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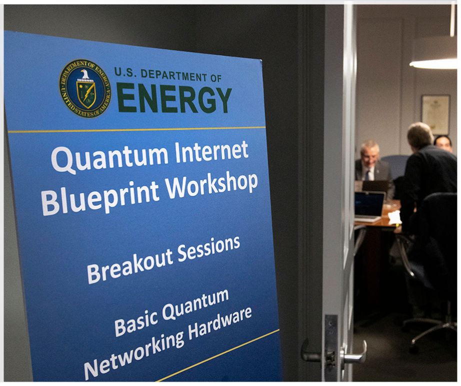
Quantum Internet Blueprint:

FROM LONG-DISTANCE ENTANGLEMENT TO A NATIONWIDE QUANTUM INTERNET



U.S. DEPARTMENT OF ENERGY | Office of Science

Quantum Internet Blueprint:

FROM LONG-DISTANCE ENTANGLEMENT TO A NATIONWIDE QUANTUM INTERNET

Quantum networking, especially with its promise of secure communication, is capturing the interest of a growing community across science, industry, and national security. Today, many scientific experts recognize that building and scaling quantum-protected and enhanced communication networks are among the most important technological frontiers of the 21st century. The international research community perceives the construction of a first prototype global quantum network—the Quantum Internet—to be within reach over the next decade. While China and Europe had taken an early lead in quantum networking technologies, the U.S. research community, including the U.S. Department of Energy (DOE) national laboratories, have achieved similar operational levels for first-generation quantum networks and are accelerating their continued progress.

At the same time, recent U.S.-based workshops, such as *Opportunities for Basic Research for Next-Generation Quantum Systems*[1], *Quantum Networks for Open Science*[2], and *Next-Generation Information Technologies*[3], have published a clear set of near-term applications for quantum networking technology, chief among them: Secure Quantum Communication, Quantum Sensor Networks, and Upscaling Quantum Computing.

In February 2020, DOE's Office of Advanced Scientific Computing Research (ASCR) held a *Quantum Internet Blueprint* workshop to define a potential roadmap toward building the first nationwide quantum Internet. The workshop participants included representatives from DOE national laboratories, universities, industry, and other U.S. agencies with serious interests in quantum networking. The resulting ***Quantum Internet Blueprint*** report identifies four Priority Research Opportunities and outlines five key milestones that must be achieved to facilitate an eventual national quantum Internet.

[1] U.S. Department of Energy, Office of Basic Energy Sciences. 2017. *"Opportunities for Basic Research for Next-Generation Quantum Systems."* Available online: https://science.osti.gov/-/media/bes/pdf/reports/2018/Quantum_systems.pdf?la=en&hash=291099097EBCCFAB99D86F60F62EA061F996424C.

[2] U.S. Department of Energy, Office for Advanced Scientific Computing Research. 2018. *"Quantum Networks for Open Science."* Available online: https://arxiv.org/ftp/arxiv/papers/1910/1910.11658.pdf.

[3] David Awschalom, Karl K. Berggren, Hannes Bernien, Sunil Bhave, et al., 2019. *"Development of Quantum InterConnects for Next-Generation Information Technologies."* Available online: https://arxiv.org/ftp/arxiv/papers/1912/1912.06642.pdf.

Priority Research Opportunities

PROVIDE THE FOUNDATIONAL BUILDING BLOCKS FOR A QUANTUM INTERNET.

Key Question: What are the key building blocks of a quantum Internet, and what performance parameters do they need to satisfy?

Today's quantum networking experiments rely on a set of devices with limited functionality and performance. However, it can be inferred from classical networks that in order to create wide-area, operational quantum networks, more capable devices with additional functionality are needed. These new devices will need to satisfy suitable requirements for reliability, scalability, and maintenance. Potential network devices may include quantum memory with efficient optical interface and satellite-to-fiber connections; high-speed, low-loss quantum switches; multiplexing technologies; and transducers for quantum sources, as well as transduction from optical and telecommunications regimes to quantum computer-relevant domains, including microwaves.

INTEGRATE MULTIPLE QUANTUM NETWORKING DEVICES.

Key Question: How will physical barriers to integrating multiple quantum network devices into high-performance quantum Internet components be overcome?

Generally, all key quantum network components remain at laboratory-level readiness to date and have yet to be run operationally in a full network configuration. Moving forward will require overcoming critical challenges toward achieving cascaded operation and connectivity, among them unifying operational properties, achieving high-repetition rates (GHz), and devising quantum memory buffers and detectors to compensate for cascading operation losses.

