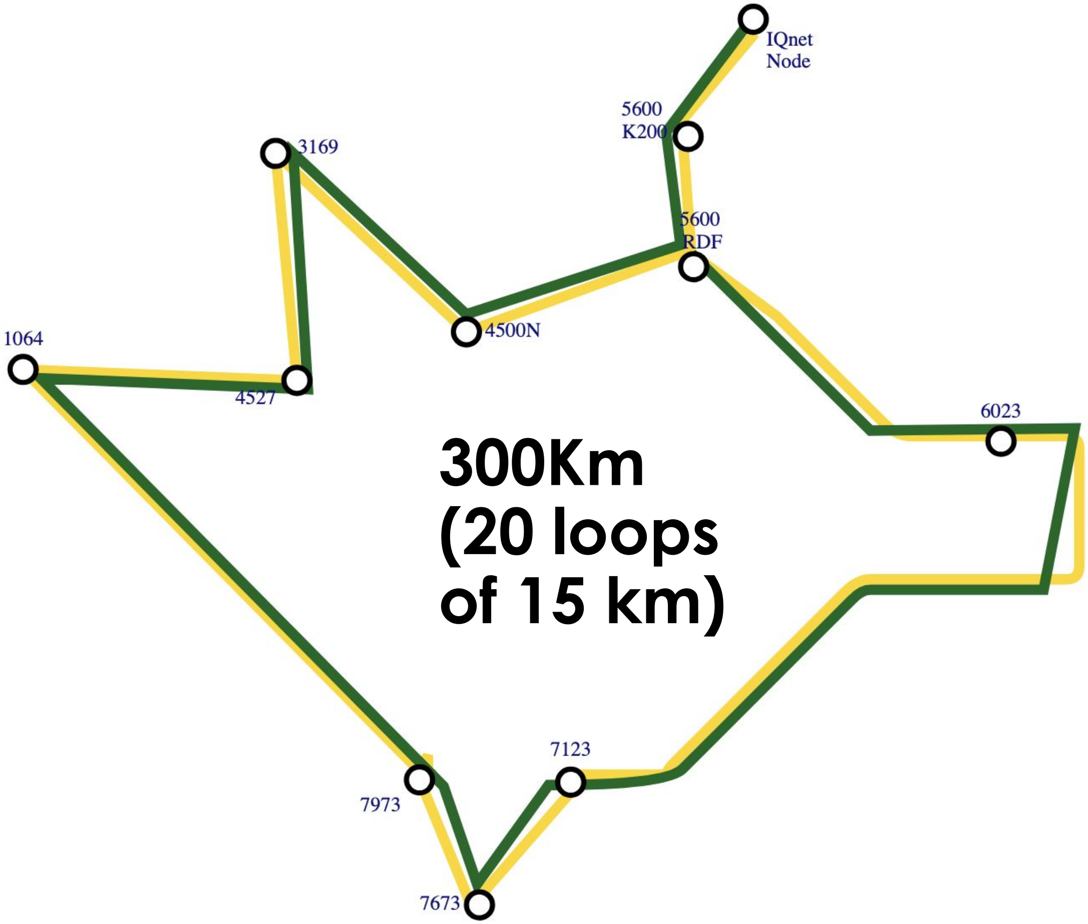


M. Alshowkan, et al., PRX Quantum 2 (4), 040304 (2021)

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



Developing a Quantum Network Testbed for Research

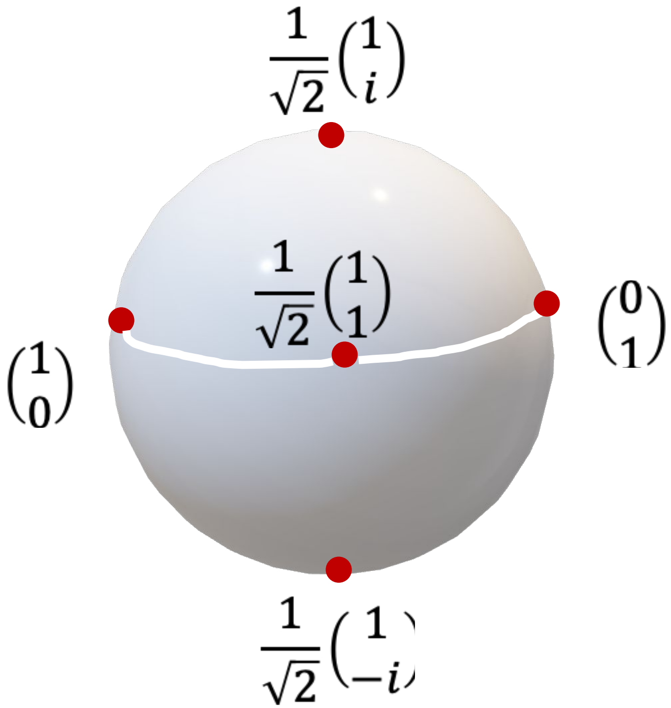


300Km (20 loops of 15 km)

- 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

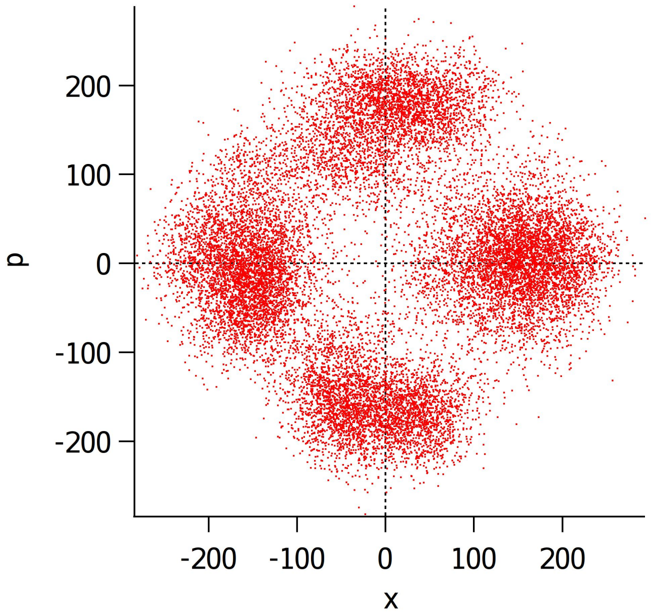
From N. Peters



Poincare Sphere (qubit)

