SUMMARY OF THE 2023 QUANTUM NETWORKING INTERAGENCY WORKING GROUP WORKSHOP

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About the National Quantum Coordination Office

The National Quantum Coordination Office (NQCO) coordinates quantum information science (QIS) activities across the U.S. Federal Government, industry, and academia. Legislated by the National Quantum Initiative (NQI) Act of 2018 and established within the White House Office of Science and Technology Policy, the NQCO oversees interagency coordination of the NQI Program and QIS activities; serves as the point of contact on Federal civilian QIS activities; ensures coordination among the consortia and various quantum centers; conducts public outreach, including the dissemination of findings and recommendations of the National Science and Technology Council (NSTC) Subcommittee on QIS, the NSTC Subcommittee on Economic and Security Implications of Quantum Science, and the NQI Advisory Committee; and promotes access to and early application of the technologies, innovations, and expertise derived from U.S. QIS activities, as well as access to quantum systems developed by industry, universities, and Federal laboratories to the general user community. More information is available at quantum.gov.

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About this Document

This document contains a summary of ideas and perspectives that were presented at an interagency workshop on quantum networking research coordination.

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1 OVERVIEW

Breakthroughs in quantum networking and communications, which offer the possibility of distributing entanglement as a resource and interconnecting quantum devices, may catalyze the development of quantum information science (QIS) technologies such as distributed modular quantum computers and coherent quantum sensor arrays. These quantum technologies are expected to have significant societal impacts. However, the field of quantum networking is still at an exploratory stage.

Building upon the Biden-Harris administration's ongoing work to ensure that the United States remains a global leader in the development of new QIS technologies, the National Quantum Coordination Office (NQCO) convened a workshop in June 2023 to bring together experts in quantum networking and communication for discussions on research goals, gaps, challenges, and opportunities for interagency coordination. The workshop was organized in collaboration with the Quantum Networking Interagency Working Group (QN-IWG) established by the Subcommittee on QIS. The workshop brought together experts from 15 Federal departments and agencies and select Department of Energy (DOE) National Laboratories and Quantum Leap Challenge Institutes (QLCIs) funded by the National Science Foundation (NSF). This document collects ideas and perspectives that were presented at the workshop.

This synopsis provides a representative, high-level snapshot of the themes discussed and major takeaways, and should not be taken as a consensus position of the attendees nor of the Subcommittee. Rather, it gathers observations from a variety of practicing experts. The workshop provided an opportunity to discuss the implementation of the national strategy for *A Coordinated Approach to Quantum Networking Research*, [1] and to look toward the future as the Subcommittee on QIS and its QN-IWG considers updating the strategy, as called for in the CHIPS and Science Act of 2022.[2,3]

Approximately 50 participants attended the workshop, which was hosted at the National Aeronautics and Space Administration (NASA) Goddard Spaceflight Center (GSFC). Dr. Makenzie Lystrup, Director of NASA GSFC, and Dr. Charles Tahan, Office of Science and Technology Policy (OSTP) Assistant Director of QIS and Director of the NQCO, welcomed the participants. Dr. Lystrup highlighted QIS efforts augmenting the NASA mission and the role that quantum science may play in deep space exploration and geoscience. Dr. Tahan discussed the recommendations in *A Coordinated Approach to Quantum Networking Research* and emphasized the need to better understand how improving entanglement distribution can raise the utility and accelerate the deployment of quantum technologies.

The workshop had two panels focused on topics such as priorities for quantum networking, the quantum networking workforce, near- and long-term opportunities for collaboration and coordination, use-case development, and next steps for addressing gaps in quantum networking at the national level. The panels were followed by five breakout sessions:

Breakout 1: Domestic Cooperation and Coordination

Breakout 2: Critical Components and Supply Chains

Breakout 3: Near-Term Applications

Breakout 4: International Activities and Considerations

Breakout 5: Interoperability and Standards

[1] https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf

[2] The CHIPS and Science Act (Pub. L. 117-167) §§ 10661 (amending NQI Act to add new section 103(h), 15 U.S.C. §§ 8813(h)).

