A Report of the

National Quantum Initiative Advisory Committee

September 2024

Quantum Networking: Findings and Recommendations for Growing American Leadership

ABOUT THE NATIONAL QUANTUM INITIATIVE ADVISORY COMMITTEE

The National Quantum Initiative Advisory Committee (NQIAC) is the Federal Advisory Committee called for in the National Quantum Initiative (NQI) Act to advise the President, the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), and the NSTC Subcommittee on Economic and Security Implications of Quantum Science (ESIX), and to make recommendations for the President to consider when reviewing and revising the NQI program. It is tasked with conducting independent and periodic assessments of trends and developments in quantum information science and technology (QIST); the management, coordination, implementation, and activities of the NQI; whether goals established in the NQI Act are helping to maintain U.S. leadership in QIST; whether a need exists to revise the NQI; whether opportunities exist for international cooperation with strategic allies; and whether national security, societal, economic, legal, and workforce concerns are adequately addressed by the NQI. The NQIAC is also tasked with submitting reports with its independent assessments to the President and appropriate committees of Congress, including any recommendations for improvements to the NQI. The NQIAC consists of leaders in the field from industry, academia, and Federal laboratories. More information is available at https://www.quantum.gov/about/nqiac/.

NQIAC Members

- Kathryn Ann Moler, Co-Chair
- Gretchen K. Campbell, Co-Chair
- Jamil Abo-Shaeer
- Fred Chong
- James S. Clarke
- Deborah Ann Frincke
- Gilbert V. Herrera
- Nadya Mason
- William D. Oliver
- John Preskill
- Mark B. Ritter
- Robert J. Schoelkopf
- Krysta M. Svore
- Jinliu Wang
- Jun Ye

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 NQI Act of 2018 and established within the White House Office of Science and Technology Policy (OSTP), 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 consortia and various quantum centers; conducts public outreach, including the dissemination of findings and recommendations of the SCQIS, ESIX, and NQIAC; 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 https://quantum.gov.

NQCO Staff

- Gretchen K. Campbell, Director
- Brad Blakestad, Deputy Director
- Tanner J. Crowder, Senior Policy Advisor and NQIAC Designated Federal Officer (DFO)
- Hilary M. Hurst, Quantum Liaison
- Thomas G. Wong, Consultant

ACKNOWLEDGMENTS

The NQIAC and NQCO thank the Institute for Defense Analyses (IDA) Science and Technology Policy Institute (STPI) team, especially Emily Grumbling, Matthew Diasio, and Abby Goldman for assistance with research and analyses.

The NQIAC and NQCO thank Elizabeth Whatcott for supporting NQIAC activities during an internship with OSTP.

EXECUTIVE SUMMARY

Quantum networking and communication (hereafter, quantum networking) enable the transmission of quantum states and the distribution of entanglement across multiple quantum information systems. This capability could one day connect quantum devices to build larger-scale quantum computers or distributed quantum sensors with sensitivity that surpasses the standard quantum limit.

Recognizing the impact that quantum networking could have on U.S. economic and national security, the National Quantum Initiative Advisory Committee (NQIAC) established a subcommittee to provide advice on focusing Federal efforts to enhance progress in the field, which builds upon decades of existing Federal investments. This subcommittee met for 9 months and engaged domestic and international stakeholders. Based on these engagements, the NQIAC found that:

1. Quantum networking capabilities will play a role in U.S. economic prosperity and national security, but the magnitude of that role will only be clarified through sustained research and development (R&D).
2. Continued investment in R&D by the U.S. Government will be necessary to determine, understand, and realize the advantages of quantum networking for practical applications.
3. Quantum networking R&D can complement and enhance progress in advancing other quantum information science technologies.
4. The term "testbed," as it relates to quantum networks, is used ambiguously. Testbeds are distinct from demonstrators, prototypes, and user facilities as per the following definition, which the NQIAC will use in its recommendations:

   A testbed is a platform or facility that is accessible to multiple users to conduct replicable and rigorous testing of component technologies, protocols, and systems integration.
5. Early quantum networking prototypes, demonstrators, and testbeds are in operation, with practical or economic impact yet to be determined.
6. Quantum networking testbeds, if strategically chosen and properly timed, can play an important role in accelerating U.S. quantum information science leadership.

