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QUANT-NET: A testbed for quantum networking research over deployed fiber

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Abstract

QUANT-NET is a three-node quantum network research testbed funded by the U.S. Department of Energy (DOE). The goal is to establish this network between two sites, Lawrence Berkeley National Lab (LBNL) and University of California, Berkeley, connected with an entanglement swapping substrate over optical fiber and managed by a quantum network protocol stack. On top of this entanglement swapping substrate the research team will implement the most basic building blocks of distributed quantum computing and quantum repeater by teleporting a controlled-NOT gate between two far trapped-ion quantum computation nodes. This paper presents QUANT-NET, its design, key technologies, and progress.

CCS Concepts

• **Networks** → **Network architectures**; • **Computer systems organization** → *Quantum computing*; • **Hardware** → **Quantum technologies**.

Keywords

Quantum Internet, Quantum Network

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1 Introduction

Quantum networks enable the transmission of information in the form of quantum bits (qubits) between physically separate quantum nodes. Based on laws of quantum mechanics, such as superposition, entanglement, quantum measurement, and the no-cloning theorem, quantum networks are envisioned to achieve novel capabilities that are provably impossible using classical networks and could be transformative to science, economy, and national security. These novel capabilities range from cryptography [4], sensing and metrology [8], distributed systems [3, 6], to secure quantum cloud computing [5]. Today, quantum networks are in their infancy. Like the Internet, quantum networks are expected to undergo different stages of research and development until they reach a level of practical functionality [12].

The U.S. Department of Energy (DOE), under the Advanced Scientific Computing Research (ASCR) program, is currently supporting Berkeley Lab (LBNL), UC Berkeley (UCB), Caltech, and the University of Innsbruck in constructing a testbed for quantum networking technologies (QUANT-NET). The goal is to establish a three-node distributed quantum computing network between two sites, LBNL and UCB, connected with an entanglement swapping substrate over optical fiber and managed by a quantum network protocol stack. On top of this entanglement swapping substrate the research team will implement the most basic building block of distributed quantum computing and quantum repeater by teleporting a controlled-NOT gate between two far trapped-ion nodes (see Fig. 1 and 2). Our research efforts are focusing on three areas: (1) Repeater-friendly quantum-node technologies, which include researching and developing trapped-ion quantum node (i.e., quantum computer) and color-center based single-photon source; (2) Quantum frequency conversion of ion-compatible narrow-bandwidth photons at near-infrared 854 nm to the telecom C-band at 1550 nm; and (3) Quantum network control, architecture and protocol stacks. The QUANT-NET project is progressing according to the plan. Significant progress has been made in designing and implementing the quantum testbed infrastructure, developing the ion trap quantum processors, and designing the quantum network control plane. In this paper, we present the QUANT-NET project from the network system's perspective. This perspective is important in order to chart a path from leading research and experiments on quantum communications in labs to integration and deployment in the field. The rest of the paper is organized as follows. Section 2 introduces the QUANT-NET's network model and architecture. Section 3 presents the QUANT-NET's design and implementation. Section 4 summarizes the project's progress and status. Finally, Section 5 concludes the paper.

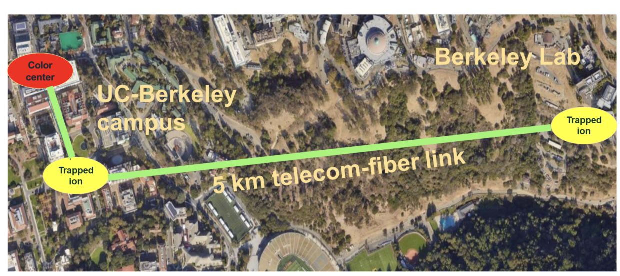

Figure 1: A three-node distributed quantum computing network at Berkeley

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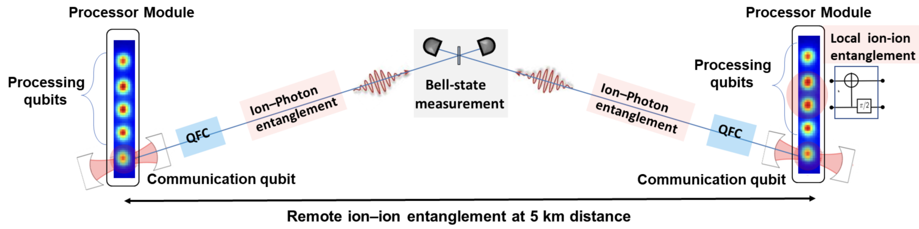