Discrete Variable (DV): qubit

Examples: polarization,
orbital angular momentum, time-bin



Continuous Variable (CV)

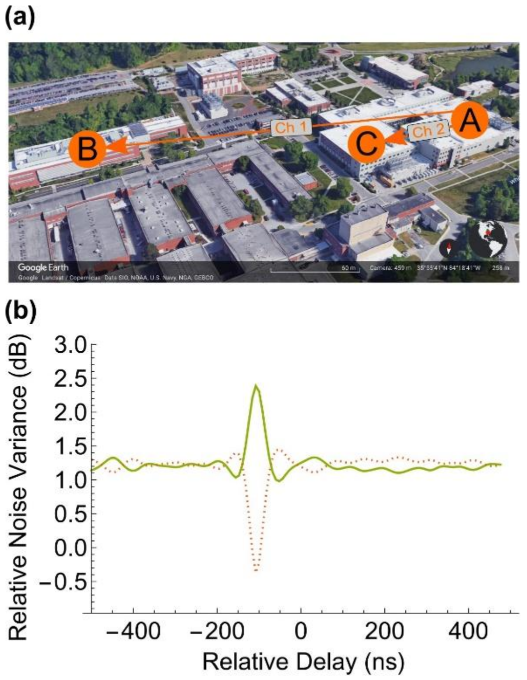
Examples:
position-momentum,
energy-time,
amplitude-phase

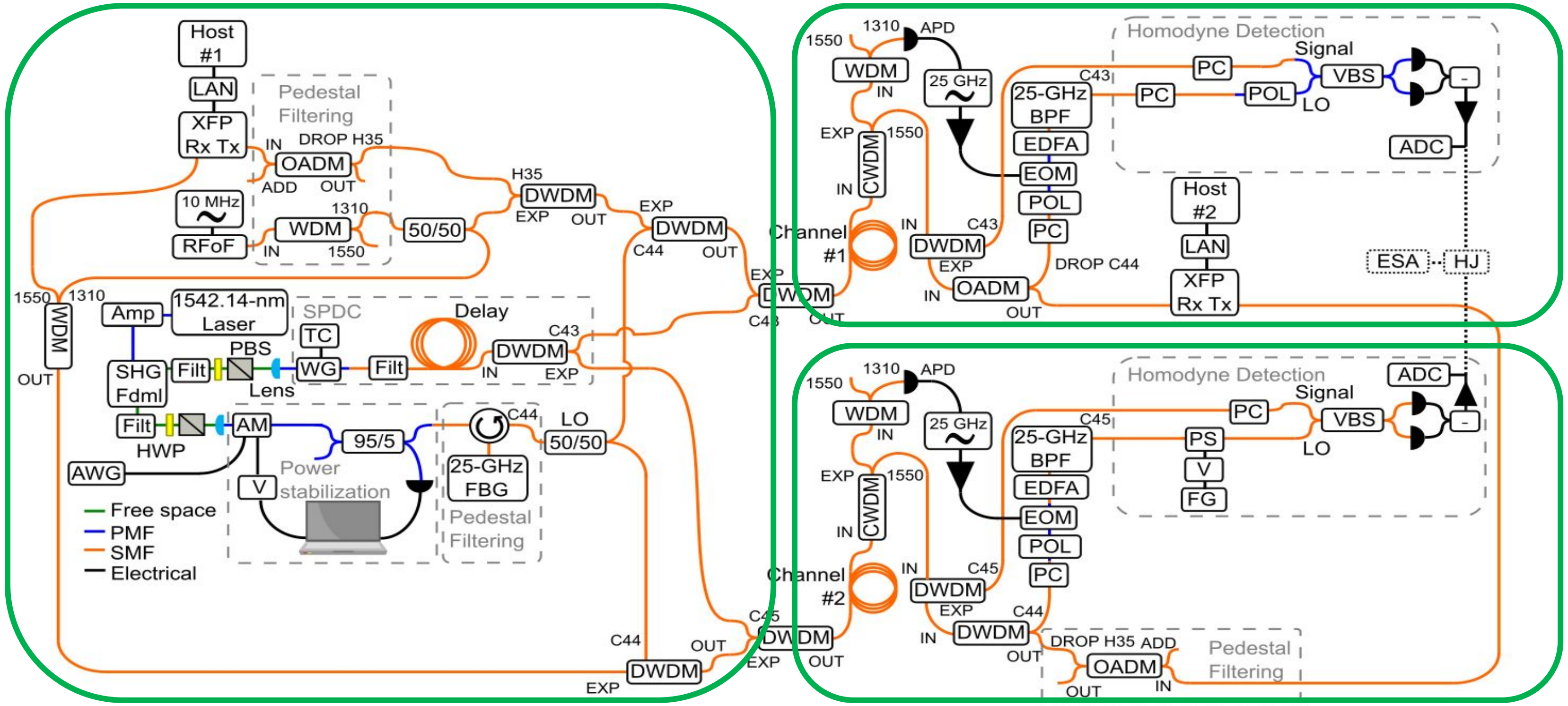
Experiments with DV and CV for various applications