From these findings, the NQIAC makes the following seven recommendations for the U.S. Government to grow American leadership in quantum networking:

1. Continue to support fundamental research in quantum networking, its applications, and its enabling technologies.
2. Encourage the definition, development, and use of metrics to measure progress on quantum networking technologies and their applications.
3. Support the development of a coordination model for describing the functional layers of quantum networks.
4. Federal funding for quantum networking testbeds should be allocated when testbeds are both "right-sized" and "properly-timed."
5. Support and facilitate industry participation in quantum networking testbeds.
6. Prioritize new funding appropriations and the development of new mechanisms to promote collaboration with international allies and like-minded partners for quantum networking R&D.
7. Leverage quantum networking testbeds to enable and train a diverse quantum workforce.

These findings and recommendations build upon those made in the 2020 National Quantum Coordination Office report on *A Strategic Vision for America's Quantum Networks* and the 2021 National Science and Technology Council Subcommittee on Quantum Information Science report on *A Coordinated Approach to Quantum Networking Research*.

INTRODUCTION

Quantum Information Science (QIS) is a multidisciplinary field that harnesses quantum mechanics and information theory to expand the application space for storing, processing, transmitting, and measuring information. In 2018, the United States launched the National Quantum Initiative (NQI), a whole-of-government effort to advance progress and U.S. competitiveness in QIS, catalyzed through the passage of the NQI Act and enhanced through subsequent legislation. Among other provisions, the NQI Act codified the roles of several entities to help coordinate QIS activities across Federal departments and agencies ("agencies," hereafter). These entities include the National Science and Technology Council Subcommittees on Quantum Information Science (SCQIS) and Economic and Security Implications of Quantum Information Science (ESIX), and the National Quantum Coordination Office (NQCO) in the White House Office of Science and Technology Policy. The NQI Act also established the National Quantum Initiative Advisory Committee (NQIAC) to provide independent advice on Federal activities to best support the NQI's goals.

In 2021, the SCQIS published *A Coordinated Approach to Quantum Networking Research*.[1] This report made four technical and three programmatic recommendations for Federal agencies to advance the Nation's knowledge base and readiness to utilize quantum networks. The Creating Helpful Incentives for Producing Semiconductors (CHIPS) and Science Act of 2022 authorized new activities related to the QIS subfield of quantum networking and called for an update to this SCQIS report.[2]

To help inform related Federal efforts, the NQIAC undertook an assessment of quantum networking developments and the U.S. strategy for quantum networking, with a specific focus on the fourth technical recommendation of the SCQIS quantum networking report: "Leverage 'Right-Sized' Quantum Networking Testbeds." In particular, the NQIAC assessed how the Federal Government might best prioritize and implement quantum networking and communications (hereafter, "networking") testbeds needed to advance the field.

The NQIAC formed a Subcommittee on Quantum Networking (hereafter, the Subcommittee) to gather information and analyze relevant issues and facts. The Subcommittee met from October 2023 through August 2024 to gather information about quantum networking research and development (R&D), technology readiness, and testbed requirements. Over the course of these meetings, the Subcommittee met with experts from across the U.S. Government and from the major U.S. QIS research centers authorized under the NQI, along with experts from academia and industry, in the United States and internationally, and consortia, such as the Quantum Economic Development Consortium (QED-C). The NQIAC deliberated the resulting findings and recommendations in a public meeting on August 6, 2024, and this report presents NQIAC's approved consensus findings and recommendations for advancing U.S. leadership in quantum networking.

NQIAC FINDINGS

FINDING 1: Quantum networking capabilities will play a role in U.S. economic prosperity and national security, but the magnitude of that role will only be clarified through sustained R&D.

Quantum networking will enable a new frontier of communication that will distribute quantum states or entanglement. Entanglement is a physical resource—fundamentally different from those transmitted through classical networks—that will be necessary to enable and advance quantum technologies such as

---

[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)).

distributed quantum computing and sensing. Quantum networks will not replace classical networks; rather, they offer opportunities for novel communication and processing that extend classical networking capabilities to the transmission of quantum information. See Box 1 for a discussion on the difference between the classical internet and quantum networks.

