
DESIGN AND IMPLEMENTATION OF THE ILLINOIS EXPRESS QUANTUM METROPOLITAN AREA NETWORK

A PREPRINT

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ABSTRACT

The Illinois Express Quantum Network (IEQNET) is a program to realize metropolitan scale quantum networking over deployed optical fiber using currently available technology. IEQNET consists of multiple sites that are geographically dispersed in the Chicago metropolitan area. Each site has one or more quantum nodes (Q-nodes) representing the communication parties in a quantum network. Q-nodes generate or measure quantum signals such as entangled photons and communicate the measurement results via standard, classical signals and conventional networking processes. The entangled photons in IEQNET nodes are generated at multiple wavelengths, and are selectively distributed to the desired users via transparent optical switches. Here we describe the network architecture of IEQNET, including the Internet-inspired layered hierarchy that leverages software-defined networking (SDN) technology to perform traditional wavelength routing and assignment between the Q-nodes. Specifically, SDN decouples the control and data planes, with the control plane being entirely implemented in the classical domain. We also discuss the IEQNET processes that address issues associated with synchronization, calibration, network monitoring, and scheduling. An important goal of IEQNET is to demonstrate the extent to which the control plane classical signals can co-propagate with the data plane quantum signals in the same fiber lines (quantum-classical signal “coexistence”). This goal is furthered by the use of tunable narrow-band optical filtering at the receivers and, at least in some cases, a wide wavelength separation between the quantum and classical channels. We envision IEQNET to aid in developing robust and practical quantum networks

by demonstrating metro-scale quantum communication tasks such as entanglement distribution and quantum-state teleportation.

Keywords Quantum networks, metropolitan area, Q-LAN, Q-MAN

1 Introduction

The full exploitation of quantum computing and quantum sensing is expected to require fully networked and distributed solutions, as is robustly shown in the classical case. The advantages presented by deploying such quantum systems come along with special challenges to the transmission of information that must be addressed to realize the full potential of networking. For example, quantum signals are very sensitive to loss and even miniscule levels of added noise. The no-cloning theorem prevents us from using approaches commonly employed in classical networks to mitigate such problems since it forbids the creation of identical copies of an arbitrary unknown quantum state. As a result, more sophisticated approaches must be employed to protect the quantum information we want to transfer (for example, through indirect channels utilizing distribution of quantum entanglement and teleportation).

While quantum optical networks will eventually be used to interconnect quantum computers, for e.g. via quantum transduction [1, 2], it is worth to mention that they provide some important near term advantages such as enhancing the security of communication via quantum cryptography and improving the sensitivity of measurements via distributed quantum sensing. While it is desirable to leverage as much of the already deployed fiber-optic infrastructure as possible, because of the quantum information transmission specific challenges we discussed above, we expect quantum network design to require major paradigm shifts from classical networks, as well as custom engineering for its systems. At the same time, it is imperative that quantum networks are able to co-exist and, eventually, interoperate with classical networks, so the design must incorporate as much compatibility with conventional networks as is practical.

The Illinois Express Quantum Network (IEQNET) is a program for developing metro-scale quantum networking over deployed optical fiber infrastructure. While new technologies, such as quantum repeaters, will be needed to realize the long-term goals of quantum networking, IEQNET focuses on leveraging currently available technology (with provision for future upgrades as technology advances), to develop architecture and systems, and test and improve them through a co-design process with deployment of metropolitan area quantum networks.

Two of the prime needs in quantum information systems are distributing entanglement and subsequently using the entanglement to perform tasks like quantum key distribution and quantum teleportation. These needs should be met while simultaneously allowing higher-power classical signals to share the same fiber, both for the purposes of enabling communications to support quantum applications and for independent coexistence of high data-rate classical channels. In this paper we introduce our architecture to realize these functions over a metro-scale network, focusing on simplicity for entanglement distribution, and discuss some of the major control and management issues that need to be addressed to enable reliable network operation. While there have been several proof-of-concept demonstrations of deployed quantum communications and networking, over both free space and fiber, in various locations around the globe, see e.g., Refs. [3–9] for an overview, there is a need to advance entanglement-based technologies to be more integrated into the (classical) networking framework beyond that of previous demonstrations. This includes scaling to more users, reaching longer link distances, allowing coexisting quantum and classical data channels on the same fiber links, testing quantum protocols in a realistic network setting, e.g., using transparent optical switches and other optical networking components, as well as optimizing and automating the software control of network operations such as synchronization between nodes.

2 Design Considerations

Despite the fact that quantum networks are not yet fully developed, it is expected that most quantum applications will require networks that support entanglement distribution to enable teleportation for quantum communications, in order to protect the quantum information. Since quantum network components essential for network deployment beyond the metropolitan scale (e.g., quantum repeaters) are currently unavailable, it is essential to advance quantum network architecture and develop quantum network technologies independently of the availability of such components. One such approach is to develop entanglement-based quantum network architecture and implementations that employ software-defined networking (SDN) technology, together with transparent optical switches to implement network functions. Such an architecture design allows the network to establish lightpaths among quantum nodes or between quantum nodes and entangled photon sources via traditional (classical) wavelength routing and assignment approaches used in transparent optical networks. In transparent optical networking, a lightpath is a path between two nodes in the network in which light passes through unmodified. This quantum network architecture approach is inspired by the

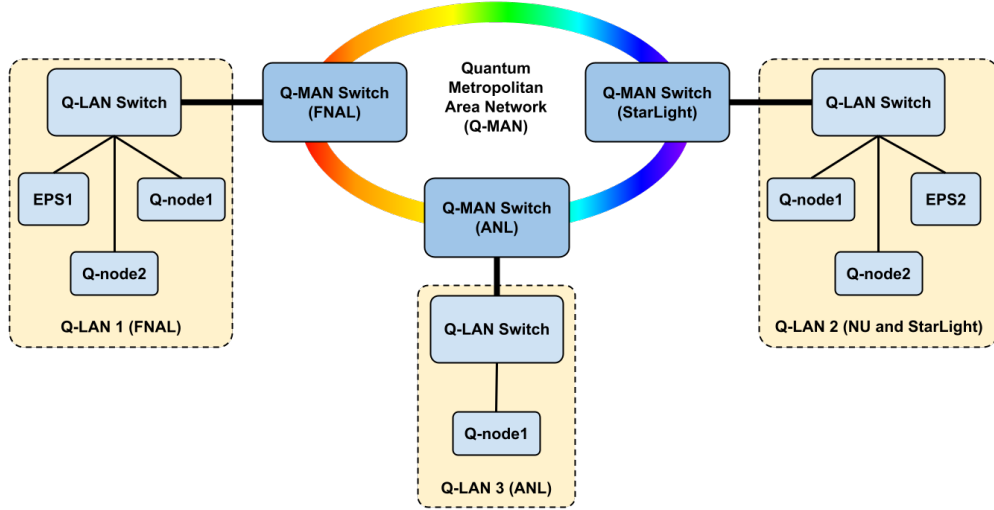


Figure 1: IEQNET topology.

vision of universal transparent quantum networks detailed in the quantum networks for science workshop report [10]. It is also desirable that the implementation of such a network should support coexistence of the quantum and classical signals in the same optical fiber transmission systems and share the same DWDM network components.

3 IEQNET Architecture and Design

3.1 IEQNET Topology and Architecture

IEQNET consists of multiple sites that are geographically dispersed in the Chicago metropolitan area with sites at Northwestern University (NU), Fermi National Accelerator Laboratory (FNAL), Argonne National Laboratory (ANL), and a Chicago-based international communications exchange (StarLight). Each site has one or more quantum nodes (Q-Nodes), which can communicate data and generate and/or measure quantum signals. Q-Nodes are connected to software-defined networking (SDN) enabled optical switches through optical fibers. The optical switches further connect with one another to form a meshed all-optical network. IEQNET contains three logically independent quantum local area networks (see Figure 1): Q-LAN1 at FNAL, Q-LAN2 at NU and StarLight, and Q-LAN3 at ANL. The Q-LANs are connected by dedicated communication channels and additional dark fibers between FNAL and ANL (already operational), as well as between ANL and StarLight and FNAL and StarLight (these connections are part of the ESnet [11] plan for quantum network infrastructure deployment). A dark fiber is essentially an unused optical fiber cable with no service or traffic running on it. In addition, IEQNET has Q-Nodes that incorporate one or multiple entangled photon sources (EPSs) shared across the network, as well as Q-Nodes that incorporate Bell state measurement capabilities (BSM nodes), which are also connected to SDN-enabled optical switches through optical fibers. An EPS generates entangled photon pairs at N wavelengths, allowing a maximum of $N/2$ user-pairs to simultaneously share bipartite entangled photons. The N wavelengths from the EPS are typically distributed via N fibers to an all optical $N \times N$ switch. Such switches are commercially available with low loss, high port counts, and transparency over the entire low-loss fiber wavelength range of 1270-1620 nm. These features allow efficient distribution of quantum photons to many users and open up wavelength options like the use of a 1310 nm band entangled photon source that allows for enhanced co-existence with classical data. A BSM node performs *Bell state measurements*, projections of two qubit states onto Bell basis, and local qubit operations for incoming photon pairs.

