Quantum Data Center Interconnect
A Cisco Vision

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A. Introduction

Quantum computing is undergoing its second wave of advancement, characterized by rapid progress from quantum processors with tens of qubits towards quantum processors with hundreds of qubits. While this marks a significant milestone, achieving a truly useful and practical quantum computer requires scaling up to tens of millions of qubits. In the journey towards building such a quantum computer, major challenges emerge, including expanding the number of qubits within monolithic architectures and providing quantum computing as a service.

In Cisco's Quantum Research group, we are convinced that Quantum Data Centers (QDCs) represent a viable approach for developing scalable and functional quantum computing services that can be offered as service to a variety of users and applications. From both scientific and engineering perspectives, QDCs offer a feasible solution for achieving scalable quantum computing. This is achieved by networking multiple smaller-scale quantum processors to form a distributed quantum computing cluster, mirroring the design of traditional data centers. QDCs are particularly appealing for several reasons. They benefit from the controlled environment and relatively short distances between quantum processors within a data center, which are crucial for minimizing loss and maximizing fidelity of quantum information. Furthermore, the controlled environment ensures the high level of precision in phase, timing, and temperature stability that is essential for the effective interconnection of quantum computers, thereby facilitating the operation of distributed quantum computing systems.

B. Quantum Data Center Architecture

Cisco's Quantum Research group proposes a design philosophy for the development of a quantum datacenter, emphasizing the following key principles:

- The architecture should be modular and scalable, facilitating a flexible interconnect setup and addition of new quantum processors.
- It should support multi-tenancy, allowing it to serve various quantum applications and algorithms simultaneously.
- The design should enable any-to-any connectivity between quantum processors.
- It should offer the ability to create multiple, co-existing, and independent logical interconnect topologies. Each topology would be specialized for optimizing the performance of specific quantum algorithms.
- The architecture should be able to support heterogeneous quantum computing platforms.

- There should be flexibility to modify the logical interconnect topology on demand during the execution of quantum algorithms. This implies the capability to optimize the interconnect topology at a sub-routine level for each algorithm, ensuring maximal performance.
- The architecture should include provisions for sharing critical and expensive resources, such as photon detectors and Bell State Measurement (BSM) devices, to enhance operational efficiency and resource utilization.
- The data center should be managed by a quantum network-aware orchestrator comprising of a network-aware quantum circuit partitioning and scheduling mechanism.

Cisco's Quantum Research group is developing a modular quantum data center network architecture which is scalable and independent from quantum computing platforms. A high-level architecture vision of the proposed quantum data center is shown in Figure 1.

