A COORDINATED APPROACH TO QUANTUM NETWORKING RESEARCH

A Report by the

SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

COMMITTEE ON SCIENCE

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS) was legislated by the National Quantum Initiative Act and coordinates Federal research and development (R&D) in quantum information science and related technologies under the auspices of the NSTC Committee on Science. The aim of this R&D coordination is to maintain and expand U.S. leadership in quantum information science and its applications over the next decade. More information on the SCQIS is available at https://www.quantum.gov.

About this Document

This document was developed by the SCQIS through its Quantum Networking Interagency Working Group. Recommendations in this report build on the *National Strategic Overview for Quantum Information Science* and identify pathways towards goals in *A Strategic Vision for America's Quantum Networks*. More information is available at https://www.quantum.gov.

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Abbreviations and Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARO	Army Research Office
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOS	Department of State
ESIX	Subcommittee for Economic and Security Implications of Quantum Science
FBI	Federal Bureau of Investigation
IARPA	Intelligence Advanced Research Projects Activity
IC	Intelligence Community
LPS	National Security Agency Laboratory for Physical Sciences
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NQI	National Quantum Initiative
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSA	National Security Agency
NSC	National Security Council
NSF	National Science Foundation
NSpC	National Space Council
NSTC	National Science and Technology Council
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUSD(R&E)	Office of the Undersecretary of Defense for Research and Engineering
PQC	Post Quantum Cryptography
R&D	research and development
USPTO	United States Patent and Trade Office
USDA	United States Department of Agriculture
SCQIS	Subcommittee on Quantum Information Science
NQIAC	National Quantum Initiative Advisory Committee
NQCO	National Quantum Coordination Office
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QISE	Quantum Information Science and Engineering
QN	Quantum Network
QN-IWG	Quantum Networking Interagency Working Group

Executive Summary

Quantum networks (QNs) transmit quantum information between quantum devices and allow distribution of quantum entanglement, a physical resource known to be useful for quantum information processing. QNs in the form of internets or intranets enable larger quantum computations by connecting quantum computers together. Entangled sensor networks may enable precision metrology beyond what is possible with the best individual quantum sensors. Quantum properties can also be utilized to secure communication in novel ways. These promises of new science and technology motivate active research into creating and understanding QNs and their constituent components.

The fundamental applications, basic building blocks, and ultimate value propositions for QNs are still immature. Misunderstanding abounds. QNs cannot provide faster-than-light communication nor can QNs teleport material objects. Although research continues on secure forms of communication that are impervious to hacking by a quantum computer, there exist classical solutions—so-called post-quantum cryptography (PQC)—which are already in active development for deployment. For this reason, QNs are unlikely to replace today's internet directly.

Given the prospects of QNs to impact the Nation's economy, security, and innovation ecosystem, the United States must continue to invest in basic research to explore and exploit QNs while properly balancing investment decisions. Discovering and developing use cases is essential to maintaining leadership in this emerging area. Research to develop QN components and testbeds will also benefit quantum information science and engineering (QISE) broadly.

Recognizing the growing number of significant and sustained efforts on quantum networking research, the following technical and programmatic recommendations (TR and PR) identify actions Federal agencies can take together to advance the Nation's knowledge base and readiness to utilize QNs:

- TR 1: Continue Research on Use Cases for Quantum Networks
- TR 2: Prioritize Cross-Beneficial Core Components for Quantum Networks
- TR 3: Improve Classical Capabilities to Support Quantum Networks
- TR 4: Leverage "Right-Sized" Quantum Networking Testbeds
- PR 1: Increase Interagency Coordination on Quantum Networking R&D
- PR 2: Establish Timetables for Quantum Networking R&D Infrastructure
- PR 3: Facilitate International Cooperation on Quantum Networking R&D

A coordinated approach to quantum networking research that leverages the unique strengths of several Federal agencies will accelerate the science and engineering necessary to develop useful QN components and applications. As the complexity and scale of QN prototypes evolve, coordination is essential to establish the knowledge needed to explore quantum networking technologies and derive otherwise unattainable benefits.

In preparing the above recommendations, members of the NSTC Subcommittee on QIS and its interagency working group on quantum networking, representing various Federal agencies, are cognizant of the fact that each Federal agency has its own set of programmatic and budgetary guidelines and constraints. As such, these recommendations are meant to provide pathways to facilitate, further inform, and enhance each agency's approach to its own mission, to QISE in general, and to quantum networking research in particular. This was a primary goal of the members of the quantum networking interagency working group from the beginning of their deliberations to the drafting of the final report.