IEQNET implements a layered quantum networking architecture, which describes how quantum network functions are vertically composed to provide increasingly complex capabilities. Other research groups have proposed layered architectures for quantum networks that resemble the classical Internet stack. For instance, Dahlberg et al. [12] [QuTech at Delft University, Netherlands] proposed a quantum network stack that perfectly maps the names of the TCP/IP stack (i.e., they have Application, Transport, Network, Link, and Physical layers). Similarly, Alshowkan et al. [13] [Oak Ridge National Laboratory, USA] proposed an architecture that considers Application, Transport, Link, and Physical layers. The authors purposely exclude a network layer because they consider this is only needed for connecting multiple independent networks like in the case of the classical Internet. IEQNET's layered quantum networking architecture relies on four key vertical layers (see Figure 2).

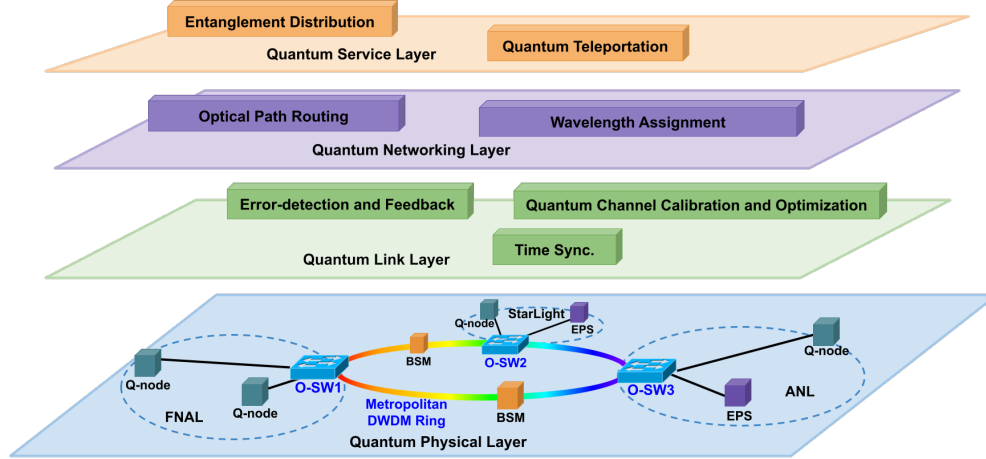


Figure 2: IEQNET’s layered quantum networking architecture relies on four key vertical layers: quantum physical layer, quantum link layer, quantum networking layer, and quantum service layer. See text for further description.

- *Quantum physical layer* deals with the physical connectivity of two communicating quantum nodes. It defines quantum channel frequencies, signal rates, photon pulses used to represent quantum signals, etc.
- *Quantum link layer* is the protocol layer in Q-Nodes that handles the transmission of quantum signals and messages across quantum channels.
- *Quantum networking layer* performs wavelength routing and assignment in optical networks to establish lightpaths between quantum nodes.
- *Quantum service layer* provides quantum services, such as entanglement distribution and quantum teleportation to users and applications.

We must emphasize that our layered architecture does not have a one-to-one mapping to the classical TCP/IP stack. Mainly because repeaterless, metropolitan-scale quantum networks do not need the equivalent of classical packet switching in the quantum domain. These networks can operate under the circuit switching paradigm, that is, establishing a lightpath between Q-Nodes before communication starts as done in IEQNET’s quantum networking layer. This explains the absence of a transport layer in our layered architecture. However, when we move from experimental demonstrators towards more realistic network applications an *Application layer* could be introduced on top of the stack to incorporate various quantum applications that use entanglement and teleportation services.

3.2 IEQNET Q-Node design

Much like their classical counterparts Q-Nodes in IEQNET, depicted in Fig. 3, represent the communication parties in a quantum network. Every Q-Node performs both conventional (classical¹) and quantum functions. The quantum functions that the node has to execute depend on the node type. These range from single and entangled photonic qubit generation to qubit measurements and processing, including Bell-state measurements. A Q-Node also performs conventional functions such as classical computation and communication. For example, a Q-Node will exchange messages with other Q-Nodes via conventional traffic channels to exchange the results of quantum measurements, e.g., to determine correlations, or execute quantum protocols. A Q-Node is assigned an Internet Protocol (IP) address to uniquely identify the node. Meanwhile the endpoints of each conventional channel within the Q-Node are identified and addressed by a physical address (a classical device that contributes to the workflow of a classical function constitutes a “conventional endpoint”). In addition, a Q-Node enumerates and numbers the quantum channels it connects to. The $\langle Q\text{-Node IP, quantum channel \#} \rangle$ pair is used to identify and address a particular quantum channel endpoint (a quantum device within the Q-Node that contributes to the workflow of a quantum function constitutes a “quantum endpoint”).

Conventional channels serve three purposes in IEQNET: (i) as communication channels between Q-Nodes to exchange data and timing messages to enable quantum (correlation) measurements, (ii) embedded signals to allow calibration and stabilization functions (e.g., polarization stabilization, calibration of quantum basis measurements, or fiber-delay stabilization), (iii) as test channels for experimentation, e.g., to determine the limits of classical/quantum channel

¹We use “classical” and “conventional” interchangeably in this article, as a qualifier for classical network functions and/or signals

coexistence. We note that the calibration/stabilization could use quantum signals directly, but the use of larger magnitude classical signals when possible can provide enhanced functionality, such as reducing set-up time when the network changes the user connections or allows high-rate feedback control to compensate time-varying parameters (like polarization).

Routing is a fundamental network function. Multi-hop networks (those in which information has to travel across more than one networking devices) require a means of selecting paths through the network. Due to technology immaturity in quantum memory and quantum computation, IEQNET does not perform routing in the quantum domain, such as entanglement routing. Instead, SDN technology is used to perform traditional *wavelength routing and assignment* in optical networks to establish lightpaths between Q-Nodes, or between Q-Nodes and entangled photon pair sources (EPSs), as appropriate (see Sec. 3.3 for more details).

3.3 IEQNET Control Plane Design

Mechanisms for generation, synchronization, and measurement of quantum states in networks are crucial for realizing a multitude of quantum information applications. They can allow high-quality distribution of entanglement throughout the network—provided errors are identified, their magnitude estimated, and steps taken for their correction. Orchestration and control mechanisms are especially important for performing advanced quantum communication tasks, such as quantum teleportation and entanglement swapping, which are based on quantum interference and thus are more susceptible to dynamical processes in a network environment, such as polarization rotations in the fiber channels or electronic control drift from local clock mismatches. IEQNET uses a centralized control approach in which SDN controllers monitor the status of key infrastructure plane metrics (e.g., loss on fiber links, status of optical switches, etc.). IEQNET’s control and management software performs such functions as time synchronization, optical path routing and wavelength assignment for quantum and classical channels, channel calibration and optimization, and error detection and feedback.

- *Time Synchronization.* Synchronizing remote locations for distribution of entanglement and their use in subsequent applications is crucial for quantum networking. For the fiber channels, this is done by distributing clock pulses in the same fiber as the quantum signals, where permitted.
- *Routing* is a fundamental network function, and multihop networks require a means of selecting paths through the network. IEQNET’s underlying quantum network is a WDM-based all-optical network. We use SDN technology to perform traditional routing and wavelength assignment (RWA) [14] to establish paths between Q-Nodes in IEQNET’s quantum physical layer. RWA is typically formulated as a multi-commodity flow problem, an NP-hard problem that is typically solved with heuristic algorithms. For IEQNET, we represent the network by an undirected graph $G(V, E)$, where V represents the set of nodes in the graph (Q-Nodes, BSM, EPSs, and optical switches) and E represents the set of edges in the graph (optical links). Each edge in the graph (optical link in the network) has the following characteristics that contribute to the computation of the edge’s metric/weight: link length, total number of wavelengths, number of wavelengths available, attenuation, etc. Each node in the graph may also contribute to the edge’s metric/weight with attributes such as insertion loss, polarization-dependent loss (PDL), and polarization mode dispersion (PMD). We use the following shortest-path RWA (SP-RWA) algorithm as the baseline (see Algorithm 1):
 1. The set of shortest paths between a source-destination pair is ordered according to the entanglement distribution requirements
 2. The set of wavelength is ordered according to the entanglement distribution requirements
 3. A new connection is routed on the first path on which a wavelength is available
 4. Among the set of available wavelengths on that path, the first one is selected, or the one that meets the requirement is selected
 5. If no path, or no wavelength can be found, the connection is considered blocked

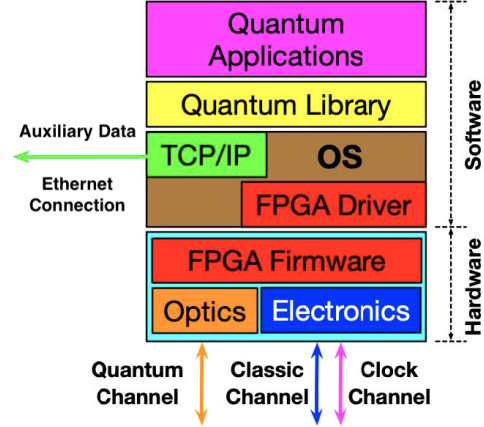


Figure 3: IEQNET Node implementation diagram. Each node performs conventional and quantum functions and has optical and electronic interfaces that are controlled by a FPGA with additional software layers running on top.

