Cisco Quantum Labs

Quantum Networks of the Future
A Cisco Vision

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A. Introduction

Cisco's Quantum Research group envisions the future of quantum networks as a network for distributing entanglement, designed to interconnect quantum computers and quantum sensing devices for distributed quantum computing and sensing as well as enhancing quantum-safe communication on a large scale.

Our efforts are dedicated to developing the theoretical foundations as well as the hardware and software technologies essential for:

1- Building a practical and useful quantum network utilizing quantum entanglement to transfer quantum bits of information (qubits). We anticipate that such networks will transcend traditional static point-to-point quantum connections, evolving into dynamic systems powered by quantum-enabled switches.

2- Developing quantum-enabled network switching technology, which is essential for forming the backbone of a practical and useful quantum network.

3- Designing network protocols and control stacks tailored for a fully autonomous and softwareized quantum entanglement network.

4- Establishing a digital twin for a quantum network that supports both long-term applications, such as quantum data centers, and short-term applications, such as quantum-safe networking.

B. Architecture

The key architectural principles defined by the Cisco's Quantum Research group for a quantum entanglement network include:

- Capability for routing, switching and regeneration of entangled qubits with high rates.
- Support for establishing bi-partite entanglement between any two nodes in the network.
- Follow the principles of software defined networking (SDN) for scalable and modular networks.
- Support for coexistence of classical and quantum channels over the same network.
- Offer quantum network resources such as entangled photons and Bell state measurement devices (BSM) as a service to network users.
- Support for quantum repeaters as well new quantum entanglement distribution and regeneration/error correction schemes for creating fault tolerant quantum network.

A high-level architecture vision of the proposed quantum network is shown in the figure 1.

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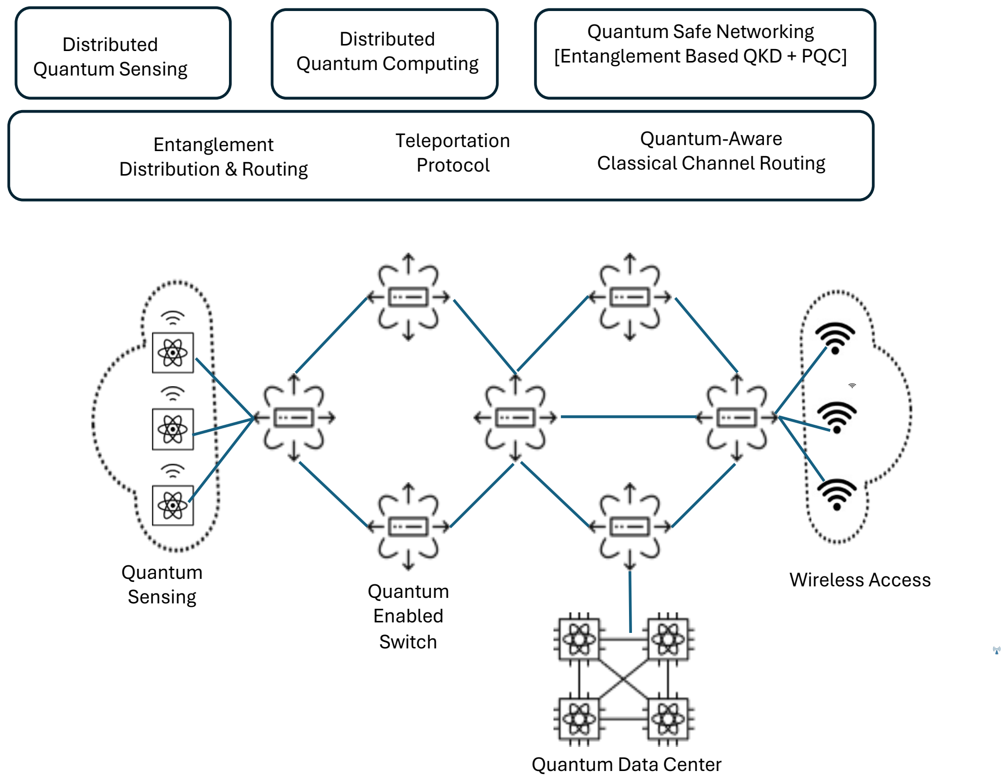

Figure 1: Architectural vision of the quantum network of the future supporting scalable quantum computing, distributed quantum sensing and quantum safe networking

