Control-plane Stack and Two-level Scheduler with Network Layers and Protocols being Developed at QUANT-NET

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  - Thomas Schenkel, Chris Tracy, Se-Young Yu, Liang Zhang

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  - Tracy Northup, Viktor Messerer

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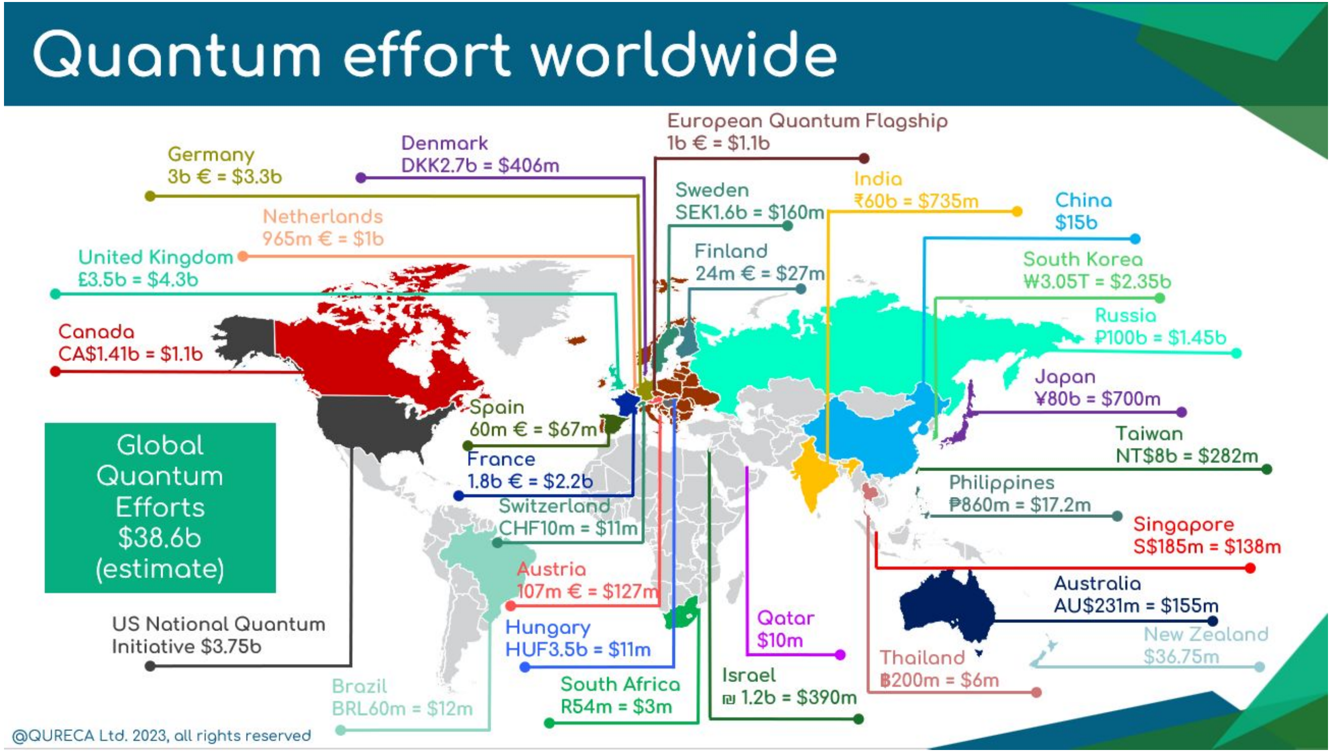
Agenda

- An Introduction to the QUANT-NET project
  - Why quantum networks?
  - A three-node quantum network testbed at Berkeley
- Quantum Network Control Basic Needs
- QUANT-NET Control Plane Design and Implementation
  - A Two-level Control Framework and the Scheduler
    - Logically centralized control
    - TDMA-like scheduling
    - Real-time control in a distributed environment
    - An open plugin framework
- Conclusion

Quantum Computing and Networking is a Worldwide Initiative



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OCTOBER 11, 2023 Editors' notes