- Quantum Channel Calibration & Optimization.** The single-photon nature of quantum communication signals makes them extremely sensitive to noise on the quantum channels. In addition, as mentioned above, protocols such as teleportation require indistinguishability in spectral, temporal, spatial, and polarization properties of the two photons arriving at the BSM node. IEQNET employs several active and automated quantum-channel calibration and optimization mechanisms to minimize quantum-channel loss, reduce background noise, and compensate for polarization and delay drifts. A common way to assess the indistinguishability is to perform a so called Hong-Ou-Mandel (HOM) experiment for the interfering photons by adjusting the relative time of arrival of the photons on the beam-splitter. This renders photons from completely distinguishable, corresponding to the case when the two photons arrive at different times and don't interfere with each other, to as indistinguishable as possible, corresponding to the case when two photons arrive at the same time at the beam-splitter. By increasing the HOM visibility we can ensure quantum indistinguishability. The monitoring of the HOM visibility provides feedback to compensate for the photons' relative time-of-flight, ensuring stable operation. Active polarization measurement and calibration using coexisting classical signals, such as clock pulses, is used to compensate for polarization drifts in fibers.

Algorithm 1 Shortest-Path RWA (SP-RWA) algorithm

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1: Input:  $G(V, E)$ ,  $src$ ,  $dst$ ,  $C$ ,  $p$ 
2: Output:  $route$ 
3:  $route \leftarrow NULL$ 
4:  $paths \leftarrow FINDANDSORTPATHS(G, src, dst, C)$ 
5: for each  $path$  in  $paths$  do
6:    $wavelengths \leftarrow SORTWAVELENGTH(path, C, p)$ 
7:   for each  $wl$  in  $wavelengths$  do
8:     if  $wl$  is available then
9:        $route \leftarrow ROUTECONN(path, wl)$ 
10:    break
11:   end if
12: end for
13: if  $route$  is not NULL then
14:   return  $route$ 
15: end if

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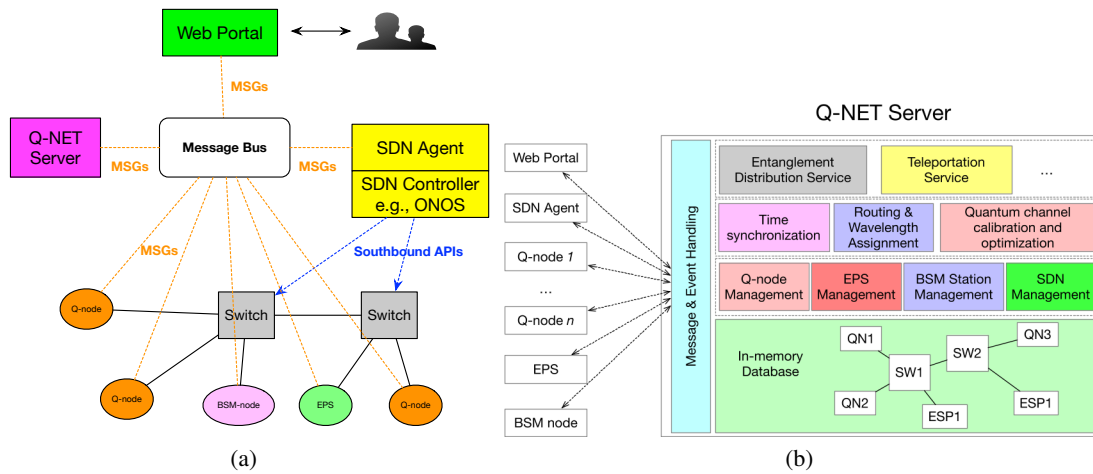


Figure 4: (a) IEQNET control plane implementation and (b) Q-NET Server block diagram.

We are implementing and deploying the SDN-based, logically centralized IEQNET control plane design described in section 3.3, concurrently with the deployment of the IEQNET Q-Nodes and carrying out of use-case demonstrators.

As illustrated in Figure 4, a logically centralized Q-NET server coordinates all activities in the network. This server manages and schedules various quantum network resources at the Q-Nodes (such as EPS, BSM, and send and receive channels) to perform key control and management functions of quantum networking services (e.g., entanglement distribution and quantum teleportation for the IEQNET use cases).

A web portal authenticates, authorizes, and audits users and applications, and allows them to access IEQNET services and functions. For example, for an entanglement distribution service request, the following information is conveyed to the Q-NET server via the web portal: the credentials of the task submitter, the Q-Nodes involved, and the entanglement distribution requirements, such as qubit type, rate, duration, etc. The Q-NET server uses this information to schedule and broker resources for the task. In addition, users are able to browse the quantum network topology or monitor the system/site status via the web portal.

As the network expands and/or changes with nodes or connections joining or going offline, an SDN agent keeps track of the quantum topology and traffic status with the aid of SDN controllers. It is also responsible for reliably updating SDN-enabled switch rules, as requested by the Q-NET server, to assign paths for quantum, clock, and classical signals/messages. SDN controllers are open-source network operating systems, such as the Open Network Operating System (ONOS) [15]. The SDN agent accesses SDN controllers through northbound application programming interface (APIs). A northbound API allows other applications to send commands to an SDN controller. One or multiple SDN agents will be deployed, depending on the size of the quantum network.

In this implementation, the Q-NET server communicates with other entities through a message queuing telemetry transport (MQTT) based message bus. Such a control plane design offers flexibility, robustness, and scalability.

3.5 IEQNET Classical Control Protocol Suite

In this section we describe the IEQNET classical control protocol suite, which is composed of two main protocols: quantum network resource and topology discovery protocol (see Figure 5) and the protocol for handling entanglement distribution requests (see Figure 6). The classical control protocol suite runs inside the Q-NET server of IEQNET's control plane implementation.

Figure 5 shows a sequence diagram of the discovery protocol, which starts when each quantum networking resource (e.g., Q-Nodes, EPS, BSM-nodes, and switches) load their own configuration from file at initialization. The next step is for the SDN agent to discover the network topology through the SDN controller's southbound API. A southbound API allows an SDN controller to communicate with networking devices such as all-optical switches. As all-optical switches are passive devices and thus classical active mechanism for topology discovery will not work, we have extended ONOS's link discovery service to build the topology from information loaded in a tag field on each optical port's configuration. Quantum network resources register to the Q-NET server by sending their features and connectivity information. The Q-NET server will request the topology from the SDN agent and will subsequently ask the SDN agent to verify the connectivity information provided by individual quantum resources. Once the topology has been verified, the Q-NET server will build a topology graph based on the updated topology and present it to users through the Web portal. This cross-verification is necessary because the current prototype of the IEQNET controller does not support active discovery (as already mentioned). As we work with configuration files, the only way the SDN Agent can know a Q-Node is connected to its designated port is by receiving a message from the Q-NET server after the Q-Node registered. This discovery protocol keeps running as quantum network resources can come and go. Furthermore, the SDN agent has the capability to notify the Q-NET server of topology changes asynchronously.

Figure 6 illustrates how IEQNET handles a user entanglement distribution request. The protocol starts with a user requesting entanglement distribution between Q-Node1 and Q-Node2. The Q-NET server will analyze this request and choose an EPS that meets the requirements specified by the user. Upon acceptance of the request, the Q-NET server will execute path routing and wavelength assignment and will establish the paths among involved entities via the SDN agent. Q-NET server will notify Q-Node1 and Q-Node2 when paths are established and initiate path verification, which involves a series of active probes from EPS to Q-Nodes (and vice versa) using both classical and quantum light. After path verification, the Q-NET server will initiate calibration and optimization processes (as described in Section 3.3) for the requested service. Once all entities send the READY signal to the Q-NET server, the entanglement distribution process starts. Q-Nodes will collect measurements until they have a long enough ebit string for the upper layer application. At that point they will send the END signal to the Q-NET server to stop entanglement distribution. Periodically during entanglement distribution, the Q-NET server will re-initiate the calibration and optimization processes. After the Q-NET server stops the EPS, all measurements will be stored at the Q-NET server and the user will be able to access them through the Web portal.

