Part II

Teleportation systems toward the quantum internet

Chapter 7

THE QUANTUM INTERNET

This chapter includes the work in preparation for publication:

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The long-term vision of quantum networks is to connect globally-distributed users in a quantum internet [1, 2]. An emerging blueprint for the quantum internet consists of regional quantum networks deployed in optical fiber infrastructure interconnected by free-space and satellite links for long-distance communications [3, 4, 5]. Regional networks, spanning metropolitan and national regions, need to be able to distribute quantum resources, such as qubits and entanglement, on the order of hundreds of kilometers. An architecture for a regional quantum network is shown in Fig. 7.1, consisting of (1) a physical layer comprised of quantum nodes (Q-Nodes) with hardware primitives such as entangled photon pair sources, single photon detectors, and quantum memories (see Fig. 7.2); (2) a control and management layer that oversees routing for user connectivity, channel calibration and synchronization; (3) a service layer that translates user-requested services to physical protocols; and (4) a software layer for user interfacing.

Over the past few decades, there has been substantial progress in developing regional quantum network testbeds [6], although the majority of field trials have focused on prepare-and-measure quantum key distribution (QKD), which typically requires only the transmission and detection of single qubits. The next generation of testbeds demand functionalities such as entanglement distribution, multiphoton interference, and transduction to achieve advanced networking protocols such as measurement-device-independent (MDI) QKD [7], distributed sensing, and ultimately networked quantum computation. Because direct qubit transmission is limited by exponential loss and decoherence, long-haul communications require entanglement-based techniques, such as quantum teleportation [8] and entanglement swapping [9], that transfer quantum information without physically propagating the qubit. These operations form the basis of quantum repeaters [10, 11], which are expected to be crucial