Figure 2: Distributed quantum computing between remote trapped-ion nodes

2 Network Model and Protocol Stack

QUANT-NET considers a quantum network that can support multiple concurrent users and multiple quantum nodes. Essentially, the quantum network consists of four major types of quantum entities as shown in Fig. 3: (1) *Quantum end nodes (Q-nodes)* are much like their classic counterparts (i.e., nodes), representing the communication parties in quantum networks. A Q-node performs both conventional and quantum functions. (2) *Quantum repeaters (QRs)*. The major function of QRs is to divide the end-to-end long distance of quantum links into shorter intermediate segments connected by QR nodes, in which errors from fiber attenuation (i.e., loss) and other sources (e.g., gate operation errors) can be corrected. (3) *Bell-State-Measurement nodes (BSM-nodes)* can perform Bell state measurement (BSM) and local Pauli operations for incoming photon pairs. And (4) *Quantum channels*. Q-nodes, QRs, and BSM-nodes are connected to optical switches through optical fibers. The optical switches are further connected among one another to form a meshed all-optical network. Dedicated wavelengths of these fibers are used as quantum channels to transmit quantum signals between Q-nodes, QRs, and BSM-nodes. Through dynamic provisioning, multiple logic quantum networks can be generated from the same underlying physical network (see Fig. 4).

QUANT-NET uses a logically centralized control style and decouples the control and data plane. In the control plane, one or multiple quantum network controllers monitor the status of the quantum network. Quantum network server(s) run on top of the controller to perform control and management functions. In the data plane, quantum signals and messages are transmitted across quantum channels between different quantum nodes. For large-scale quantum networks, multiple quantum network controllers and servers may be required, which synchronize and cooperate to control and manage the underlying networks. Having multiple controllers and servers will improve reliability, performance, and scalability.

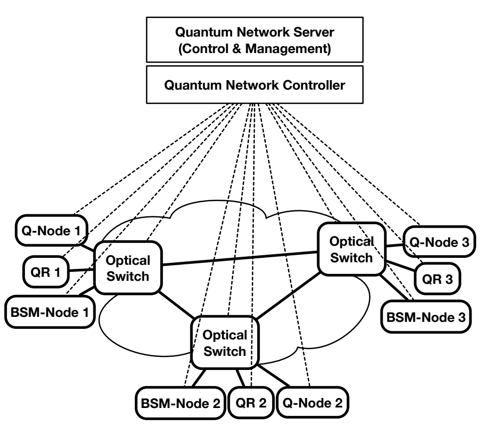

Figure 3: QUANT-NET Network Model

Inspired by the TCP/IP architecture, QUANT-NET implements a similar layered quantum networking architecture (see Fig. 4), which describes how quantum network functions are vertically composed to provide increasingly complex capabilities. The layered quantum networking architecture relies on five key vertical layers:

- *Quantum physical layer.* This layer deals with the physical connectivity of two communicating quantum nodes.
- *Quantum link layer.* The quantum link layer handles robust entanglement generation between neighboring nodes (e.g., Q-node, BSM-node, and QR). Key error mitigation mechanisms, such as heralded entanglement generation (HEG) [1, 2, 11], and heralded entanglement purification (HEP) [7, 10, 11], have been proposed to suppress loss and operation errors in quantum networks. QUANT-NET makes use of these advanced mechanisms to build quantum link layers. The quantum link layer functions are implemented distributively between Q-nodes, BSM-nodes, and QRs at the control of *quantum network server.*
- *Quantum network layer.* This layer is responsible for entanglement routing, which selects a path in the network along which to establish end-to-end entanglement links between a Q-node pair by performing entanglement swapping at intermediate QRs. It also selects intermediate nodes along the path to perform entanglement purification if necessary. The quantum network layer functions are mostly implemented in the *quantum network server.* After the path has been successfully chosen, the QRs along the path perform low-level functions, such as entanglement swapping, entanglement purification, or quantum error correction, at the control of the server.
- *Quantum transport layer.* This layer provides an end-to-end quantum signal transfer service to users and applications. It handles end-to-end entanglement generation and entanglement purification to provide high-fidelity entangled pairs between Q-nodes. Quantum signals are transferred by teleportation. Quantum QoS requirements such as fidelity and entanglement generation rate are specified by the high-level quantum application layer. The quantum transport layer

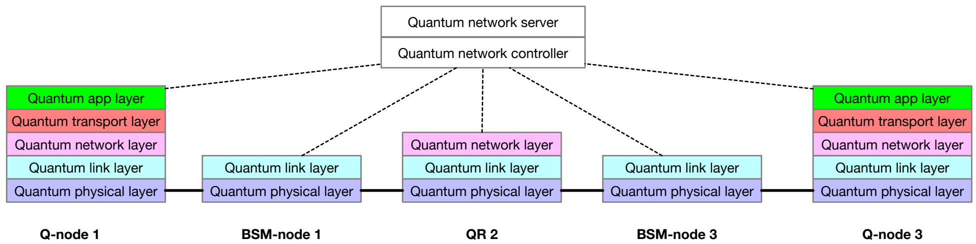

Figure 4: Quantum networks. Logic quantum networks can be created from the same underlying physical network (e.g., Fig. 3) through dynamic network provisioning.

functions are implemented in Q-nodes at the control of the *quantum network server.*

- *Quantum application layer.* The application layer provides the interfaces and protocols needed by users of a quantum network. Through the interfaces, quantum transport endpoints can be specified, and quantum QoS requirements such as fidelity and entanglement generation rate can be negotiated or specified.

The above layered quantum network architecture and protocol stack function assignments are tentative and experimental. When research has been conducted, lessons will be learned and experiences will be gained. We may then determine whether new layer(s) and/or function(s) need to be added, or whether existing layer(s) and/or function(s) need to be changed or modified.

3 QUANT-NET Design and Implementation

3.1 Key mechanisms

The QUANT-NET design is based on fundamental properties of quantum communications. Here we list a few key mechanisms:

- *Network-wide time synchronization.* QUANT-NET is a distributed system. A few critical quantum network functions require network-wide synchronization to provide a global notion of time. For example, entanglement provides a means to enables long-distance quantum communications. At present, due to technology immaturity, entanglement has been produced probabilistically over short distances with a short duration. Bell state measurement (BSM) is an essential function for entanglement generation over long distance. However, BSM can only be performed if both photons arrive at a BSM-node simultaneously. In addition, quantum measurement requires accurate timekeeping to correlate physically remote events. QUANT-NET achieves network-wide synchronization by using a master clock. All nodes synchronize with a single master clock. Dedicated high-resolution signal generators (e.g., Marconi signal generator) will be used as clocks.
- *Pulse-driven operations.* QUANT-NET operates on a pulse-driven basis to simplify quantum network operations. Critical pulse-driven quantum network functions include: (1) a trapped ion is driven by a sequence of laser pulses to generate photons, and ion-photon entanglements. Therefore, a Q-node can vary its photon generation time by properly controlling drive pulses. For BSM, because the photons' time-of-flight from two Q-nodes to a BSM-node are different, the two Q-nodes can vary their photon generation time accordingly so that the generated photons can arrive at the BSM-node simultaneously. (2) Pulse-gated detection of photons helps to reduce dark counts to improve detection accuracy.
- *Real-time control in a distributed environment.* Timing constraints to perform entanglement swapping to generate high-fidelity entanglements between remote ions (5+ km) are stringent. In addition, the accurate control and manipulation of trapped ions requires a time resolution of ns scale. This means that QUANT-NET requires tight timing control, which imposes hard real time constraints at the lowest levels. QUANT-NET applies a systematic approach to meet time constraints:
  - Time-critical functions running on dedicated ARTIQ-based real-time control systems [9].
  - Dedicated ctrl&clk channels established for real-time communication between relevant entities.
  - Non-real-time functions such as monitoring proper functioning of all components, re-initiating calibration, and data analysis are executed in software in the CPU domain.
  - Non-real-time communications running through TCP/IP channels.
- *Active quantum channel monitoring, calibration, and optimization.* The single-photon nature of quantum communication signals makes them extremely sensitive to noise on the quantum channels. In particular, QUANT-NET generates and distributed polarization photon qubits that are vulnerable to polarization drifts. Protocols such as teleportation require indistinguishability in spectral, temporal, spatial, and polarization properties of the two photons arriving at a BSM-node. QUANT-NET employs several active and automated quantum-channel calibration and optimization mechanisms to minimize quantum channel loss, reduce background noise, and compensate for polarization and delay drifts.
  - Active quantum channel monitoring and active quantum signal-to-noise ratio estimation. If necessary, a new quantum channel with less noise will be selected.
  - Hong-Ou-Mandel (HOM) measurement and calibration is used to ensure quantum indistinguishability. The HOM signal provides feedback to compensate for the photons' relative time-of-flight, ensuring stable operation (See Subsection 3.2).
  - Active polarization measurement and calibration is used to compensate for polarization drifts in fibers.