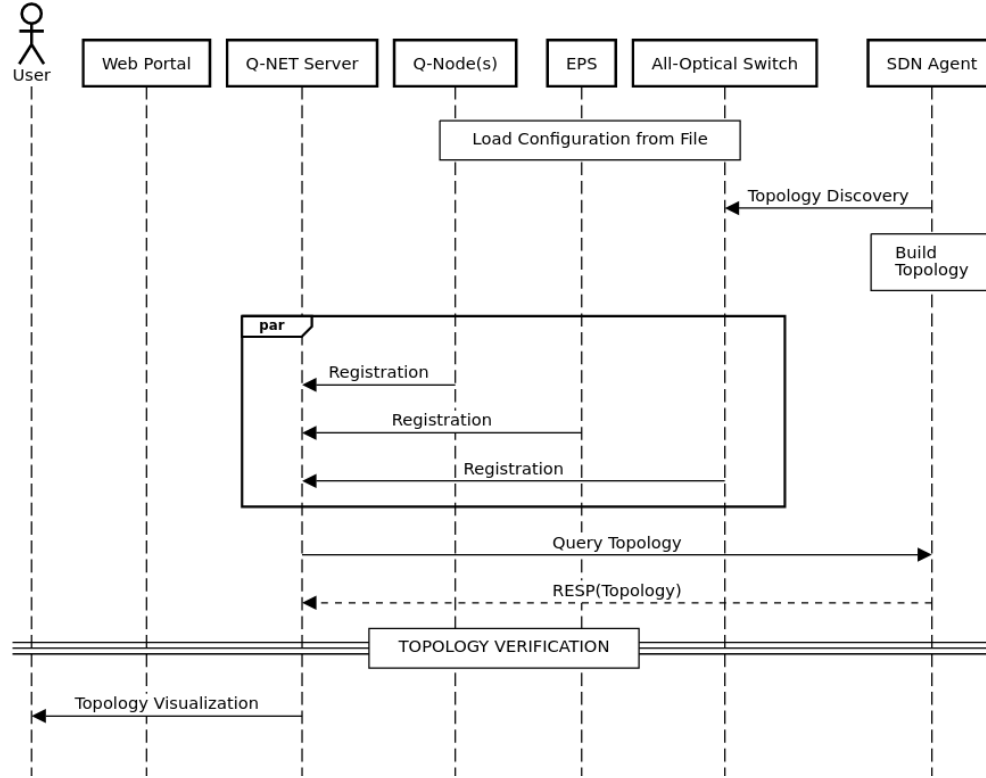


Figure 5: Quantum network resource and discovery protocol.

3.5.1 Entanglement Distribution Protocol

In this subsection we expand the description of the entanglement distribution protocol shown in Figure 6. The corresponding IEQNET protocol is characterized by the following message flow between the entities:

1. A user sends a request to IEQNET controller for entanglement distribution between Q-Node-1 and Q-Node-2.
 - Qubit types (polarization, time-bin,...)
 - Start/END time
 - Q-Node pair
 - Common measurement basis for calibration
2. IEQNET controller analyzes the request and chooses an EPS that meets the requirement, or the request is rejected.
3. IEQNET controller executes path routing & wavelength assignment and establishes paths among involved entities.
4. IEQNET controller notifies Q-Node-1, Q-Node-2 and EPS node that paths are established
5. Q-Node-1, Q-Node-2, and EPS test and verify paths. If there are failures, they send negative acknowledgements (NACKs) to the IEQNET controller and the flow goes back to step 3. Otherwise, they send acknowledgement (ACKs) to IEQNET controller.
 - Verification of the path from EPS to Q-Node1 is done in two stages. First a classical light (some light of known power for example) is sent from EPS to Q-Node1. The received power is measured at Q-Node-1 and communicated to the IEQNET controller. This will be used to establish losses.
 - Next step is to send quantum light from EPS which is measured in the single photon detectors (SPDs) and upon receiving expected clicks, the Q-Node-1 will send a message to the IEQNET controller saying that the path has been verified. Similar steps are used to verify the path between EPS and Q-Node-2. Assuming the EPS is calibrated and the losses from EPS to Q-Nodes are also known from the previous step, the expected clicks will be $R * \eta$ where R is the rate of photon generation at EPS and η the loss

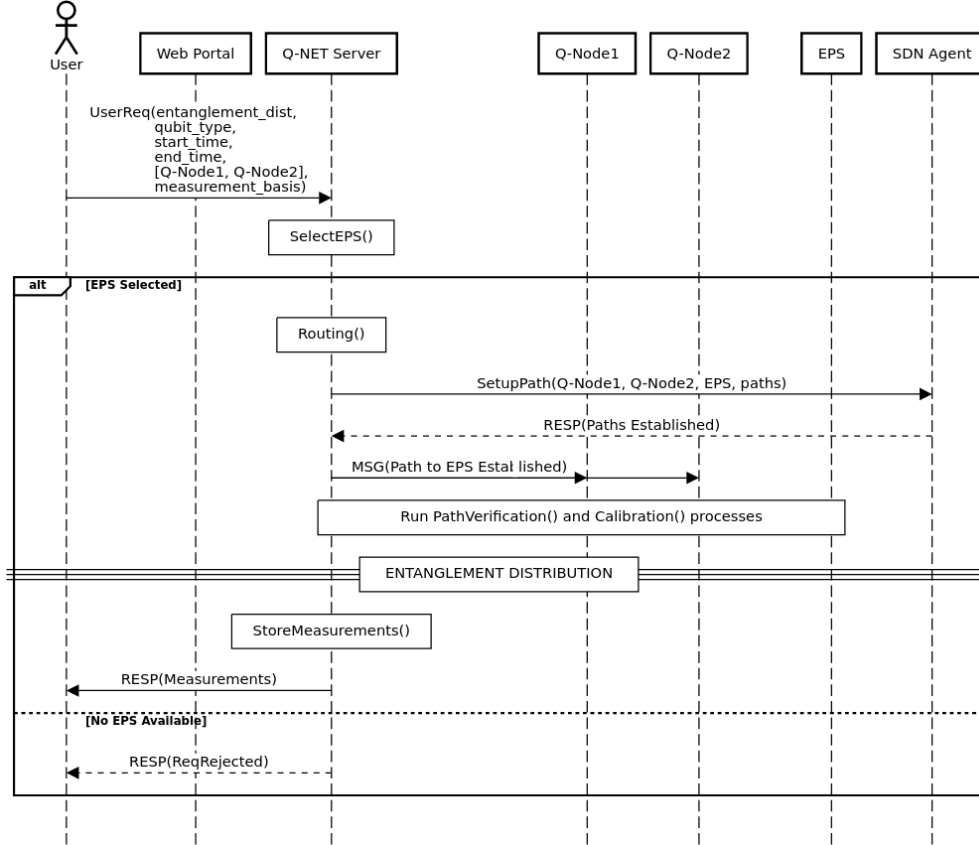


Figure 6: The protocol for handling entanglement distribution requests. The steps inside the alt box are only executed if the `SelectEPS()` procedure returns a successful ESP, otherwise the request is cancelled.

between the EPS and the Q-Node. Measure the “noise” on the detector by switching off the quantum light from EPS. Calculate the ratio of noise/rates and if the ratio is less than some specified threshold (e.g. $1/6$) declare it as a success. Similar steps are followed for the clock paths too.

6. IEQNET controller performs calibration and preparation for entanglement distribution.

- The classical signals to be exchanged between the two receiver stations for sync and channel monitoring are assigned the wavelength of $\lambda_{\text{sync}} = 1551.72 \text{ nm}$ (DWDM ITU Channel C32). These signals can go back and forth between the two receiver stations.
- Measurement basis alignment
 - (a) Polarization Qubit:
 - Add classic alignment light at EPS [16].
 - IEQNET controller notifies EPS to send out alignment signals. The controller will specify the basis.
 - Q-Node tunes its analyzer to maximize the output so that measurement basis(es) are aligned with the EPS basis(es).
 - Q-Node stops and notifies IEQNET controller.
 - (b) Time Bin qubit:
 - IEQNET controller notifies EPS to send early,early photons. Q-Node will identify the “early” timing with respect to the local clocks. Then the EPS will send late, late photons which will then allow Q-Nodes to identify the “late” timing.
 - If the receivers are using the same detectors to detect in time and phase basis then IEQNET controller asks EPS to send the entangled photons and receiver stations identify the so-called early, middle and late bins from the histograms of the detection signals obtained locally.
 - For interferometer alignment at both locations we add classic interferometer alignment light at EPS.

- IEQNET controller notifies EPS to send out interferometer alignment signals. The controller will specify the phase.
 - Q-Node tunes its interferometer phase to maximize the output to the corresponding phase so that phases are aligned at both the Q-Nodes.
 - Q-Node stops and notifies IEQNET.
- In order to connect two types of networks a straight forward conversion between polarization and time-bin qubits can be performed [17].
 - In the calibrate phase, the entangled photons received by both are detected in a common measurement basis which is agreed upon before. The detection results are encoded onto a laser with wavelength (λ_{sync}) and exchanged back and forth between the two stations.
 - These results are used then to achieve bit level sync using local time-taggers / coincidence analyzers at each receiving station.
 - This is also where the correlation delay can be established. Ideally the controller has a range of possible delay values that may work for measuring correlations at a given node, which it communicates to the node. While the measurement bases are aligned the node can scan the electrical delay (in integer clock units) until heightened correlations are observed. Typically the node can determine if the delay setting is likely to be right or wrong after ~ 10 coincidence counts are measured (standard deviation of the measurement is then $\sqrt{10}$). If it is likely to be correct then another 10 coincidence counts should verify it.
 - Proceed to entanglement distribution (steps 8-11)
 - Note that λ_{quantum} , λ_{clk} , and λ_{sync} can all be multiplexed onto a single fiber strand or just the classical ones onto a different fiber strand as envisioned for the initial phases of the project.
 - Choose a suitable duty cycle of the experiment and repeat the calibration step at the start of each cycle.
7. EPS, Q-Node-1, Q-Node-2, and other related entities notify READY to IEQNET controller.
 8. IEQNET controller sends START to EPS.
 9. EPS starts to distribute entanglement pairs; Q-Node-1 and Q-Node-2 receive entangled photons.
 10. Q-Node-1 and Q-Node-2 measures the entangled photons, and exchange results. They store the results locally until they have long enough e-bit string for the required application and communicate END to the IEQNET controller.
 11. IEQNET controller stops EPS with an END command.
 12. The results will be posted to the IEQNET controller and will be stored.