The race is on for a new internet

by Jonathan O'Callaghan, Horizon: The EU Research & Innovation Magazine

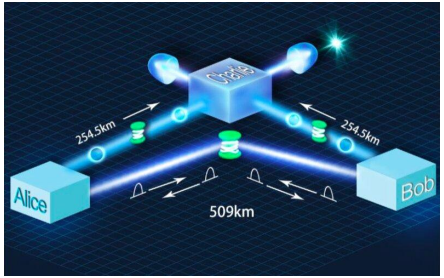
Credit: AI-generated image

Europe is pushing to create a network infrastructure based on quantum physics.

What is a quantum network good for?

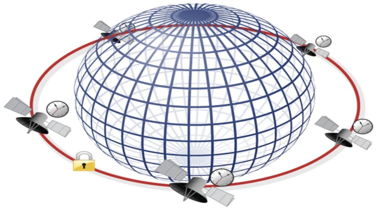
Secure quantum communication

Secured by quantum physics laws



Sensing and metrology

Komar, Peter, et al. "A quantum network of clocks." *Nature Physics* 10.8 (2014): 582-587.



Seismic Sensing Using Quantum Cryptography Network

May 2, 2022 • *Physics* 15, 63

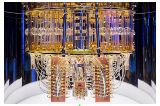
An experiment demonstrates that quantum key distribution networks, which are part of highly secure cryptography schemes, can also detect and locate earthquakes.

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.128.180502

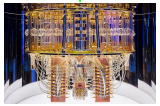
Scalable quantum computing

A quantum computer is limited in size. Connected by quantum networks, multiple quantum computers can work together as one big quantum computer.

quantum computer

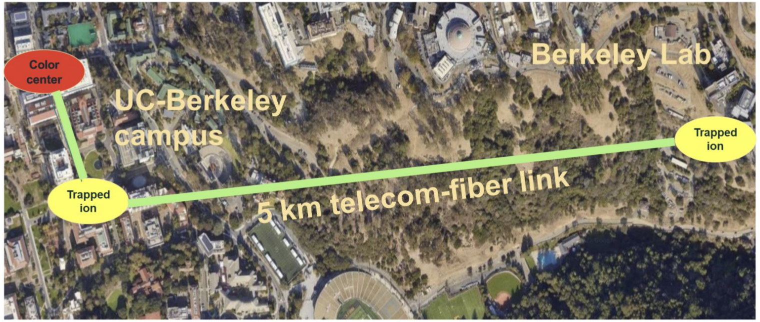


quantum computer

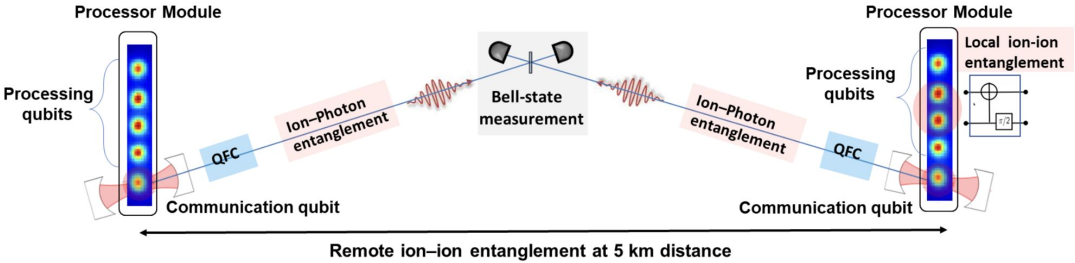


The QUANT-NET testbed

- A DOE/ASCR funded quantum network research project (Oct 2021 - Oct 2026)
  - Berkeley Lab, UC Berkeley, Caltech, the University of Innsbruck
- Project goals:
  - Develop a three-node quantum networking testbed system at Berkeley demonstrating the basic elements of distributed quantum computing, quantum repeaters, and quantum hybrid systems based on the trapped ion and color center technologies.
  - Architect and implement scalable quantum network protocols, control, and monitoring for the testbed