[3] https://www.quantum.gov/wp-content/uploads/2022/08/NQIA2018-NDAA2022-CHIPS2022.pdf

Sections 2 and 3 of this document provides a brief description of the discussions from the panels and the breakout sessions, respectively.

2 PANEL DISCUSSIONS

The two panels focused on center-scale quantum networking initiatives being undertaken across the United States. Panelists represented the Air Force, Army, Washington Metropolitan Quantum Network Research Consortium (DC-QNet), DOE, Navy, NASA, National Institute of Standards and Technology (NIST), and NSF, as well as Argonne, Brookhaven, Lawrence Berkeley, and Oak Ridge National Laboratories, and the Hybrid Quantum Architectures and Networks (HQAN) and Quantum Systems through Entangled Science and Engineering (Q-SeNSE) NSF QLCIs. The panels focused on ongoing quantum networking activities at each of these entities and forward-looking needs.

Priorities and Goals: The panelists described the wide variety of efforts that are underway at the various institutions. A common topic mentioned amongst panelists was that a science-first approach is still needed in quantum networking, with many small, lab-scale efforts needing further investigation and fundamental technology discovery before heavily developing large-scale demonstrators. The support of fundamental science, advanced components, and prototypes across diverse technical areas was discussed, as was the need for metrology in quantum networking.

A recuring theme brought up by the speakers representing institutions engaging in research and development (R&D) was the need to investigate and demonstrate entanglement across heterogenous quantum systems and interfaces. Several speakers noted the importance of both matter- and photon-based (stationary and flying) qubits. Another articulated need was to consider how to optimize entanglement distribution, with the end goal of having a fully functional, regional quantum network providing mission-relevant applications.

Panelists discussed the goal of demonstrating the basic elements and technologies for distributed quantum systems while looking toward scalability, including: synchronization; quantum state control and coexistence of classical and quantum signals; repeater-friendly quantum-node technologies; quantum network control; a commercialized quantum memory; devices and methodologies to connect quantum technologies across signal domains, such as those supporting transduction and frequency conversion; and “plug and play” components for future quantum networks. Some of the field’s broad goals included: entanglement swapping; entanglement distribution; use-case development and demonstrations; developing the workforce; developing labs and user facilities with integrated quantum sensors, distributed quantum computing, and collaborative experiments.

Infrastructure and Use-Case Development: The panelists discussed the balance needed between the development of infrastructure, such as testbeds, and the fundamental R&D that must still be undertaken to create many of the components needed for quantum networking. One panelist offered a historical note, pointing out that in 1999 NSF held a workshop on QIS where the “quantum internet” and “quantum repeaters” were discussed. Shortly thereafter, in 2001, the highly cited DLCZ approach to building a quantum repeater was proposed. Yet, while the community has made some progress on quantum networking and repeater R&D, both are still in the fundamental stage of research. Furthermore, the field lacks a compelling use case that would justify a significant reprioritization of efforts. The participant challenged the QN-IWG to consider how to responsibly create a sense of urgency and pursue a realistic and sustained outlook for quantum networking R&D. Another panelist commented that building a fully functioning quantum network may be one of the more difficult problems in QIS, yet it lacks convincing applications. Therefore, application development, such as connected quantum sensors, should be a focus. Clock synchronization for gravimetry was presented as a potential proto-use case for quantum networks.

Many of the future envisioned use cases of QIS systems will require distributed entanglement in various operating environments, and to chart a path in that direction, the field should encourage some experiments to move beyond laboratory demonstrations. How far beyond the lab was a topic of discussion for the panelists, for example, when to move beyond connecting two different labs, to local area or fielded networks, wide area networks, or to space. Multiple panelists described in-house testbeds and network prototypes located at a single institution, with some commenting on additional efforts to connect the testbeds between both Government and non-Government facilities. The panelists discussed the value proposition of testbeds and noted the importance of testbed environments utilizing both free-space and fiber links for the analysis and evaluation of quantum networking concepts, components, protocols, and architectures, as well as the importance of nodes. Some panelists advocated for advancing national goals for intracontinental quantum networking by connecting regional testbeds, with an argument also being made against prioritizing resources toward testbeds, highlighting the many lab-based challenges that need to be overcome before doing so.