Introduction

Quantum mechanics enables capabilities beyond those that can be achieved with classical methods. Over the past century, harnessing quantum aspects of nature has produced essential technologies such as lasers, transistors, magnetic resonance spectroscopy, and atomic clocks. These technologies have tremendous impact on society, enabling today's internet, computers, medical imaging, and GPS navigation. Looking towards the future, the scientific and engineering community has shown that exploiting deeper, more esoteric properties of quantum mechanics, such as quantum superposition, entanglement, and measurement has profound implications for information processing, communications, remote sensing, and basic science, and may lead to a technological revolution. Past experience with disruptive advances suggests that applications envisioned today for quantum technologies may be dwarfed by not-yet-imagined discoveries that may be developed in industry, academia, and government labs in the United States and around the world. Early and sustained explorations that pioneer the application of these quantum properties will promote U.S. leadership in this emergent field and provide advantages for the Nation's economy, security, and innovation ecosystem.

A quantum network's greatest value comes from its ability to distribute entanglement. A unique property of quantum objects such as atoms or photons, entanglement is a fundamental physical resource for both probing scientific questions and for the development of advanced quantum information technologies. Perfectly entangled objects behave as a single quantum state regardless of how far apart they are and manifest correlations that cannot be obtained classically. Quantum networks provide a mechanism to coherently interconnect quantum devices so they work as a united quantum system, and can thus achieve goals that are impossible or impractical with classical technology.

Quantum networks will one day be able to distribute entanglement across several nodes that are composed of different quantum technologies, separated by a range of physical distances. Local quantum networks (intranets) may require diverse components such as quantum interconnects and quantum memories. Terrestrial quantum networks may include ground-, air-, and sea-based platforms. Some applications may benefit from satellites with quantum networking platforms in orbit. Most quantum protocols require support from a classical layer, so interfacing a quantum network with classical components will be critical. A fully functional network will require advancements in several enabling technologies such as sources, detectors, transducers, and repeaters for quantum states of light and matter. Cost-benefit determinations and decisions to develop particular technologies will depend on a deeper understanding of the underlying concepts of quantum systems and on the anticipated applications.

Cutting-edge Quantum Information Science and Engineering (QISE) research is needed in order to address the challenges of generating, distributing, and utilizing quantum entanglement. As summarized in *A Strategic Vision for America's Quantum Networks*[1] and the *Quantum Frontiers Report*[2], research efforts to develop foundational components, enable quantum state transduction, interconnect quantum devices, and explore new use cases for quantum networking are required. These efforts will produce new concepts and technologies in a diverse set of heterogeneous quantum systems and their interactions and catalyze progress in multiple disciplines, such as materials science, electrical

[1] https://www.whitehouse.gov/wp-content/uploads/2017/12/A-Strategic-Vision-for-Americas-Quantum-Networks-Feb-2020.pdf
[2] https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf

engineering, quantum computing and metrology. Presently, the realm of quantum networking technology that remains to be explored is very large, and the field is in an exploratory phase of research and discovery.

Understanding Quantum Networking
The term *quantum networking* encompasses more than its most commonly known forerunner of quantum key distribution (QKD). QKD is a specific communications protocol that has stimulated research and development (R&D), but its value in real applications faces significant challenges[3]. Quantum networking is also quite different from post-quantum cryptography (PQC), which consists of classical algorithms operating on classical computers. As described by the National Institute of Standards and Technology (NIST), "The goal of post-quantum cryptography, also called quantum-resistant cryptography, is to develop cryptographic systems that are secure against both quantum and classical computers, and can interoperate with existing communications protocols and networks."[4] Post-quantum cryptography is critically important to protecting the Nation's communication infrastructure, and PQC-related standards, development, and deployment is underway. However, PQC is distinct from quantum networking research. Quantum networks enable applications beyond what is possible with purely classical methods, but they do not break the laws of physics. Quantum entanglement and the quantum networks that enable its distribution do not allow the transfer of information faster than the speed of light. And while quantum networks can teleport quantum information, the notion of teleporting material objects remains firmly in the realm of science fiction. As a final point of clarification, because quantum networks will likely perform vastly different tasks than classical networks, a quantum internet is not a replacement for the classical internet.