A three-node quantum networking testbed at Berkeley

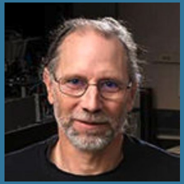


Distributed quantum computing between remote trapped-ion nodes

The QUANT-NET research team

Leadership

Inder Monga
Berkeley Lab
(PI)



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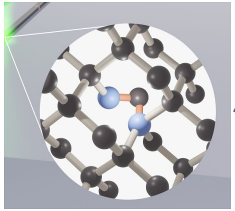
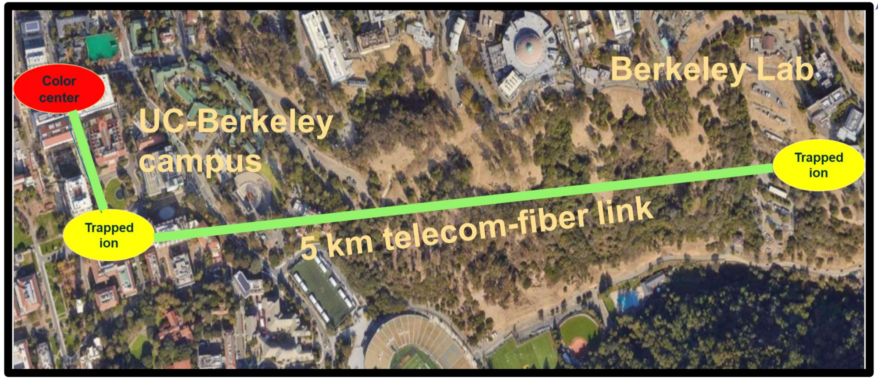
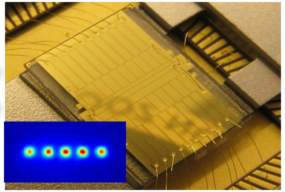
Three main areas of research



Color-center based
Single-photon source

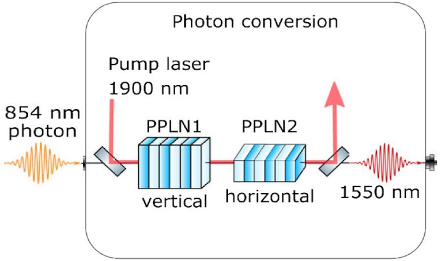
1. Repeater-friendly
Quantum-node technologies



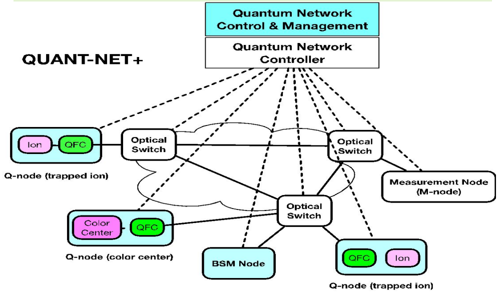


Trapped-ion
quantum computer

2. Quantum frequency conversion



3. Quantum network control



For our quantum network control R&D, we strive to:

- To build a quantum network control plane to orchestrate and manage all the physical layer technologies.
  - E.g., trapped ions, superconducting qubits

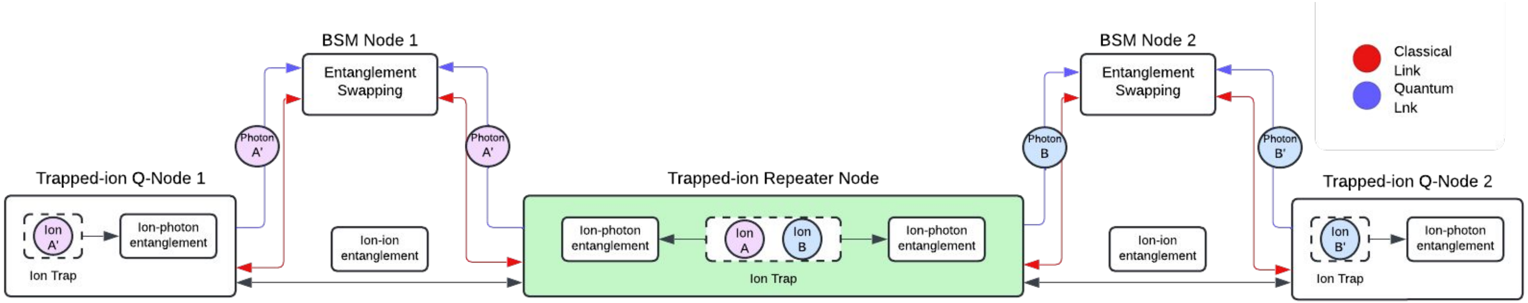
- Explore what a quantum network control plane should look like in the future, so as to automate high-rate and high-fidelity entanglement generation, distribution, and storage in an efficient, reliable, and cost-effective way.

