Experimental Ambitions for DC-Area Quantum Network Testbed

Oliver Slattery
Information Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899
Email: oliver.slattery@nist.gov

Adam T. Black
Optical Sciences Division
US Naval Research Laboratory
Washington, DC 20375
Email: adam.black@nrl.navy.mil

***Abstract*—Quantum networks [1] bear the promise of one day enabling diverse applications such as secure communications, distributed quantum computing, distributed sensing, and time distribution, in addition to other applications not yet identified. In recent years, leaders at several DC-area federal research agencies observed a need for a US-government-centered, non-proprietary environment for test and evaluation of quantum networking concepts, components, protocols, and architectures. The Washington Metropolitan Quantum Network Research Consortium (DC-QNet) was codified in 2022 by an interagency Memorandum of Understanding to advance cooperation among government agencies in quantum network research and development. Within DC-QNet, a variety of Working Groups were established to foster technical collaboration. The Experimental Working Group's goals include identification of suitable experimental topics and facilitation of collaborative experimental activities. Here we describe the collaborative experimental topic areas identified by the DC-QNet Experiments Working Group.**

***Keywords*—quantum networking;**

I. Introduction

The Washington Metro Quantum Network Research Consortium, codified by an inter-agency Memorandum of Understanding (MOU) that became effective on May 18th 2022, consists of six research institutions in the Washington DC metropolitan area that have pooled their resources to implement the DC-QNet, a functional quantum network testbed dedicated to their unique needs and capabilities.

DC-QNet efforts will lead ultimately to an open engineering research network testbed. The consortium is fostering collaborations and coordination amongst its members while providing a fertile environment for the development of quantum network components, infrastructure, protocols and architectures through foundational quantum networking experiments. This network will be built on the solid foundation of metrology with the goal of ensuring greater interoperability of quantum network nodes and more seamless integration of new quantum components.

The first phase of DC-QNet technical work focuses on two parallel thrusts: (1) the development and implementation of the physical infrastructure, software architecture and analytical tools for emulation, modeling and simulation of the DC-QNet and (2) the development and demonstration of foundational quantum network processes through multiple relevant experiments. Advances made in these efforts will lay a foundation for implementing a quantum networking testbed among the member organizations.

Three Working Groups, reporting to an Executive Steering Committee and Executive Director, have initiated technical collaborations among member organizations. These Working Groups focus on Fiber Infrastructure, Network Interfaces, and Experiments. The present paper focuses on the work of the Experiments Working Group. The Experiments Working Group's goals are (1) to identify suitable experimental activities within DC-QNet; (2) to identify unique or advantageous features of DC-QNet and identify the needs of US government organizations and the scientific community with respect to quantum networking; and (3) to facilitate collaborative experimental activities through communication, exchange of expertise, and identification of resources to further experiments.

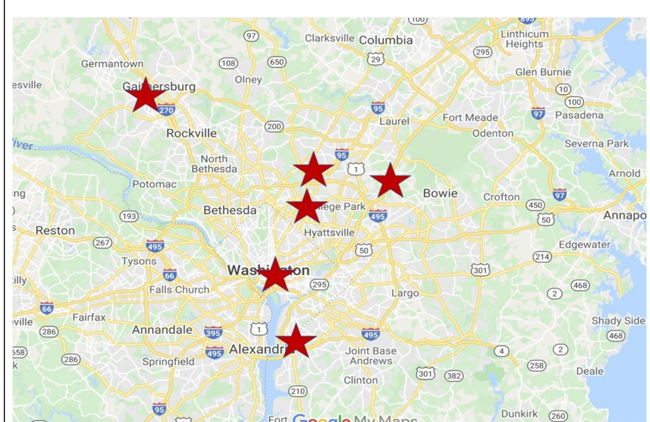

Fig. 1. Map of DC-QNet sites.

II. Experiment Topics

In this section we briefly describe the various topics for collaborative experimental efforts identified by the DC-QNet

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Experiments Working Group. For each topic, we provide background motivation and objectives.

