# Draft Report
# Roundtable Discussion on Quantum Networks for Open Science

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**Background**
Quantum information science is a rapidly changing interdisciplinary field that will have important implications for the nation in computing, sensing, and communications. Many aspects of quantum information science have direct bearing on Department of Energy (DOE) interests, including, for example, materials modeling, molecular dynamics, and high-energy physics.

One of the most highly anticipated capabilities that will emerge from the quantum information revolution is quantum computing, in which computations are implemented in systems that obey the laws of quantum mechanics. It has been shown that quantum computers will be able to perform certain types of computations—including many that align with DOE interests—more efficiently than classical computers. However, the full capability of the anticipated transformations enabled by quantum computing will not be fully realized without **Quantum Networking** to support distributed quantum information processing. Quantum networks will enable the transmission or exchange of quantum information (quantum bits, also called qubits) between physically separated quantum subsystems such that the quantum mechanical properties, including entanglement, are preserved without quantum-to-classical-to-quantum conversion along its path.

With a prominent leadership role in high-performance computing, DOE is keenly interested in the emergence of quantum computing. DOE leadership has led, not only to some of the most powerful high-performance computing systems, but also to state-of-the-art high-performance networks that have brought major contributions to modern Internet technologies. The fact that DOE innovation in communication networks has paralleled the growth of high-performance computing (HPC) is not a coincidence. The distributed nature of the DOE science environment drives the need for state-of-the-art network innovation, which must now evolve to include quantum networking capabilities. Indeed, computing today without the benefit of the Internet is almost unimaginable. It is anticipated that the relationship between computing and networking will continue through and be a driver of the quantum revolution: the inevitable existence of quantum computing capabilities at multiple sites establishes the need for a quantum network; and such a network will enable scientific advances that will not be possible with isolated quantum processors. Just as quantum computing will be a transformative capability for post-Moore's Law computing, a quantum network supporting that capability will be critical to realizing the full quantum potential.

**Roundtable Discussions Findings and Observations**
It is in this context that DOE convened a half-day roundtable meeting attended by multi-discipline experts in classical optical networks, quantum information processing, and computer science from academia, national labs, and government on December 4, 2017, to discuss and explore the potential of quantum networks in the DOE open science infrastructure. The discussions covered a broad range of technical challenges and opportunities that the science community faces in the development of a quantum communication network to support distributed quantum information science. The meeting participants were charged to carry the discussion in the context of end-to-end large-scale nation-wide quantum networking protocols, architectures, and hardware subsystems critical to the development of quantum network components such as quantum buffers, quantum repeaters, and quantum routers and switches. The scope of the network systems covered in the discussions included quantum inter-/intra-chip interconnects, Quantum Local Area Networks (Q-LANs), Quantum Metropolitan Area Networks (Q-MANs), and Quantum Wide Area Networks (Q-WANs). The discussions on quantum information transmission medium were centered around photonic or fiber-optical communication medium, although free space wireless and satellite quantum communications were also discussed briefly. The

discussion continued after the meeting through email and phone calls. Below is the summary and some of the key observations distilled from the meeting discussions:

***Finding and Observations No. 1***
***Quantum Networks – A Strategic Technology for Open Science:***
*Quantum network technology is a critical component of the DOE's overall future strategic computing and communications portfolio being considered to address emerging post-Moore's Law challenges. In order for the United States to maintain its leadership position in high-performance computing and communications network technologies, quantum networks must be identified as a research and development priority. Several other countries are active in the field, with notable projects from Austria, Japan, China, Canada, Switzerland, and the United Kingdom.*

***Finding and Observations No. 2***
***Large-scale Quantum Networks R&D for Open Science in DOE:***
*DOE science activities are carried out in a highly distributed science environment. Consequently, the buildout of quantum computing subsystems and applications will be similarly geographically distributed. In this context, DOE, through a well-structured R&D program, must provide the leadership to develop the first large-scale quantum wide area network to support distributed quantum information science. The development of a large-scale quantum networks R&D program would benefit other DOE quantum programs in complementary ways. Because a quantum network will require the production, manipulation, and detection of qubits, it shares many of the same challenges facing quantum computing, and advances in quantum network technology will accelerate the development of quantum computing.*