From N. Peters

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

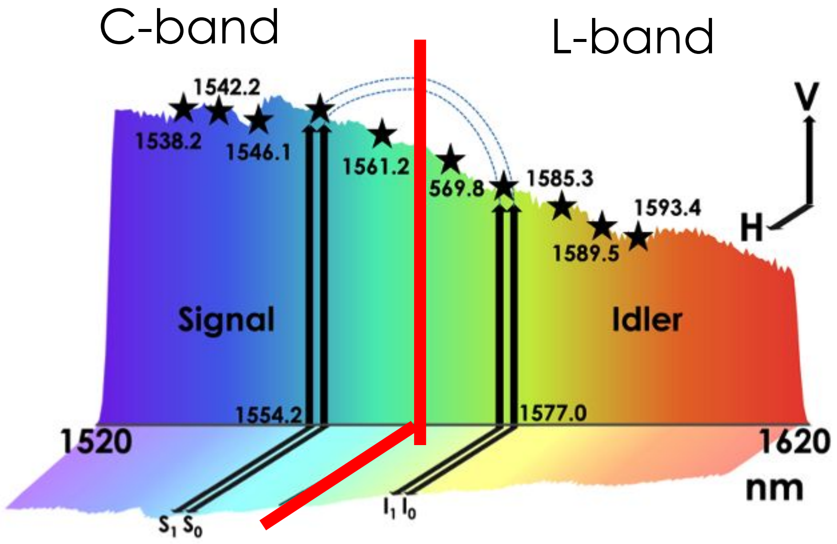


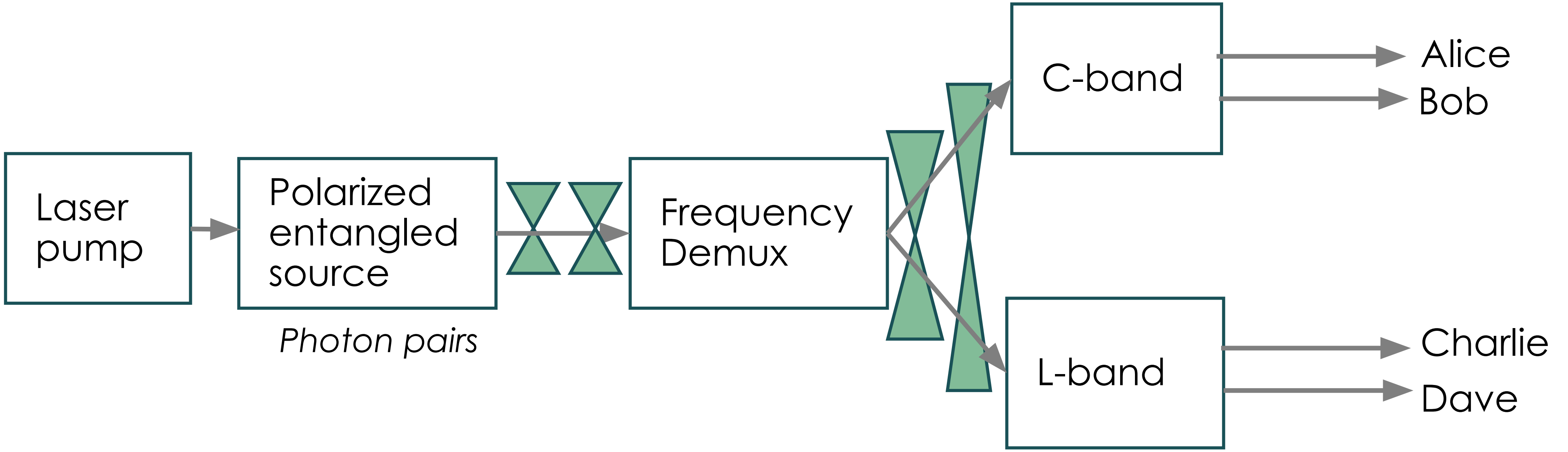


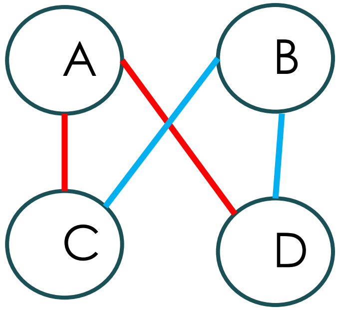
Chapman et al., "Two-Mode Squeezing Over Optical Fiber Coexisting with Conventional Communications ." Optics Express, (2023)

Distributing Entanglement across Distance

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





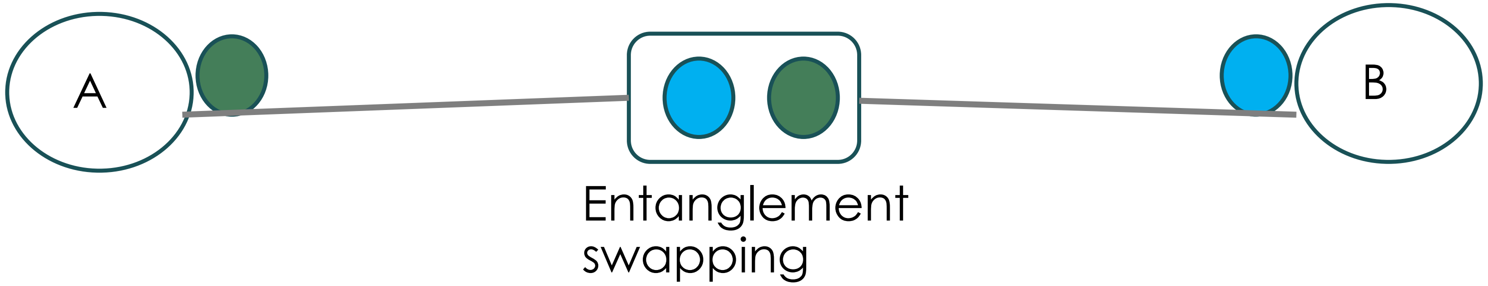


H Lu et al. Optics Letters (2023)

How Far can Entanglement Travel?

