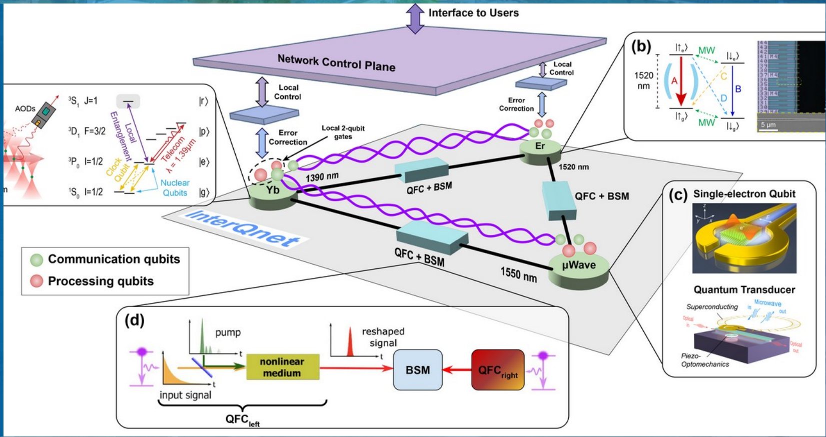
CHI-NOG 13 – MAY 28, 2026

INTERQNET: A HETEROGENEOUS FULL-STACK APPROACH TO CO-DESIGNING SCALABLE QUANTUM NETWORKS



JOAQUIN CHUNG
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OUTLINE

I. Introduction to Quantum Networks

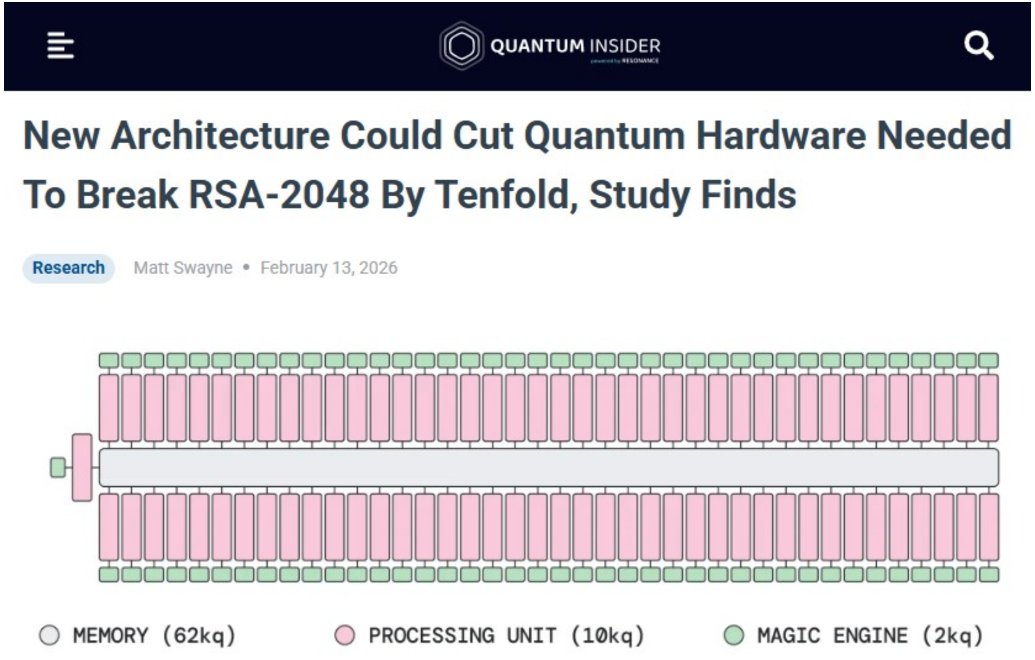
II. Overview of InterQnet

III. Q&A

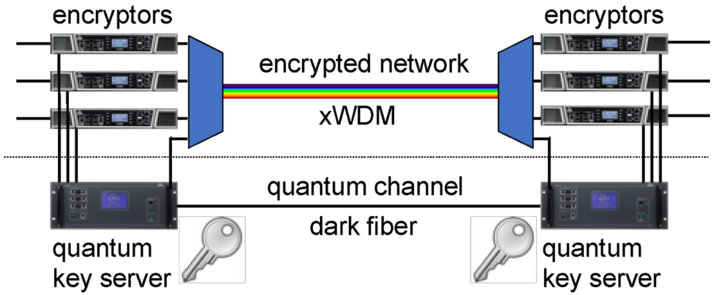
INTRODUCTION TO QUANTUM NETWORKS

MOTIVATION

Quantum-secure Communications



Quantum key distribution (QKD) to the rescue

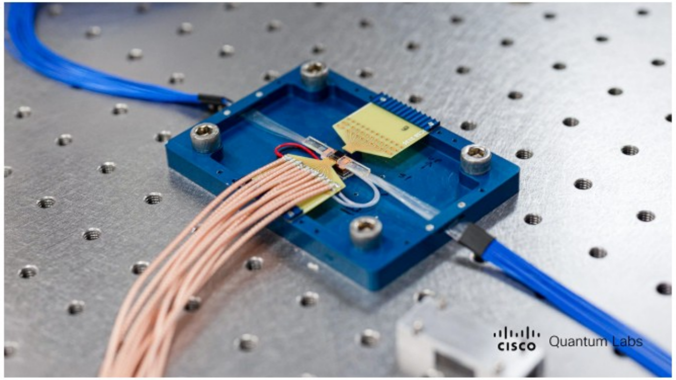


MOTIVATION

Quantum Data Centers

Press Release · Nov 20, 2025 · 6 min read · 9 min listen

IBM and Cisco Announce Plans to Build a Network of Large-Scale, Fault-Tolerant Quantum Computers

