Building the Quantum Internet

Stony Brook University and Brookhaven National Laboratory are constructing the world's first quantum-enabled internet

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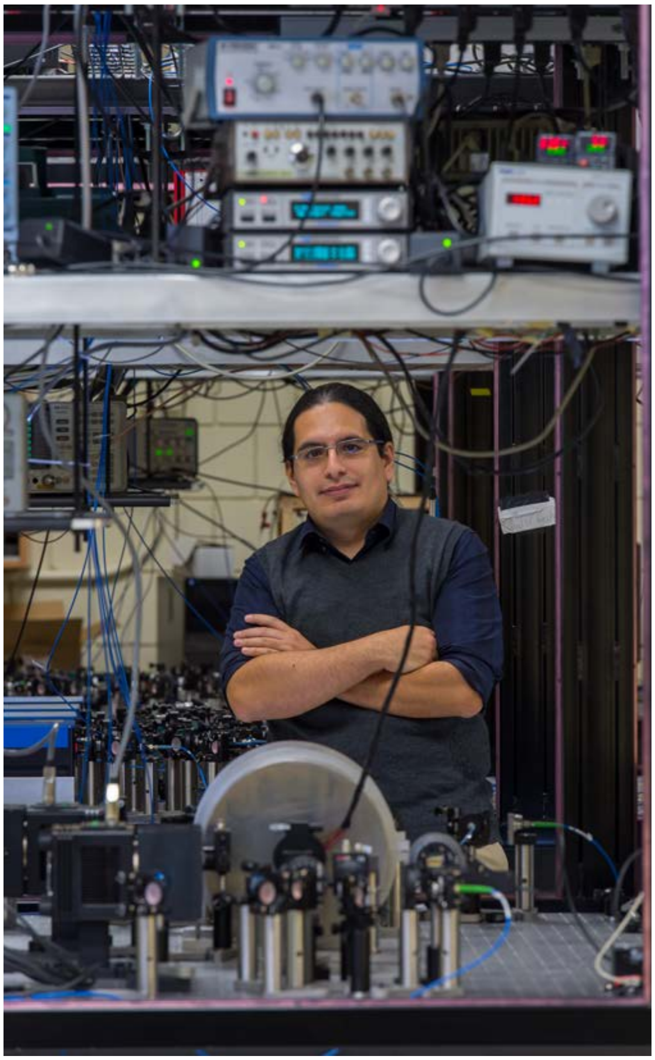

Eden Figueroa in his Quantum Information Technology lab at Stony Brook University. A "twin" version of this laboratory is housed within the Instrumentation Division at Brookhaven National Laboratory.
Photo: John Griffin

INTRODUCTION

Harnessing quantum entanglement using quantum networking is capturing the interest of vast communities across science, industry, and national security. Indeed, many people recognize that building, scaling, and discovering new scientific frontiers of a global communication network—the Quantum Internet—is among the most important scientific tasks of the 21st century. From financial trading, personal data handling, power grid security, to accessing new sensing frontiers assisted by networked quantum devices, quantum communication is slated to become a once-in-a-century technology, touching all aspects of economy, society, and scientific discovery. This relevance has already been recognized by China, the European Union and the U.S., which are making concerted efforts to construct large quantum networks. Despite this promise, quantum networking remains at a nascent phase. Many challenges remain before the full potential of large quantum communication systems can be realized. Thus, it is of paramount national relevance to develop first realizations of large intercity quantum internet prototypes.

This envisioned Quantum Internet is a system of quantum interconnects (e.g., nodes interfacing quantum matter and light) linked using optical quantum communication channels. Through the use of quantum repeaters, these distantly-located quantum processing nodes will be connected on-demand via quantum entanglement. Critically, the operation of entanglement distribution is assisted by heralding, or confirming the presence of a photon in the memory, and subsequently holding the entanglement in place until user-requested teleportation operations can be carried out. Figure 1 shows the concept of interconnected quantum nodes using photonic entanglement.