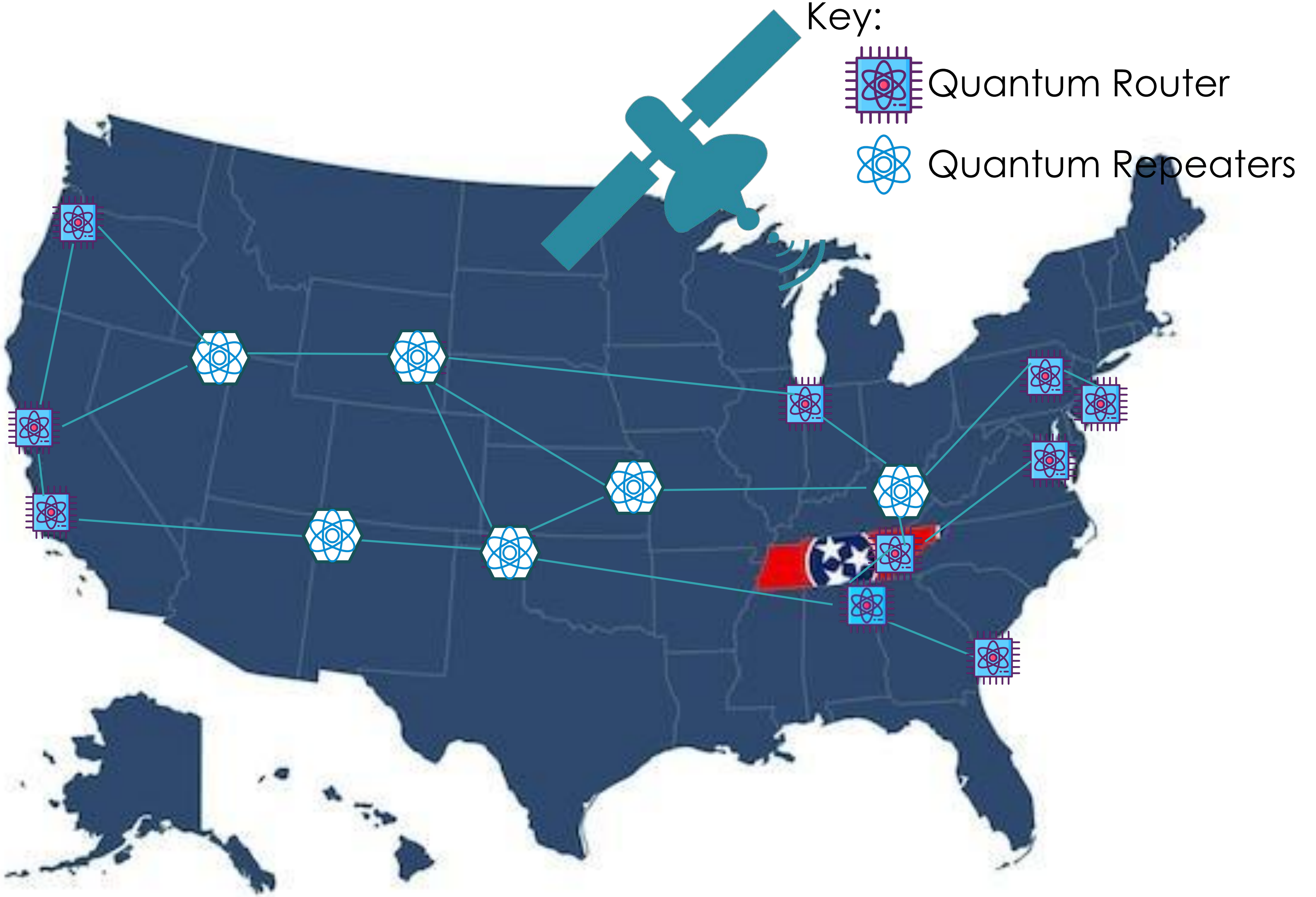
Examples	Distance
Entanglement using trapped ion (Hajdusek et al.) (2023)	50 km
LANL/NIST (2007) QKD	148.7 km
Teleportation Free space (Zeilenger et al.) (2012)	144 km
China (Wei Pan et al.) (2021)	4600 km

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



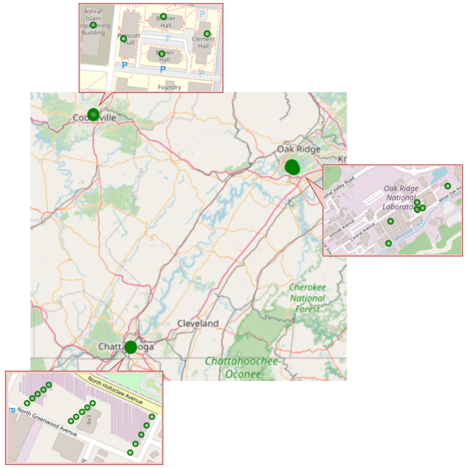
Repeaters, Infrastructure, Protocols and more

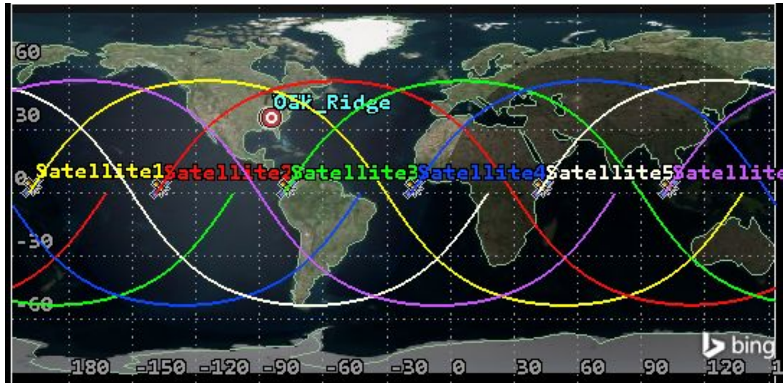
- Impact of fiber quality, working with providers – Loss, fidelity
- Research needed:
  - Quantum memory
  - Splicing
  - Reducing loss (fiber)
  - New routing algorithms (graph problem)