Quantum network control plane design goals

Goal 1: Support high-rate and high-fidelity entanglement generation, distribution, and storage in an efficient, reliable, and cost-effective way.

- Entanglement is the fundamental building block of a quantum network.
- Key entanglement-related functions include entanglement generation, entanglement swapping, and entanglement distillation etc.
  - Involve in-network operations
  - Rely on the maintenance of states inside the network

Divergence from the end-to-end principle for the traditional Internet design



A control plane that supports such a paradigm is required

Quantum network control plane design goals (Cont.)

Goal 2: Schedule synchronized operations in a distributed environment.

Key characteristics of entanglement functions in a quantum network:

- Multiple quantum objects (e.g., qubits) involved in a distributed environment
- Quantum objects in the Noisy Intermediate-Scale Quantum (NISQ) era
  - Fragile, sensitive to noise
  - Limited coherence time
- A set of operations to be executed
  - It is necessary to execute the set of operations in a tightly synchronized manner before decoherence destroys the quantum information

Quantum network control plane design goals (Cont.)

Goal 3: Schedule calibrations that are to executed regularly in a quantum network.

A practical and useful quantum network requires:

- Long coherence-time qubits
- High-fidelity quantum gate operations
- High-fidelity quantum communications

To enable such capabilities, each quantum network device and channel must be actively monitored, calibrated, and optimized in a periodically manner.

Quantum network control plane design goals (Cont.)

Goal 4: Support real-time control in a distributed environment.

- Accurate control and manipulation of quantum objects in a quantum network requires a time resolution of μs scale or less.
- Control plane requires tight timing control, imposing hard real-time constraints at the lowest levels.

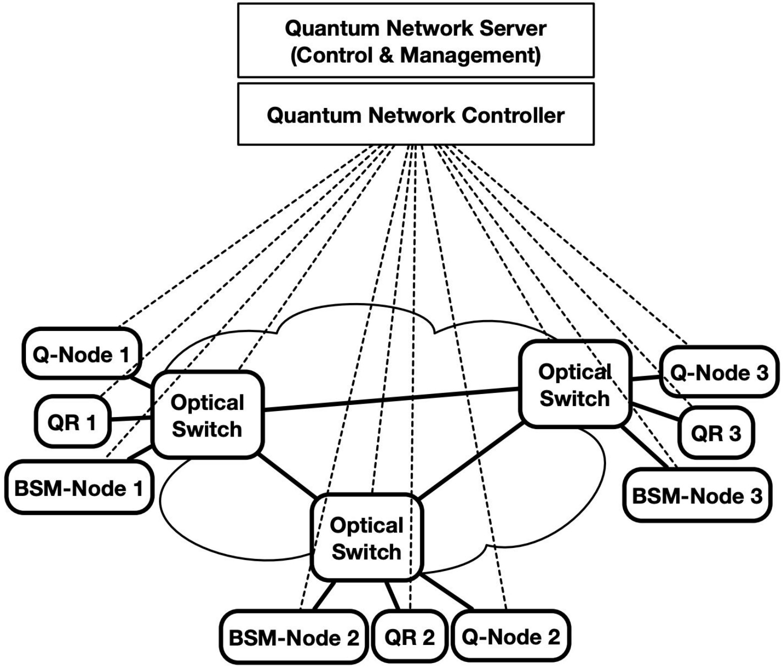
Goal 5: Ability to discover network resources, build and maintain network topology, make routing decisions, manage and configure quantum network devices, and monitor network status

The challenge is to developed an efficient, extensible, robust, and reliable control plane to provision these functions.