CREATE REPEATING, SWITCHING, AND ROUTING FOR QUANTUM ENTANGLEMENT.

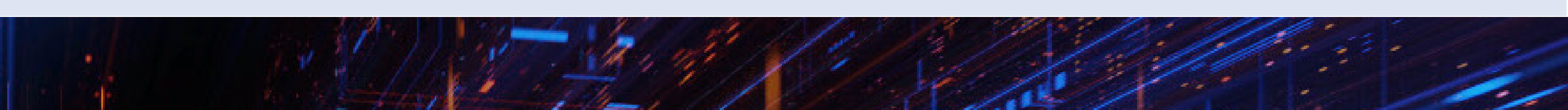
Key Question: How can fundamental network functions for a nationwide quantum Internet be created?

Multi-hop networks require a means of strengthening and repeating signals along with selecting paths through the network. While physical and software solutions are used in classical networks, an equivalent has not been found for quantum networks. Challenges include different forms of quantum entanglement generation, swapping, and purification protocols over multiple users, as well as coordination and integration of traditional networks with quantum networks technologies for optimal control and operations.

ENABLE ERROR CORRECTION OF QUANTUM NETWORKING FUNCTIONS.

Key Question: How can fault tolerant network functions be achieved?

A fundamental difference for quantum networks arises from the fact that entanglement, whose long-distance generation is an essential network function, is inherently present at the network's physical layer. This differs from classical networking, where shared states typically are established only at higher layers. In this context, solutions must be found to guarantee network device fidelity levels capable of supporting entanglement distribution and deterministic teleportation, as well as quantum repeater schemes that can compensate for loss and allow for operation error correction.



Blueprint Roadmap Milestones

The workshop further suggested a set of five key milestones to mark progress along the route to building the first nationwide quantum Internet.

CROSS-CUTTING: BUILD A MULTI-INSTITUTIONAL ECOSYSTEM BETWEEN LABORATORIES, ACADEMIA, AND INDUSTRY TO TRANSITION FROM DEMONSTRATION TO OPERATIONAL INFRASTRUCTURE.

To implement this quantum communication infrastructure and actualize it into a full-fledged prototype of a quantum Internet, coordination and cooperation among federal agencies are paramount. Interaction and integration of complementary infrastructures across agencies with substantial quantum networking portfolios and those with key mission needs in this space, including DOE, National Science Foundation, National Institute for Standards and Technology, Department of Defense, National Security Agency, and National Aeronautics and Space Administration, are particularly relevant. While pursuing these alliances, critical opportunities for new directions and spin-off applications should be encouraged by robust cooperation with quantum communication startups and large optical communications companies. Early adopters can deliver valuable design metrics.

MILESTONE I: VERIFICATION OF SECURE QUANTUM PROTOCOLS OVER FIBER NETWORKS.

Prepare and measure quantum networks. In this quantum network prototype, end users receive and measure quantum states, but entanglement is not necessarily involved. Applications to be achieved in this kind of network include exchanges between non-trusted nodes with (comparatively) higher tolerance on timing fluctuations, qubit loss, and errors.

MILESTONE 2: INTER-CAMPUS AND INTRA-CITY ENTANGLEMENT DISTRIBUTION.

Entanglement distribution networks. In this type of quantum network, any two end users can obtain entangled states, requiring end-to-end creation of quantum entanglement in a deterministic or heralded fashion, as well as local measurements. These networks provide capabilities by enabling the implementation of device-independent protocols, such as measurement device-independent QKD and two-party cryptography. The tolerance for fluctuations, loss, and errors is lower than the previous class (Milestone I). Initial integrations of classic and quantum networks exist.

MILESTONE 3: INTERCITY QUANTUM COMMUNICATION USING ENTANGLEMENT SWAPPING.

Quantum memory networks. In this type of quantum network, any two end users (nodes) can obtain and store entangled qubits and teleport quantum information to each other. End nodes can perform measurements and operations on the qubits they receive. The minimum memory storage requirements are determined by the time for round trip classical communications. This quantum network stage enables limited cloud quantum computing in the sense that it allows a node with the ability to prepare and measure single qubits to connect to a remote quantum computing server.

MILESTONE 4: INTERSTATE QUANTUM ENTANGLEMENT DISTRIBUTION USING QUANTUM REPEATERS.

Classic and quantum networking technologies have been integrated. Successful concatenation of quantum repeaters and quantum error corrected communication with respect to loss and operational errors over continental-scale distances will pave the way for operational entanglement distribution networks covering longer distances, enabling a quantum Internet to be created.