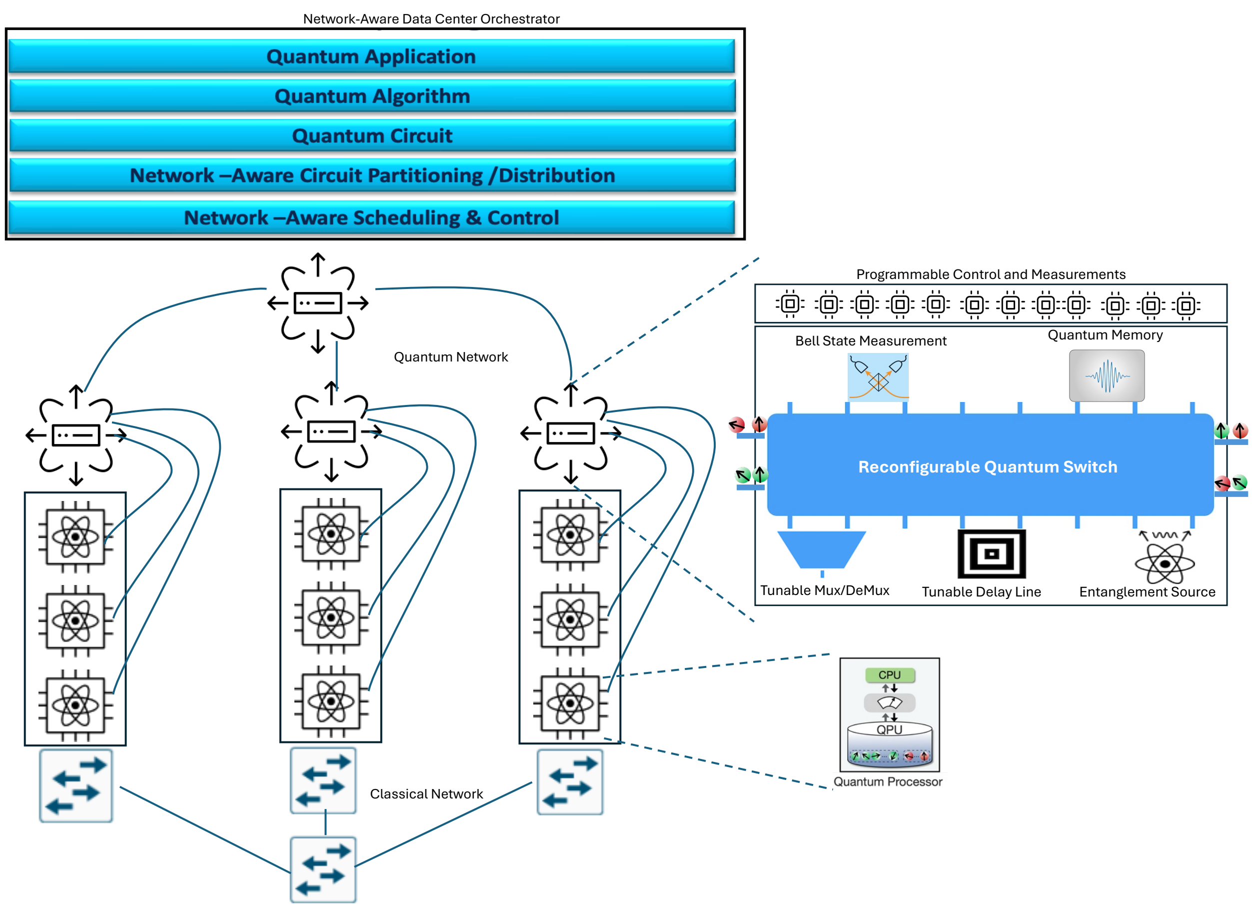

Figure 1: Quantum data center architecture comprises: a dynamically switched quantum entanglement network; a classical network supporting classical information exchange such as measurements as well as synchronization; a network aware orchestrator coordinating network configuration (classical and quantum) with distribution and placement of quantum algorithms

C. Quantum Data Center Interconnect Network

At Cisco's Quantum Research group, we envision a dynamic quantum entanglement network as the key building block for realizing the outlined architectural principles. Such a network can establish entanglement between any two processors within the data center. Although a multi-partite entanglement network could offer a more efficient and flexible method for connecting quantum processors, practical limitations and challenges in implementing such a network lead us to focus exclusively on bi-partite entanglement networking scenarios.

We are focusing on development of the core elements of a dynamically switchable quantum entanglement network, notably the Cisco Quantum Entanglement Switch. This research prototype is currently under development within the Cisco Quantum Research Lab, with several key features:

1. High connectivity: Non-blocking switching of entangled photons from any input port to any output port.
2. High flexibility: Supporting multiple modes of entanglement including time bin, frequency bin, and polarization-based entanglement.
3. High accuracy and efficiency: Ultra-low loss and time jitter port to port switching, allowing cascading of switches.
4. On-demand scalability: Supporting pluggable functional blocks (e.g. BSM, detectors, delay lines, memories) for on-demand sharing between quantum processors.
5. Support for classical communication: Capability for routing and switching of quantum and classical channels independently.

A functional block diagram of the Quantum Switch is shown in Figure 2:

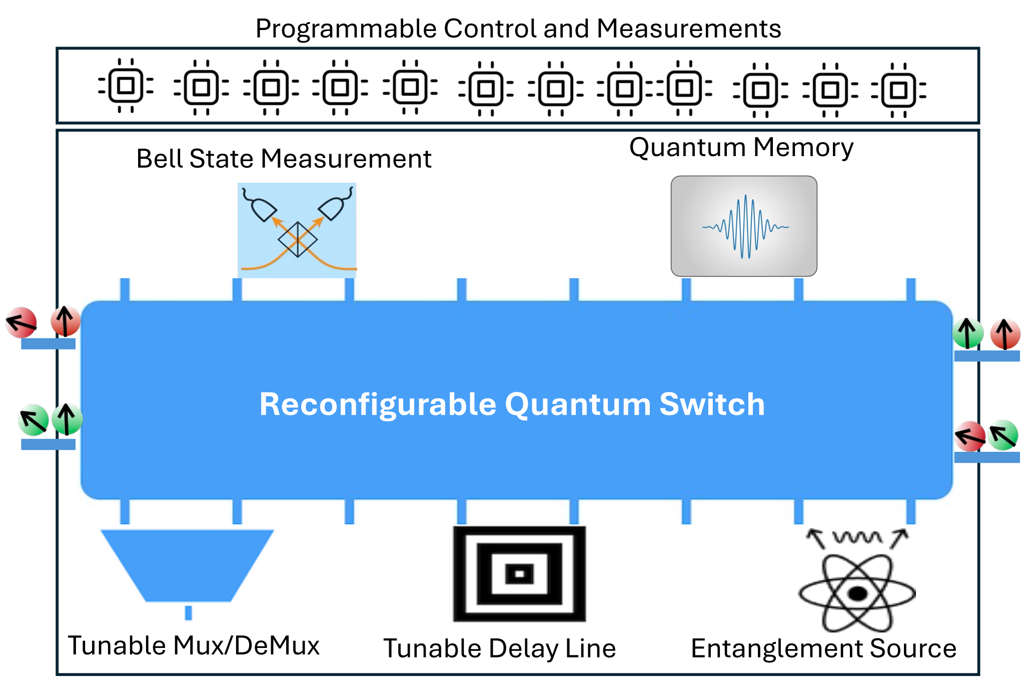

Figure 2: The Quantum Switch comprises a switching fabric suitable for quantum and classical photonic channel switching. It includes devices required for entanglement distribution in the network.

D. Network-Aware Quantum Data Center Orchestrator

While the development of algorithms and methodologies for the distribution of quantum algorithms and circuits is undergoing significant progress, with many research groups focusing on this area, most current approaches assume an ideal and fixed network connectivity platform. At Cisco's Quantum Research group, we believe that the performance of distributed quantum computing will be markedly impacted by quantum network interconnect performance. To address this crucial aspect of quantum data centers, we are developing a Quantum Data Center Orchestrator. The orchestrator includes two main mechanisms: 1. A network-aware quantum algorithm compiler 2. Protocol suites for entanglement distribution and teleportation.

A network-aware quantum algorithm compiler is designed to partition distributed quantum algorithms. This compiler translates quantum algorithms into a distributed circuit for both gate-based circuits as well as measurement-based quantum computing settings. It provides an underlying graph that specifies the sequence of circuit partitions, gates, measurements, and corrections, along with the mechanisms needed to allocate network resources to different subroutines within a quantum algorithm. The compiler aims are:

- Provide network configuration for different subroutines within a quantum algorithm.
- Optimize against penalties introduced by interconnect networks such as loss and latency.
- Maximize the number of quantum algorithms that can be processed simultaneously in a quantum data center, while minimizing the ratio of communication qubits to computing qubits required for executing an algorithm in a distributed manner.

Protocols for entanglement distribution and teleportation are critical for connecting quantum processors and facilitating distributed quantum computing. However, existing propositions are based on point-to-point, static connectivity between two remote nodes. At Cisco's Quantum Research group, we are developing advanced protocols for entanglement distribution and teleportation in a dynamically switched quantum entanglement network. This includes novel features such as entanglement routing algorithms that are cognizant of time and resource constraints as well as dynamic synchronization and measurement protocols, positioning us at the forefront of innovation in quantum networking.

E. Relevant publications

[1] H. Zhang, J. Ruan, H. Shapourian, R. R. Kompella, and Y. Ding, "Oneperc: A randomness-aware compiler for photonic quantum computing," arXiv preprint arXiv:2403.01829, 2024.
[2] H. Zhang, A. Wu, Y. Wang, G. Li, H. Shapourian, A. Shabani, and Y. Ding, "Oneq: A compilation framework for photonic one-way quantum computation," in Proceedings of the 50th Annual International Symposium on Computer Architecture, 2023, pp. 1–14.
[3] H. Zhang, K. Yin, A. Wu, H. Shapourian, A. Shabani, and Y. Ding, "Compilation for quantum computing on chiplets," arXiv preprint arXiv:2305.05149, 2023.
[4] Y. Zhang, D. Niu, A. Shabani, and H. Shapourian, "Quantum volume for photonic quantum processors," Physical Review Letters, vol. 130, no. 11, p. 110602, 2023.
[5] H. Shapourian and A. Shabani, "Modular architectures to deterministically generate graph states," Quantum, vol. 7, p. 935, 2023.

[6] Yihui Quek, Eneet Kaur, Mark M Wilde, "Multivariate trace estimation in constant quantum depth", Quantum 8, 1220 (2024).