While quantum networks promise to enable new and powerful applications, they also present new security considerations. The United States will benefit from continuing to nurture R&D in quantum networking in order to understand more fully the economic and security benefits and risks associated with it and its applications.

Although the NQIAC foresees the value of quantum networking for some applications, such as distributed quantum computing, its impact for other applications is not as well understood or agreed upon. Nevertheless, failure to fund R&D to investigate the potential of quantum networking would bear risk, such as the loss of domestic expertise and supply chain, as well as the loss of a first-mover advantage of disruptive technologies, especially given continued global investment. It is therefore prudent for the Nation to continue to invest in quantum networking R&D—whether through quantum networking-enabled communication, sensing, or distributed quantum computing.

Box 1. Today's Internet vs. Quantum Networking

Quantum technologies, as they are known today, will not replace their classical counterparts, but instead offer new capabilities. Just as quantum computers will not outperform classical computers for all computational tasks, quantum networking will not replace classical communications or the internet. The present understanding of quantum networking technologies is that they cannot match the data rates or networked packet switching capabilities that make today's internet what it is. However, quantum technologies present novel modalities for communication that the classical internet could not match. These hinge on the ability to distribute quantum states or entanglement.

Distributing entanglement serves as a new resource for networking and communication applications that will extend capabilities of classical networks, and may augment both classical and quantum nodes. Just as the impact of the internet could not have been foreseen when the first classical networks were established, it is not possible to fully anticipate future use cases of quantum networks 10, 20, and 50 years into the future.

FINDING 2: Continued investment in R&D by the U.S. Government will be necessary to determine, understand, and realize the advantages of quantum networking for practical applications.

The NQIAC finds that many scientific and engineering R&D challenges must be addressed in order to understand, develop, and utilize quantum networking applications. These efforts will require sustained R&D in areas ranging from the theoretical underpinnings of the field, to device development and systems integration, to use cases, metrics, and downstream impacts of these technologies. Importantly, R&D is especially needed to identify domains in which quantum networks will offer a significant advantage over current technologies and deliver economic value.

As outlined in Box 2, the quantum networking applications most cited by experts consulted by the Subcommittee were quantum key distribution (QKD), distributed quantum computing, and distributed quantum sensing. Depending on implementation details, these application areas may require a wide range of different components, operational environments, or use contexts. Correspondingly, the research domains and infrastructure required to make progress are also diverse.

The NQIAC finds that continued U.S. Government R&D investment will be needed to achieve advantage with quantum networking, to build domestic expertise and supply chain capacity, to enable U.S. industry to be first to market with important new technologies employing quantum networking, and to understand if and when new quantum networking infrastructure investment is warranted.

Box 2. Most Commonly Cited Potential Application Areas of Quantum Networking Technologies by Experts Consulted

Quantum key distribution (QKD) leverages the distribution of quantum states to establish cryptographic keys for classical encryption protocols. Commercial providers of QKD services have identified a market for its deployment and use. The National Security Agency (NSA) does not currently approve the use of QKD for national security systems due to both security issues and implementation difficulties,[3,4] but NSA does not oppose continued research in the field.

Distributed quantum computing uses entanglement distribution across multiple quantum information processors or computers for quantum computation. At short distances (device or lab-scale), quantum networks are needed to connect modular quantum processors to create larger-scale quantum computers. This approach offers a path to overcome potential architectural constraints that would limit the number of qubits in a single quantum processor. At long distances, quantum networking has vastly different requirements than shorter length scale quantum networks—namely, the requirement of quantum repeaters. Connecting quantum computers across large distances through quantum networks may potentially enable joint quantum computation using remote quantum computers when sufficient capacity is not available locally.

Distributed quantum sensing uses quantum entanglement shared across separate quantum sensors to achieve measurements with a sensitivity and/or precision beyond the classical or single quantum sensor limit. For example, one envisioned application utilizes entanglement distribution for very long baseline interferometry for improved astronomical observations. Another application may be entangled atomic clocks to enable precise geodesy measurements for scientific, industrial, or civil engineering applications. As with distributed quantum computing, varying length-scales and sensor platforms will require different technological advancements. Additionally, because quantum sensors are poised to offer near-term impacts, networked quantum sensors could serve as an earlier-term demonstrator for quantum networking.