- *Active trapped-ion Q-node monitoring, calibration, and optimization.* Realizing practical and useful quantum networks requires long coherence-time qubits and high-fidelity quantum gate operations. To enable such capabilities, each trapped-ion Q-node in QUANT-NET is actively monitored, calibrated, and optimized in a periodical manner. Table in Fig. 5 lists a few trapped-ion Q-node parameters that need to be periodically calibrated. In particular, the cavity length and the cavity drive phases need to be calibrated in sub-ms level. An electronic feedback laser is dedicated to executing such functions. On the other hand, within the cavity of a trapped-ion Q-node, the magnetic field axis/atomic quantization axis defines measurement basis. Because QUANT-NET has multiple trapped-ion Q-nodes, it is necessary to align the measurement basis of different systems to the same basis. QUANT-NET achieves network-wide basis alignment by using a master Q-node. All nodes synchronize with a single master Q-node.

Trapped-ion Q-node parameters	**Calibration cycle**
Cavity length	<< ms
Cavity drive laser phase	<< ms
Cavity drive laser intensity	Every 10-60 minutes
Cavity position along the z axis	Every 10 minutes
Cavity drive laser detuning	Every 12 hours
Cavity waist position	Every 12 hours

Figure 5: Trapped-ion Q-node parameters periodically calibrated

3.2 Trapped-ion Q-node and BSM-node Design and Implementation

A trapped-ion Q-node is a few-qubit quantum computer with a photonic interconnect. It is designed to perform both conventional and quantum functions. Major functions include: (1) local quantum computations using trapped ions, (2) single photon generation whose polarization is entangled with one of its trapped-ion qubits, (3) quantum frequency conversion (QFC) between the native wavelengths of trapped ions (854 nm) and telecom bands (1550 nm), and (4) conventional computation and communication to control the flow of quantum information. For example, a Q-node exchanges messages with other quantum network nodes via conventional traffic channels to act on successful entanglement generation and demands for quantum resources, or simply to perform quantum channel calibration and optimization. The former requires real time control while the latter usually is not very time critical. Fig. 6 illustrates a trapped-ion Q-node design. It has one or multiple ions trapped in a cavity. An ARTIQ-based real-time control system controls the amplitude, frequency, and phase of laser light as well as the voltages used to manipulate the internal as well as motional degrees-of-freedom of the trapped ions in real time at the sub-microsecond time scale. Non-real-time operations such as triggering calibration sequences, analysing their results and feedback of the newly determined parameters are executed in software in the CPU domain. A Q-node has three types of communication channels: (1) *quantum channel(s)* to send quantum signals and messages. (2) *ctrl&clk channel(s)* to transmit/receive control and clock signals and messages to support time-critical operations. And (3) *a TCP/IP connection* to transmit conventional messages for non-real-time operations.