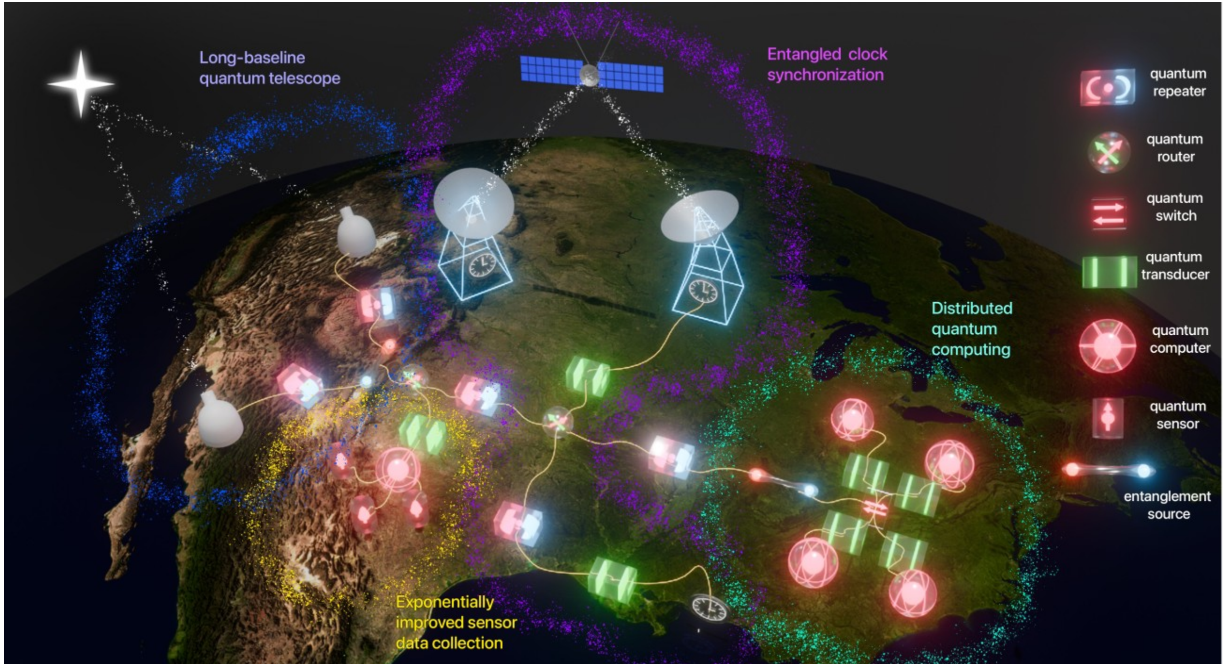


News Summary:

- New collaboration plans to unite strengths of both leaders to design a connected network of large-scale, fault-tolerant quantum computers, targeted by early 2030s
- Companies plan to deliver an initial demonstration of multiple networked quantum computers within five years
- Distributed quantum network could lay groundwork towards quantum computing internet defined by quantum computers, sensors, and communication in the late 2030s

MOTIVATION

A future quantum internet

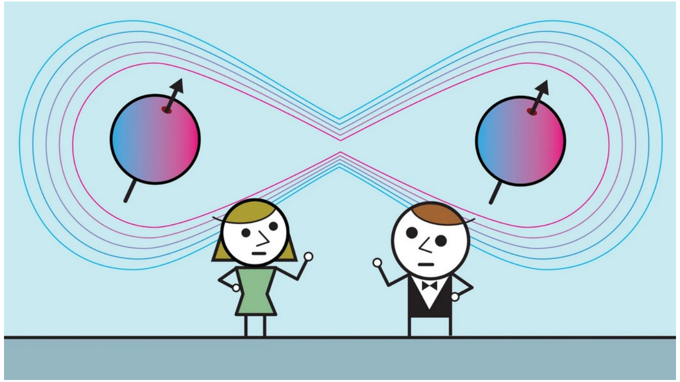


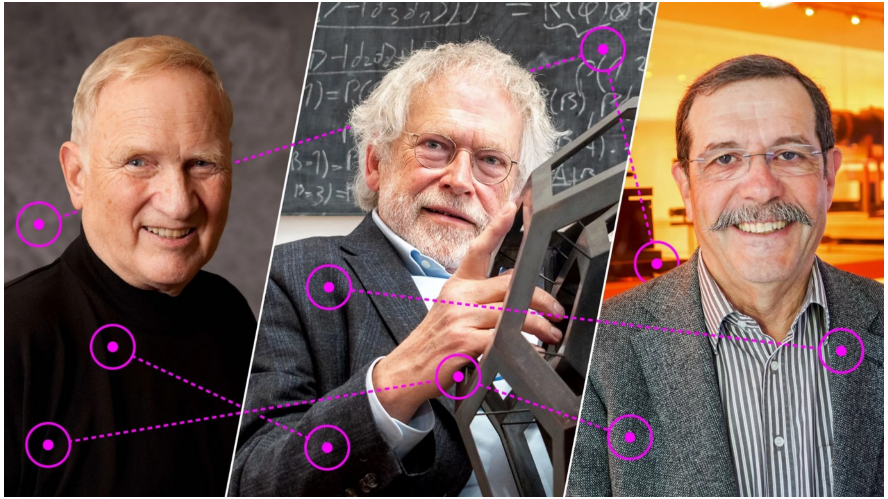
Source: US Department of Energy - 2024 Quantum Information Science Applications Roadmap

QUANTUM ENTANGLEMENT

Foundation for near-term quantum networks

Phenomenon in which two or more particles are connected in such a way that they cannot be described independently. Moreover, they will remain connected despite distance.

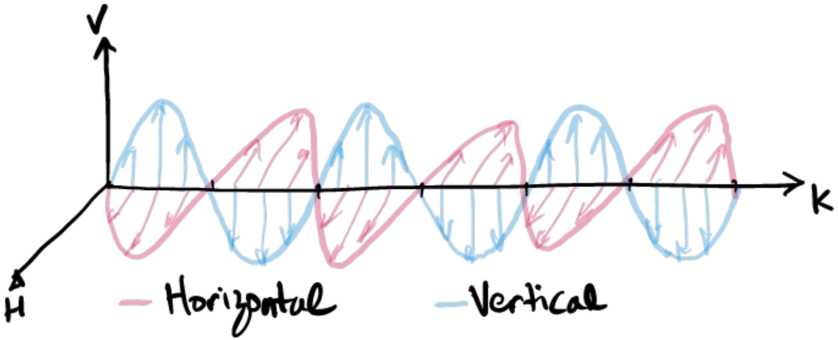


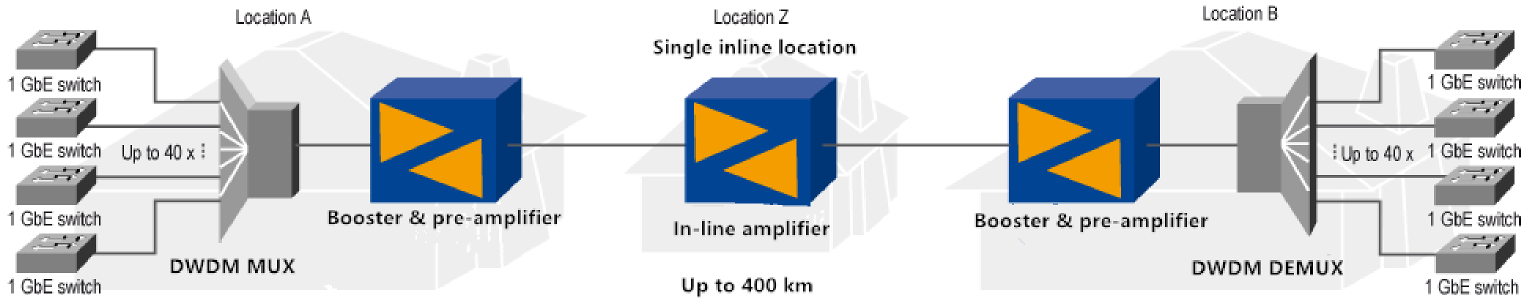


John Clauser, Anton Zeilinger and Alain Aspect, winners of the 2022 Nobel prize in Physics for their work in quantum entanglement