The Long Island Quantum Information Distribution

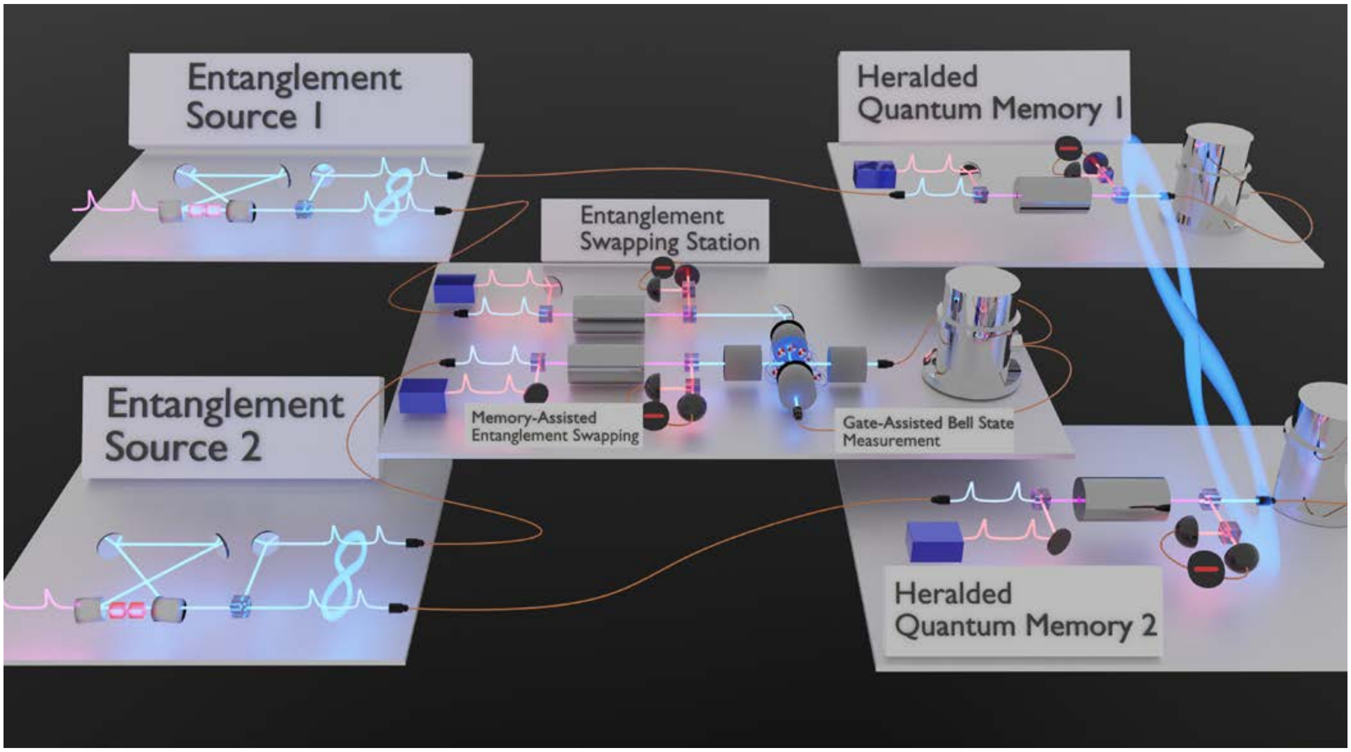

Figure 1: A first look at the quantum technology components of the quantum-enabled internet being built between Stony Brook University and Brookhaven. Top and bottom left display sources of entangled photons tuned for operation with atomic nodes. Middle platform illustrates the process of entanglement swapping using heralded quantum memories and assisted by photonic quantum logic gates. This results in the remotely located memories (top and bottom right) becoming entangled over intercity distances, as illustrated by the blue lemniscate. Figure courtesy Dillion Cottrill

Network (LIQuIDNet) is an experimental collaboration between Stony Brook University, Brookhaven and Qunnect Inc., aimed at distributing entanglement between quantum processing nodes located in New York City and Commack (over 260 km in fiber), assisted by entanglement generation nodes in Brookhaven and Westbury, and an entanglement swapping node at Stony Brook (see Figure 2 for the real quantum network deployment over Long Island).