A. Characterization of fiber-based links between DC-QNet agencies

Background: In classical optical communication systems, the development of improved measurements and telemetry facilitated each new generation of technology. It is essential that robust quantum metrology protocols, procedures, and tools be developed to characterize quantum networks, links and components so as to ensure optimal integration of systems and network operation.

Objectives: The objective is to develop methods and tools for the in-situ characterization of optical fiber-based links (which can comprise of fiber, optical switches, wavelength division multiplexers, routers, etc.) across DC-QNet. These methods include link probing schemes to enable automated characterization of fiber-based links in various environmental conditions with real-time generation of metrics. The ultimate goal is to develop and deploy comprehensive metrology and telemetry infrastructure (including hardware, software and methods) across DC-QNet that will provide users with a multidimensional set of fiber link parameters (such as noise, loss, time/distance variance, polarization and phase stability).

In the short term, objectives will focus on schemes to provide certain types of telemetry data, including fiber link loss, noise and polarization stability; coordination with other experiments to provide synchronization and phase stability data; and development of protocols to share and use the generated data in a network management plane.

B. Distribution and characterization of polarization entangled light over fiber

Background: The distribution of quantum entanglement around a quantum network is the essence of the network and a key objective of the DC-QNet. Polarization-entangled photonic (flying) qubits are transmittable and functional; therefore, they have been chosen as the platform for this experiment. The quality of the distributed polarization-entangled single-photon signals must be measured, understood and optimized.

Objectives: This effort will distribute and characterize polarization-entangled light to DC-QNet agencies through an all-optical fiber-based network, including switching entanglement through different frequency channels to multiple agencies. It will also provide quantum state tomography to dynamically characterize the fidelity of end-node entanglement using commercial or self-built entangled light sources and analyzers. Ultimately, we will use distributed pairs of photons and demonstrate entanglement swapping involving multiple agencies.

Short-term objectives are to demonstrate routing of polarization-entangled photon pairs between two or more agencies across the DC-QNet. Each participating agency will establish entangled photon pair source and analysis capabilities. Because the photons will be entangled in polarization, polarization monitoring and compensation techniques will be developed and deployed. Initial entangled pair distribution experiments will perform coincidence measurements and state tomography locally and between agencies.

C. Quantum network characterization and stabilization using classical interference

Background: Optical fiber provides a convenient environment for photonic quantum networks, enabling light transmittance over a long distance with high isolation from environmental noise and with modest loss. However, real-world conditions over long fiber lengths create phase instability, and most quantum applications require some level of fiber phase stabilization. Classical interference provides a natural way to characterize and maintain phase stabilization of the optical layer to enable such applications.

Objectives: The effort will characterize the short- and long-term stability of the DC-QNet fiber infrastructure using classical interference. It will develop classical phase control methods that can coexist with quantum channels throughout the network for real-time phase stabilization. Ultimately, we will enable network protocols and applications that require interferometric stability.

Short-term objectives are to characterize the phase noise of network links and develop phase-stabilized links using classical interference. We will use high-performance stabilized laser sources and deploy testing equipment to participating DC-QNet facilities to measure network phase stability between participating agencies. We will analyze crosstalk of a classical (stabilization) channel with quantum channels and find the most advantageous configuration of classical and quantum channels in the network.

D. Indistinguishable quantum sources for Hong-Ou-Mandel (HOM) experiments

Background: Quantum networks will be a hybrid of different quantum technologies, and these technologies will need to be interoperable. In many quantum applications and experiments, photons from different sources must be indistinguishable. While a variety of single photon sources exist, few have demonstrated single-photon emission with high indistinguishability at telecom wavelengths. Developing and deploying such sources will be essential for quantum networks.