Real time control of the Q-nodes is required, allowing the system to make complex decisions based on both external communication as well as from the Q-node itself. Specifically, the Q-node acts on an external trigger when to stop the entanglement attempts, but also when new demands for entanglement arise. Also, the Q-node is designed to react to external demands for teleportation, i.e. to implement a local BSM, communicate its result, and/or act on results on local BSMs of other Q nodes, or BSM nodes.

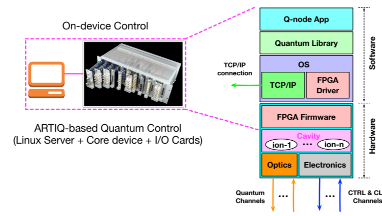

Figure 6: An ARTIQ-based trapped-ion Q-node

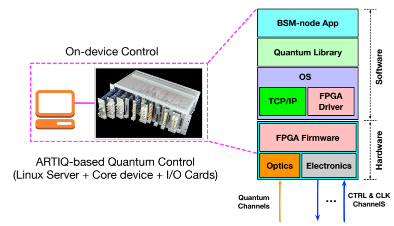

Figure 7: An ARTIQ-based BSM-node

A BSM-node is designed to perform bell state measurement (BSM) of polarization photon qubits. As illustrated in Fig. 7, a photonic BSM is typically implemented using a beam splitter followed by measurement devices. Its major functions include:

- *Channel calibration and optimization with classical pulses.* A BSM node implements an active and automated channel calibration and optimization mechanism to minimize polarization and frequency drifts. This classical calibration will be interleaved with quantum network operation and HOM analyzing unit operation.
- *HOM analyzing unit*. A BSM-node implements a HOM analyzing unit to ensure photon indistinguishability for bell state measurement. The HOM analysis is carried out in temporal, polarization, and spectral degrees of freedom by keeping an updated analysis of interference visibility. *(a) In temporal degree of freedom.* By real-time monitoring HOM interference visibility at different time delays, the HOM analysis can accurately determine the arrival time difference of two photons at the BSM-node. The time difference is fed back to the related Q-nodes so that they can vary the two photons' generation time to allow them to arrive at the BSM-node simultaneously. The time difference will also be used to herald successful entanglement generation. Only coincidences in the interference window will be used as successful entanglement heralding events. *(b) In polarization and spectral degrees of freedom.* After arrival time difference has been actively compensated, the HOM analysis can be similarly performed by varying polarization and frequency, respectively. The

analysis results are fed back to the corresponding entities in the quantum network to allow for control and optimization. Depending on the types of visibility reduction, polarization control, or frequency re-optimization can be achieved if interference window is narrowing, to minimize polarization and frequency drifts. Polarization control can be implemented locally in the BSM-node, which is relatively straightforward. However, frequency re-optimization may require a systematic calibration and tuning of laser, trapped-ion cavity, QFC, and filtering, across multiple quantum network nodes.

- *Bell-state measurement*. Most importantly, a BSM-node performs Bell state measurement (BSM) of polarization photon qubits. Two-photon interferometry is used to identify two of the four bell states. The measurement results are transmitted in real time (few 100 ns) to the related quantum nodes in the network. A real-time communication mechanism, either via a dedicated fiber or electrical cable, will be developed to support such a function.

Each node is assigned an IPv6 address to uniquely identify it. Each channel of a node is numbered and thus uniquely identified. Important guiding principle will be to make each node as autonomous as possible, i.e. it calibrates itself as much as possible and requires only minimal information from the outside. This will ensure that the system is as reliable and scalable as possible. The concept of autonomy will apply both to the real time control level where success of BSMs, requests for teleportation, and readiness will be handled, as well as on the soft time level where resource allocation as well as overall synchronization will be taken care of. However, each node will communicate its status to the central control plane for monitoring and debugging purposes.