QUANT-NET control plane design & implementation

Design choices	Targeted Goal(s)
1. Logically centralized control ● Centralization of control state and logic inside a logically centralized control plane support faster and more efficient entanglement operations	Goal 1
2. TDMA-like scheduling ● Support synchronized operations in a distributed environment ● Allow calibrations to be executed regularly	Goal 2 and 3
3. Real-time control in a distributed environment ● Time-critical functions run on dedicated real-time control systems ● Dedicated channels for real-time communication	Goal 4
4. An open plugin framework ● Allow for dynamic insertion of new services and functionalities in the control plane	Goal 5

QUANT-NET network model & architecture



Major quantum entities

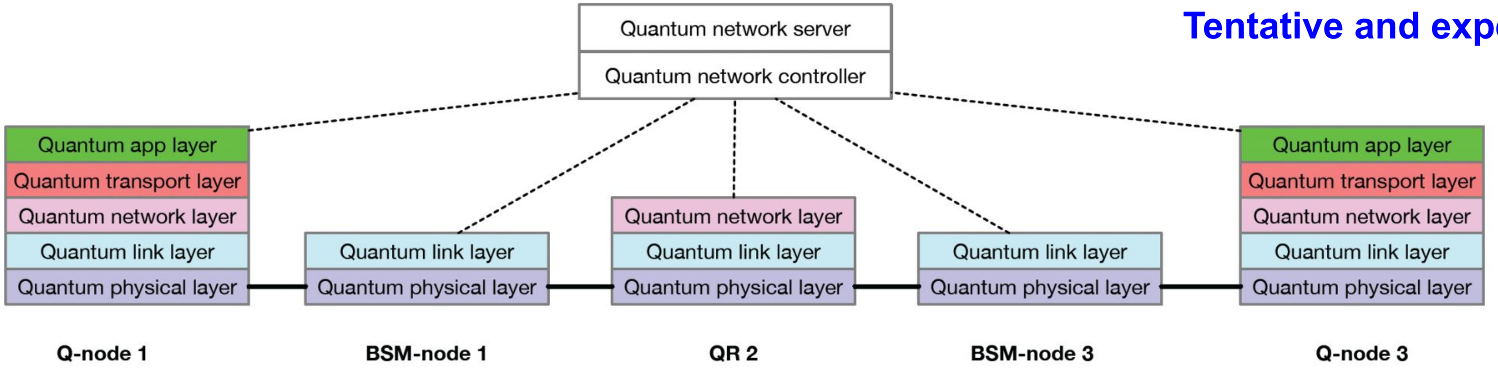
- Quantum end nodes (Q-nodes)
  - To perform both classical and quantum functions
- Quantum repeaters (QRs)
  - To extend quantum networks into larger distance
  - To correct errors and mitigate loss
- Bell-State-Measurement nodes (BSM-nodes)
  - To perform Bell state measurements and local Pauli operations for incoming photon pairs
- Quantum channels
  - To transmit quantum signals between Q-nodes, QRs, and BSM-nodes

➢ **A logically centralized control**

➢ **Decoupled control and quantum plane**

➢ **Multiple quantum network controllers and servers required for a large-scale quantum network**

QUANT-NET network model & architecture (Cont.)