The teleportation protocol can be devised in similar manner.

4 IEQNET Demonstrators

In this section we present experimental results that demonstrate system capabilities necessary for the deployment of the IEQNET quantum network architecture. These involve quantum teleportation and quantum/classical signal co-existence experiments performed at both Q-LAN1 and Q-LAN2 of IEQNET. Demonstrating co-existence in real-world conditions is a major goal for IEQNET and a very desirable development for the deployment of quantum networks. Classical communications are a fundamental part of many quantum communications protocols that require the transmission of the results of quantum measurements amongst the node connections, such as remote state preparation and teleportation. Furthermore, classical signals for time synchronization in quantum networks will be required. Beyond purely quantum-based applications, future quantum networks will likely have fiber connections that are already populated with light from the classical internet, which is predominantly in the C-band. If quantum communications can coexist in the same fibers carrying such high powers, the entire classical internet fiber infrastructure is available for quantum network deployment. This would significantly reduce the cost of deploying quantum networks as dark fibers will not be required and increase the number of available fiber connections between node locations. Dark fibers are expensive to lease due to the high demand for installed fibers from the expansion of the classical internet. We demonstrate engineering approaches to achieve this such that the network could be deployed anywhere within the fiber infrastructure.

Q-LAN1 has nodes deployed in two separate locations at Fermilab, connected by 2.5 km of optical fiber. Q-LAN1 is used to demonstrate time-bin qubit teleportation, although these initial tests are performed in a single location to allow for experimental flexibility and enable faster debugging. We perform teleportation over 44 km of lab-deployed fibers at 1536 nm and achieve above 90 % teleportation fidelities with a semi-autonomous system that can sustain stable operation via modern data-acquisition systems and integrated feedback mechanisms. We also discuss the commissioning results of a clock distribution system, co-existing in the same optical fiber as the quantum channel, and where we

measured a time jitter of 5 ps. These co-existing clock distribution systems will pave the way towards synchronizing multiple nodes in remote locations and thus allowing more complex quantum protocols.

Q-LAN2 connects the Quantum Communications Lab at Northwestern University in Evanston, IL to the Starlight Communications Facility located on the Chicago campus of Northwestern. This underground fiber link is 22.8 km, with the option of operating in loop-back mode to reach 45.6 km. The experimental measurements reported in this section operate at the Northwestern site using the 45.6 km loop-back configuration. The Starlight facility also has access to a short-reach fiber connection to 600 S. Federal building and a 16x16 all-optical switch. Q-LAN2 distributes polarization entangled photons, and includes the use of classical alignment signals to account for the unknown polarization transfer function of the distribution fiber. This network uses the O-band (1310 nm band) for the quantum signal, which is chosen so that substantial amounts of co-existing classical communications in the C-band (1550 nm band) can be tolerated on a shared optical fiber. Our experiments and data analysis are guided and supported by a phenomenological model which can be quickly compared with experimental data. We discuss the model and its utilization in our results.

4.1 Quantum Teleportation of Time-bin Qubits and coexistence with telecommunication O-band classical signals at Q-LAN1

The Q-LAN1 nodes are deployed in two separate locations at Fermilab, one at the D0 Assembly Building (DAB) and one at the Fermilab Computing Center (FCC). The two labs supporting the Q-LAN1 nodes at these two locations are connected by ~ 2.5 km of optical fiber going through a 16×16 (Polatis 6000s Ultra) all-optical switch. The Q-LAN1 setup with its two locations, short separation by field-deployed fiber, and optical switch serves as an internal IEQNET “testbed” to test and validate performance of IEQNET protocols before connecting the three Q-LANs (first Q-LAN1 and Q-LAN3 at Argonne, and then Q-LAN2, the sequence in the order of increasing distance). The first set of Q-LAN1 experiments were performed at the DAB lab.

4.1.1 Quantum teleportation

The Q-LAN1 fiber-based experimental system, summarized in the diagram of Figure 7, allows us to demonstrate a quantum teleportation protocol in which a photonic qubit (provided by Alice) is interfered with one member of an entangled photon-pair (from Bob) and projected (by Charlie) onto a Bell-state whereby the state of Alice’s qubit can be transferred to the remaining member of Bob’s entangled photon pair. Up to 22 (11) km of single mode fiber is introduced between Alice and Charlie (Bob and Charlie), as well as up to another 11 km at Bob, depending on the experiment. All qubits are generated at a clock rate of 90 MHz, with all of their measurements collected using a data acquisition (DAQ) system. The measured teleportation fidelities with and without the additional fiber are presented in Figure 8. To illustrate network compatibility, teleportation is facilitated using semi-autonomous control, monitoring, and synchronization systems, with results collected using scalable acquisition hardware. Our system can be run remotely for several days without interruption and yield teleportation rates of a few Hz using the full length of fiber. The Q-LAN1 systems are identical to those utilized in [18], with the DAB lab nodes being part of these original experiments. Our qubits are also compatible with erbium-doped crystals, e.g. Er:Y2SiO5, that is used to develop quantum network devices like memories and transducers [19–21]. The collaboration is currently working towards achieving teleportation rates appropriate for practical, real-world applications by increasing the clock rate from 90 MHz to 4 GHz.

4.1.2 Clock distribution

While quantum teleportation has been achieved with state-of-the-art fidelities and overall performance parameters capable of supporting network functions, the demonstration has nevertheless been restricted to a single node. In a real world network containing more than one node, clock distribution to synchronize the various nodes is critical. Since photons are identified by recording their times of generation and detection, an accurate clock distribution system must be in place to reduce the error rate to a negligible level. To this end, we developed a clock distribution system based on the demonstration presented in [22]. The system relies on a stable clock oscillator measured to have a jitter below 700 fs. The oscillator is used to synchronize all the RF components of the experiment in the main Q-node and additionally drive a 200 MHz clock signal in the O-band which is directed to two independent nodes to adjust their local clocks. C-band photon pairs, originating from a source based on spontaneous parametric down-conversion, are co-transmitted with the classical clock signal. We find that the clock distribution system can allow for high-fidelity qubit distribution despite the presence of (Raman) noise. We measure the coincidence to accidental ratio (CAR) of the photons arriving at the remote Q-node. Figure 9 shows the difference in arrival time from the pair source (Δt) for different input clock powers. We measure that the clock distribution reduces the CAR from 344 ± 22 to 246 ± 14 , this resulting CAR will ensure high-fidelity qubit distribution using this clock system. The clock distribution was measured to have a jitter below 2 ps as it is 2 or 5, as we say in the intro paragraph?. The observed timing jitter between clocks at the central and

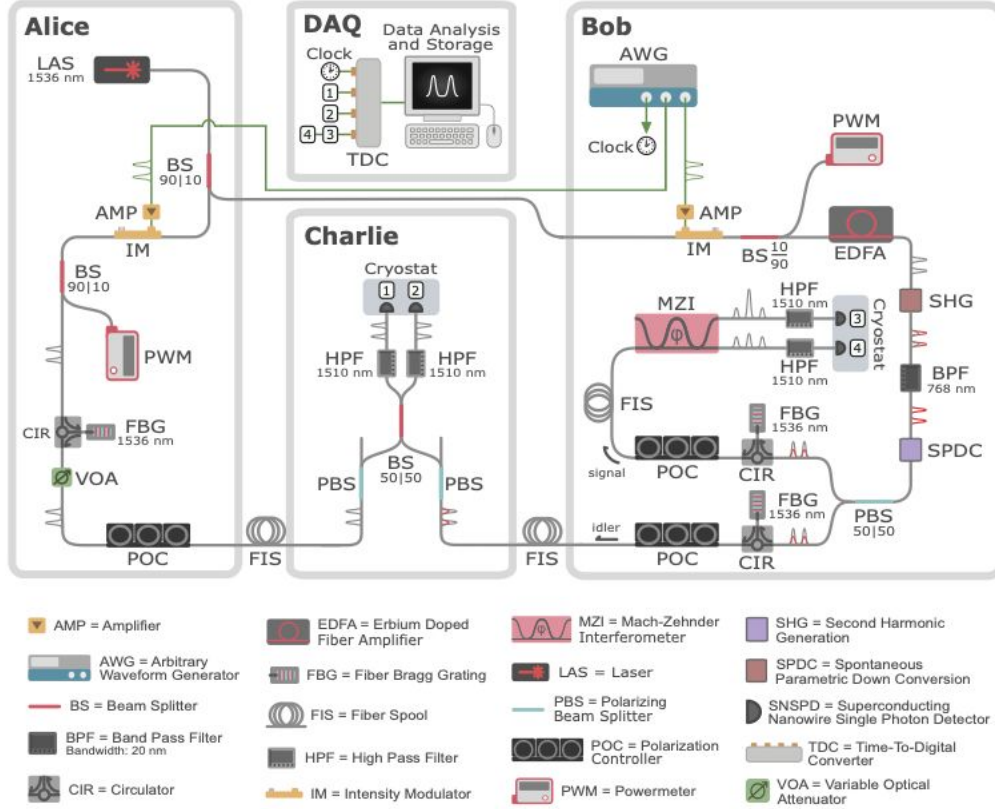


Figure 7: Schematic diagram of the quantum teleportation system consisting of Alice, Bob, Charlie, and the data acquisition (DAQ) subsystems. One cryostat is used to house all SNSPDs, it is drawn as two for ease of explanation. Detection signals generated by each of the SNSPDs are labelled 1-4 and collected at the TDC, with 3 and 4 being time-multiplexed. All individual components are labeled in the legend, with single-mode optical fibers (electronic cables) in grey (green), and with uni- and bi-chromatic (i.e. unfiltered) optical pulses indicated.

end nodes, suggests that our method can be used for high-rate networks. The deployment of such a system will pave the road towards implementing important multi-node quantum functions for scalable networks.