3.3 Underlying quantum technologies

The underlying technologies in the QUANT-NET testbed nodes are trapped-ion quantum processors, quantum frequency conversion systems, and color-center based single-photon sources. The trapped-ion technology relies on the integration of a high-finesse optical cavity with a novel chip-based trap for Ca^+ ions. This system allows for generating high-rate and high-fidelity ion-photon entanglement using an improved Raman interaction scheme. The resulting photons at 854 nm are subsequently converted to a telecommunication wavelength at 1550 nm for performing the experiments between UCB and and LBNL over deployed fiber. Relying on the long lifetime of Ca^+ qubit, remote entanglements are generated via BSM measurements between two trapped-ion systems at these two locations.

The quantum frequency conversion module for telecom operation is based on the difference frequency process using the established integrated quantum photonic technologies. In this approach, an input 854 nm-photon (emitted from a Ca^+ ion) is coherently mixed with a strong pump field at 1900 nm in a non-linear medium, leading an output telecom-photon at 1550 nm. In conjunction with a proper arrangement of the crystal geometry and filtering, this technique will preserve the quantum states of the input photons while providing high conversion efficiencies and low-noise operation for the planned experiments.

Finally, a solid-state device technology relying on a G-center in silicon serves as a single-photon source towards testing heterogeneous quantum networks. This technology offers photon emission in the telecom O-Band and full integration with silicon nano-photonics for scalability. Furthermore, the emitted single photons exhibit a high-level of indistinguishability that is required for BSM measurements, as recently demonstrated by the QUANT-NET teams. Based on this feature, the QUANT-NET aims to demonstrate quantum state teleportation from a single-photon (emitted from a G-center) to a Ca^+ qubit by alleviating the issue of spectral mismatch between these systems with advanced bandwidth conversion methods

3.4 Entanglement generation and distribution

Entanglement is a fundamental building block in quantum networks. Key entanglement-related operations include entanglement generation, entanglement distribution, entanglement routing, entanglement swapping, and entanglement purification. QUANT-NET uses entanglement as a resource to route quantum information between quantum nodes via teleportation and local (quantum) operation using a classical networking layer. An ion-ion entanglement establishing process between two trapped-ion Q-nodes is illustrated in Fig. 8. This process will rely on the synchronous preparation of ion-photon entanglement in the spin and polarization degrees of freedom within the Q-nodes. Each cycle starts with ion state initialization, followed by a Raman pulse that triggers an emission of a near-infrared photon in the cavity mode. After quantum frequency conversion, the resulting telecom photon, entangled with the ion, are sent towards a BSM-node as an attempt to create ion-ion entanglement via projection measurements in the polarization states of photons. If no detection or single detection is measured from the BSM-node, the Q-nodes continues the entanglement generation attempts. If a two-fold coincidence is measured at the BSM-node (heralding the creation of ion-ion entanglement), then the trapped-ion Q-nodes decides to hold the resulting entanglement. This ion-ion entanglement is stored until the quantum network requests to use it as a resource, for instance, to transmit quantum information via teleportation.

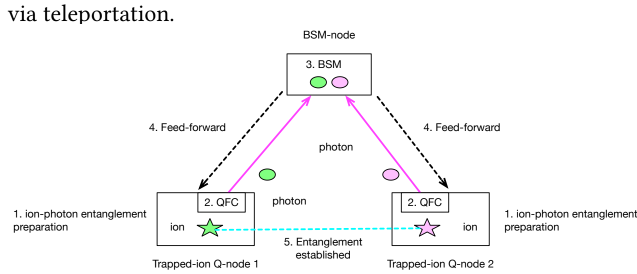

Figure 8: ion-ion entanglement establishing process between two trapped-ion Q-nodes