PHOTONS AS FLYING QUBITS

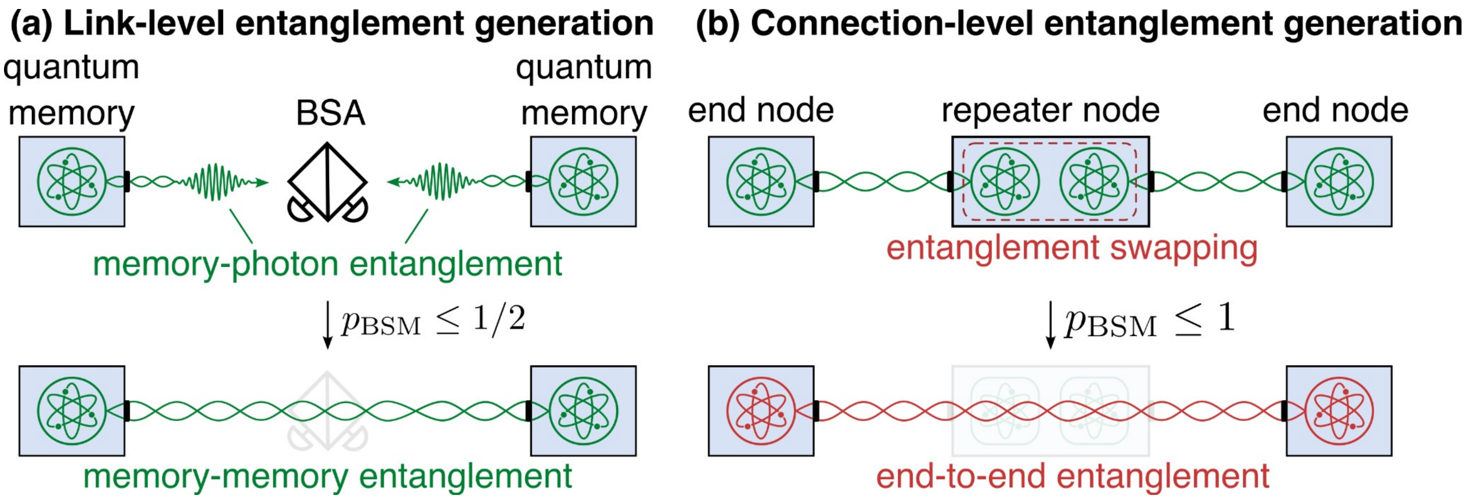
- Can encode quantum information in several degrees of freedom: polarization, frequency, time, etc.
- Still very susceptible to loss → direct transmission is not practical for long distance
- No cloning theorem





REMOTE ENTANGLEMENT GENERATION

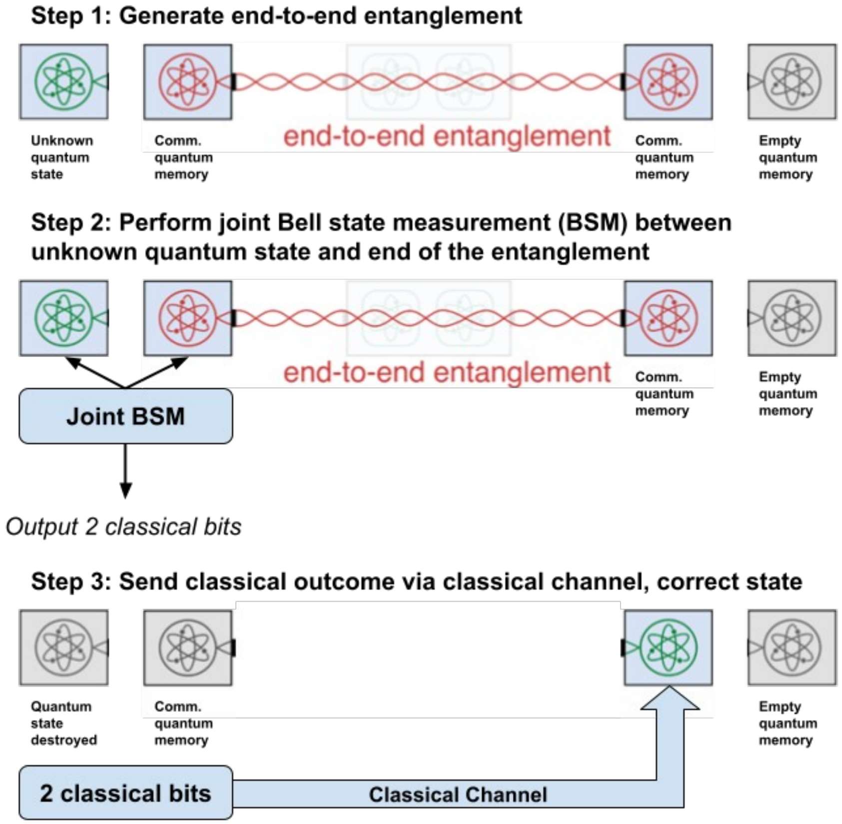
Elementary functions



(a) Entanglement generation using photonic Bell-state measurement (BSM) at the Bell-state analyzer (BSA) in the memory-interference-memory (MIM) link architecture. Success probability is denoted by p_{BSM}.
(b) After successful generation of two neighboring links, the repeater performs entanglement swapping on its quantum memories to create an end-to-end entangled connection.

QUANTUM TELEPORTATION

- Transfers an unknow quantum state from point A to point B using pre-shared entanglement and classical communication
- Not application, more like `socket.send(msg)`
- **No! There is no faster than light communication!!!**