Panelists commented that developing the supply chain with cross-cutting components and R&D will hedge risk in quantum networking. Better materials R&D will yield improved components like memories for repeater development, and the co-development between computer architecture specialists and quantum scientists will help develop quantum networking protocols.

Cooperation and Coordination: Panelists described active collaborations within and between academia and Federal departments and agencies, but many are looking to expand. Specifically, within the Federal Government, there is a need to advance cooperation amongst agencies to understand how quantum networking will augment mission spaces. Connecting testbeds was mentioned as a mode of cooperation, while one participant took the position that instead the focus should be placed on moving the entire field forward together, while staying within the mission space of the respective agencies. Jointly funded cross-agency projects, such as component development and ensuring that the testbeds are interoperable, were mentioned as mechanisms for cooperation.

Many participants highlighted the diverse skill sets necessary to advance quantum networking R&D. These included the criticality of interfacing with different hardware modalities to distribute entanglement across a multi-node network for a full quantum ecosystem and integrating engineering, computing, and physics across institutions for hybrid distributed computing and networking. In classical computers, there are many computing platforms to achieve specific use cases, such as, Central Processing Units (CPUs), Graphics Processing Units (GPUs), and Field Programable Arrays (FPGAs). The quantum ecosystem may have analogous systems that leverages the long coherence times of trapped ions, high gate fidelities of superconducting qubits, and the networking capabilities of photonics. Nurturing collaborations between these fields was highlighted as a mode of advancing America's quantum networking R&D portfolio.

Cutting-edge R&D is occurring internationally, and participants noted the importance of global collaboration. An overarching framework that would facilitate international collaboration would be of value. An avenue mentioned for international collaboration would be to fund projects for students to work together. Panelists commented on the need for an international collaboration strategy and encouraged the exchange of talent. Panelists also noted the importance of industrial engagement and the opportunity for startups to accelerate the transition of quantum networking technology.

Workforce Development Needs: Many panelists acknowledged the workforce challenges that face quantum networking, as well as QIS at large. A panelist remarked that the workforce challenge encompasses a talent shortage across all skill levels of QIS. The DOD agencies remarked upon the additional requirement that their employees be U.S. citizens, further limiting the talent pool. Participants noted there is a need for a workforce that is balanced between foundational (research) and applied (engineering) disciplines. In addition to the demand for QIS experts, some of the critical workforce needs mentioned included: instrumentation control and hardware programming; systems engineering, integration, design and testing; software simulation; machine learning for automation; advanced packaging; and classical expertise in link stabilization.

Panelists recognized the challenges in developing and training the workforce, including developing curricula that will equip students with a broad skillset that also supports QIS, allowing students to have multiple on and off ramps; an example of such a curriculum would be linear algebra in the context of QIS, which provides insights into the field, but also teaches to a fundamental skillset. Another participant cautioned against focusing too much on digital quantum mechanics, such as qubits, since there is still a need to teach the analog aspects, such as resonators and quantum harmonic oscillators, for both non-physics majors and those who want to pursue quantum mechanics outside of QIS. To aid in employment after school, a success story mentioned was a program that built collaborative spaces with shared labs with the ultimate goal of transitioning students to startups.

Technical Needs: The panelists acknowledged the many outstanding technical challenges. These challenges included resource and workforce constraints, and the need to maintain the funding imperative for quantum networking, with sustained and predictable funding, while demonstrating near-term successes for mission-driven R&D.

The outstanding technical challenges that were mentioned included the loss of carrier photons and information signals, as well as the general problem of mitigating noise and decoherence; generating native telecom photons without quantum frequency conversion; integrating free-space and fiber platforms for long-distance quantum communication; reliable quantum memories; and classical-quantum signal co-existence. Light sources and transduction to connect quantum processing units were mentioned as a great need.

Multiple participants mentioned concerns over proposed export controls, remarking that controls make collaborations difficult and therefore, from the panelists' perspective, should be avoided when possible. A remark was made that open and collaborative academic environments facilitate discoveries and attract top talent, and with a question of how to balance export control issues with emerging quantum networks.

3 BREAKOUTS

Breakout 1: Domestic Cooperation and Coordination

The first breakout focused on domestic cooperation and coordination. There were two sessions and each session discussed current levels of cooperation, benefits and obstacles to cooperation, and opportunities for future collaborations.