Examples of Quantum Networking Research Activities in the United States

The *Quantum Frontiers Report*[5] and the website www.quantum.gov[6] cite several dozen federally-funded QISE workshop reports relevant for quantum networking research. As an early example, the phrase *quantum internet* appeared in a 1999 QIS workshop and conference[7]. More recent research workshops devoted to quantum networking include the DOE ASCR workshop on quantum networks[8]; the NSF workshop on Quantum Interconnects[9]; the DOE Quantum Internet Blueprint Workshop report[10]; and the NASA-NIST workshop on space quantum communications and networks[11].

Investments by several U.S. agencies over three decades have seeded and developed the field of quantum networking. The variety of research programs funded by the civilian, defense, and intelligence funding agencies[12] illustrates how QISE and quantum networking research aligns with the missions of multiple agencies.

Department of Defense (DOD) has provided funding for quantum networking R&D for at least 25 years. A variety of Multidisciplinary University Research Initiatives (MURI) programs laid a foundation for quantum memories and quantum interconnects. The DARPA Quantum Information Science and

[3] https://www.nsa.gov/what-we-do/cybersecurity/quantum-key-distribution-qkd-and-quantum-cryptography-qc/
[4] https://csrc.nist.gov/projects/post-quantum-cryptography
[5] Ibid, https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf
[6] https://www.quantum.gov/
[7] https://nsf.gov/pubs/2000/nsf00101/nsf00101.htm; see also the 1999 Gordon conference on atomic physics
[8] https://info.ornl.gov/sites/publications/Files/Pub124247.pdf
[9] https://arxiv.org/ftp/arxiv/papers/1912/1912.06642.pdf
[10] https://www.energy.gov/sites/prod/files/2020/07/f76/QuantumWkshpRpt20FINAL_Nav_0.pdf
[11] https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings
[12] NQI Annual Report, *National Quantum Initiative Supplement to the President's FY 2021 Budget*

Technology (QuIST) program realized a QKD network demonstration[13] in 2007. Later, the DARPA QUINESS program explored long-distance quantum communication. The Army Research Laboratory (ARL) Center for Distributed Quantum Information program[14] focused on distributing entanglement beyond two nodes. Other current investments in quantum networking include the ARO Quantum Network Science MURI[15], AFOSR, ARO and ONR single investigator awards.

The Air Force Research Laboratory (AFRL) quantum networking research program focuses on a heterogeneous quantum network testbed to distribute entanglement across a multi-node network with both terrestrial- and space-based components. AFRL is also pursuing trapped ion and superconducting quantum bits (qubits) for memory, integrated photonics for information processing and transmission, and space-based optical channel development with both night and daytime operation. The AFRL testbed will include an open research component in the Innovare Advancement Center, applied research in AFRL laboratories, and test sites coordinated with multiple AFRL Technical Directorates.

Joint programs and cross-agency collaborations have advanced targeted sub-areas through sustained investments, for example with the DARPA Optical Radiation Cooling and Heating in Integrated Devices (ORCHID) and Quantum-Assisted Sensing and Readout (QuASAR) programs, and the Office of Naval Research (ONR) Quantum Optomechanics MURI and the Quantum Transduction MURI jointly supported by the Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO) and Laboratory for Physical Science (LPS). The LPS Cross Quantum Technology Systems (CQTS) program is another example of a program advancing critical component technologies, namely, high-fidelity qubit transduction. The Washington Metro Quantum Network Research Consortium[16] also provides an opportunity for cooperative research.

The National Institute of Standards and Technology (NIST) is developing a small, compact, and robust quantum repeater prototype. NIST also supports research to create a small 3-5 node heterogeneous quantum network[17] and to develop single photon detectors. A NASA-NIST workshop recently explored the possibility of space-based quantum communications demonstrations[9]. The National Science Foundation (NSF) QISE research portfolio includes the Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks[18], the Engineering Research Center for Quantum Networks[19], a program on Engineering Quantum Integrated Platforms for Quantum Communication[20], a program on Advancing Communication Quantum Information Research in Engineering[21], an Convergence Accelerator project titled, "Interconnecting Quantum Computers for the Next-Generation Internet," and quantum networking research in several NSF core programs[22] and center-scale efforts[23]. Department of Energy (DOE) National QIS Research Centers[24] and DOE Office of Science QIS programs[25]