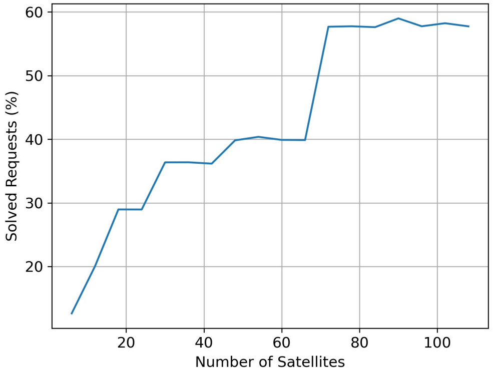
Investigating Satellite Communications

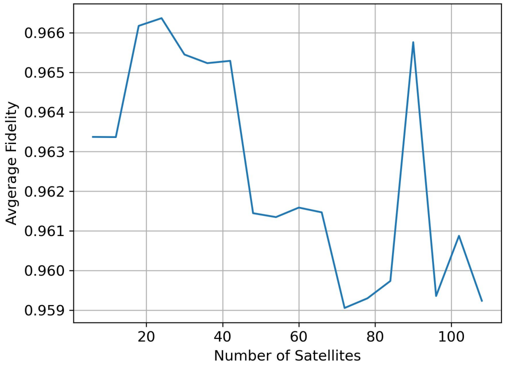
- New optimization algorithms in simulation; until we get satellite access
- Connecting (100 miles apart)
  - EPB Chattanooga
  - ORNL
  - Tennessee Tech





- Optimum number of satellites
  - 108 satellites provides 55.17% day coverage
  - 57.75% of entanglement distribution
  - Average fidelity of 0.96

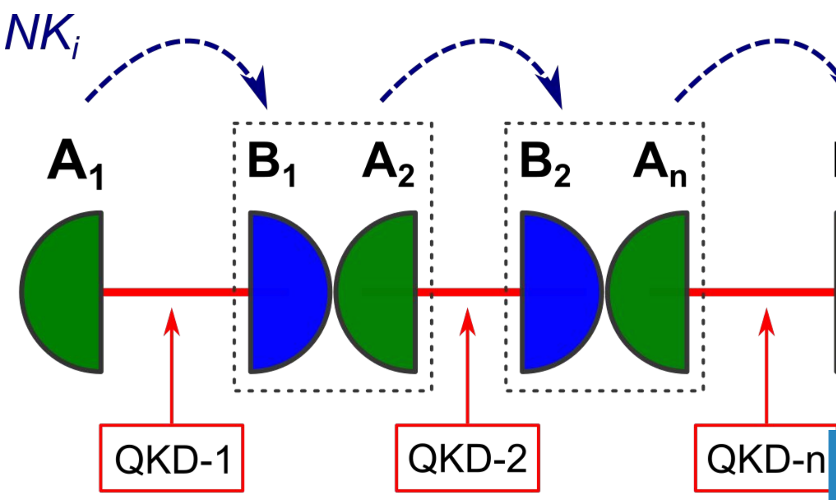




M. Mohammed, et al., INDIS SC (2024)

Quantum Key Distribution as a Key Application

- Distance limitation with QKD
  - Can extend distance with trusted classical relays (upgrade to repeaters later)
- Interest from banks, governments e.g. EU OpenQKD project



NK_i – network/device keys

QK_i^n – quantum keys for link *n*

M_i^n $= NK_i \oplus Qk_i^n$

“hop by hop method”

Energy Infrastructure: Use Case for Quantum Security

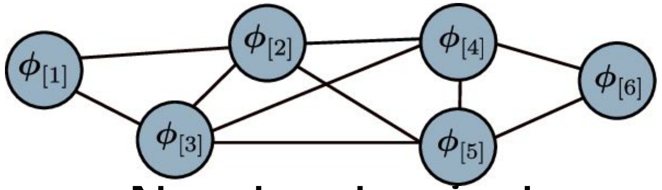
1. Electrical substations: ideal sites for trusted relays
2. Performance requirements match current QKD capabilities

M. Takeoka, S. Guha, & M. M. Wilde, Nat. Commun. **5**, 5235 (2014)

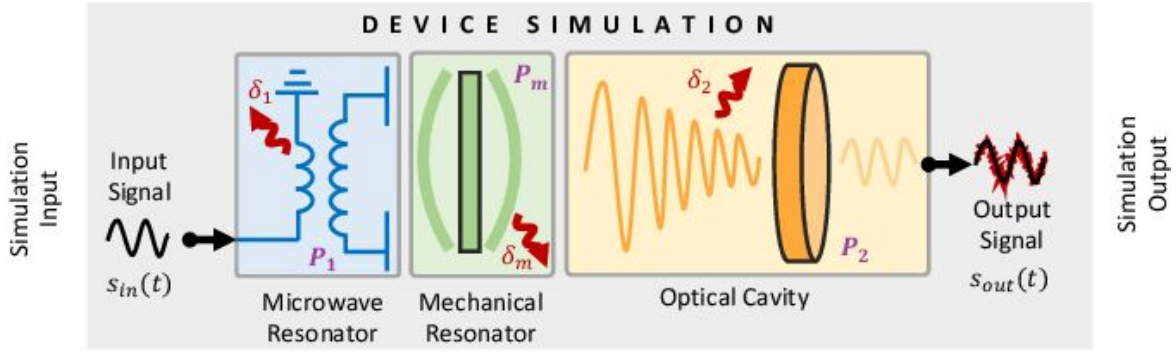
Cybersecurity Challenges and Research Gaps

- It is not clear how to standardize quantum security
  - Cannot use standard cryptography certification approach
  - Regulatory approval for critical infrastructure is an open question
- Secure time distribution
- How do we best use Quantum Random Numbers
- Quantum Key Distribution, Quantum Secret Sharing, and Quantum Digital Signatures experimental demonstrations
- Photonic-Electronic integration

Quantum Sensors as a Key Application



- Quantum Sensors connected over Quantum network
- Qubits converted to photons by frequency modulation or transducer. Need a classical network underneath
- Transducers has shown success up to 60% of successful conversion by Google.
  - New materials can help build better transducers
  - Deep Reinforcement Learning for optimal control or improved conversion efficiency for transducers