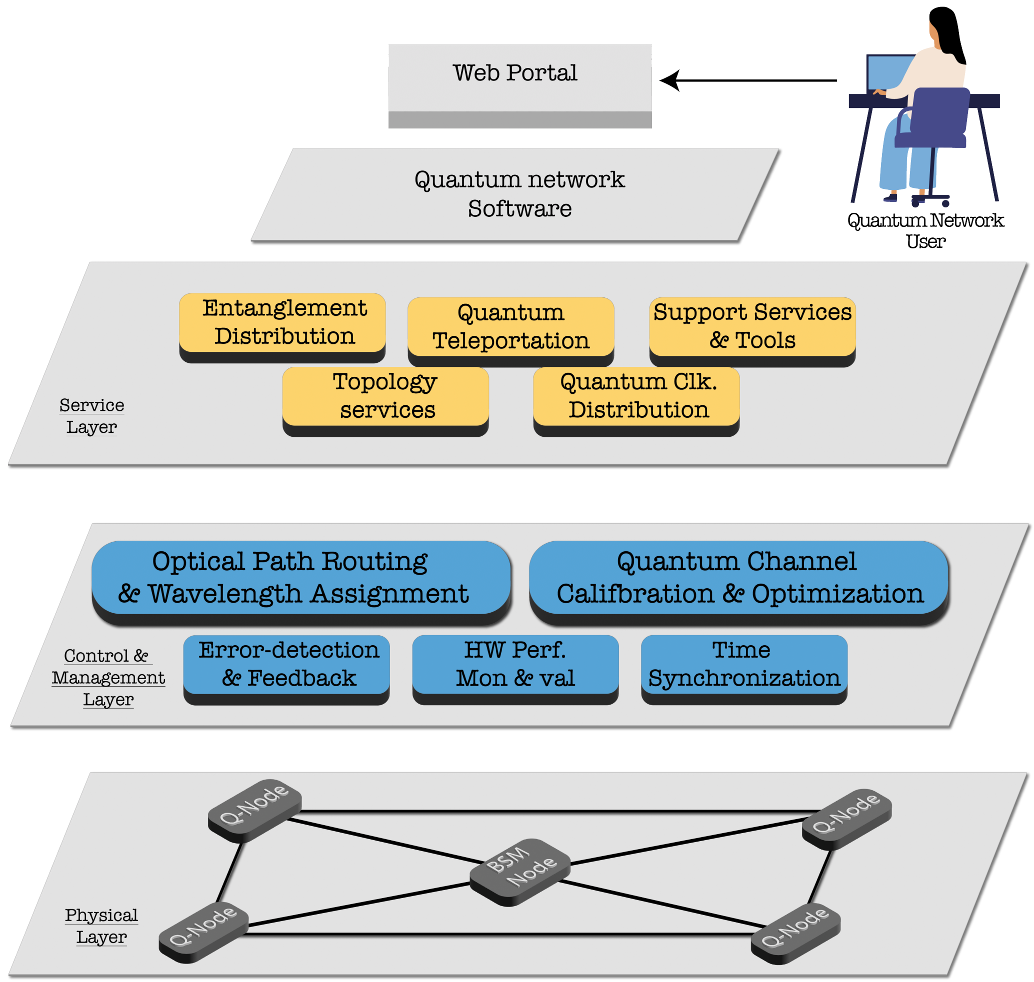

Figure 7.1: Depiction of the regional quantum network architecture. Users interface with the network through a web-based portal linked to quantum software that orchestrates interactions across multiple layers. The service layer translates user-requested services into the necessary protocol-level controls. The control and management layer oversees key operational functions such as optical path routing for user connectivity, quantum channel calibration, clock synchronization, and channel syndrome measurement. The physical layer comprises multiple quantum nodes (Q-Nodes) interconnected through a central node, enabling end-to-end quantum communication.

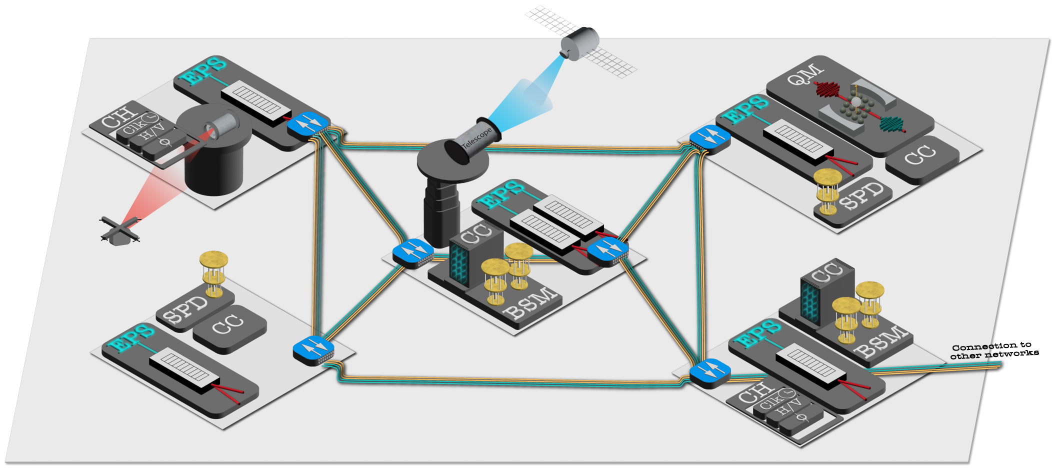

Figure 7.2: Detailed depiction of the physical layer of a regional quantum network. Quantum nodes (Q-Nodes) comprise key components of quantum networks, including the Entangled Photon Source (EPS), Single-Photon Detector (SPD), Channel Stabilizer (CH), Bell-State Measurement (BSM) module, Quantum Memory (QM), and a Classical Computer (CC). These nodes are interconnected via optical fiber and free-space links. Yellow fibers represent dark fibers dedicated solely to quantum communication, while cyan fibers denote optical fibers where quantum and classical communication coexist. Free-space communication links connect Q-Nodes to quantum satellites for long-distance quantum communication and to drones for short-range, line-of-sight quantum communication.

for fault-tolerant long-distance quantum communications in the quantum internet [12].

7.1 Regional quantum networks

Quantum network testbeds have evolved to support a wide array of protocols and applications, transitioning from early demonstrations of QKD to implementations of entanglement-based protocols such as quantum teleportation and entanglement swapping. Deployed in 2004, the DARPA quantum network [13] demonstrated the first 10-node multi-protocol QKD network between Boston and Cambridge, implementing both weak-coherent-state and entanglement-based QKD protocols over fiber and free-space links. In 2008, the SECOQC project [14] in Vienna demonstrated a city-wide QKD network integrating BB84 [15], SARG [16], and continuous variable QKD protocols. SECOQC implemented a modular, multi-layer architecture that separated the quantum, key management, and application layers, enabling compatibility with classical telecommunication infrastructure. The Swiss Quantum Network [17] later validated the long-term stability of QKD, maintaining continuous operation over months and establishing QKD as a reliable protocol for secure communication in operational environments. In 2011, the Tokyo Quantum Network [18] demonstrated a metropolitan QKD network integrating six different systems that supported GHz-clocked links for secure TV conferencing over 45 km and showcased features such as secure mobile phone interfaces, eavesdropper detection, path rerouting, and key relay via trusted nodes.