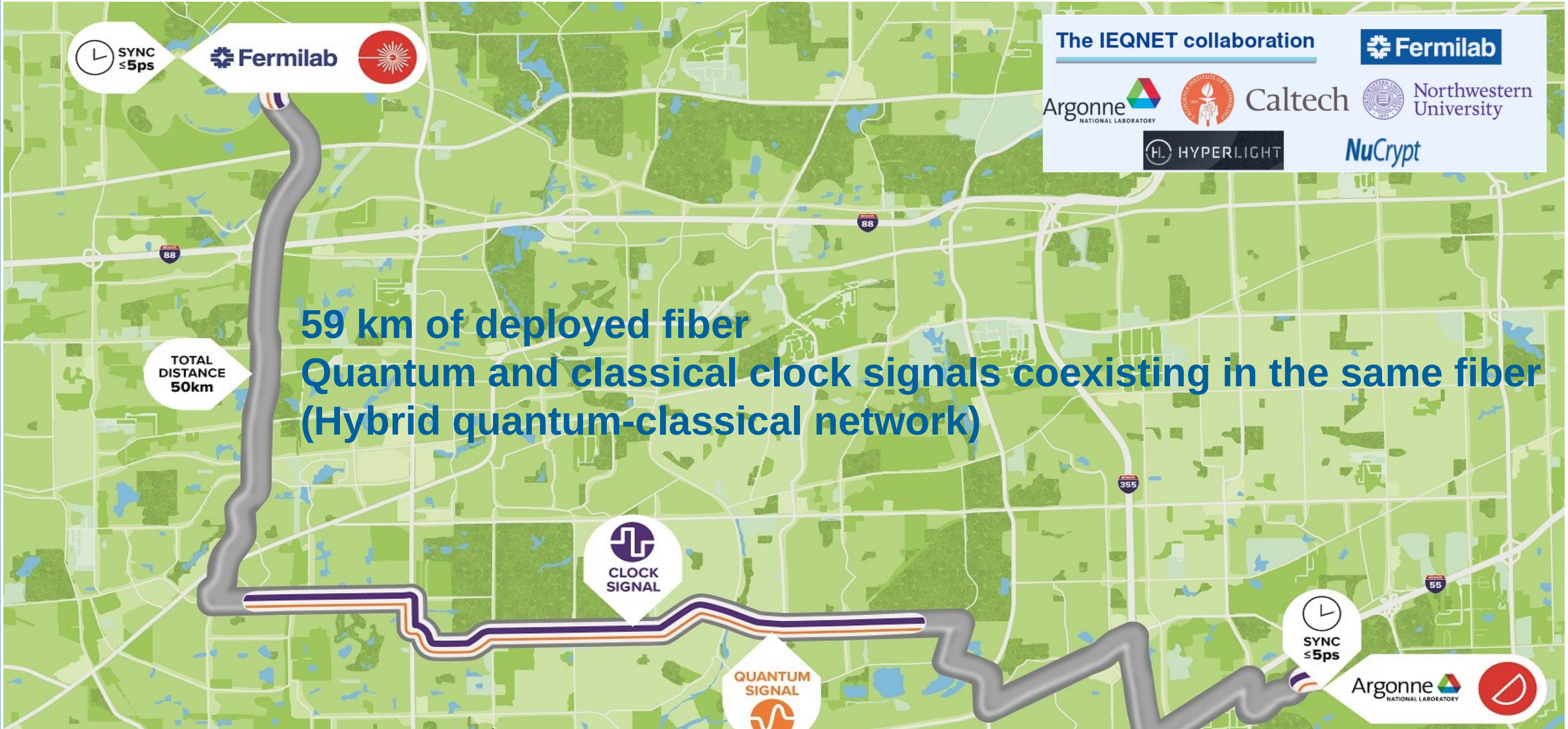


ENTANGLEMENT GENERATION DEMONSTRATION IN CHICAGO

ENTANGLEMENT DISTRIBUTION OVER A 26 MILE LOOP

Awschalom, Dibos, Heremans et. al

REMOTE ENTANGLEMENT BETWEEN ARGONNE AND FERMILAB



59 km of deployed fiber

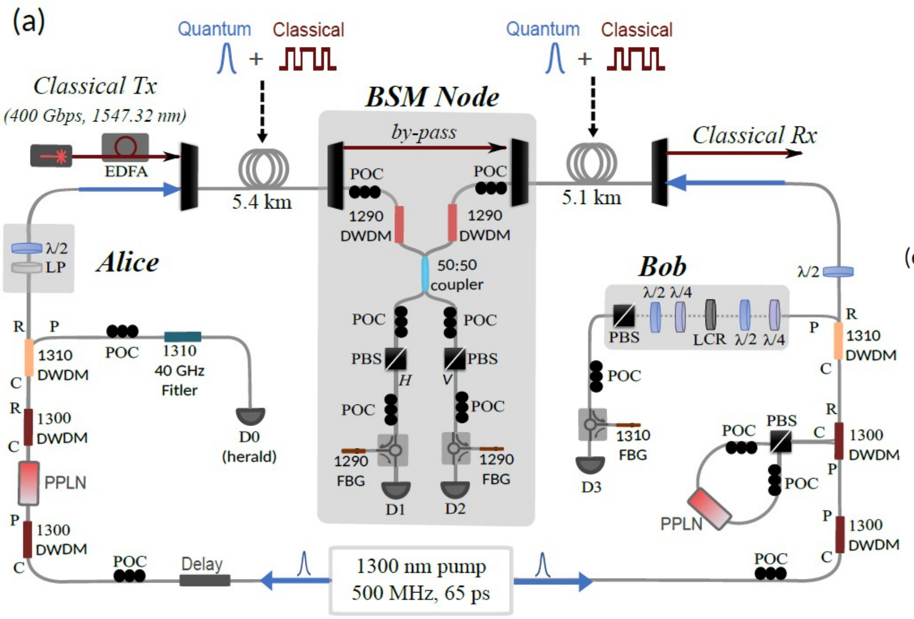
Quantum and classical clock signals coexisting in the same fiber

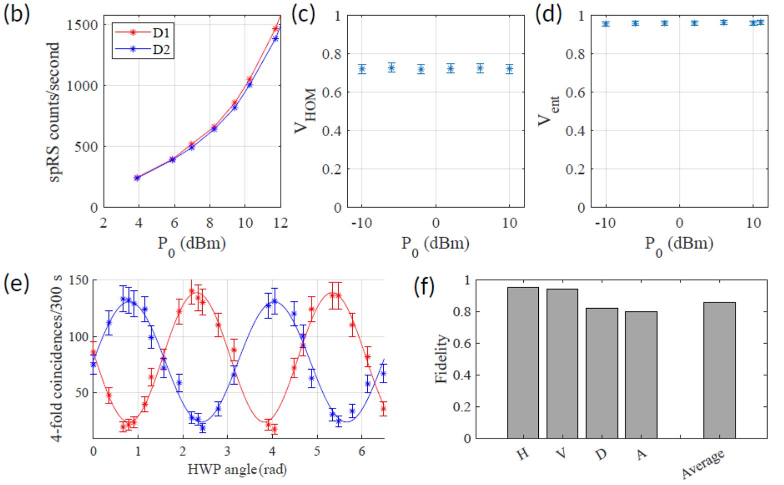
(Hybrid quantum-classical network)

K. Kapoor, S. Xie, J. Chung, R. Valivarthi, C. Peña, L. Narváez, N. Sinclair, J. P. Allmaras, A. D. Beyer, S. I. Davis, G. Fabre, G. Iskander, G. S. Kanter, R. Kettimuthu, B. Korzh, P. Kumar, N. Lauk, A. Mueller, M. Shaw, P. Spentzouris, M. Spiropulu, J. M. Thomas, and E. E. Wollman, "Picosecond synchronization system for the distribution of photon pairs through a fiber link between Fermilab and Argonne national laboratories," IEEE Journal of Quantum Electronics, pp. 1–1, 2023.