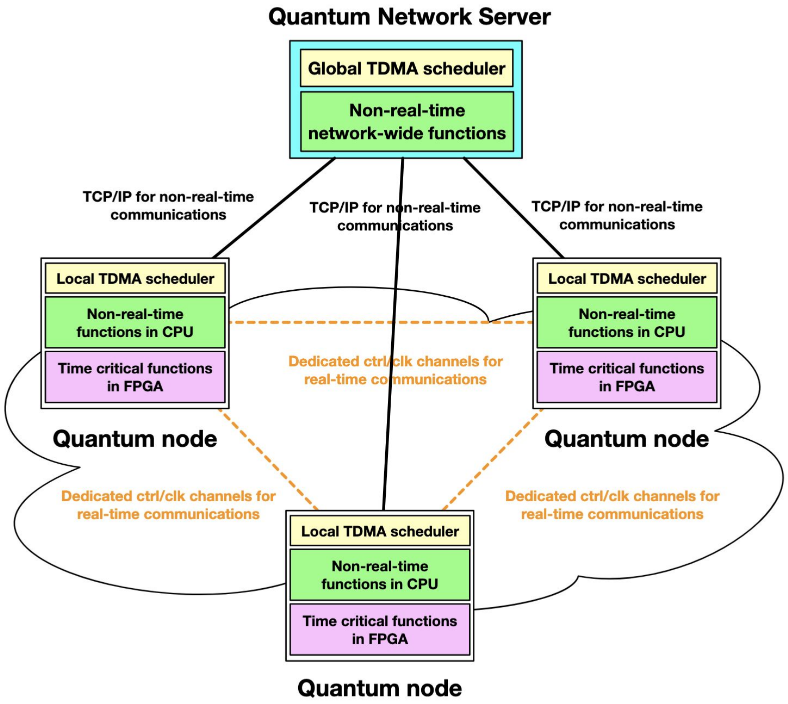


Tentative and experimental

Inspired by the TCP/IP protocol suite, QUANT-NET implements a similar layered quantum network architecture

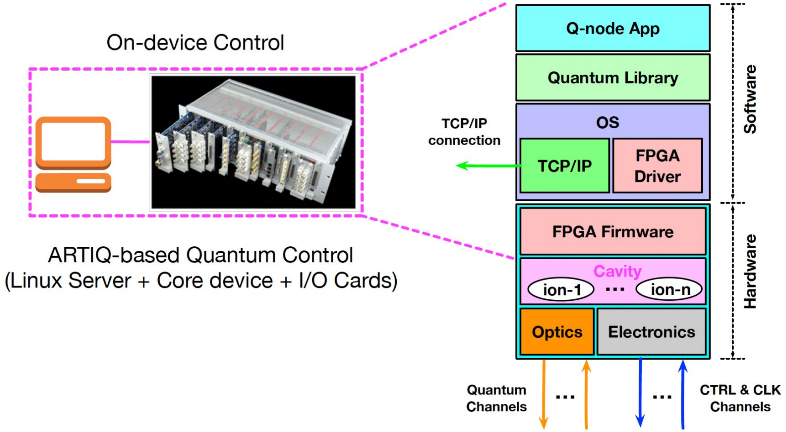
- **Quantum physical layer**
- **Quantum link layer**
  - Heralded entanglement generation
  - Heralded entanglement purification
- **Quantum network layer**
  - Entanglement routing
  - Entanglement swapping
- **Quantum transport layer**
  - End-to-end entanglement generation
  - End-to-end entanglement purification
  - QoS specification/negotiation
- **Quantum application layer**

Two-level control framework

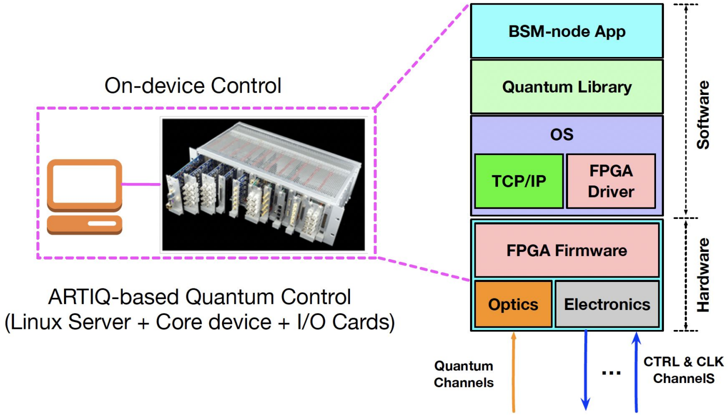


- **Network-wide (global) non–real-time control**
  - A logically centralized Quantum Network (QN) server
  - A global TDMA-like scheduler handles network-wide non-real-time functions
    - Topology discovery, monitoring, link calibration and optimization
- **Node-wide real-time control**
  - Each node is built using a dedicated real-time control system
  - A local TDMA-like scheduler handles node-wide real-time functions:
    - Qubits control, gate operations
    - Node calibrations