In the past five years, quantum network testbeds have expanded to larger scales and advanced architectures. In 2020, the Bristol Quantum Network [19] demonstrated an eight-user metropolitan network in a fully-connected mesh topology with reconfigurable wave division multiplexing (WDM) over deployed fiber. In 2021, the Beijing-Shanghai [3] quantum network reported a fiber backbone spanning over 2,000 km with more than 700 QKD links in a trusted relay structure. The network interfaces with two satellites for space-to-ground quantum communication, enabling high-speed QKD with total network connectivity over 4,600 km. In parallel, the emergence of twin-field QKD (TF-QKD) [20] has drawn attention due to its ability to surpass the repeater-less PLOB bound [21] without trusted relays. In 2021, the Jinan-Qingdao QKD Network [22] reported a TF-QKD demonstration over 511 km using a 12-fiber bundle, the sending-or-not-sending protocol, and active odd-parity pairing. Recently, field trials have generated secure keys over 830 km of deployed fiber [23] and 1,002 km of ultra-low-loss fiber spool using a sending-or-not-sending protocol [24], illustrating TF-QKD's potential for ultra-long-distance secure links.

Going beyond QKD, testbeds are increasingly exploring the implementation of quantum teleportation and entanglement distribution. In 2022, the Munich Quantum Network [25] demonstrated heralded entanglement between two Rubidium (Rb) atoms (400 m apart) via a Bell state measurement node with fiber links up to 33 km. The demonstration leveraged quantum frequency conversion (QFC) to convert a photon emitted by a Rb atom at 780 nm to the telecom band (1570 nm). Two years later (2024), the Delft-Hague Quantum Network [26] reported the development of a three-node midpoint network over 25 km of deployed fiber for the demonstration of heralded entanglement of diamond nitrogen vacancy spin qubits using a single-click protocol. In the same year, the Hefei Quantum Entanglement Network [27] reported a four-node star network with Rb atomic ensemble memories and QFC to the telecom O-band (1342 nm) for the demonstration of three-qubit matter-photon entanglement via the DLCZ protocol [28].

Literature	Description	Sources	Detectors
Joshi et al. (2020) [19]	Eight-user metropolitan network with reconfigurable DWDM over deployed fiber (10 m–16.6 km). Fully connected graph topology without trusted nodes. BBM92 protocol with polarization-entangled photon pairs distributed via in-fiber beam splitters and 100 GHz DWDM. Each user has PAM hardware and two detectors.	One MgO:PPLN Type-0 source in Sagnac loop (1550.217 nm), producing 8 frequency-multiplexed polarization-entangled pairs.	SNSPDs, SPADs
Chen et al. (2021) [22]	TF-QKD over 511 km with 12-fiber bundle, using sending-or-not-sending protocol and active odd-parity pairing. Three weak coherent sources in X basis, random Z-basis pulses, decoy-state analysis.	Continuous wave fiber lasers locked to ultra-low-expansion cavity (Alice: 1550.12460 nm).	SNSPDs
van Leent et al. (2022) [25]	Three-node network with midpoint; fiber links up to 33 km. Heralded entanglement between two Rb atoms 400 m apart, with telecom QFC. BSM for entanglement heralding.	Rb atoms emit 780 nm photons, converted to 1517 nm via PPLN QFC. Spin-photon entanglement in Zeeman substates.	SNSPDs
Stolk et al. (2024) [26]	Three-node midpoint network over 25 km deployed fiber. Heralded entanglement of diamond nitrogen vacancy (NV) spin qubits using single-click protocol.	NV center spin qubits; 637 nm photons converted to 1588 nm (L-band) via NORA/PPLN QFC.	SNSPDs
Liu et al. (2024) [27]	Four-node star network with Rb atomic ensemble memories and QFC to 1342 nm (O-band). Links of 9.6–11.5 km to central server. Three-qubit matter-photon entanglement via DLCZ protocol.	Rb atomic ensembles in ring cavities; photons converted via PPLN QFC.	SNSPDs

Table 7.1: Summary of regional quantum network testbeds, highlighting key technologies, protocols, and architectures. BSM: Bell state measurement; DWDM: dense wavelength division multiplexing; NV: nitrogen vacancy; PAM: phase amplitude modulation; PPLN: periodically poled lithium niobate; QFC: quantum frequency conversion; SNSPDs: superconducting nanowire single photon detectors; SPADs: single-photon avalanche detectors; TF-QKD: twin-field QKD.