QUANTUM TELEPORTATION OVER OPTICAL FIBERS CARRYING CONVENTIONAL CLASSICAL COMMUNICATIONS TRAFFIC

Hybrid quantum classical networks



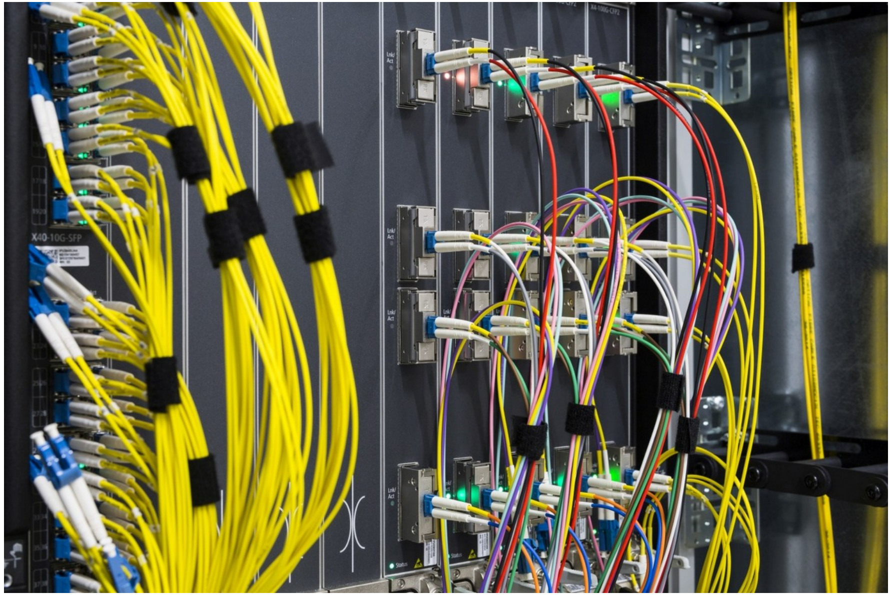


Jordan M. Thomas, Fei I. Yeh, Jim Hao Chen, Joe J. Mambretti, Scott J. Kohlert, Gregory S. Kanter, and Prem Kumar, "Quantum teleportation coexisting with classical communications in optical fiber," Optica 11, 1700-1707 (2024)

The scalability of quantum networking will benefit from the ability to operate beyond dark fibers. We report the first demonstration of quantum teleportation coexisting with conventional communications, where quantum state transfer is achieved over 10.5 km SMF-28 fiber simultaneously carrying a 400 Gbps classical signal.

QUANTUM NETWORKS ARE STILL IN THEIR INFANCY

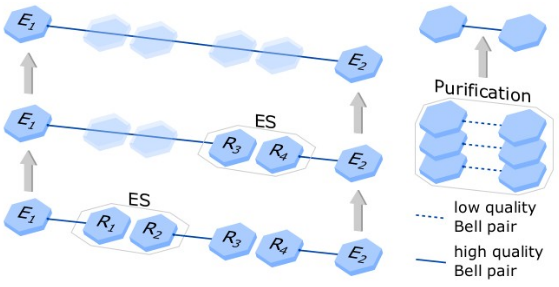
How to Scale Quantum Communication Networks?



THE STATE OF THE ART

Long distance entanglement and Quantum Internet Visions

- Current state of the art focuses **mainly on scaling a chain of repeaters**, *but* other dimensions of scalability don't get enough attention: heterogeneity of devices, number of users, diversity of services provided, and resilience
- Early attempts to define a protocol stack try to **map quantum networks to the TCP/IP stack**, *but* this translation may be impossible and may oversee other important functions for maintaining and operating a network



Van Meter et al., 2021

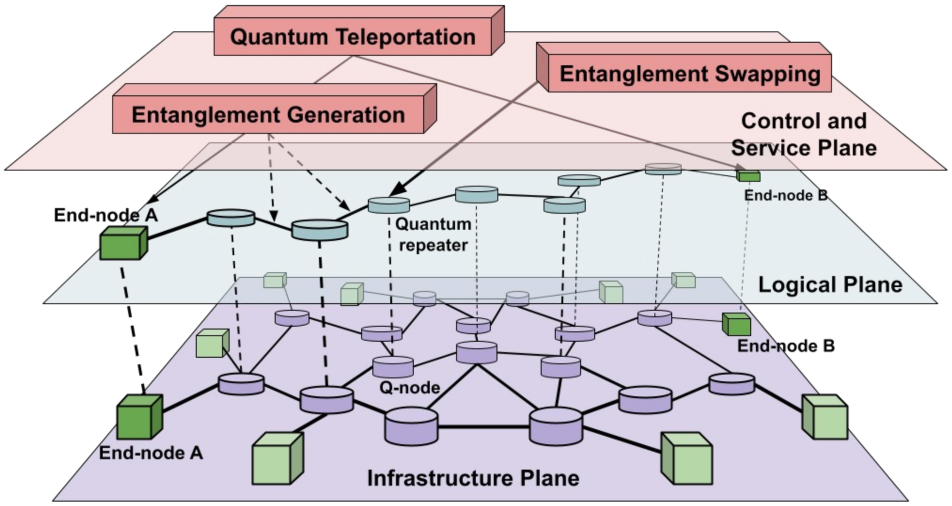
Application	
Transport	Qubit transmission
Network	Long distance entanglement
Link	Robust entanglement generation
Physical	Attempt entanglement generation

Dahlberg et al., 2019

THE SCALABILITY CHALLENGE

To go beyond repeater chains and replicas of TCP/IP...

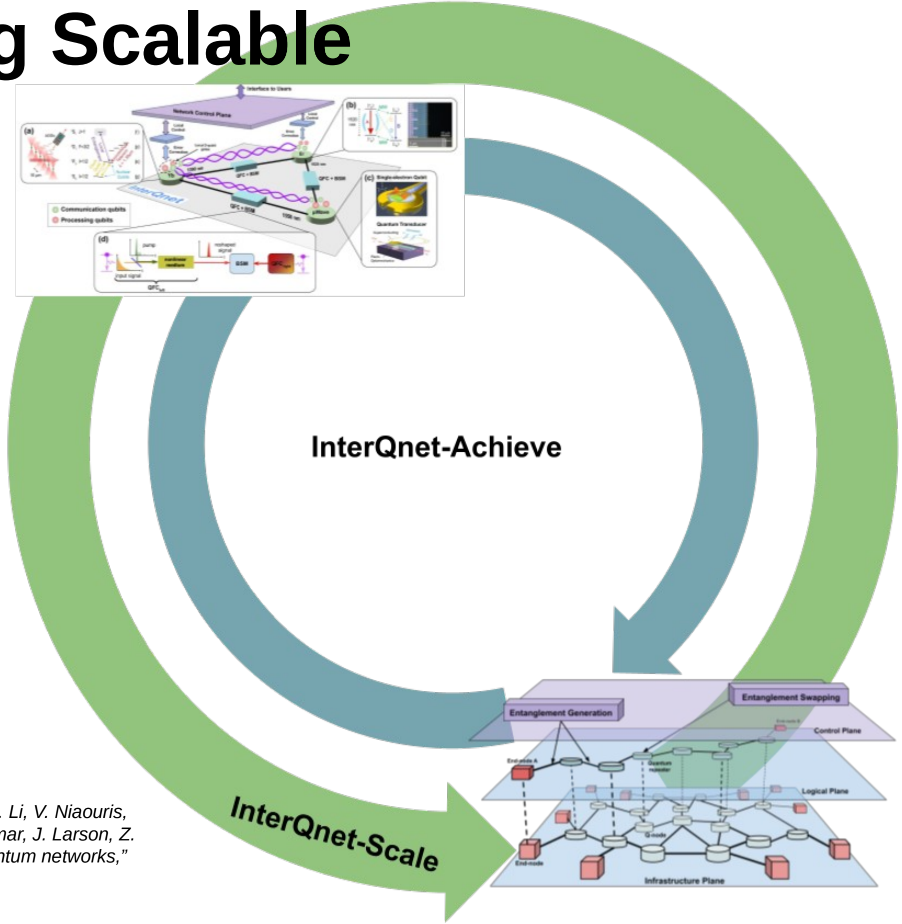
- To develop an understanding of scalable quantum communication networks from the perspective of less studied dimensions of scalability:
  - —Heterogeneity of devices
  - —Diversity of applications
  - —Scale of user demands