Two-level control framework - node-wide real-time control



An ARTIQ-based trapped-ion Q-node



An ARTIQ-based BSM-node

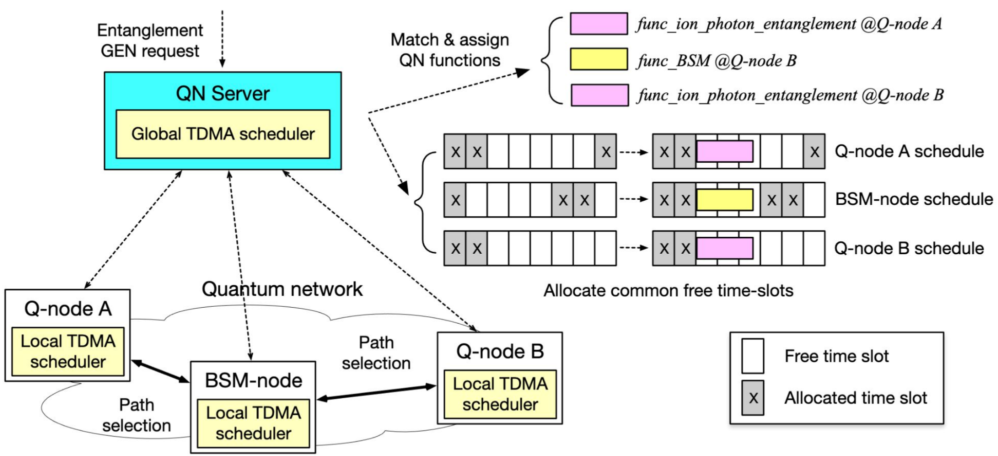
Major functions:
- Local quantum computations using trapped ions
- Single photon generation
  - Ion-photon entanglement
- Quantum frequency conversion
  - 854 nm → 1550 nm
- Conventional computation and communication

Major functions:
- Channel calibration and optimization
  - Classic pulses
- HOM analyzing unit
- Bell state measurement

ARTIQ (Advanced Real-Time Infrastructure for Quantum physics) https://m-labs.hk/experient-control/artig

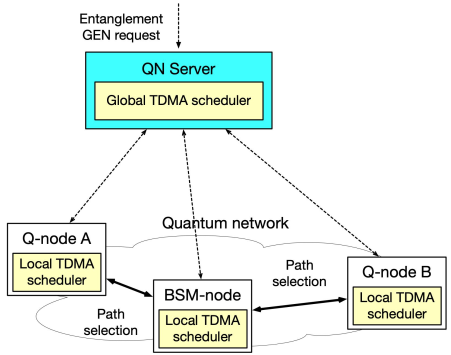
Two-level control framework - the scheduler

- TDMA-like operations
  - The total duration of quantum network operations is divided into fixed interval time-slots that run continuously.
  - Allocate free time-slots and schedule quantum network operations for specific quantum devices in allocated time-slots.
- The global scheduler schedules global quantum network operations:
  - On a periodic basis, for example, to schedule link calibration tasks.
  - On a event-driven basis, to handle user requests.

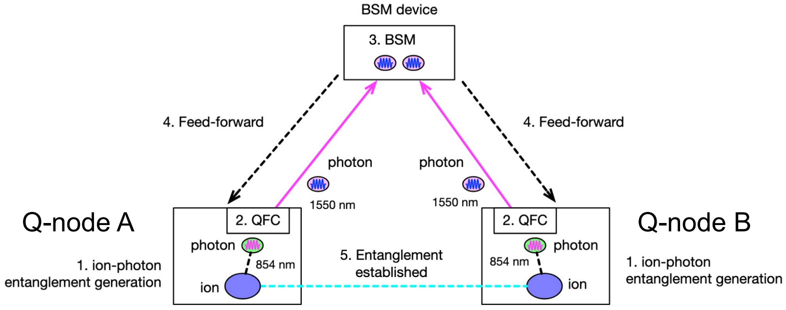


- **Support synchronized operations in a distributed environment**
- **Allow calibration tasks to be executed regularly**

