Distributed Quantum Processing via Integrated Regional Quantum Networks Using Free-Space Optical Links

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Topic: Quantum Networking Models and Applications

1. Challenge: Integration of regional quantum networking infrastructure.

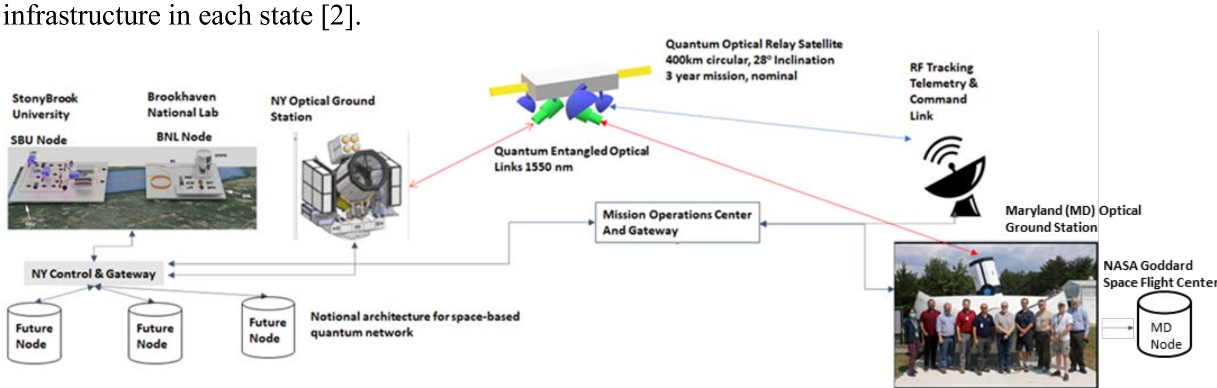
The landscape for scalable quantum processing is rapidly evolving with the development of quantum computers and the emergence of future science enablers, such as distributed quantum computing and hybrid computing scenarios where quantum and classical computing assets work cooperatively. Quantum entanglement distribution is also advancing with multiple regional quantum networks and testbeds maturing across the nation. These quantum networking testbeds typically include multiple access points with a heterogeneous mixture of capabilities interconnected by fiber spanning anywhere from tens to hundreds of kilometers; many such networks incorporate a classical networking framework. Alongside these quantum connectivity advancements in the infrastructure, the maturation of quantum sensing technology presents an opportunity to expand the body of quantum networking use-cases that are presently possible. Along these lines, bridging the present collective progress in quantum computing and quantum networking will enable us to develop new use-cases. One such use-case is enabling future quantum computing applications via integrated regional quantum networking infrastructure in neighboring locations like New York and Maryland, both states are home to robust classical and quantum networking capabilities. To enable near-term distributed quantum computing applications via the practical integration of regional quantum networking infrastructure, free-space optical links via satellite communications will be essential to avoid the exponential loss commonly observed with fiber implementations [1]. There is both an urgent need and a practical justification for pursuing such space-based integration scope now.

2. Opportunity: Quantum Applications using space-based quantum networking.

It is paramount to develop applications that can take advantage of the special nature and non-locality of entanglement. Present applications include blind quantum computing, unprecedented space-science data processing algorithms to advance fundamental physics research, and the ability to break all current forms of cryptography that are not post-quantum hardened. Additionally, applications in quantum sensing are already emerging. Ultimately, the advantages that exist for classical space communications will be enhanced by the novel resources and insights that these quantum applications will provide. To effectively enable such quantum applications over long distances, legacy classical optical communications must be adapted for space-based quantum networking scenarios. In order to achieve first realizations of space-based quantum links, it will be necessary to develop new quantum-ready components, to design integrated classical/quantum systems performance, to envision novel concepts of operation and enhanced end-to-end data flow paradigms, and to address flight/orbital dynamics challenges and precision pointing, acquisition and tracking needs for ground segment telescopes. In the near-term we can envision an extension of classical networks to include the ability to pass quantum entangled data through the network. In this scenario, the "heavy lifting" in terms of data rate, and performance should be confined to the classical channels. The quantum channel should be used for functions such as entanglement and entanglement swapping. Additionally, augmenting the Open Systems Interconnection (OSI) protocol stack will be required to accommodate the inclusion of quantum data flow in the network. Furthermore, network security, including quantum and post-quantum cryptography methods must be designed into all the network elements. Further progress can be achieved by further developing quantum devices such as quantum memories and entanglement sources, which exist primarily in laboratories and testbeds, into miniaturized systems that can be implemented in spacecraft with a reasonable size, weight, power, and cost (SWAP-C) within a reasonable timeframe. These challenges can be investigated at the laboratory level now and national programs should incentivize the near-term demonstration of these solutions in the context of space-based projects. The future of such space-based quantum-network missions will also depend on the ability of legacy optical communications commercial off the shelf (COTS) sources, detectors, and optics to be used with little or no modifications. Therefore, an intentional commercialization strategy must be an additional spin-off of lab- scale and/or larger-scale quantum-networking research and national investment programs. By reducing and eventually removing the overhead of non-recurring engineering for key quantum networking components and systems designed to perform over target functional ranges, quantum local area networks around the country will be able to scale up their network capacity and availability in an efficient manner and thus accelerate their readiness for integration and intracontinental operations aided by space-based optical communications links. The ability to space qualify key components and parts is also a challenge to overcome.

3. Assessment: Establishing LEO or MEO space- based optical quantum communication.

A targeted and nationally supported program is needed to enable the practical tasks associated with defining, developing, testing, evaluating, and operating a free-space connection to interface regional quantum networking access points where quantum computing assets can either be remotely leveraged or physically co-located to implement science enabling distributed quantum processing tasks. Success of such a program would be defined as the ability of the New York and Maryland collaborations to communicate via network protocols that include exchange of quantum entanglement via a LEO or MEO space- based optical communications flight asset with ground terminals coupled to terrestrial quantum networking infrastructure in each state [2].



4 Maturity: Achieving *operational* competency in spaced-based quantum networking.

It took several decades to mature the current world-wide internet from its origins in the ARPANET program. This maturation process was accelerated by the development of Ethernet, TCP/IP, UDP, and other data communication protocols. Simultaneously, the physical layer infrastructure had to be laid into place. The same situation exists today regarding the development of spaced-based quantum networking and distributed quantum computing. The United States has spent years maturing key quantum components, devices, systems, executing studies, analysis, while also building quantum-enabling infrastructure. Furthermore, there is a wealth of classical networking infrastructure and approaches widely used now that could serve as a guide to where adaptations are needed. The ability to form spatially diverse worldwide quantum optical communications networks will involve free space communications through the atmosphere to earth orbiting relay satellites, which can use our well established abilities to build and operate earth orbiting relay satellites and ground stations and to operate effective mission control. Within this framework, collaborations between domestic organizations with government support should help achieve national *operational* competency in spaced-based quantum networking. The impact of success would be a tangible demonstration of intracontinental quantum computing along the east coast of the United States, realizing a subset of the objectives set forth in the national quantum strategy.

[1] Science 356, 1140–1144 (2017), [2] EPJ Quantum Technology 5, 6 (2018).