OVERVIEW OF INTERQNET

InterQnet: A Heterogeneous Full-Stack Approach to Co-designing Scalable Quantum Networks

- Advance the state of the art in scalable quantum communications
- Realize two interrelated overarching goals:
  - **InterQnet-Achieve** – Practical realization of a full-stack heterogeneous quantum network
  - **InterQnet-Scale** – Systems study of a scalable quantum network architecture

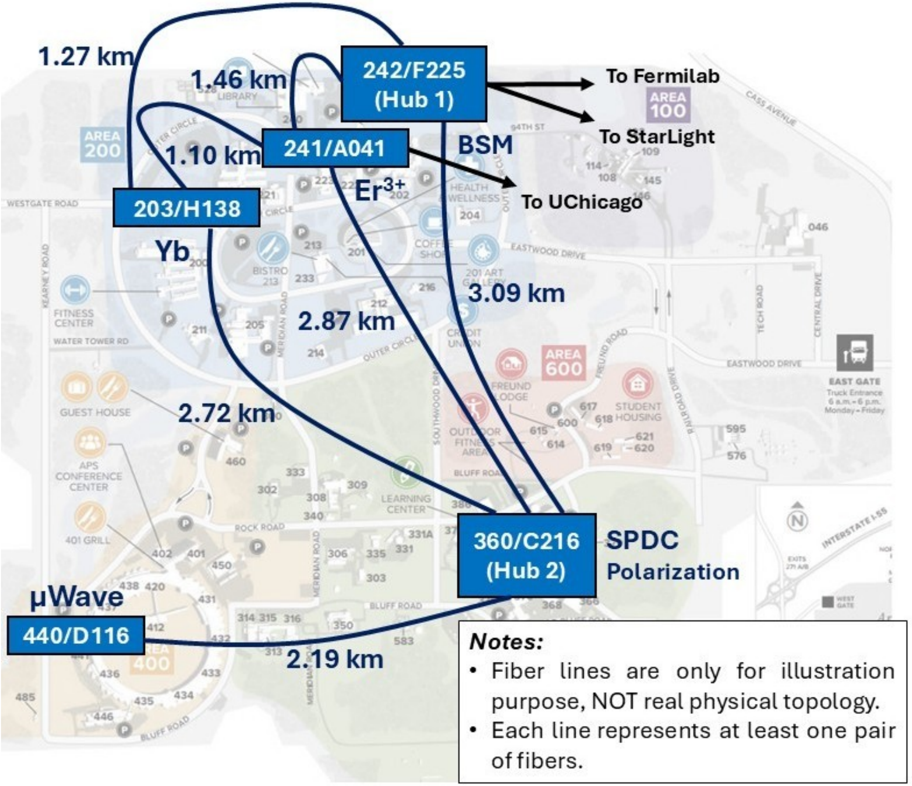


J. Chung, D. Dilley, E. Eastman, A. Gonzales, K. Hokenstad, M. S. Islam, V. Jorapur, J. Petrullo, A. C. Y. Li, B. Li, V. Niaouris, A. Ramesh, A. Singal, Z. Ye, C. Zhan, M. Bishof, E. Chitambar, J. P. Covey, A. Dibos, X. Han, L. Jiang, P. Kumar, J. Larson, Z. H. Saleem, and R. Kettimuthu, "InterQnet: A heterogeneous full-stack approach to co-designing scalable quantum networks," IEEE Transactions on Quantum Engineering, pp. 1–21, 2026.

ARGONNE QUANTUM NETWORKING TESTBED

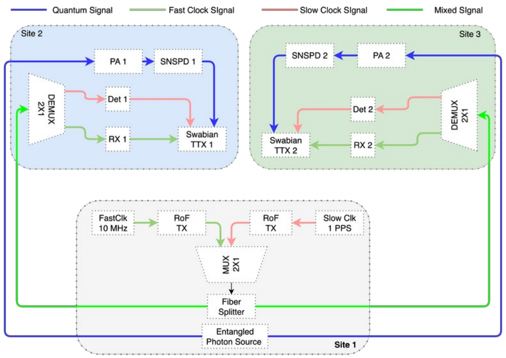
InterQnet-Achive

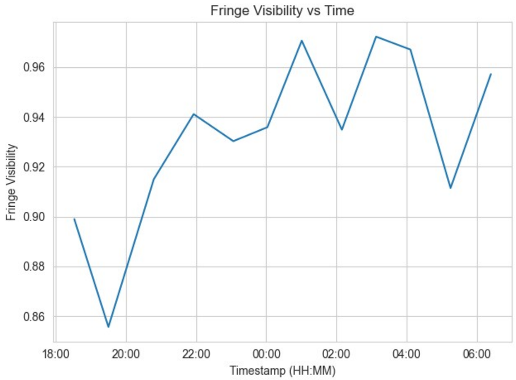
- Connects **5 buildings in the Argonne campus** on a partial mesh topology using deployed optical fiber
- Development of **three qubit platforms**: Ytterbium atoms, Erbium ions, and superconductiong microwave qubits
- **Long distance connections** to Fermilab, UChicago, and StarLight using dark fiber