[13] https://apps.dtic.mil/dtic/tr/fulltext/u2/a471450.pdf
[14] https://www.army.mil/article/227712/army_project_brings_quantum_internet_closer_to_reality
[15] https://www.arl.army.mil/wp-content/uploads/2020/02/arl-baa-005-FY-2021-W911NF20S0009-MURI.pdf
[16] https://www.nrl.navy.mil/news/releases/two-quantum-research-conferences-focus-navy-federal-collaboration
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[18] https://nsf.gov/awardsearch/showAward?AWD_ID=2016136
[19] https://nsf.gov/awardsearch/showAward?AWD_ID=1941583
[20] https://nsf.gov/publications/pub_summ.jsp?ods_key=nsf18062
[21] https://nsf.gov/awardsearch/advancedSearchResult?Keyword=efri+AND+acquire
[22] https://www.nsf.gov/mps/quantum/quantum_research_at_nsf.jsp; https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505283
[23] https://www.quantum.gov/action/large-qis-efforts/
[24] https://science.osti.gov/Initiatives/QIS/QIS-Centers
[25] https://science.osti.gov/Initiatives/QIS/Program-Offices-QIS-Pages

support quantum networking research. Furthermore, the DOE recently announced A Blueprint for the Quantum Internet[26,27] and increased funding in Fiscal Year 2021 for quantum networking research[28].

No single agency can provide all of the approaches and capabilities that are required for accelerated progress in this field. Building on these activities and research programs will require increased coordination, as projects get more sophisticated and interconnected.

Challenges and Goals

The goal of creating functioning, adaptable, and scalable quantum networks to explore a growing range of scientific applications is a formidable endeavor. Quantum networking research requires multidisciplinary expertise and sustained, coordinated support from multiple agencies. Above all, the potential benefits to society to build a large quantum network versus the resources required to do so must be understood more fully.

In the near term (1 to 5 year timeframe), core components with benefits across multiple QISE areas are needed. These components include, but are not limited to, sources, detectors, interconnects, transducers, and repeaters. Sustained efforts over ten years may be needed for the development of more sophisticated platforms. These platforms may include novel materials and devices for quantum memory, testbeds of various scales, and satellite-based systems for space-based quantum network links. Additionally, sustained efforts may include the continued development of quantum algorithms and protocols optimized for quantum network architectures and applications.

The development of testbeds capable of distributing entanglement to heterogeneous subsystems (e.g., solid-state or atomic quantum computers, memory, and sensor nodes) is aligned with the missions of several agencies. Developing and operating prototypes, both large and small, can answer open questions about system-level behaviors, protocols, performance, and applications. Utilizing minimal, or "right-sized" testbeds, i.e., testbeds of minimum complexity or scope to answer the scientific and engineering questions in play, are a means to mitigate risk.

Entanglement distribution over long distances can support applications that differ from those addressed by short-range testbeds; both are important to pursue. Proposed applications for long distance quantum networking proving grounds include long-baseline interferometry, space-to-ground quantum networking for quantum communication, novel sensor arrays for fundamental physics or environmental monitoring, and enhanced navigation capabilities[29]. While these and other ideas need additional feasibility studies and rigorous research to develop, they illustrate the potential and challenges of large testbeds. As previously noted, QKD does not currently motivate the U.S. Government to build large quantum networks[30]; however, QKD can serve to validate the functionality of some subsystems (e.g., link budgets, timing, and detectors).

Exploring potential satellite-mission scenarios is stimulating research on applications and components suitable for space-based entanglement distribution. Given the long lead time to develop such infrastructure, exploratory efforts mitigate risk and will prepare the United States to engage swiftly if and when more strategic or compelling applications for space-based quantum networking emerge.