FINDING 3: Quantum networking R&D can complement and enhance progress in advancing other quantum information science technologies.

Advances in quantum networking are likely to impact and accelerate work in other domains of QIS. For example, advances in transduction—converting a quantum state from one physical embodiment to another, such as from matter-based to photonic qubits—may advance both distributed quantum computing and distributed quantum sensing. Similarly, advances in memories, photon sources and detectors, and integrated photonics will likely be relevant across quantum sensing and computing platforms as well as connecting quantum systems to classical platforms. Continued Federal quantum networking R&D funding will help identify common enabling technologies as they mature.

In addition, developing a fundamental understanding of the role of distributed quantum entanglement in QIS will ultimately impact the theoretical underpinnings of quantum algorithms, quantum information theory, and other areas. Uses of distributed quantum states have not been fully explored, and research advances are likely to uncover new applications. As we become more adept at creating and using

[3] https://www.nsa.gov/Cybersecurity/Quantum-Key-Distribution-QKD-and-Quantum-Cryptography-QC/
[4] https://www.ncsc.gov.uk/whitepaper/quantum-security-technologies

entanglement, other QIS fields will in turn benefit, and spinoff technologies could find applicability in other areas.

FINDING 4: The term "testbed," as it relates to quantum networks, is used ambiguously. Testbeds are distinct from demonstrators, prototypes, and user facilities as per the following definition, which the NQIAC will use in its recommendations:

> ***A testbed is a platform or facility that is accessible to multiple users to conduct replicable and rigorous testing of component technologies, protocols, and systems integration.***

Prototypes, demonstrators, user facilities, and testbeds serve important roles in the R&D process When meeting with stakeholders, the Subcommittee found a lack of consistency in how the term testbed was used, which, in turn, caused misconceptions about testbed deployment in the United States. *Prototypes* allow testing at a software layer, device, component, or subsystem level. Often, they are in a laboratory setting, with the purpose to improve understanding and design of a technology. *Demonstrators* showcase an early instantiation of a particular technology, but do not focus on iterative improvement and comparative technology testing. *User facilities* give researchers access to common experimental infrastructure that is used to conduct R&D, but not necessarily for the goal of improving that infrastructure.

By contrast, a *testbed* enables a team of cross-disciplinary researchers to study and iteratively improve the performance of a system composed of a combination of technologies through replicable, comparative testing of different technologies, protocols, and system configurations to learn how best to implement a robust system. Therefore, while prototypes, demonstrators, and user facilities are important, they do not take the place of testbeds as defined. Some user facilities, such as those in the Department of Energy (DOE) Office of Science, are also testbeds if users can interchange the components or protocols of the facility in order to test how the changes affect the system.

A quantum networking testbed will need to incorporate multiple layers of the system—hardware, software, and protocols—to create a functioning platform. Testbeds may be categorized by what distance scales and/or applications they address. Testbeds are especially useful when they also allow components to be interchanged or reconfigured for comparative testing and when they uncover new R&D needs or use cases.

FINDING 5: Early quantum networking prototypes, demonstrators, and testbeds and are in operation, with practical or economic impact yet to be determined.

Quantum networking is different from today's classical networking in that it aims to capitalize on new quantum resources—superposition and entanglement of quantum states. Building a functional and scalable quantum network is a formidable challenge and will require advancements in multiple disciplines. Since the passage of the NQI Act, the U.S. Government has invested on the order of $500M in quantum networking R&D.[5] Additionally, there have been considerable commercial and nation-state investments in quantum networking systems, both domestically and internationally. Quantum networking testbeds exist around the globe, including the United States, with substantially more demonstrators and prototypes.

While the field has progressed significantly, the basic technologies employed in these early quantum networking systems are not yet mature enough for distributed quantum computing or sensing applications. Demonstrations focused on QKD or very low-rate entanglement distribution are relatively

[5] According to data reported in annual NQI Supplements to the President's Budget, https://www.quantum.gov/wp-content/uploads/2023/12/NQI-Annual-Report-FY2024.pdf

early in their development and operate at a small scale, making it difficult at present to assess their impact on the field or potential for broader-scale use.