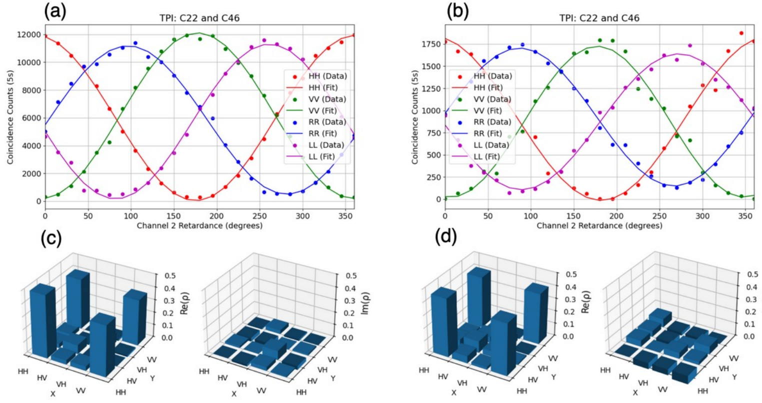


ARQNET CONTROLLER PROTOTYPE AND PRELIMINARY RESULTS

- **Implementation:**
  - Agents enable remote control of devices (e.g., EPS, SNSPD, all-optical switches, and time taggers)
  - RF over Fiber custom clock synchronization system
  - Communication over gRPC
  - Centralized control, automated calibration, and continuous operation
- **Evaluation:**
  - Two-photon interference and Quantum state tomography
  - Observed fringe visibility ~95%
  - Continuous fringe visibility measurements over 12 hours with polarization drift compensation







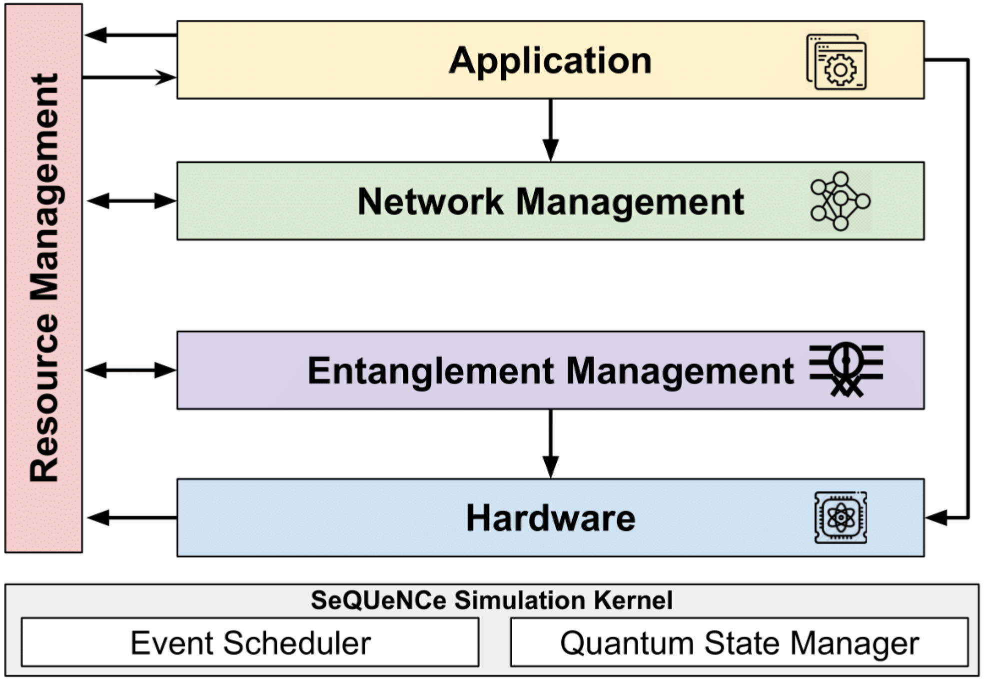
arXiv:2511.01247v1

SIMULATOR OF QUANTUM NETWORK COMMUNICATION (SEQUENCE)

https://github.com/sequence-toolbox/SeQUeNCe

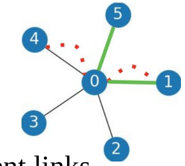
SeQUeNCe Simulator Overview

- Modularized discrete event simulator with a clear separation of functionality
- Simulates quantum communication at photon-level with picosecond accuracy
- Allows simulations with different parameters, protocols, topologies, and network architectures
- Hardware models of single-atom memories, entanglement generation, swapping, and purification protocols

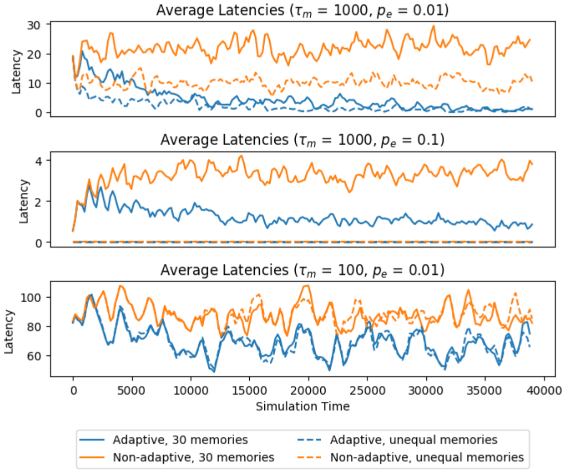


Simulation Studies with SeQUeNCe (Part 1)

Adaptive, Continuous Entanglement Generation [INFOCOM WKSHPS 2022]



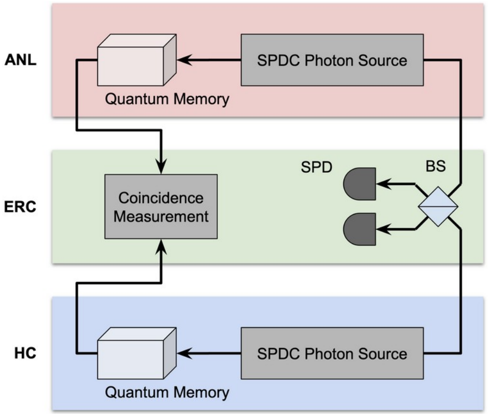
- Pre-generate entanglement links
- Adapt to historical entanglement usage



- Advantage over non-adaptive continuous generation, thus over on-demand generation
- Importance of resource allocation in network

complex scenarios

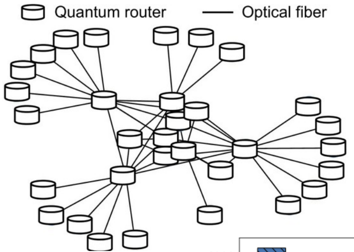
Absorptive Memory Entanglement Generation Simulation [QCE22]

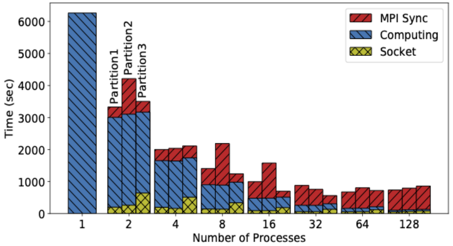


- Hardware components, quantum state representation, error models for network simulation
- Effective fidelity, generation rate calculation
- Density matrix reconstruction simulation
- To be extended to more realistic, complex scenarios

Parallel Quantum Network Simulation [TOMACS'23]