[26] https://www.energy.gov/articles/quantum-internet-future-here
[27] https://www.energy.gov/articles/us-department-energy-unveils-blueprint-quantum-internet-launch-future-quantum-internet
[28] https://www.energy.gov/sites/prod/files/2020/02/f71/doe-fy2021-budget-fact-sheet.pdf
[29] Ibid, https://www.nasa.gov/directorates/heo/scan/engineering/technology/quantum_communications_workshop_proceedings
[30] Ibid, https://www.nsa.gov/what-we-do/cybersecurity/quantum-key-distribution-qkd-and-quantum-cryptography-qc/

However, launching a full-scale mission entails significant costs. Therefore, synergistic efforts and interagency cooperation should be explored, and care should be taken so resource allocations for large-scale demonstrations do not negatively impact fundamental QISE studies with smaller testbeds. The approach of the United States to this scientific pursuit is not directed from the top, but rather is comprised of efforts spread across several agencies with different missions.

Mechanisms for Coordinating Quantum Networking Research

The National Quantum Initiative Act[31] calls for the National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science (SCQIS), with support from the National Quantum Coordination Office (NQCO), and advice from the National Quantum Initiative Advisory Committee (NQIAC), to coordinate QISE R&D efforts across the Federal government. The NQI program authorizes new QIS Research Centers and increases to core funding programs in quantum computing, quantum sensing, quantum networking, supporting technologies, and basic QISE. In addition, the NQI Act called on NIST to establish an industry consortium which is realized in the Quantum Economic Development Consortium (QED-C). Recognizing the need to facilitate coordination specifically on quantum networking R&D efforts, the SCQIS established the Quantum Networking Interagency Working Group (QN-IWG) in 2020 with representation from several agencies listed in the frontmatter of this report.

To promote U.S. leadership in this emerging field, priority should be placed on foundational science and engineering research that will underpin the development of future quantum networks. This prioritization is aligned with the National Quantum Initiative Act, the *National Strategic Overview for QIS*[32], and *A Strategic Vision for America's Quantum Networks*[33]. It is also consistent with input from the research community, summarized in the *Quantum Frontiers Report*[34]. Effective coordination will mitigate risk, accelerate progress, and position U.S. agencies to pioneer new quantum technologies in support of their missions.

Recommendations

The SCQIS, with input from the QN-IWG, has identified that coordination of basic R&D efforts to exploit quantum entanglement with quantum networks can accelerate breakthroughs in several QISE fields and will be a key enabling technology for future quantum information applications. The following technical and programmatic recommendations highlight critical steps that must be undertaken to accelerate U.S. leadership in quantum networking research.

Agencies should pool their knowledge to determine what minimal testbed functionalities are necessary to address the most pressing questions in quantum networking research. Cross-agency efforts that avoid redundant investments in costly infrastructure and pre-mature commitments to overly constrained approaches or modalities is part of the recommended strategy. Furthermore, to leverage test ranges and accelerate the discovery of valuable applications, coordinated efforts should increase the user base and provide access to a broad range of QISE and other research communities. Interagency coordination, from the bottom up, is therefore recommended to develop the tools and capabilities for quantum networking on all scales, motivated by the strategy of studying the fundamental science first.

[31] https://www.congress.gov/115/plaws/publ368/PLAW-115publ368.pdf
[32] https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf
[33] https://www.quantum.gov/wp-content/uploads/2021/01/A-Strategic-Vision-for-Americas-Quantum-Networks-Feb-2020.pdf
[34] Ibid; https://www.quantum.gov/wp-content/uploads/2020/10/QuantumFrontiers.pdf

Technical Recommendations (TR)

Four technical recommendations encourage continued research to explore applications, develop components, source supporting technologies, and leverage testbeds.

TR 1: Continue Research on Use Cases for Quantum Networks

Developing useful applications for quantum networks will require substantial and sustained basic research. Only a handful of anticipated use cases have been identified. More important, the cost and complexity of such quantum networks for specific applications are presently not fully known but are expected to be large. Fundamental limitations for quantum networks (or particular quantum network architectures) should be studied in order to understand and accurately guide the development of practical capabilities. This goal will require a combination of experimental and theoretical research on algorithms and protocols with consideration of feasible realizations. The United States must continue to invest in research on the potential advantages (and associated requirements) of quantum networks to justify future development.

TR 2: Prioritize Cross-Beneficial Core Components for Quantum Networks

Quantum networking requires unique components such as sources, detectors, memories, repeaters, transducers, and interconnects. Many of these quantum components are in an early stage of development and therefore require continued R&D in, for example, materials science, quantum optics, electrical engineering, fabrication, and quantum control. At this early stage it is impractical to choose a singular approach for a given class of components, or to select a particular subset of components to pursue, as different applications may require different functionalities and specifications. However, recognizing that some components will be valuable for multiple QISE sub-fields and even classical technologies, an initial focus on cross-beneficial modular components with a later expansion into development of more specialized components should yield the greatest benefit. The United States should prioritize increasing the technological readiness level of core components necessary for quantum networking with a coordinated approach to R&D efforts, including private sector opportunities such as via the QED-C.