***Finding and Observations No. 3***
***Joint DOE and Industry Partnership:***
*Quantum network technology is not sufficiently mature to be carried forward solely by industry; accelerated development will depend critically on collaboration with DOE. The unique needs of a quantum network for computing are such that DOE efforts are likely to be complementary to (rather than competing with) other federal research initiatives.*

***Finding and Observations No. 4***
***Quantum Network Workshop:***
*A workshop is needed to further explore the opportunities and challenges in the development of quantum networks for open science. Of particular interest are the key challenges that must be overcome (see sections below), as well as a better understanding of the capabilities and benefits in the near term (3-5 years) and longer term (5-10 years). The workshop should bring together all the stakeholders from government, industry, and academia in order to crystallize a coherent vision for the development of quantum network technology and its deployment.*

**Quantum Networks: Current Perspectives and Trends**
A quantum network is, quite simply, a network that facilitates the transport of quantum information from one location in the network to another. Such a network might connect quantum computers in different parts of the country; or it might connect different parts of a laboratory or campus; a smaller room-size network might connect different quantum processing units in a distributed quantum computing environment, or supporting a quantum-HPC hybrid system; and chip scale quantum processing units will likely utilize quantum networks on chips and interconnecting chips.

There have been several quantum communications network demonstrations, with notable examples from the US, Austria, Japan, China, and Switzerland. The large majority have been focused on quantum key distribution (QKD) and to a lesser extent on entanglement distribution. Long-distance quantum links have relied on the use of trusted node relays, which achieve networking functionality in the classical domain by performing logical operations between keys distributed from independent links terminating at a given node.

QKD application-focused networks are typically optimized in a way which is unsuitable for quantum computing needs. This is because the goal of QKD is to share random bits that will serve as private keys between two parties on the network. Hence, there is no need to send a specific quantum state, and there is no need for quantum error correction. However, for a computing-centric quantum network, the requirements are dramatically different. One would need to transfer specific photonic qubit states with probability which approaches unity and at error rates below the fault tolerance threshold. At present, fault-tolerant quantum error corrected quantum communication is underdeveloped, with the first theoretical study published in 2014. As of today, the analysis of qubit errors affecting the computing accuracy and efficiency in a distributed quantum computing network is not well understood.

With that said, there is a large body of research that has shown that much of the technology in traditional optical networks can be used in a quantum network with little modification. Transparent quantum network demonstrations have shown that quantum signals work with standard telecom switches and can automatically recover after network path reconfiguration. It has also been shown that an erbium doped fiber amplifier (EDFA) may be bypassed to avoid in-band noise, and that out-of-band quantum signals may co-exist with telecom traffic in a conventional network. Further, there have been a number of experiments utilizing passive or active multiplexing/demultiplexing such as wavelength or time division multiplexing.

**Challenges and Research Opportunities**

The state of quantum networks today is strikingly similar to that of classical fiber-optic networks of several decades ago: communication was limited to point-to-point links over modest distances because of signal degradation stemming from optical loss. Although the technology revolution that led to the fully connected, high-speed, data networks of today comprised thousands of advances, arguably, three can be identified as having the most significant impact: amplifiers to overcome the optical loss limitations; routers to enable full any-to-any connectivity; and control plane technologies to manage traffic flow. If the full potential of quantum networks is to be realized, then advances will be needed in the quantum analogs to these three (quantum repeaters, quantum routers, quantum network control and management), and possibly other yet undetermined, technologies. In addition, new test and measurement tools will be needed, as well as modeling and simulation support. However, the full scope of the research challenges is not known, but could be explored in the workshop described in the 'Findings and Observations' section above. **This workshop should bring together experts from academia, industry, national labs, and government to develop a coherent plan for the development of quantum network technology and its deployment. Such a workshop would also lead to a better understanding of how a quantum network will coexist with ESnet, as well as how the latter will be leveraged to develop a nationwide quantum network capability.**