Two-level control framework - support synchronized operations



1. Quantum network topology



2. Remote ion-ion entanglement generation process

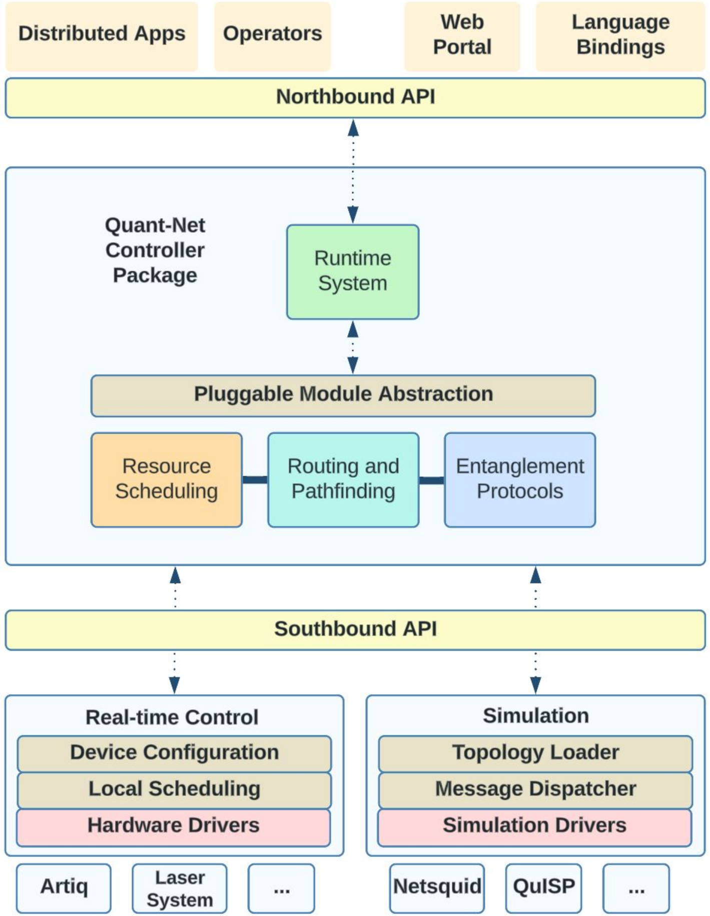
3. How the control framework supports such a process

Two-level control framework - an open plug-in framework

- A framework for exploring a range of quantum networking approaches
  - Include working reference implementations but within a modular, extensible software platform
  - Demonstrate real code on real hardware but also create a bridge to simulation

- Create an opportunity for the quantum network community to evolve together

Allow for dynamic insertion of new services and functionalities in the control plane



Conclusion

- The talk discusses a two-level control framework for quantum networks. Within such a framework, a two-level scheduler is implemented to support TDMA-like scheduling, network-wide non-real-time control, and node-wide real-time control.

- The two-level scheduler is currently being evaluated in the QUANT-NET testbed and will be released to the community upon completion of internal testing.

- The two-level control framework and the scheduler are not only designed specifically for the QUANT-NET testbed, but can also be extended to support other types of quantum networks.

Further reading

- Project website: https://quantnet.lbl.gov
- Physical World report: QUANT-NET's testbed innovations: reimagining the quantum network
- QuNet'23 paper: QUANT-NET: A testbed for quantum networking research over deployed fiber
- QCE'24 paper: The QUANT-NET Testbed Development and Preliminary Results
- OFC'25 paper: Experimental Test of Bell-state Measurements for Narrow-band Ion-photon Interfaces in the QUANT-NET Testbed (submitted Oct 2024)
- OFC'25 paper: A two-level control framework for quantum networks (submitted Oct 2024)