FINDING 6: Quantum networking testbeds, if strategically chosen and properly timed, can play an important role in accelerating U.S. QIS leadership.

Historically, testbeds have been known to provide a key technological resource to the scientific community when developing emerging technologies provided there is sufficient maturity to warrant rigorous testing in real-world environments, virtual simulations of possible systems, or the integration of multiple components to assess system designs. For example, early testbeds for ARPANET accelerated the adoption of the internet,[6] and various testbeds have been built to develop and test security and intrusion detection in industrial control systems including smart grid applications.[6,7] Testbeds can also surface systems engineering challenges and integration complexities across the system stack that may not be present in a pristine laboratory setting.

The NQIAC finds that strategically chosen and properly timed quantum networking testbeds will similarly serve an important role in developing the theoretical underpinnings, technologies, security models, and application scenarios for using quantum resources in networking and communication. They will help to advance the understanding of QIS and quantum mechanics. Quantum networking testbeds should be a resource to evaluate and compare component technologies and protocols and enable studies of system-level models and implementations, thus helping to promote a more successful and rapid deployment of quantum networks and the technologies dependent on them.

Some component technologies are at a low maturity level and will benefit from continued R&D investment through laboratory-scale prototypes or demonstrators. On the other hand, technologies that are more mature and can be integrated into a functioning system will likely benefit from the rigorous and repeatable testing that a testbed provides. Properly-timed testbeds composed of sufficiently mature technologies will be essential for improving scalable deployment and real-world operation of quantum networks.

NQIAC RECOMMENDATIONS FOR THE U.S. GOVERNMENT TO GROW AMERICAN LEADERSHIP IN QUANTUM NETWORKING

RECOMMENDATION 1: Continue to support fundamental research in quantum networking, its applications, and its enabling technologies.

The United States has made good scientific progress in the field of quantum networking. However, there are many unexplored and underexplored frontiers. Concepts like quantum advantage for networking remain nebulous and present an opportunity to establish clear goals and metrics to achieve applications with an agency mission-focus or demonstrable improvements over classical approaches. Understanding the scientific and economic drivers for distributing entanglement is a key challenge and opportunity for the field of quantum networking. Therefore, the NQIAC recommends that the U.S. Government should continue funding fundamental science and engineering research by the Department of Defense, DOE, National Aeronautics and Space Administration, National Institute of Standards and Technology, and National Science Foundation for the key devices and components required for quantum networking, as well as funding for additional agencies as the field advances. An emphasis should be placed on identifying useful and impactful applications that require quantum networking and show promise to vastly improve

[6] https://www.darpa.mil/about-us/timeline/arpanet

[7] A Survey on Industrial Control System Testbeds and Datasets for Security Research, doi:10.1109/COMST.2021.3094360

performance over those without it. Input on potential applications from the research community, industry, consortia, and focused workshops will help converge on the key opportunities.

Several technical challenges remain prior to realizing a functional quantum network, some of which are outlined in this report, and expanding the U.S. quantum networking effort will be necessary to rapidly solve them. Major advancements are needed in components such as quantum memories, quantum state transducers, quantum repeaters, photon sources and detectors, and advanced transmission media. In addition, full-stack engineering and integration of devices, components and systems, protocols, network operating systems, algorithms and other required technologies are also needed to solve systems engineering challenges. As technologies and devices show promise for enabling practical applications, they should be identified for further investment.

Quantum networking is not a siloed subfield of QIS; advances made will translate to computing, sensing, and our fundamental understanding of quantum mechanics. Funding for quantum networking should therefore be commensurate with other areas of QIS, and support for R&D in quantum networking should be coordinated with the objectives for other areas of QIS.

RECOMMENDATION 2: Encourage the definition, development, and use of metrics to measure the progress on quantum networking technologies and their applications.