4.1.3 Entanglement swapping

Furthermore, by building on the current capabilities, the systems are being upgraded towards entanglement swapping [23], a key requirement for building long distance quantum networks. By performing a BSM between individual members of two entangled photon sources, entanglement is swapped onto the photons that have never interacted before. Using the newly commissioned FCC Q-node, we have measured the indistinguishability of the photons from two photon pairs sources using a Hong-Ou-Mandel analysis [24]. The experimental results closely match a model of our experimental setup which predicts, under these experimental conditions, a high swapping fidelity.

4.2 Polarization Entanglement Distribution with Coexisting C-band Classical Light over Real-World Installed Fiber at Q-LAN2

In addition to time-bin entanglement distribution, IEQNET also supports the distribution of polarization entanglement. Here, we demonstrate methods for monitoring and compensating polarization birefringence effects during transmission of photon pairs over installed fiber, which is required for quantum applications and measurements in polarization entanglement-based networks. Classical alignment signals are used to transmit information about the birefringent rotations during transmission over a fiber connection to polarization control systems (PCSs) at receiving nodes. Using this information, inverse unitary transformations are applied such that each Q-node that is connected to a source at Q-node_A shares a universal polarization reference frame defined during the entanglement generation at the source.

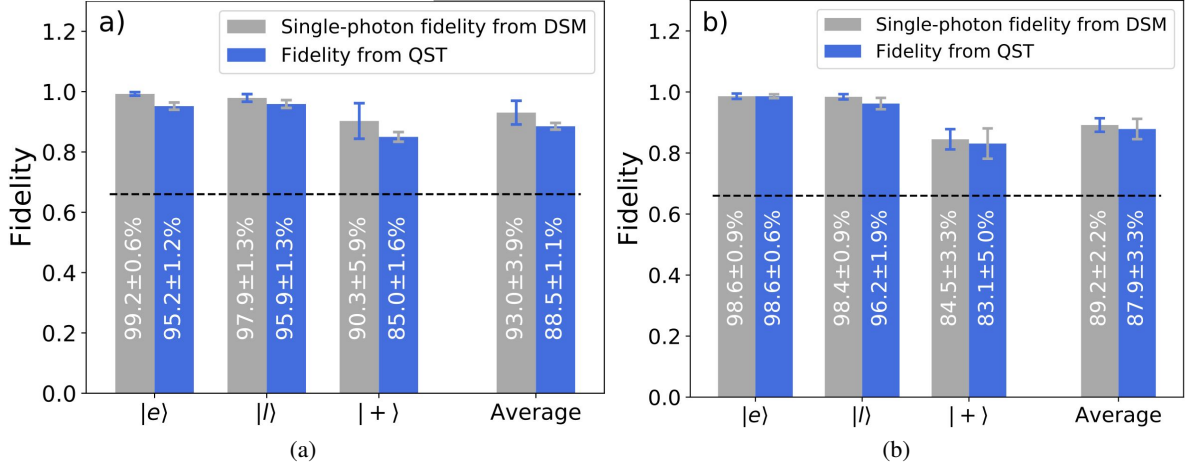


Figure 8: Quantum teleportation fidelities for $|e\rangle_A$, $|l\rangle_A$, and $|+\rangle_A$, including the average fidelity. The dashed line represents the classical bound. Fidelities using quantum state tomography (QST) are shown using blue bars while the minimum fidelities for qubits prepared using $|n=1\rangle$, F_e^d , F_l^d , and F_+^d , including the associated average fidelity F_{avg}^d , respectively, using a decoy state method (DSM) is shown in grey. Panels a) and b) depict the results without and with additional fiber, respectively. Uncertainties are calculated using Monte-Carlo simulations with Poissonian statistics

Further, the Q-LAN2 installed fiber connection explores the implementation of alternative wavelength allocation for quantum signals to make the physical layer more robust to noise photons generated from classical communications coexisting inside the same fiber connection [25]. The polarization entangled quantum signal is allocated to the O-band, which is shown to be optimal for scenarios in which the fiber connection is occupied with C-band classical communication with high enough power that the amount of generated photon noise is fatal to C-band quantum communication [26].

These studies are conducted at Q-LAN2, which is an underground installed fiber link that connects the Quantum Communications Lab at Northwestern University in Evanston to the Starlight Communications Facility located on the Northwestern Campus in Chicago (link distance of 22.8 km) where we loop the connection back to the Evanston Lab (total round-trip distance of 45.6 km).

4.2.1 Coexistence with C-band classical light

The wavelength allocation of quantum and classical signals to implement quantum network protocols is flexible when dark fibers are available, allowing the lowest-loss C-band to be used for optimal rate-loss quantum signal transmission. In this scenario, classical signals for quantum network control can be allocated to other wavelength bands (such as the L or O-bands) to minimize noise crosstalk into the quantum bands. However, the design of full integrated networks must presume that high-power classical communications in the same fiber will unavoidably occupy the C-band, making quantum signal allocation to the C-band impractical at some threshold power level due to the presence of spontaneous Raman scattering (SRS), four-wave mixing (FWM), and amplified spontaneous emission (ASE) from optical amplifiers. This noise disrupts the ability to perform quantum communications protocols in the C-band, requiring the reconsideration

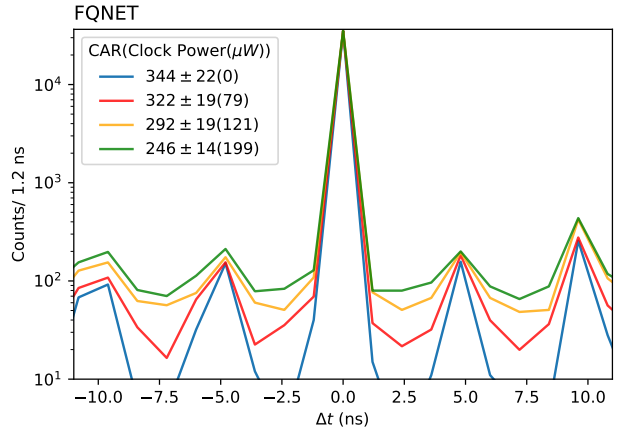


Figure 9: Time difference between photons from the pair source (Δt). The main peak at around $\Delta t = 0$ corresponds to the coincidence peak while the secondary peaks are the accidental counts. Different input power for the co-propagating clock signal in the O-band (1310 nm) are shown in different colors. The increasing heights of the accidental peaks with the higher clock power indicate more Raman noise.

of the quantum physical layer’s wavelength allocation scheme. We mitigate the noise limitations caused by C-band classical coexistence by wavelength allocating the quantum entangled photon pairs to the O-band. Due to the comparatively narrow bandwidths of FWM and appropriate filtering of the ASE, these effects have no noticeable cross-talk into the O-band. Further, since the O-band is far detuned from the C-band on the anti-Stokes side (~ 35 THz), noise photons generated from SRS are significantly reduced. Since the O-band has reasonably low loss in standard installed fibers (~ 0.33 dB/km), metro-scale quantum communication can still be performed while noise from classical communications is drastically reduced compared to the C-band.

There have been numerous experimental implementations of a variety of coexistence scenarios in the context of quantum key distribution (QKD) using weak coherent states (WCS) from attenuated laser light with a strong focus on the O-band/C-band quantum/classical wavelength allocation scheme described above [27–33]. These studies were primarily performed via single quantum channel schemes with WCS. However, fully operational quantum networks beyond QKD will require the distribution of quantum entanglement. This means that two channels must be considered simultaneously, one for each photon in the pair of the entangled state. In contrast to the single quantum channel experiments, the signal to noise trade-off for entanglement-based networks depends on the coincidence detection of correlations in the signal and idler pair’s time, frequency, and entangled degree of freedom. Due to the correlations in time-of-arrival and energy conserving frequency correlations, tight temporal and spectral filtering in coincidence detection can be used to distinguish the quantum entangled signals from the uncorrelated background noise generated from classical communications.

As a demonstration of the above-mentioned engineering considerations, we show experimentally that metropolitan scale entanglement-based quantum communications can be achieved in installed fiber using the O-band with copropagating classical C-band power levels that would make C-band quantum transmission infeasible. We show that polarization-entangled quantum light can successfully copropagate with milliwatt power-level classical light over 45.6 km of installed underground fiber. One photon from a polarization entangled source at the Northwestern Evanston location is transmitted over the Q-LAN2 connection to the Starlight facility where it then loops back to the Evanston lab, while the other photon is kept locally. Polarization analyzers and low-dark-count superconducting nanowire single photon detectors (SNSPDs) are used for quantum characterization of the returning noise degraded quantum signal, which have 30% detection efficiency in the O-band. The equivalent measured loss rate in the underground fiber link is 0.43 dB/km at 1310 nm, which is higher than expected in modern fibers typically used in laboratory experiments, making the equivalent loss closer to a 60 km distance if newer fibers and low loss splicing were used. The use of O-band/C-band quantum/classical wavelength allocation as well as tight temporal and spectral filtering at receiver nodes allows us to achieve high copropagating classical powers (about 7 dBm) while still maintaining nonclassical visibility ($> 70.7\%$) in polarization entanglement two-photon interference.