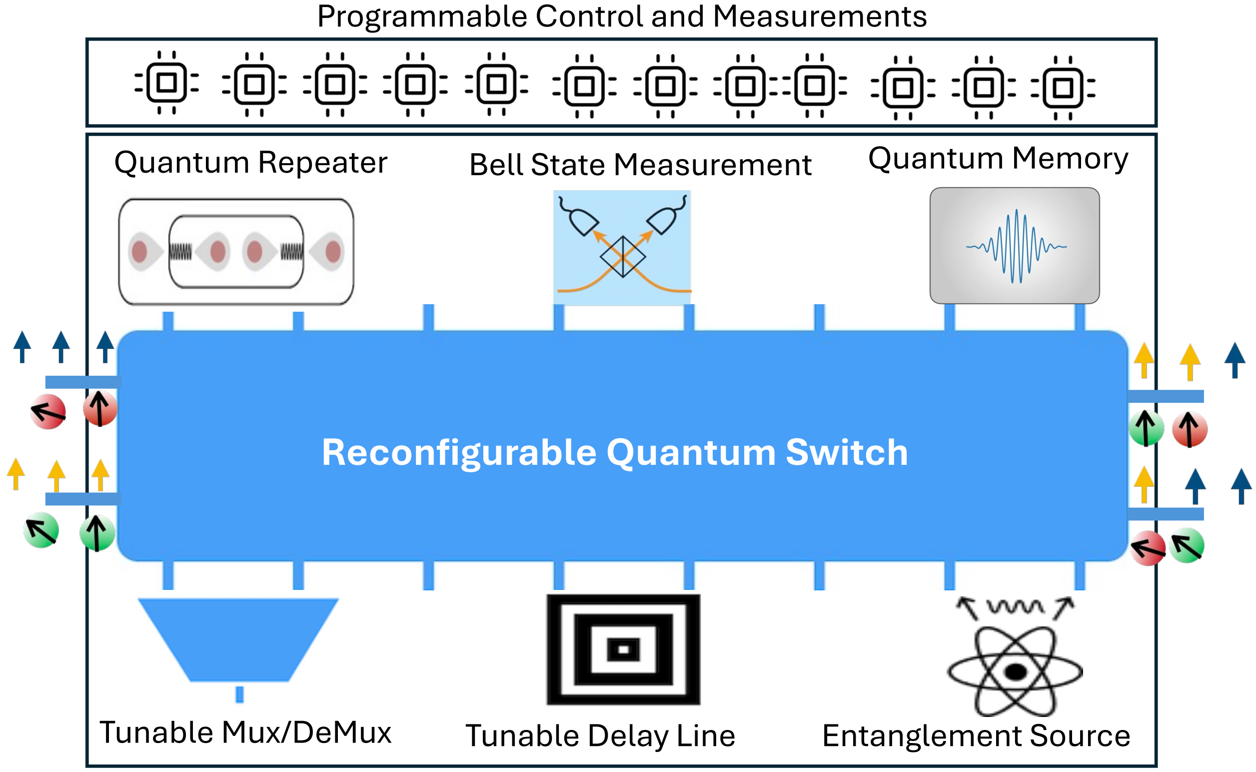

Figure 2: Quantum switch comprising a switching fabric suitable for quantum and classical photonic channels switching. It includes devices require for entanglement distribution in the network.

C. Quantum Enabled Switch

Cisco's Quantum Research group is focusing on development of the core element of a dynamically switchable quantum entanglement network, notably the Cisco Quantum Enabled Switch. This research prototype, currently under development within the Cisco Quantum Research Lab, will have several key features:

- Non-blocking switching of entangled photons from any input ports to any output ports.
- Supports a fine granularity of multiplexing.
- Supports multiple modes of entanglement including time bin, frequency bin, and polarization-based entanglement.
- Ultra-low loss and time jitter port-to-port switching allowing cascading ability of switches.
- Supports pluggable components such as BSM, detectors, delay lines, quantum sources, quantum memory and quantum repeaters for versatile quantum networks.
- Support for new quantum regeneration and error correction schemes enabled by quantum memories and BSM attached to switch.
- Capability for routing and switching of quantum and classical channels independently.

A functional block diagram of the Quantum switch is shown in the figure 2.

D. Software Defined and Autonomous Quantum Network Control

At Cisco's Quantum Research, we are committed to the principle of software-defined networking as the foundation for implementing the control plane within quantum networks. Our team is at the forefront of developing a protocol stack designed for entanglement distribution and quantum teleportation. This effort includes the creation of advanced protocols aimed at efficiently managing entanglement distribution and teleportation within a dynamically switched quantum entanglement network. One of the main objective of the protocol is achieving quantum entanglement networking utilizing repeater as well as new quantum entanglement distribution and error correction schemes enabled by the flexible architecture of the Cisco's quantum enabled switch. Additionally, our protocol layer aims to abstract the complexities of the physical layer, thus facilitating more streamlined control and routing. In parallel, we are pioneering the development of an autonomous network control system. This system integrates artificial intelligence, heuristic algorithms, and graph theory to optimize quantum network operations. The network control system is engineered with two primary functionalities. First, the efficient routing of entangled photons. In this area, we are also focusing on developing solutions for co-existence of quantum and classical channels in the same fiber. Second, the strategic scheduling of shared network resources. The quantum network devices within the network as discussed are valuable resources, so optimal scheduling of their use will be critical. Our approach aims to harness the full potential of quantum networking, ensuring robust, efficient, and scalable quantum communication infrastructures.