Research in quantum computing has spawned community engagement, including conferences on metrics to characterize qubit materials, devices, processors, and quantum computing systems. Several metrics exist and are used to track the progress of qubits, for example, that depend on the specifics of qubit devices and applications. Similarly, it is important to develop and track metrics for quantum networking technologies and systems, and to encourage forums—including conferences and workshops—to rigorously discuss and evaluate these new metrics. Therefore, where appropriate, the NQIAC recommends that efforts to develop quantum networking technologies and testbeds should also encourage the development of relevant metrics that enable comparison and tracking of technology development.

When technologies reach a maturity level that enables user-level assessment of quantum networking, it will be possible to develop application-based metrics that inform and guide system-level technology implementation. For example, distributed quantum computing will likely require knowledge of entanglement metrics such as rate, fidelity, latency, and timing jitter to compile applications. Quantum network performance could also affect distributed quantum sensing, but in distinct ways that may be dependent on the type of sensor employed.

RECOMMENDATION 3: Support the development of a coordination model for describing the functional layers of quantum networks.

The NQIAC recommends investment in research to define a coordination model for quantum networking, inclusive of classical networking components and requirements. A coordination model defines the abstraction layers, interfaces, and functions of a network, enabling cross-disciplinary R&D and the inclusion of diverse experts across the stack and system.

For classical networking, one example of a coordination model is the Open Systems Interconnection (OSI), which categorizes network functions into seven layers, starting with a physical layer (optical transceivers and fiber) and ending in the application layer (for example, how a web browser uses internet data). This model allows for modular system design and troubleshooting and improved clarity in protocol development. An analogous model for quantum networking should include both classical and quantum layers to implement protocols and to configure and control the quantum network features.

Testbeds should test protocols and aggregate more complex system functions as technologies develop and mature to create this new quantum networking layer model. Although quantum networking is in an early research stage, it is already possible to define some of the model's layers and to think about necessary interactions between the quantum and classical networks. Consequently, testbeds should encourage the participation of researchers from a variety of disciplines to enable exploration of the complex trade space of classical and quantum technologies, protocols, and applications. Testbeds could speed and track progress in quantum networking by enabling the evaluation and analysis of each of the model's layers or functions for an appropriately chosen set of metrics or performance measures.

RECOMMENDATION 4: Federal funding for quantum networking testbeds should be allocated when testbeds are both "right-sized" and "properly-timed."

Right-sizing a testbed in terms of investment, scope, and objectives requires clarity on what is being tested. Properly timing when to establish a testbed requires sufficient technological maturity. Therefore, to right size and properly time testbeds, the NQIAC recommends that new government-funded testbeds should:

- Articulate clear scientific or economic promise,
- Define specific scientific or engineering research objectives,
- Propose metrics to measure progress toward those objectives,
- Explain the need of a dedicated testbed over prototypes and demonstrators, and
- When possible, strengthen and incorporate unique regional academic and industrial capabilities and investments in quantum networking technologies.

Over time, the different length scales and operational environments of testbeds will become important for testing different aspects of quantum networks. Many quantum networking technologies currently lack the maturity to warrant a testbed. Agencies should gather input from stakeholders when developing testbed programs, and the funding of testbeds should keep pace with technology needs. In the following, the NQIAC has identified some potential examples of testbeds.

For instance, it is possible now to create small- to medium-sized testbeds that enable researchers and technology developers to measure the rate and fidelity of quantum state transmission in various media (fiber, free-space, etc.) at relevant wavelengths and distances. New transmission approaches, like hollow-core fiber or vacuum beam waveguides, could be compared with legacy media. Such testing data are required to make an informed cost/benefit analysis for future infrastructure investments when deploying quantum networking technologies.

Current technologies could be used for testbed length scales of a few kilometers to establish figures of merit for scientific experiments such as those involving distributed entanglement, time transfer, or QKD. Other point-to-point quantum networking testbeds would be warranted when transduction devices are mature enough to demonstrate useful function in entanglement distribution applications, such as distributed quantum sensing or computing.

Long-distance testbeds will require quantum repeaters and significantly more resources, and should only be funded when technological maturity can support promising economic or scientific applications—for example, very long baseline interferometry or longer-distance entanglement distribution for computation. Complex, long-distance quantum network testbeds may require additional appropriations when justified by scientific or technical promise.