SIMULATION PARAMETERS

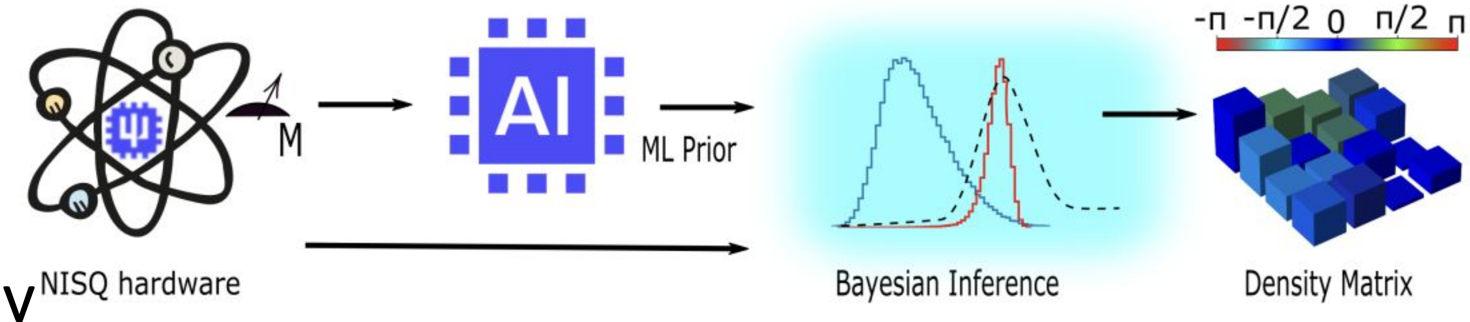
δ_1 – *microwave resonator damping rate*
δ_2 – *optical cavity damping rate*
δ_m – *mechanical resonator damping rate*
P_1 – *microwave resonator parameters*
P_2 – *optical cavity parameters*
P_m – *mechanical resonator parameters*

Proctor et al. Physical Review Letters 2017

Metcalf et al. Optica, 2022

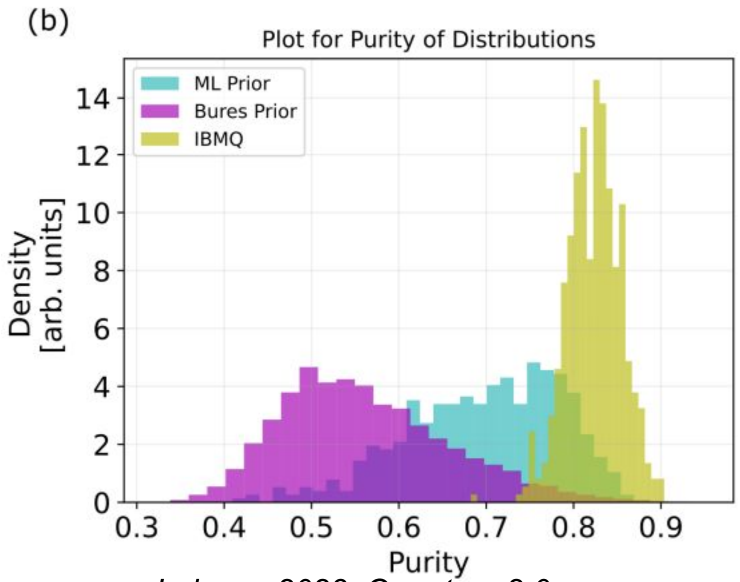
Other SIAM applications: State estimation

- Bayesian quantum state estimation to help
  - Quantum uncertainty
  - Estimates under conditions
  - Reduce MSE



- Important to improve quality of hardware being produced

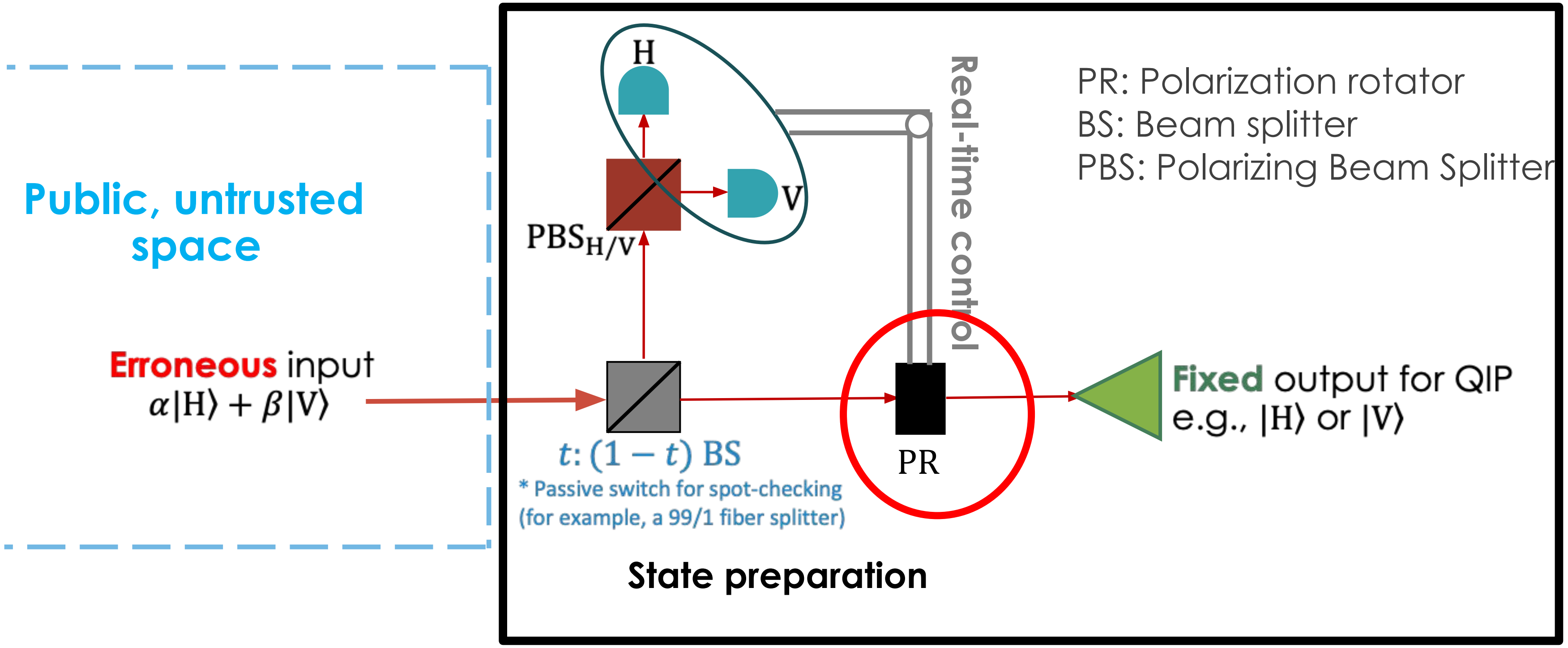
- Novel ways of using ML or prior knowledge to help ‘train’ states and produce better design