E. Quantum Network Digital Twin

At Cisco's Quantum Research, we are pioneering the development of a comprehensive Quantum Network Digital Twin. This platform encompasses a suite of software tools linked to a quantum network test-bed within the Cisco Quantum Lab, enriched by a library of simulated quantum network elements mirroring real-life physical devices and experimental setups. As a digital twin, it maintains real-time connectivity with Cisco's quantum network testbed, enabling immediate interaction with an operational quantum network. This includes the collection of monitoring data and the observation of the effects resulting from modifications tested in the digital twin.

This innovation opens avenues for Cisco customers and partners to conceive and implement their quantum networking scenarios over Cisco's quantum testbed in our lab or over future field-deployed networks. It facilitates the evaluation of performance for specific quantum network scenarios, tailored to their unique use cases and applications. Additionally, it offers the capability to assess the scalability of various quantum networking scenarios, leveraging a blend of physical testbeds, emulation, and simulation. This tool is instrumental in advancing the understanding and implementation of quantum networking, providing a bridge between theoretical constructs and practical, real-world applications.

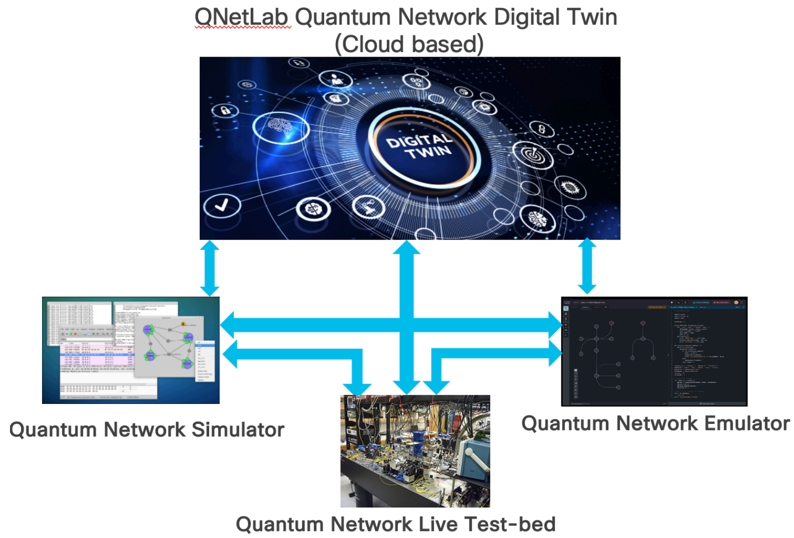

Figure 3: Quantum Network Digital Twin

F. Use cases

- Use Case 1: Quantum Cloud Computing and Quantum Data Center

At Cisco's Quantum Research, we are pioneering Quantum Data Centers (QDCs) as the pathway to scalable and functional quantum computing services. Quantum cloud computing is defined as an infrastructure that enables a large number of users to securely access remote quantum computing facilities, i.e. QDCs, in the same way that today's Google and Amazon cloud computing services serve their users. Cloud-based QDCs are designed to serve diverse users, supporting a wide range of applications including advanced concepts like blind quantum computing. From both scientific and engineering viewpoints, QDCs represent a practical approach to scale quantum computing. This scalability is achieved by interconnecting multiple quantum processors with smaller qubit counts, a concept inspired by traditional data center architectures. Our vision extends to a dynamic quantum entanglement network, which we believe is crucial for the construction of a QDC as well as providing a scalable access network for applications such as blind quantum computing. This network is tasked with generating entanglement links between any two nodes in the network, which is vital for distributed quantum computing and can also facilitate a quantum connection between the user and the quantum computer. At Cisco's Quantum Research, our efforts are concentrated on developing the fundamental components of this network, including the innovative Cisco Quantum Entanglement Switch, which is central to our dynamic entanglement networking strategy.