LONG-DISTANCE ENTANGLEMENT DISTRIBUTION

Our objective is to create entanglement between the quantum states of two distant quantum memories using a procedure called entanglement swapping. For that purpose, we will first create two independent pairs of entangled photons (each containing a signal and an idler photon, respectively) in the BNL and Westbury quantum nodes. The state of the two entangled photon pairs can be written as:

$$\left(\frac{|H_{\text{Idler1}}\rangle|H_{\text{Signal1}}\rangle + |V_{\text{Idler1}}\rangle|V_{\text{Signal1}}\rangle}{\sqrt{2}}\right)\otimes \left(\frac{|H_{\text{Idler2}}\rangle|H_{\text{Signal2}}\rangle + |V_{\text{Idler2}}\rangle|V_{\text{Signal2}}\rangle}{\sqrt{2}}\right)$$

After long-distance propagation, the two signal photons will be stored in quantum memories in Commack and in NYC, while the two idler photons will be stored in Stony Brook. In order to know if a photon is stored, the quantum memories must be able to be read, which is often referred to as heralding. Additionally, the storage time of the memories must be variable in order to assure the synchronous read out of the four memories. After heralding, the total stored state in the four quantum memories will then have the form:

$$\left(\frac{|H_{\text{COM-QM}}\rangle|H_{\text{SBU-QM1}}\rangle + |V_{\text{COM-QM}}\rangle|V_{\text{SBU-QM1}}\rangle}{\sqrt{2}}\right)\otimes \left(\frac{|H_{\text{NYC-QM}}\rangle|H_{\text{SBU-QM2}}\rangle + |V_{\text{NYC-QM}}\rangle|V_{\text{SBU-QM2}}\rangle}{\sqrt{2}}\right)$$

Figure 2: The Long Island Quantum Information Distribution Network (LIQuIDNet) testbed. Three Quantum nodes are located at BNL, SBU and NYC. They are connected using auxiliary nodes with entangled sources (1025 Connect colocation facility in Westbury) and heralded quantum memories (mindSHIFT in Commack). There exist two embedded physical optical networks: i) the quantum layer, that includes all quantum devices and forwards quantum signals and ii) the classical layer, for all other data signals, including timing and control. A separate digital control plane orchestrates the remote control of all quantum and classical devices in the network nodes. Figure courtesy Dimitrios Katramatos

The entangled photon production will be repeated at high repetition rates until heralding indicates the capture of photons in all four memories. After the heralding is confirmed, the two memories in the Stony Brook node will be read out and their photons sent to a Bell-State-Measurement (BSM) setup, based upon memory-assisted Hong-Ou-Mandel (HOM) interference. Successful detection of a Bell state after storage of the two idler photons will *herald the swapping of entanglement* to the most distant quantum memories in nodes located at NYC and SBU, forming the following, long-distance entangled state:

$$|\Psi^-_{\text{COM-QM/NYC-QM}}\rangle = \frac{1}{\sqrt{2}}\Big(|H_{\text{COM-QM}}\rangle|V_{\text{NYC-QM}}\rangle - |V_{\text{COM-QM}}\rangle|H_{\text{NYC-QM}}\rangle\Big)$$

Successfully establishing these foundational memory-assisted long-distance entanglement connections will be the pivotal basis for many novel scientific applications that can push the state of the art in many disciplines. Particularly important applications include enhanced optical interferometry of celestial objects, large line-of-sight arrays of entangled sensors, quantum networks of atomic clocks and quantum processing using interconnected quantum computers.

INTEGRATING KEY QUANTUM NETWORKING TECHNOLOGIES

Entangled photon pairs sources are the cornerstone of our envisioned entanglement distribution network. We are currently developing high-efficiency entanglement sources compatible with quantum memories and long-distance quantum networking operation. They are based on tunable high-finesse optical parametric amplifiers (OPAs) which enhance the production of photon pairs and select the photons' frequencies and bandwidths to be compatible with atomic interaction.

We have also developed and patented in-out quantum memories based upon rubidium vapor, capable of receiving and storing arbitrary quantum states and releasing them later on-demand with high fidelity. Our recent experiments have shown that the qubit retrieval fidelity is greater than 95%, which will allow for proof of principle long distance experiments. Currently, these systems are the only ones in the world that operate at room temperature, which facilitates the scaling to larger networks. Additionally, we are developing the methods to herald the presence of the stored entangled photons in the quantum memories, which is the key consideration to achieve high-rate entanglement swapping operations. In LIQuIDNet, these heralding operations will