Lukens, 2023, Quantum 2.0

AI for Error Minimization or Drift control

Task: Learn the input error, which is unknown and drifting slowly, and then correct the error.



PR: Polarization rotator
BS: Beam splitter
PBS: Polarizing Beam Splitter

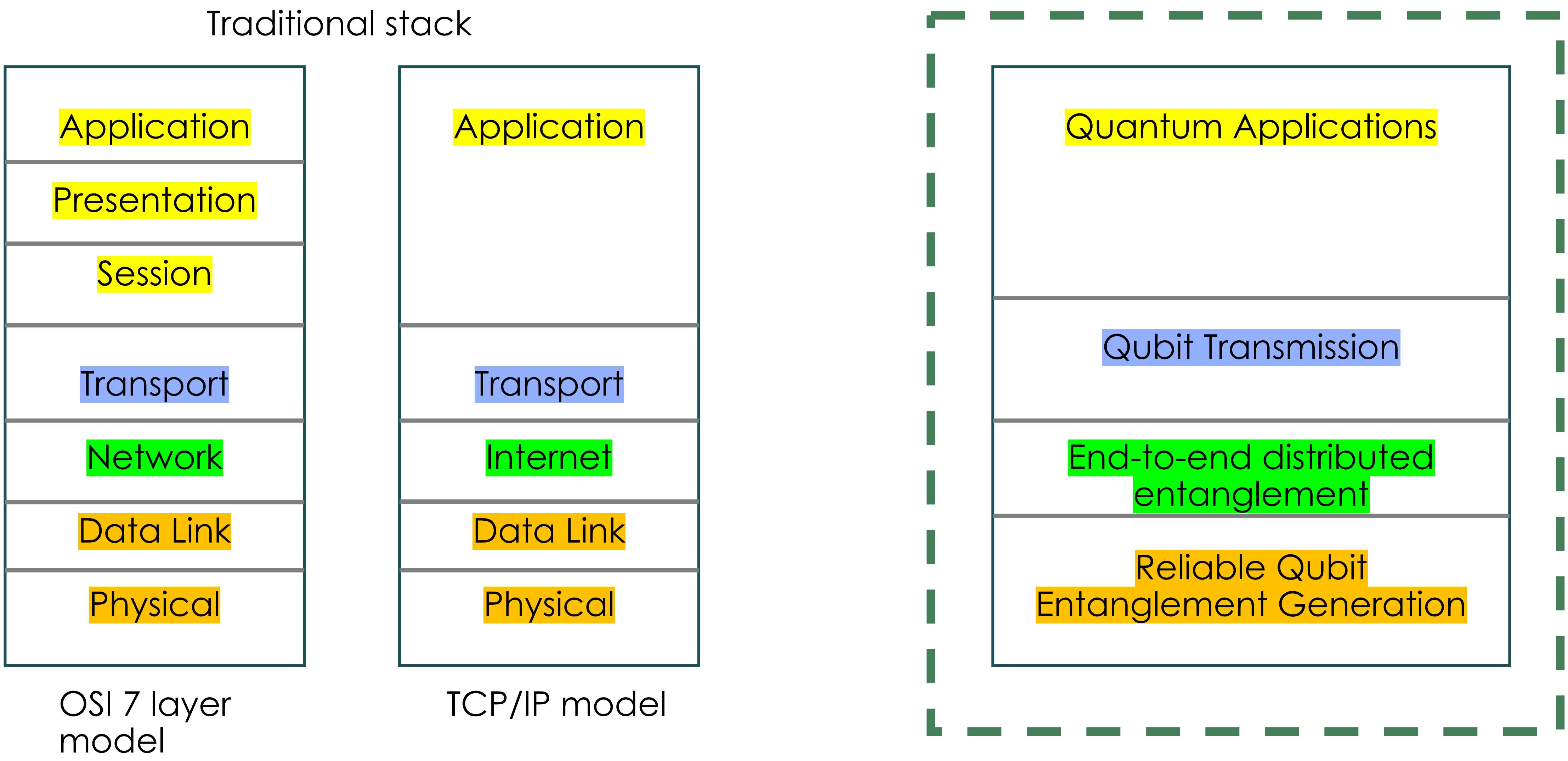
- Reinforcement Learning control to help improve state preparation or more complex cases like entanglement
- Simulation-based to practical demonstration

Y. Zhang, Spot Checking Experiment

Open for New Research Contributions

Quantum Protocol Stack

Traditional stack



OSI 7 layer model	TCP/IP model	Quantum Protocol Stack
Application	Application	Quantum Applications
Presentation		
Session		
Transport	Transport	Qubit Transmission
Network	Internet	End-to-end distributed entanglement
Data Link	Data Link	Reliable Qubit Entanglement Generation
Physical	Physical	

Key Takeaways

General Applications for Quantum Networks

Application	Description
Quantum Key Distribution*	Entangled photons used to securely share encryption keys
Quantum sensing	Measure magnetic fields over large distances with high precision
Secure Cloud Computing or ‘Central Servers’	Secure access to quantum computers in the cloud
Distributed Quantum Computation	Distributed quantum processing across geographically distributed quantum computers