Objectives: We will build indistinguishable single-photon sources in the telecom band using different physical systems, including quantum dots (QDs), spontaneous parametric down-conversion (SPDC), and spontaneous four-wave-mixing (SFWM). A long-term goal is to demonstrate Hong-Ou-Mandel (HOM) interference using these sources located at different DC-QNet agencies as a building block for quantum networking using single photon sources.

Short-term objectives will continue ongoing efforts in developing photon emission in the telecom band from three physical systems at different agencies: semiconductor QDs, non-linear crystal SPDCs, and micro-resonator SFWM.

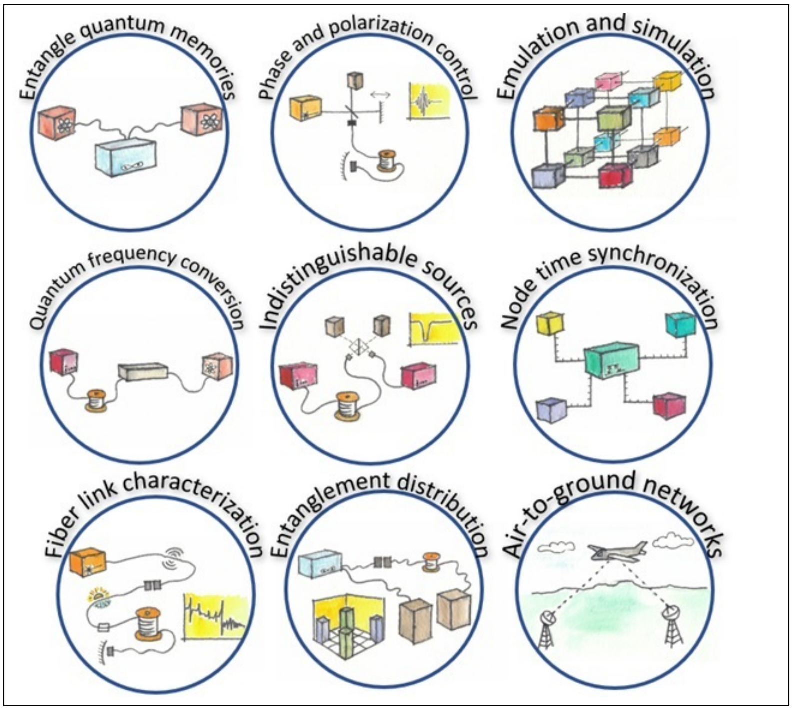

Fig. 2. Experimental topics identified by DC-QNet for collaborative activities.

E. Synchronization and timing techniques for quantum networking

Background: Synchronization and timing are long-standing issues in electronic and optical communications in general but are especially critical for quantum communications and quantum networks [2]. Specialized techniques that include compensation and more recently, commercial approaches, have been developed that will be suitable for applications. Deploying suitable systems over long-distances will be essential for any quantum network development.

Objectives: To develop and test the synchronization systems needed for quantum-network nodes. Explore compensation techniques for fluctuations in delay through the fiber links and target synchronization accuracy in the range of tens of picoseconds. Investigate co-existence of timing and quantum channels using commercial and novel system. Finally, to develop and test the synchronization systems needed to support continuous Hong-Ou-Mandel (HOM) or Bell-state measurements between photons from remote quantum-network nodes in the DC-QNet.

The short-term objective is to develop two-node synchronization where a master oscillator is distributed to generate the local clock for the remote node to which a local laser can be locked. This forms the most basic building block of a network synchronization system and can be scaled to multiple nodes. We will test commercial timing synchronization systems and characterize drift and jitter.

F. Quantum Frequency Conversion for long-distance and hybrid quantum networking

Background: Quantum frequency conversion (QFC) [3] is essential in establishing long-distance multi-site networking with quantum memories. To ensure low-loss propagation of quantum states of light, and to achieve wavelength compatibility between distinct memory node types, it is necessary to convert between the natural emission wavelength of the memory node and low-loss telecommunications wavelengths.