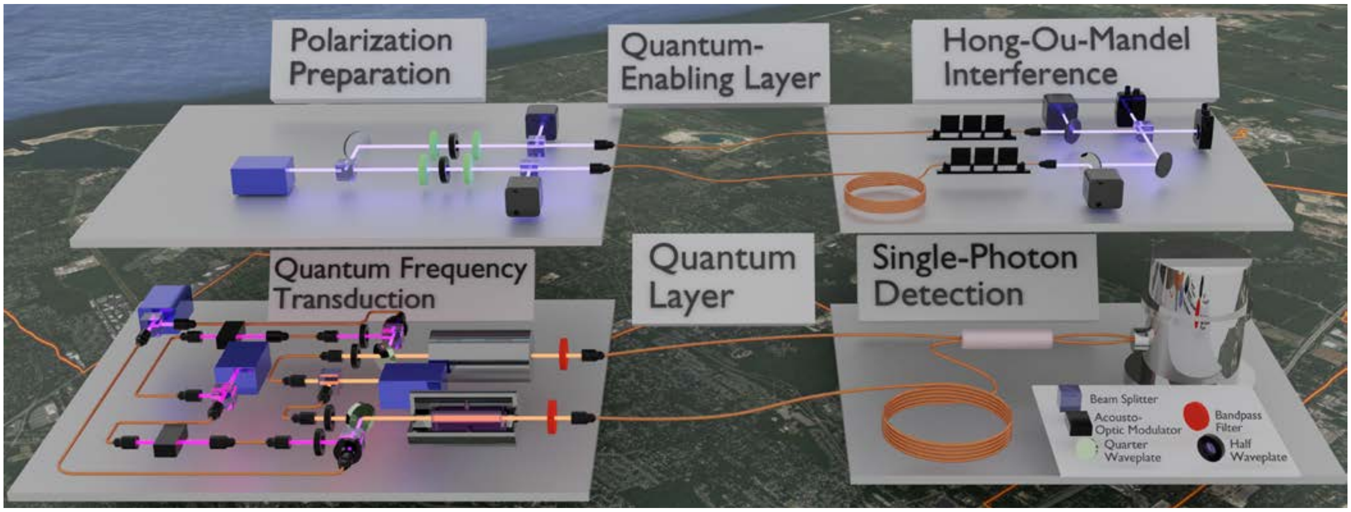

Figure 3. The layers of an elementary quantum internet prototype. (Upper layer) Quantum-enabling sub-network including time-synchronization and polarization maintenance subsystems. (Bottom layer) Quantum network including room temperature quantum memories, frequency conversion, long-distance quantum communication links and qubit detection systems. Figure courtesy Dillion Cottrill and Dounan Du

be done via real time quantum state tomography of heralding photons probing the state of the memory. Detecting subtle changes in the electric field of the heralded photons is the key to know if the memory is in a prepared state.

TELECOM FREQUENCY CONVERSION AND NETWORK CONTROL

Connecting the LIQuIDNet quantum nodes using quantum entanglement will require interfacing quantum memories with current fiber optics infrastructure. The entanglement transmission in the network will rely on high-efficiency Quantum Frequency Conversion (QFC), to connect the quantum sources, quantum memories, and quantum detectors, and to establish high-rate entanglement connections between arbitrary points in the network.

Additionally, in our experiments, the quantum information is encoded in the polarization state (PS) of photons. A particular bottleneck for long-distance fiber-based applications is that of polarization fluctuations. To overcome this issue, we have engineered dynamic compensation of polarization drifts to maintain quantum information integrity in all node-to-node links. This requires specialized equipment which reads the polarization state of a reference laser, then via a machine learning algorithm, modifies the polarization to the corrected state. Once the laser's polarization has been stabilized, this allows us to transport photons in the fibers while maintaining their polarization entangled state. Maintaining the polarization along orthogonal axes ensures the purity of the transmitted qubits at their destination/measurement station, and their suitability for Hong-Ou-Mandel interference and/or Bell-state measurements in different bases. Figure 3 shows how these optical networks are operated together.

With all the described pieces together, we have demonstrated several milestone experiments towards an elementary quantum internet. They include the longest transmission distance (18 km) for photon entanglement over commercial fiber in the U.S. (in May 2019), the longest (~140 km) quantum communication qubit fiber link in the U.S. (in July 2020) and the first world-wide connection of matter quantum memories over 158 km (in August 2021). These accomplishments have solidified LIQuIDNet as one of the premier quantum internet testbeds in the world and paved the way for future experiments in which quantum entanglement distribution and quantum teleportation will become user-defined internet services.