TR 3: Improve Classical Capabilities to Support Quantum Networks

Quantum networks will require sophisticated support from classical technologies including communications, time-transfer protocols, photonics, electronics, and software. Advances in classical components and protocols can provide benefits not only for quantum networking research but for QISE studies more broadly. While the required performance attributes of supporting classical technologies will depend on the particular quantum protocols and applications to be implemented, the United States should continue to invest in the integration of classical approaches that are necessary to support the operation of quantum networks. Particular focus should be placed on methods that improve time and frequency information, expand quantum network throughput, and support networks of quantum sensors.

TR 4: Leverage "Right-Sized" Quantum Networking Testbeds

Quantum networking testbeds, demonstrators, and prototypes are crucial for guiding R&D. Flexible, reconfigurable, and adaptable testbeds are needed to explore scientific questions about quantum network behaviors and applications as the field evolves. This includes studies on how entanglement can be generated, transduced, stored, and swapped across multiple, heterogeneous nodes, and used for particular applications. Entanglement distribution over both short and long distances should be explored, as these entail different challenges and opportunities. To avoid premature spending on expensive efforts with limited adaptability, the United States should build "right-sized" quantum network testbeds to guide the development of quantum components and useful applications. At the same time, feasibility studies and exploratory research for long-distance test ranges—including satellite platforms—should continue, especially given the discovery potential and the long lead time for such infrastructure. Continued studies and analyses coupled with interagency coordination will reduce the likelihood of premature design choices and increase the scientific impacts, for example, by providing access to users from a broad range of QISE and other research communities.

Programmatic Recommendations (PR)

Coordination is vital for United States leadership in quantum networking research. Progress will require the capabilities and expertise of several agencies to ensure the requisite interoperability of components, testbeds, protocols, and applications. Three programmatic recommendations encourage continued and enhanced coordination, planning, and cooperation.

PR 1: Increase Interagency Coordination on Quantum Networking R&D

The broad scope and complexity of quantum networking R&D necessitates that agencies work together to maximize the return on government investment. Coordination at several levels will be essential: information sharing about R&D portfolios and plans; synchronized and complementary investments among agencies; and jointly funded and managed projects. Facilitation of this cooperation by the NQCO will ensure the early identification of best practices and gaps in the research portfolio, ultimately leading to accelerated progress.

PR 2: Establish Timetables for Quantum Networking R&D Infrastructure

Coordinated, interagency timetables for investment and expected capabilities should be developed, in accordance with published agency budgets, to avoid unnecessary delays and allow for long-term planning. Planning will engage stakeholders with long term research agendas and provide a forcing function to focus resources on the most promising and relevant component technologies. Understanding the triggers, dependencies, and gateways for useful quantum networking components, testbeds, and infrastructure will increase the impact of such investments on timeframes ranging from 5 to 20 years.

PR 3: Facilitate International Cooperation on Quantum Networking R&D

Promoting international cooperation with partners who adhere to the foundational principles of research integrity, such as openness, reciprocity, transparency, and merit-based competition fosters good-faith cooperation, accelerates the advance of fundamental science, and is particularly beneficial for quantum networking R&D. Because of the broad range of possible technologies and the unknowns in the application space, it is to the Nation's benefit to partner globally to explore the potential of quantum networks. As quantum networking technology develops, the United States must also participate in the establishment of standards and metrics for components and protocols, as appropriate.

Summary

The Subcommittee on Quantum Information Science recommends a coordinated approach to quantum networking research which leverages the strengths of multiple Federal agencies working together. The United States must understand the scientific and technological benefits and costs of quantum networks in computing, sensing, timing, and communications in order to justify and accelerate further development of this technology.

Four technical recommendations encourage continued research and development of quantum networking applications, components, and supporting technologies. Three programmatic recommendations emphasize the importance of continued and enhanced coordination among Federal agencies, identification of relevant timetables that streamline coordinated activities, and cooperation with international partners.