- Parallelize simulator to improve performance, while preserving realism
- Identify key challenges
- Develop parallel simulation kernel
- Identify scheme for improved lookahead
- Test different methods of partitioning network for parallel processes

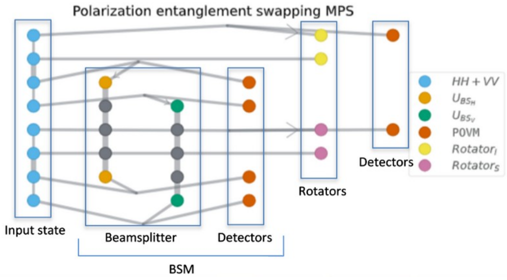




Simulation Studies with SeQUeNCe (Part 2)

Simulation of Polarization Entanglement Swapping using Tensor Networks [FiO 2024]

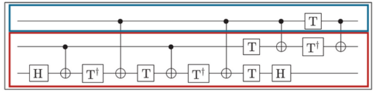
- Simulation of polarization entanglement distribution and swapping using tensor networks to avoid exponential scaling of density matrices for several composite Hilbert space modes.



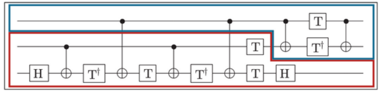
- Evaluate performance of Tensor networks against sparse density matrix simulations for varying simulation parameters like mean-photon number and local Hilbert space dimension (truncation).

Towards Distributed Quantum Computing by Qubit and Gate Graph Partitioning Techniques [QCE'23]

- Explore two different approaches to partitioning a quantum circuit for the distributed quantum computing

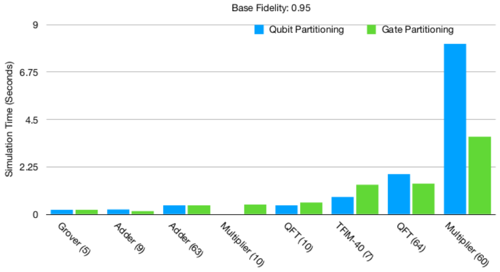


Qubit partition



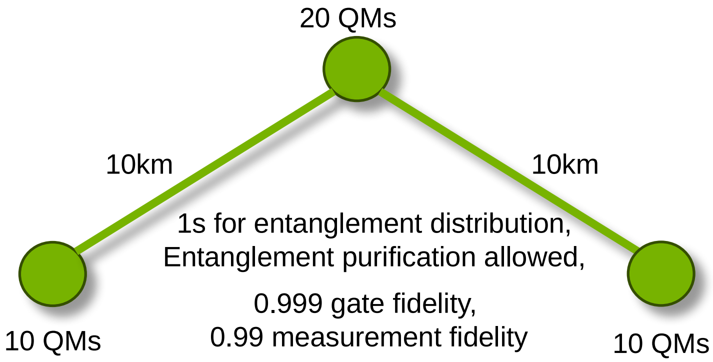
Gate partition

- Use SeQUeNCe to evaluate the overhead introduced by entanglement generation and purification



Quantum Advantage in Distributed Sensing with Noisy Quantum Networks [arXiv:2409.17089]

- Global GHZ state has the potential to enable quantum advantage in distributed sensing



- Simulation of GHZ state distribution through realistic, noisy quantum network stack.
- Evaluate GHZ state quality under different scenarios via success probability p, relative quantum advantage for distributed sensing η and GHZ state fidelity F conditioned on success, and normalized relative advantage $\tilde{\eta} = p \cdot \eta$ (the larger the better, relative advantage below 1 means no quantum advantage)

Simulation Studies with SeQUeNCe (Part 3)

Adaptive Continuous Entanglement Generation Protocol (ACP) [QCNC 2025]

- Continuously generate entanglement links with neighbors, while adapting to request patterns
- Distributed, online, and asynchronous ACP implemented in SeQUeNCe
- Customized single heralded entanglement generation protocol that is aware of pre-generated EPs

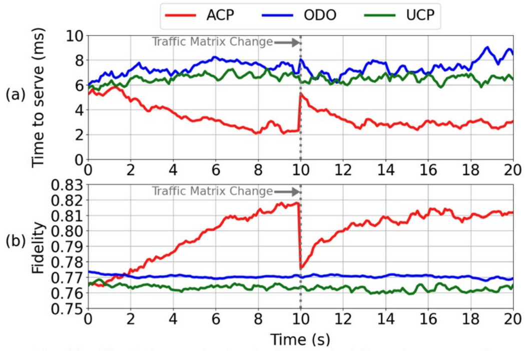
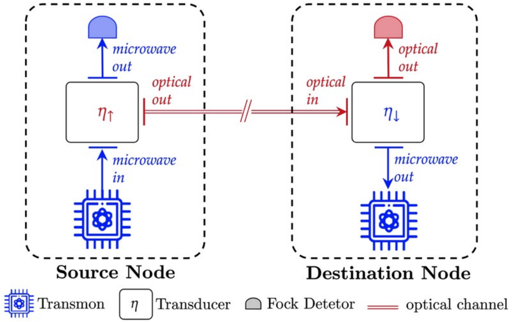


Fig. 10. Simulation results for the 200-Node AS topology network.

- Request's time to serve is decreased by 60%~94% and the end-to-end fidelity is increased by 0.01~0.05

Quantum Transducer Simulation [QCE25]

- Quantum transducer: the quantum interface that converts microwave photons into optical photons and vice-versa.

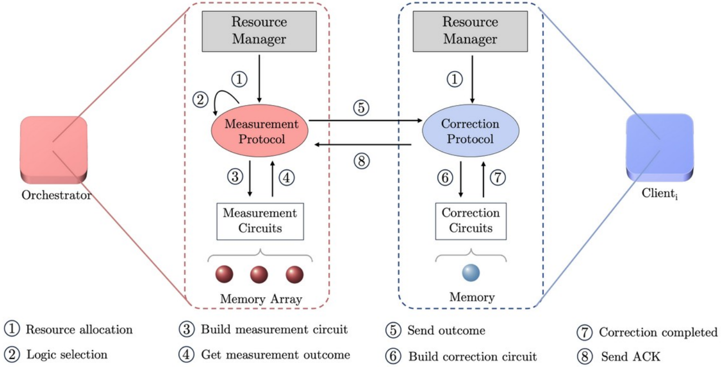


- Model the quantum transducer as a beam splitter
- Implement two quantum transducer protocols in SeQUeNCe:

1) Direct quantum transducer
2) Entanglement-based quantum transducer

Quantum Local Area Network (QLAN) Simulation [ICC 2025]

- QLAN: Envision to be the building block of the future Quantum Internet



- One Centralized orchestrater: locally generate and distribute multipartite entangled state
- Multiple clients: EP between any pair of clients can be established by manipulating a pre-shared multipartite entanglement.
- We implemented a measurement protocol and correction protocol. Verified the correctness of QLAN

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