3.5 The QUANT-NET testbed

Fig. 9 illustrates the QUANT-NET testbed system diagram. The testbed runs as a distributed system. A Quantum Network (QN) server coordinates all activities in the network. It controls and manages the underlying Q-nodes and BSM-nodes through a general message bus implementation and broker service. Device models for each class of testbed node have been developed along with well-defined protocol functions to provide validation and verification of expected system behavior. A QN server typically handles *global (network-wide) non-real-time* functions such as quantum network topology discovery, quantum network monitoring, and periodically scheduling quantum network calibration and optimization etc. It also handles user requests on an event-driven basis. When serving a user request, the server cycles QUANT-NET alternatively between calibration and operational modes to achieve a sustained high-fidelity quantum network. As opposed to the QN Server orchestration layer, ARTIQ-based Q-nodes and BSM-nodes form the underlying data plane (i.e., quantum plane). Each node handles *local (node-wide) real-time functions* that have tight time constraints.

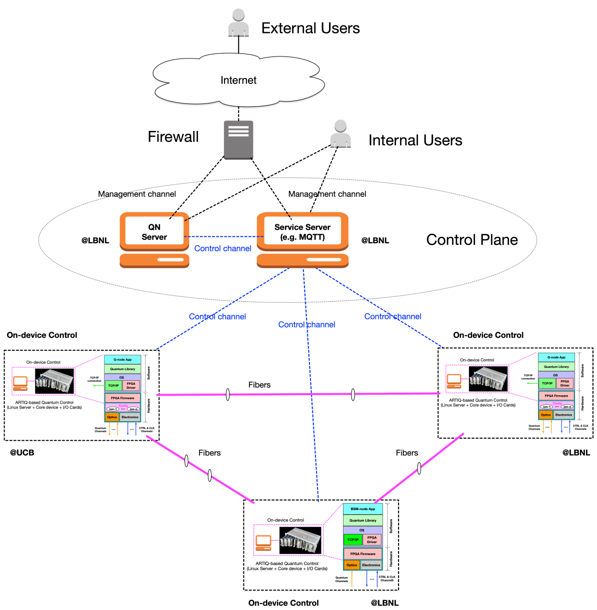

Figure 9: QUANT-NET testbed system diagram

4 Progress and Status

The QUANT-NET project is almost finished with its second year of effort. Significant progress has been made in designing and implementing the testbed:

- The design and implementation of the quantum testbed infrastructure is completed, which includes the fiber construction between UCB and LBNL, and building a quantum lab at LBNL.
- The design and development of trapped-ion Q-node is under progress. The research team is constructing a pyramid trap-cavity system and exploring a new Raman excitation scheme to optimize the cavity-assisted ion-photon generation.
- The QFC design is completed. A QFC prototype is under evaluation.
- A color-center single photon source has been developed. Indistinguishable photon generation using color centers in silicon photonics has been successfully demonstrated.
- The initial design of quantum network architecture and protocol stack is completed. The control plane development is under progress.

The upcoming goal for the project is to test and characterize the various components of the testbed independently, publish results, and focus on integration and tuning of these elements into an operating quantum research testbed. With the network system principles in mind, our focus will also be on automating the various elements of a quantum network testbed that typically might be manually tuned or calibrated in a lab environment. This design and automation will also enable us to incorporate quantum testbed components from other research teams or industry in the future.

5 Conclusion

This paper describes the network architecture and systems approach taken by the QUANT-NET project to build the first quantum network testbed focused on distributed quantum computing application in the United States. Even though the underlying quantum physical layer concepts are very different from the digital network, we see an alignment in architectures by using classical Internet concepts of network layers and abstractions, and focusing on the protocols that enable automation of real-time control of distributed quantum nodes. One of the ongoing challenges is to continue defining and refining the abstractions for the various layers as the testbed is being built, and as the capabilities of the quantum physical layer evolves. Aligning these abstractions with other quantum network efforts in progress around the world is also important, though we understand that at this early stage of research, differing and incompatible approaches will be the norm.

We hope that the system design and our testbed approach will enable easier integration of new component quantum technologies from other research teams and industry, will provide for a rapid prototype-test-integrate cycle to support innovation, and will contribute to an accelerated understanding of how to build a scalable Quantum Internet that co-exists with the Classical Internet.

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