4.2.2 Polarization Entanglement Distribution Calibration

The quantum networking layer will control routing and assignment of lightpaths between nodes, which means every time a new switched fiber connection has been established, re-calibration of the pair of paths needs to be performed. Further, occasional re-calibration will also be required. Inevitably, time-dependent birefringence due to a variety of environmental disturbances (temperature fluctuations, fiber stresses on hanging fiber, etc.) will cause an initial polarization state to drift over time. Thus, a crucial part of polarization entanglement network control is to ensure that drift from the intended quantum state can be accurately and reliably monitored to re-establish the desired quantum correlations between node pairs. Here we explain a simple protocol for polarization calibration between nodes in the network using broadband classical light sources that are built into the entanglement source’s design.

Basis-alignment can be performed via the transmission of alignment signals which can be analyzed to extract the polarization transformations that occur from the source to receivers. Then, unitary operations at receiving nodes can be performed to compensate for birefringence in the fibers and establish well-defined relative polarization reference frames amongst nodes in the network for performing correlated measurements. The design of polarization monitoring highly depends on the timescales of the drift from the intended transmitted state. For slowly varying fiber birefringence, alignment can be maintained for hours of operation with little drift from the intended quantum state, however some fiber connections may have drift timescales where re-calibration may be required more frequently. In some situations, particularly when loss is less prevalent and drift timescales are slow, using the output of the quantum entanglement source itself can be used to align measurement basis. This method is limited by the transmission rate of the quantum source, which significantly increases the calibration duration and complexity due to low singles or coincidence count rates, especially over long-distance fiber connections with high loss. Active monitoring of polarization rotations can be performed by multiplexing in low power classical light at neighboring wavelengths to monitor polarization changes [34, 35] at the expense of increased design complexity and coexisting classical channels, which may introduce some noise into the quantum band

We choose to use a broadband classical alignment signal that is built into the O-band quantum entanglement source. The broadband nature of the signal means that when the alignment signal is turned on, classical light is then sent throughout the network to each node connection deriving from the EPS for basis alignment. Since the alignment signal is in the same wavelength band as the quantum signal, it contains wavelength dependent polarization effects and propagates the fiber network connections defined by the wavelength routing/assignment and switching connections for quantum channel configurations without additional modifications to the network physical design. This introduces light into the quantum band, temporarily disrupting quantum communications. However, the classical nature of the alignment signal allows us to de-couple the alignment procedure from quantum source rates, allowing the signal to overcome long distance or high loss fiber connections by arbitrarily controlling the power transmitted and thus significantly reducing off-line calibration time due to the strong feedback signal for alignment regardless of link distance. For situations with many connections, it may be desirable to only select a few channels that need alignment. By including WDMs and variable attenuators, our signal can be modified to selectively send to a single or subset of receiving nodes such that quantum communications are not disrupted over the entirety of the network connections.

Our alignment procedure consists of multiplexing in broadband amplified spontaneous emission (ASE) covering the entire O-band to transmit a signal $|V \text{ align}\rangle$ for alignment in the H/V basis followed by a $|diag \text{ align}\rangle$ signal used to align in the D/AD basis via polarization control at each node. The two non-orthogonal signals allow for full alignment of the Poincare sphere at nodes Bob and Charlie to that defined during entanglement generation at Alice [34]. The broadband spectrum of the ASE is carved by the WDM filters defined for transmission of the entangled pairs, which allows for wavelength dependent birefringence to be accounted for. The ASE photons are then received by the same polarization analyzers (PAs) as the quantum signals and is then detected by the single photon detectors. Active feedback from the single photon counts from the detectors are used to perform basis alignment by adjusting birefringence compensating waveplates in the PAs.

4.2.3 Q-LAN2 Experiment

Figure 10 shows a schematic of our experiment. We generate the polarization entangled quantum signals via cascaded second harmonic generation-spontaneous parametric down conversion (c-SHG-SPDC) in a single periodically poled lithium-niobate waveguide (PPLN) [36]. The cascaded second order interaction acts as a quasi-spontaneous four wave mixing process used in fiber-based sources of entanglement [37], where the pump, signal, and idler wavelengths all occupy same wavelength band. Since our cascaded second order nonlinear source is analogous to a fiber-based entanglement source, we easily adopt the built-in alignment signal design used in previous fiber-based sources of polarization entanglement [16, 38] for this SPDC based source. The PPLN waveguide is phase matched for SHG of the 1320 nm pump pulse train at 417 MHz repetition rate with 80 ps pulse-width. We place the waveguide inside a polarization Sagnac loop to generate polarization entangled photon pairs. The pump light entering the loop is split by a polarizing beam splitter (PBS_A) into two counter-propagating directions. The c-SHG-SPDC generates broad-bandwidth quantum amplitudes for photon pairs centered around 1320 nm in both directions. Upon recombination at the PBS, the two photon state exits the Sagnac loop in a polarization entangled state $|\phi\rangle \propto |HH\rangle_A + e^{i\phi_{EPS}}|VV\rangle_A$, where ϕ_{EPS} is due to a relative phase between the H and V components of the pair generation pump.

We then separate the signal/idler photons into bands using a standard coarse wavelength division multiplexer (CWDM). The CWDM outputs 20 nm wide bands with center wavelengths of 1310 and 1330 nm. The broadband spectrum of the c-SHG-SPDC allows the source to support distribution over the full O-band to easily scale the network to more users by carving the spectrum into more WDM output channels by either using the 1290 and 1350 CWDM bands or by further carving the 20 nm wide channels into multiple narrower channels.

For alignment, broadband ASE from a Praseodymium-doped fiber amplifier (PDFA) is multiplexed in to transmit polarized signals in the wavelength bands defined by the spectral filters in each fiber link connection. The alignment procedure consists of sending two sequential alignment signals, one with a vertical ($|V \text{ align}\rangle$) polarization and the other with a signal for diagonal ($|diag \text{ align}\rangle \propto \frac{1}{\sqrt{2}}(|H\rangle_A + e^{i\phi_{EPS}}|V\rangle_A)$) alignment, which the receiving nodes at Bob and Charlie use to orient their waveplates while counting single photons to align their polarization basis with that at Alice. A 100 GHz DWDM filter centered at 1320 nm passes the pump wavelength (1320 nm) and rejects the broad ASE spectrum into another fiber. For H/V basis alignment the ASE signal is injected into one arm of the Sagnac loop in Alice's source to be reflected at PBS_A such that it emerges vertically polarized (defined by Alice's PBS) and propagates through both fiber channels to the PAs. At PA_{Bob} and $PA_{Charlie}$, we initially set the projective measurement waveplates to 0 degrees, with a liquid crystal retarder aligned at 0 degrees. The horizontal basis is then aligned via rotating the first QWP/HWP pair to minimize the single count rates in both Bob and Charlie's single photon detectors.

The diagonal alignment signal is generated by injecting ASE via a 99:1 splitter into the source pump path such that the output signal carries the same relative weighting and phase of H and V polarizations as the entangled photons. At both PAs, the projection HWPs are set at 22.5 degrees to project onto the D basis while an automated search scans the