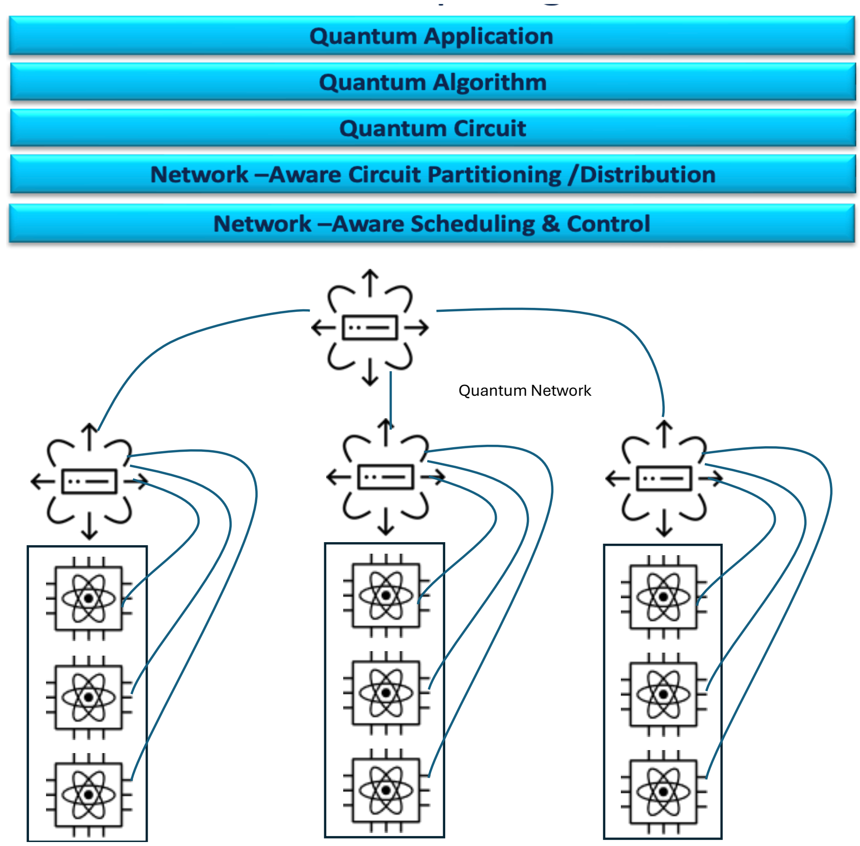

Figure 4: Quantum Data Center

- Use Case 2: Distributed Quantum Sensing:

Emerging quantum sensing technologies are capable of achieving unprecedented sensing performance. Quantum sensing has proven to be a powerful paradigm for various applications, including future telecom networks. Entangled quantum sensors distributed across distances have the potential to achieve measurement sensitivities far surpassing those of classical sensors. This highly accurate, distributed quantum sensing can be leveraged for operational functionalities in future telecom networks, such as exceptionally precise and high-resolution spectrum sensing, as well as highly accurate synchronization and accurate localization.

- Use Case 3: End-to-end quantum safe networking:

Cisco's quantum entanglement network technologies can be used to implement Quantum Key Distribution (QKD), potentially overcoming traditional limitations such as scalability. At Cisco's Quantum Research, we believe that any quantum-safe networking solution must be scalable and end-to-end, encompassing wired, wireless, and data center networks. In line with this vision, our entanglement-based quantum network solution is designed to implement QKD and seamlessly integrate with Post-Quantum Cryptography (PQC), which can be deployed more broadly. This ensures scalable, end-to-end quantum-safe networking, including secure wireless communications, while addressing some of the limitations of QKD protocols. We refer to this integrated approach as hybrid QKD and PQC quantum-safe networking. To facilitate this, we've developed an intelligent Key Management System (KMS) that manages and orchestrates keys (including quantum keys) as a resource across various network segments—wired, wireless, and data centers—leveraging both PQC and QKD technologies. As a cornerstone of our quantum-safe networking efforts, Cisco's Quantum Research has created a prototype Quantum Random Number Generator (QRNG). This technology has multiple applications, including generating seed numbers for cryptographic algorithms like PQC. The QRNG can be provided as a standalone unit or as a service through cloud and web services, offering flexible solutions to meet diverse application needs.

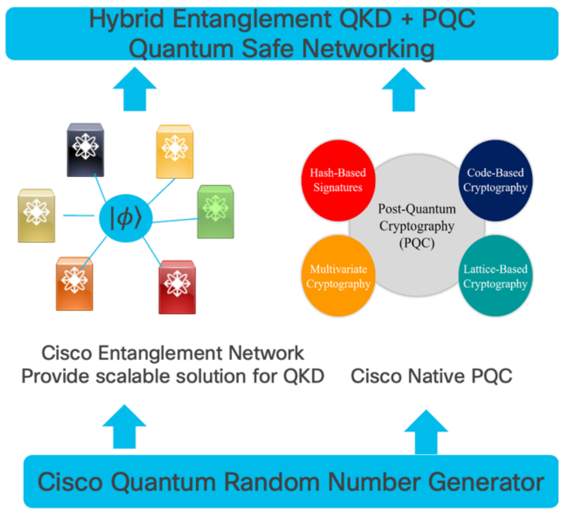

Figure 5: Hybrid QKD and PQC Networks

G. Relevant publications

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