RECOMMENDATION 5: Support and facilitate industry participation in quantum networking testbeds.

Industry expertise and participation are critical in the scoping and utilization of quantum networking testbeds. This expertise includes operational environments, transmission media, cost/benefit analysis, manufacturability and scalability requirements, and coordination models, as well as considerations related to security, adversarial vectors, ethical practices, systems integration, and broad customer needs. Industry incorporation and participation in testbed development will be essential to ensure that the technologies are tested and implemented in ways that support commercialization and deployment by both industrial and government users. Since industrial partners' businesses depend on discovering valuable applications, including them in testbed development will increase the economic impact of quantum networking technologies.

Through participation in quantum networking testbeds, industry also has the opportunity to learn from government and academia through a mixture of technology assessments by government agencies or other entities. Such feedback provides additional understanding of the operational requirements, performance, and potential technological risks. Therefore, industry can contribute to and also learn from participation in testbeds.

The Federal Government should also consider existing regional investments by State, Local, Tribal, and Territorial governments, as well as academia and industry when establishing testbeds. Including regional capabilities in testbed planning may have ripple effects, such as aiding workforce training and accelerating technology development by leveraging regional resources, thereby increasing the impact of Federal funding.

RECOMMENDATION 6: Prioritize new funding appropriations and the development of new mechanisms to promote collaboration with international allies and like-minded partners for quantum networking R&D.

Around the globe, other nations and regions have invested heavily in quantum networking technology demonstrators, prototypes, and some testbeds. There are many world-class, non-U.S.-based scientists and institutions with impressive R&D expertise, advances, and collaborative demonstrators in important areas related to quantum networking. International collaboration with like-minded nations can help avoid the surprise of non-U.S. breakthroughs and accelerate the U.S. R&D program by helping address technical challenges that are too great in number for any one nation to pursue alone. These collaborations also support scientific diplomacy through the spirit of cooperation and joint research. Finally, collaborations with leading international institutions can help grow, attract, and develop talent.

Agencies should continue to fund international collaboration in R&D in accordance with their mission needs. In addition, the NQIAC recommends that the U.S. Government establish new dedicated funding for jointly funded international R&D with allies and partners. Priority should be given to international collaborations that are mutually beneficial, will accelerate progress in R&D, or can offer capabilities more advanced than those in the United States. These collaborations will further our competitiveness by staying abreast of and leveraging international investments in the field.

RECOMMENDATION 7: Leverage quantum networking testbeds to enable and train a diverse quantum workforce.

Quantum technologies and the infrastructure to test them are costly. Quantum networking testbeds can lower the financial barrier to entry of new approaches, thereby broadening participation in the field to academic, government, and industry researchers and innovators. Testbeds can also be made accessible to individuals from a variety of disciplines to enable scientific research, cross-functional capabilities, and integration into a wide variety of existing technologies and environments.

As technologies mature, the U.S. Government should ensure that quantum networking testbeds provide students, scientists, engineers, technicians, and operators with a platform for education and training in a system-level, realistic setting. These testbeds should complement ongoing facilities, programs, and industrial activities, and should be structured to ensure broad access to researchers across the Nation. The NQIAC recommends consideration of regional capabilities when siting testbeds, including non-R1 universities; Historically Black Colleges and Universities and Minority-Serving Institutions; vocational programs; industry; and infrastructure, to ensure that a diverse and broad set of scientists, researchers, students, and engineers have the opportunity to learn new QIS skills.

CONCLUSION

The NQIAC finds that quantum networking will have important implications for U.S. economic and national security. However, open questions remain about the scale, magnitude, and nature of this impact. Continued U.S. Government investment in R&D and infrastructure is needed to achieve the benefits and understand the risks of quantum networks.

This report lays out six findings and seven recommendations that, if followed, will help focus U.S. Government resources on the leading technological challenges, promote clarity when describing quantum networking concepts such as testbeds, and enhance the Nation's ability to leverage the breadth of NQI research. The technological landscape will continue to evolve, and U.S. policy may need to adjust as the scientific understanding matures. In conclusion, the United States must continue to invest wisely to retain and enhance its leadership position in QIS and, specifically, in quantum networking.