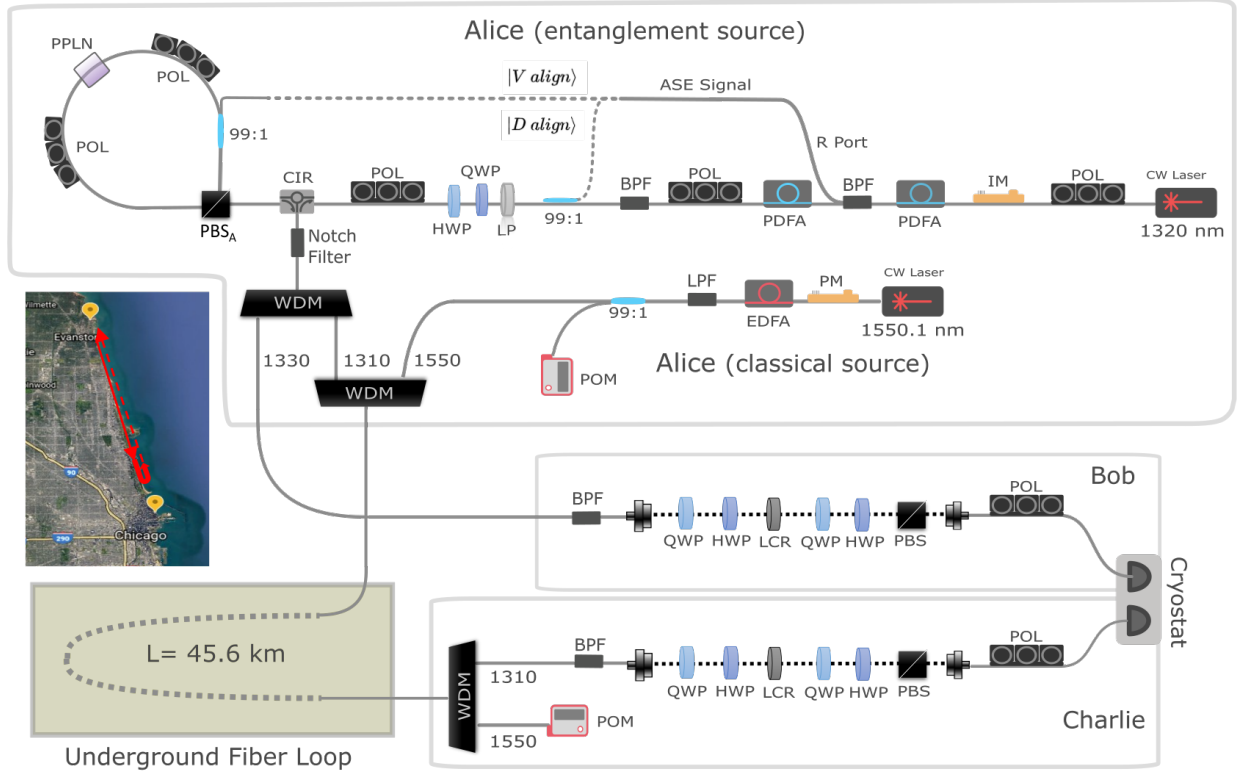


Figure 10: Q-LAN2 experimental design.

voltages applied to the LCR, which adjusts the relative phase between H and V components until the singles count rates are minimized. After the optimal voltages are found for both PAs, the relative phase has been set to zero degrees resulting in the arrival of the symmetric Bell state $|\Phi\rangle_+ = \frac{1}{\sqrt{2}}(|H_B H_C\rangle + |V_B V_C\rangle)$ shared between Bob and Charlie, where $|H\rangle$ and $|V\rangle$ are defined at Alice's PBS.

To demonstrate coexistence, we amplify C-band laser light at 1550.1 nm with an Erbium-doped fiber amplifier (EDFA) and multiplex it into the underground fiber to copropagate with the O-band quantum signal. We phase modulate the C-band light to broaden its spectrum which emulates a data channel and inhibits stimulated Brillouin scattering. At the receiver, we demultiplex out the C-band light while further filtering the remaining signal and idler photons with 100 GHz bandpass (BP) filters centered at 1306.5 and 1333.5 nm, respectively. We detect the photons with SNSPDs, which are followed by a time-tagging correlation detection system. We apply an electronic delay between the two channels to account for the fiber delay and perform coincidence measurements using a coincidence correlation time window of 0.5 ns, which is set such that the arriving photon pair pulse would not drift outside the window due to timing jitter from transmission over the fiber.

We send one photon of the polarization-entangled photon pair over a 45.6 km loop of underground installed fiber. The underground fiber link connects the Quantum Communications Laboratory at Northwestern University in Evanston to the Starlight Communications Facility located on the Northwestern Campus in Chicago (link distance of 22.8 km) where we loop the co-propagating light back to the Evanston laboratory for characterization with polarization analyzers and low-dark-count superconducting nanowire single photon detectors (SNSPDs).

Polarization measurement apparatuses described above at Bob and Charlie first use the classical basis alignment signals from Alice to set their measurement basis to the same reference frame defined by Alice's source. After basis alignment is done, two-photon interference (TPI) measurements are made to analyze the performance of entanglement distribution without (Figure 11(b)) and with (Figure 11(c)) copropagating classical light. TPI records coincidence-count fringes in two non-orthogonal basis states, and the resulting fringe visibility is a metric of entanglement quality. TPI fringes with $V > 70.7\%$ are consistent with violating Bell's inequalities and are strongly non-classical. To record a TPI, the basis state measurement of one location is fixed (say in the H or D orientation) by appropriate alignment of the polarization

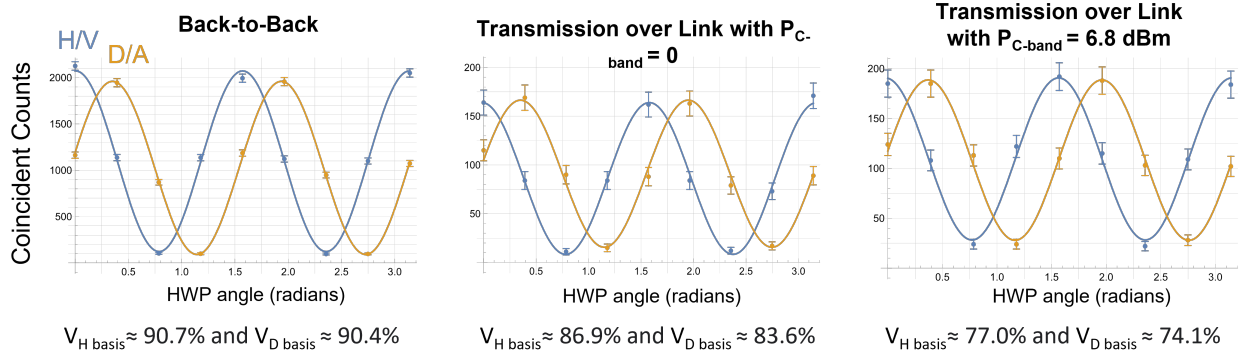


Figure 11: (a) Back-to-back entanglement visibility measurements. (b) Entanglement visibility after transmission over 45.6 km installed fiber link. (c) Entanglement visibility with 6.8 dBm copropagating C-band power.

control elements, while the basis state measurement of the other location is scanned along a Great Circle of the Poincaré sphere. For reference, Figure 11(a) shows the back-to-back TPI fringes, where visibilities are roughly 90%. The low back-to-back visibilities are a result of increasing the source rates at the expense of visibility in order to achieve distribution over the lossy fiber. Figure 11(d) shows TPI fringes after the transmitted photon has propagated alongside 6.8 dBm of C-band launch power, where a visibility of 77% is observed in the HV basis and 74% in the DA basis. Both values are $> 71\%$ and thus fall in the nonclassical regime of two-photon interference.

Due to the lack of active temporal drift monitoring for electronically shifting the correlation window around the 100 ps pulse, we use a 500 ps correlation window to make sure the coincidence counts stay within the same time window. Active monitoring and shifting of a narrower correlation window would significantly increase visibility. In the frequency domain, narrowing our frequency filtering even further to less than 5 GHz could presumably reduce Raman noise by another factor of 20, which would allow for even higher copropagating powers to be used. The powers used in our experiment clearly demonstrate that O-band quantum networks can coexist with the majority of modern classical communications channels in the C-band. Further improvement to the quantum source and the optimization of SNSPDs for the O-band ($>80\%$ efficiency) would significantly increase the detection rates.

In summary, we have demonstrated that O-band/C-band quantum/classical wavelength allocation along with temporal and spectral filtering in coincidence detection are useful noise mitigation methods for coexistence scenarios in fiber-optic quantum networking. High visibility two photon interference fringes are demonstrated over 45.6 km of installed underground fiber with a copropagating 7 dBm classical launch power. An O-band classical alignment signal is built into the entanglement source to align each node in a polarization entanglement network to the same polarization reference frame. The combination of these two methods allows for robust polarization entanglement networks to be integrated into real world installed fiber networks.

5 Conclusions and Future Work

The network architecture described above, where SDN technology is used to decouple the control and data planes and perform network functions, could be easily extended to include pair sources that are able to create entangled pairs over a broad wavelength range. This in turn would allow for simultaneous distribution of entanglement from a single node to multiple users in a network by using wavelength-division multiplexing and by flexible assigning of the available frequency pairs to the different user pairs. Furthermore, to fully take advantage of this capability, solutions to achieving photon-packet interference from sources of different wavelength are needed, e.g. by using tuneable narrow band filters. This gives the network much more flexibility allowing a more efficient and dynamic quantum network.

The next steps on the way to the actual implementation of our quantum network will be distribution of the entangled photon between Fermilab (Q-LAN1) and Argonne National Lab (Q-LAN3) and demonstration of entanglement swapping operation at the Q-LAN1 for two independent entangled photon pair sources that are located at two distant Q-LAN1 labs within Fermilab. To perform this task it is crucial that the photons that are used for the Bell state measurement arrive at the same time. This requires high degree of synchronization between participating locations. To achieve this we will use the recently developed clock distribution system [22] and characterized at the QLAN1. This system allows for synchronization at the few ps second level by sending optical clock signals using the same optical fiber as quantum signal, hence also demonstrating the ability of quantum-classical communication co-existence.

We will also continue to pursue co-existence demonstrators and quantum protocols at the Northwestern University locations (Q-LAN2) using different telecom wave bands for the classical and quantum signals. In the next step for the network deployment we will implement conversion between time-bin and polarization qubits and vice versa, which would allow us to perform teleportation and entanglement swapping between Q-LANs that use different types of entanglement. Further steps include connections to node-based hybrid systems such as superconducting resonators <https://arxiv.org/abs/2204.08605>, mechanical cavities or spins by direct transduction or teleportation [1], growing to a quantum internet.

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