*Current implementations
Hardware developments turn-key installs

Testbeds being developed across USA

Testbed	Authors
EPB Quantum Network (deployed and in operation)	EPB Chattanooga, Tennessee
Oak Ridge Quantum Network Testbed	Oak Ridge National Lab, Tennessee
Center for Quantum Networks (CQN)	Tuscon, Arizona
Boston- Area Quantum Network (BARQNET)	MIT, Harvard, et al.
MIT quantum Network testbed	Boston
Chicago Quantum Exchange (CQE)	Chicago, Illinois
Quantum Application Network testbed for Novel Entanglement Technology (QUANT-NET)	LBNL
AFRL Quantum Network	Rome, NY
NYSQIT Stony Brook	BNL
NICT Quantum Network	National Institute of Information and Communications Technology
DC-Qnet	Washington DC
Los Alamos Quantum network	LANL
QuDIT	LLNL

Simulation toolkits for Research (examples)

	language	Protocol supported
Quisp	C++	Quantum repeaters, memories, QEC
Sequence	python	QKD, Entanglement management, routing
QuNetsim	python	No repeaters yet, Model network, transport layers, Routing experiments
Netsquid	python	Nitrogen vacancy centers in diamond repeater chains, support for Netconf, Quantum Switch
SimQN	python, C/ C++	QKD, entanglement, routing

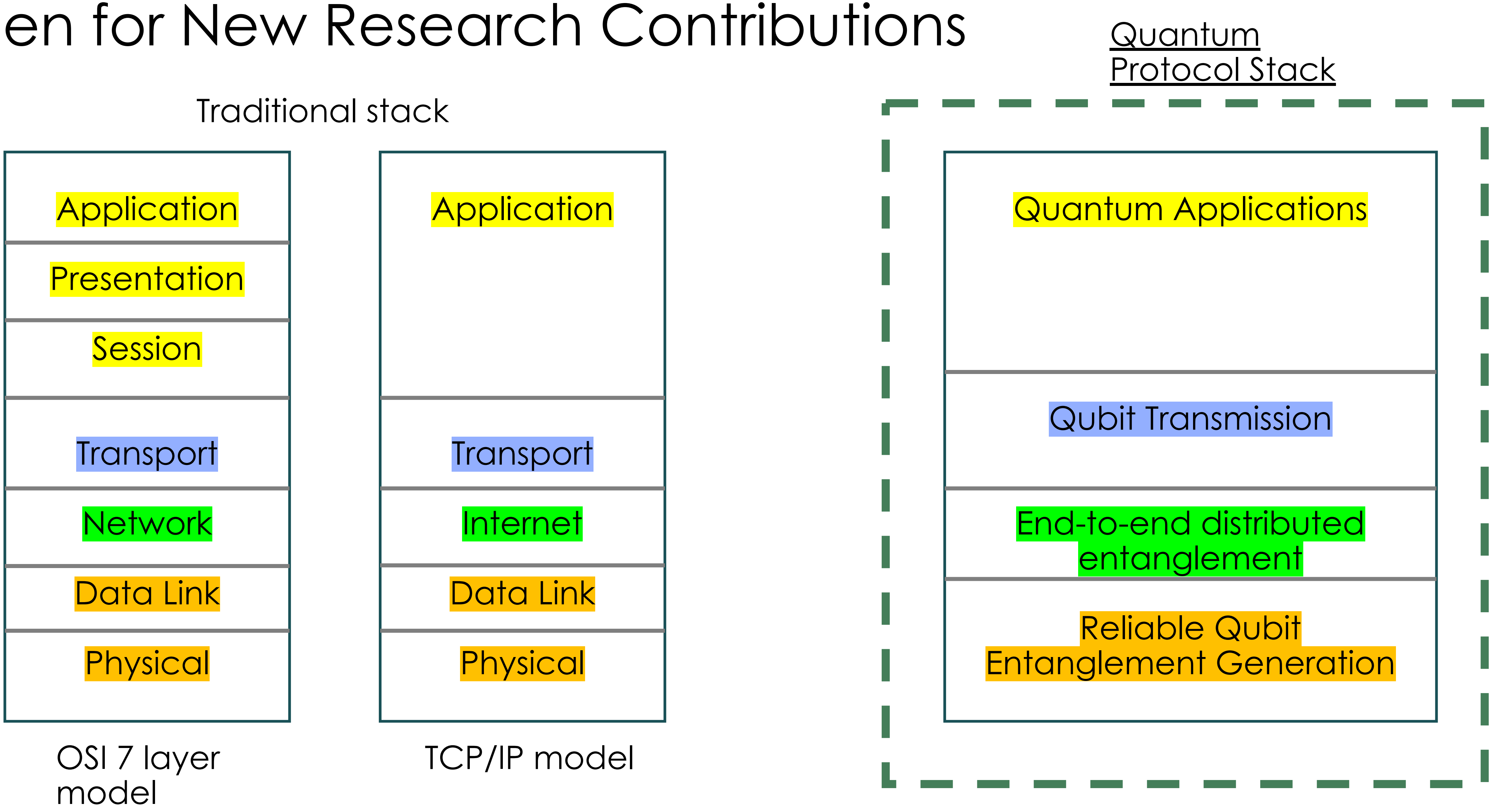
Quantum Networks <u>are essential for Progress</u> in Quantum Computers

- Examples of multiple skills working together
- Patience to listen and understand each other
- Dialogue, internships at labs (SULI, GRO), gain experience
- Open positions at ORNL, Please apply or reach out!

- **Email: <kiranm@ornl.gov>**

- Extra slides

Open for New Research Contributions



Traditional stack

OSI 7 layer model

- Application
- Presentation
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- Physical

TCP/IP model

- Application
- Transport
- Internet
- Data Link
- Physical

Quantum Protocol Stack

- Quantum Applications
- Qubit Transmission
- End-to-end distributed entanglement
- Reliable Qubit Entanglement Generation

- Overview of the field of quantum

- Bayesian estimation of state recontruction, maths for simulation
- Linear optical circuit optimization for frequency processor
- Maths to do gate decomposition… matrix- how we can do this in operations to get thing to do…