Participants noted that good cooperation exists within regional pockets and is mostly driven by informal scientific interactions. Contractual, formalized, or jointly funded efforts, including between testbeds, is limited to a few examples. However, participants commented that a simplified process to formalize cooperation would facilitate larger-scale partnerships. Some benefits of cooperation mentioned included reducing redundancy, resource sharing (especially workforce), communicating technical and engineering solutions to common issues, and eventually targeting networking projects that require larger demonstrations spanning multiple agency mission spaces and technical competencies. There was a sense that there are many fundamental crosscutting challenges that could benefit from cooperation. Large cooperative efforts can be distracted by conversations of use cases; rather, participants argued that we should be focusing on scientific discovery in quantum networking collaborations. Other obstacles included administrative overhead and differences in mission spaces across the Government, along with intellectual property issues for cooperation with industry.

A technical workshop focused on common ‘science and engineering’ aspects of quantum networking was proposed as a mechanism for increasing cooperation and enhancing scientific-level interactions. Potential topics included timing, co-existence, polarization control, metrology, the implementation of different network stack models, and the development of common abstractions.

Talent exchanges of students, post-doctoral researchers, and staff scientists are another vector for collaboration, which increases awareness of others’ approaches. Some participants noted that a concerted effort may be essential to accelerate collaboration and coordination. Such an effort could also help address the essential need for workforce development, and it may be necessary for regional connectivity and the co-development of resources with academia. Participants’ views regarding broader nationwide physical connectivity of regional prototype networks ranged from essential and urgent on one hand to undesirable and unnecessary on the other. As mentioned in Breakout 5, identifying needs for interoperability may be a short-term goal to plan for how regional networks may be connected in the future. Participants noted that nationwide cooperation among scientists and program awareness will prepare researchers for when nationwide connectivity is needed.

Breakout 2: Critical Components and Supply Chains

In the breakout focused on critical components and supply chains, participants noted the need for common infrastructure that could advance R&D, such as user-type facilities that would enable groups to leverage large, expensive, or specialized equipment, or provide opportunities to participate in fabrication runs. Shared infrastructure or resources of this nature would help reduce the barrier to entry for academic groups, and, as some participants noted, it may increase diversity as the high cost of many quantum networking experiments is an obstacle. Some noted that creating a database of available resources, such as testbeds and user facilities, would be valuable to the R&D community as many facilities have different operating models and capabilities.

Another discussion topic centered around paths for the community to expand the user base for specialized devices and ways to incentivize companies to fabricate both quantum and classical devices that support quantum networking. Since current markets are still emerging for many quantum components, supply is limited. Maintaining a list of necessary components and suppliers of those components to understand gaps in the supply chain was suggested. Participants questioned if there are better ways to utilize the Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) programs. Some in the group thought the current system could be optimized to better target the needed technologies and others asked if more agency coordination across the various SBIR/STTR programs might help. Along the same lines, some participants asked if there could be more reciprocity across nations toward needed infrastructure or enabling components.

Finally, the breakout group discussed benefits to more interagency cooperation and whether there were underutilized Government resources that could be brought to bear, such as existing dark fiber networks. There was also a suggestion to define the larger, common needs and solutions across the different activities and target those as a starting point to focused coordination.

Breakout 3: Near-Term Applications

A Coordinated Approach to Quantum Networking Research noted that developing useful applications for quantum networks will require substantial and sustained basic research. Participants acknowledged that applications such as distributed quantum computing and very-long baseline interferometry are promising future use cases, but that many of the potential use cases are bound to the advancement of other quantum technologies. Instead, this breakout considered opportunities and challenges to developing near-term applications, and what applications would require to justify moving beyond the laboratory to small, local, regional, and wide-area quantum networks.

The participants discussed some of the pitfalls across the space. For example, the tendency to focus on scale and applications rather than fundamental revolutions in the underlying technology. Another example was that the quantum networking community does not have a clear goal to work toward, as opposed to quantum computing or sensing, and that a lack of common goals may hinder progress. In addition, the timescale for use cases in quantum networks may be slower than quantum computation, due to the inherent lack of highly-controllable conditions in the field. Performing cost/benefit analyses to a few proposed applications may help set directions for the community.