Objectives: DC-QNet researchers will evaluate, compare, and implement techniques for QFC of photons to and from telecommunications wavelengths. These techniques include difference frequency generation (DFG) in poled nonlinear crystals, nonlinear interactions in hot or cold atomic vapors, and integrated-photonic QFC devices. We will evaluate conversion fidelity, efficiency, noise processes, and bandwidth. Ultimately, this effort will identify and demonstrate the optimal QFC schemes for DC-QNet operations.

Initially, the DC-QNet QFC effort will identify node wavelengths and suitable telecom band wavelengths. Bidirectional conversion of photons to and from telecommunications wavelengths will be demonstrated through detection of photons transmitted on the fiber network. We will begin studying the application of QFC and outlining the topology for implementation of QFC in a two-node network.

G. Entanglement Distribution with Quantum Memories

Background: Quantum memories [4] are key components of scalable quantum network architectures due to their ability to store and retrieve arbitrary quantum states. In quantum repeater protocols, they will enable long-distance entanglement distribution.

Objectives: DC-QNet researchers will develop photon-coupled quantum memories, entangled photon sources, and interfaces for entanglement distribution between quantum memories. Three quantum memory types are being developed: (1) trapped Ba+, (2) Rydberg-coupled neutral Rb ensembles, and (3) neutral Cs ensembles. To entangle these memory types over long distances, we will first entangle memories with telecom-wavelength photons. Ultimately, the team plans to entangle quantum memories located at remote nodes.

Initial tasks include characterizing the transmission of memory-coupled photons in a fiber network outside the lab. Intrinsic and total photon transmission rates will be measured and evaluated against quantum network requirements.

H. Free-space quantum networking

Background: In many quantum networking scenarios, free-space quantum links are required [5]. These include satellite-based quantum communications, battlefield networks, or ship-to-ship networks. For ground-based network nodes separated by long distances, the lowest losses will be achieved using satellite-based, rather than fiber-based, networking. Free-space links will therefore be preferred for such large-scale networks, at least until efficient and robust quantum repeater technologies are developed.

Objectives: DC-QNet researchers will develop a free-space quantum networking capability by leveraging the quantum resources within DC-QNET and a terrestrial optical terminal [6]. They will demonstrate polarization state tomography on entangled photons distributed over a free-space channel between an aircraft and an optical ground terminal. Portable entangled photon pair sources will generate the photons. An eventual ground-to-space demonstration is anticipated. Ultimately, to implement a free-space quantum network connecting DC-QNet agencies.

In the short term, DC-QNet researchers will make key steps in experimentally determining requirements for a ground-to-air quantum network link, leading to a preliminary demonstration of the transmission of quantum states of light (e.g., polarization-entangled states) over a free-space link between ground-based stations.

I. Theory, Modeling, Simulation and Emulation of Quantum Networks

Background: A theoretical understanding of quantum network operation is essential for predicting the performance of a metro-scale network and guiding the use of resources [7]. Knowing the impact of non-ideal components, developing network performance metrics, and modeling future quantum networks will improve our ability to design and implement quantum networks.

Objectives: This project will develop models to analyze, predict, and inform DC-QNet experiments. These tools will be used to investigate the impact of nonidealities on network performance, the development of metrics, and the development of routing protocols and applications. We will investigate the impact of error correction and mitigation strategies on quantum network performance. The project will develop emulation tools that operate with sufficient rate and fidelity to be integrated into quantum networking testbeds.

Short-term objectives include identifying critical operational parameters of the DC-QNet quantum network through modeling of quantum network components, devices, and protocols. Through network simulation, we will understand the impact of component nonidealities on network performance and security. Create real-time models that can be integrated into an emulation environment that can support the development of network architectures.

III. Outlook

Experimental and modeling efforts in the areas described above have already begun via collaborative efforts between the member agencies. In most cases, these activities build on preexisting single-agency programs, but in all cases a path toward multiagency quantum networking experimentation has been identified.

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