Some participants made the point that there may be “stepping stone” applications, such as linking/synchronizing clocks, classical-quantum coexistence that would support classical and quantum capabilities, and secure direct communication, which could establish many of the fundamental R&D needed for quantum networking. Participants mentioned that fundamental R&D would be the driver of use-case and application development in the near term and noted the challenges to creating an effort solely devoted to use-case discovery. Multiple participants acknowledged that while use cases will ultimately drive investment in quantum networks, the near-term applications will likely be oriented toward scientific inquiry.

Breakout 4: International Activities and Considerations

International cooperation was a programmatic recommendation of *A Coordinated Approach to Quantum Networking Research* and is a policy pillar of the National Strategic Overview of QIS. Since 2019, the United States has signed QIS cooperation statements with 10 countries. Further, the CHIPS and Science Act of 2022 amended the NQI Act to task the QN-IWG to assess the relative position of the United States with respect to other countries in the global competition to develop, demonstrate, and utilize quantum networking and communications technology. This breakout discussed the importance of encouraging international cooperation, while also balancing the risks to such collaborations. Challenges mentioned by multiple participants included inexperience in navigating the bureaucratic process involved in formalizing international collaborations, with some agencies describing a multi-year process to complete and implement international agreements. A lack of coordinated funding for international collaborations was an additional challenge that was stressed. The group also discussed being mindful of research security and technology protection during international collaborations.

Overall, many participants agreed collaborations should be built from the bottom up, while stressing the importance of developing high-level policies to help encourage such collaborations. Science should be the motivator and establishing common goals will help spur this collaboration and avoid redundant efforts. Leveraging joint infrastructure was also mentioned as a potential motivator for international collaboration. Accounting for the existing collaborations and opportunities, such as NSF lead agency agreements, would help the community identify additional gaps in our ability to work with international partners.

Breakout 5: Interoperability and Standards

The fifth breakout focused on interoperability and standards, which is an area tasked to the QN-IWG by the CHIPS and Science Act of 2022. The participants noted that more standards have been proposed for quantum networking than the other QIS subfields; however, out of the QIS subfields, networking may be the least ready for standardization. Participants noted that this push may be due to both the competitiveness aspect of standardization, as well as the natural tendency to standardize methods of communication. However, concerns were raised about setting standards too early. For example, once the standardization process is started, it may cause a spate of new, and potentially restricting, proposals. Participants noted that there is a need to consider interoperability before formalized standards, and interoperability could provide enough agreement to perform technical functions. In addition to identifying paths toward interoperability, participants noted that developing a common set of definitions for terms related to quantum networking would be more appropriate and serve as an initial step toward eventual standardization. Many participants acknowledged that when standards are adopted, they should be done in a way that does not negatively impact the progress of science.

The participants of this breakout session coalesced around two high-level take-aways:

1. The current QIS platforms are still nascent and heterogeneous. There are many optimistic prospects for quantum networking platforms and supporting technologies, and there is no consensus candidate for the best of any component or specification in quantum networking. It is therefore premature to standardize a particular platform.
2. A lack of interoperability may stress and dilute the supply chain. A community-led stakeholder meeting to determine what components or specifications are needed for interoperability could help focus supply chain needs. The candidate specifications should be chosen purposefully with joint experiments or testing in mind.

4 CONCLUSION

This Quantum Networking Workshop brought together Federal QIS R&D researchers, program managers, representatives from academia, and several DOE national laboratories to discuss the current state of quantum networking and how the field is evolving in the near-term. This workshop was held at the midway point between the publication of *A Coordinated Approach to Quantum Networking Research* and the legislative tasking to QN-IWG by the CHIPS and Science Act of 2022. It provided a retrospective on the status of implementation, as well as looking forward toward new activities. Many high-level challenge areas and opportunities were identified. Common themes emerged from the breakouts, such as enhanced coordination to address common gaps and problems, while also reducing redundancy. Technical workshops focused on the outstanding challenges and priorities that were also identified in multiple breakouts as a mechanism to aid in co-development and coordination.