Table 7.1 summarizes recent developments in regional quantum network testbeds. Open challenges include co-designing a scalable, multipurpose quantum network capable of supporting multipartite entanglement-based protocols, with quantum information sent through fiber or free-space links at varying wavelengths or encodings, while ensuring that entanglement distribution operates seamlessly alongside coexisting classical control channels required for real-world deployment. To this end, I report the development of regional quantum network testbeds at Caltech and Fermi National Accelerator Laboratory (referred to as FNAL or Fermilab). The Caltech Quantum Network (CQNET) is designed to eventually interface with free-space quantum communication links at NASA Jet Propulsion Laboratory (JPL), while the Fermilab Quantum Network (FQNET) is designed to eventually interface with adjacent laboratories and universities as part of the U.S. Department of Energy's roadmap for a quantum internet prototype connecting the seventeen national laboratories [29].

7.2 Caltech and Fermilab quantum network testbeds

Our dual-site approach involves first prototyping networking systems at Caltech in parallel with detector R&D at the NASA-JPL Microdevices Laboratory, leveraging access to state-of-the-art superconducting nanowire single-photon detectors (SNSPDs). These detectors ultimately set the performance limit of quantum communication protocols, and developing systems in close coordination with detector development allows for co-design and optimization. Next, we commission these systems at Fermilab, which offers robust facilities and access to deployed fiber infrastructure interconnecting various on-campus labs, Argonne National Laboratory, and nearby research institutions such as Northwestern University and the University of Illinois, which host advanced quantum technologies including atomic memories and superconducting qubits.

Our testbeds focus on entanglement-based protocols, particularly quantum teleportation and entanglement swapping, with time-bin qubits for robust, long-distance communications over optical fiber (see Figs. 7.3 and 7.4). We first constructed teleportation systems at CQNET and FQNET using optical fiber-coupled devices at telecom-band wavelengths, achieving record teleportation fidelities of $\geq 90\%$ for time-bin qubits transmitted over 44 km of fiber (Chapter 8). To complement these experiments, we developed theoretical models based on a phase-space formalism to account for realistic imperfections, yielding analytical predictions for performance metrics including Hong–Ou–Mandel interference visibility, entanglement visibility, and teleportation fidelity, that guide system design and optimization (Chapter 9).

We then upgraded the FQNET system to support entanglement swapping, demon-

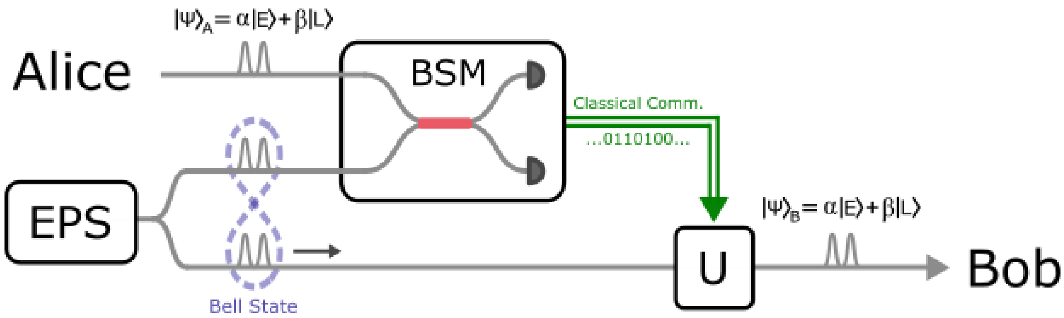

Figure 7.3: Quantum teleportation with time-bin qubits. Alice wants to send a time-bin qubit ($|\psi_A\rangle = \alpha\,|E\rangle + \beta\,|L\rangle$) to Bob. A Bell state measurement (BSM) is performed on her qubit and one member of a Bell pair produced by an entangled photon pair source (EPS). The other member of the Bell pair is sent to Bob. The outcome of the BSM is classically communicated (e.g., in a bit string) to Bob, who applies a unitary transformation (U) to his qubit conditioned on the BSM measurement outcome. As a result, Alice's original qubit is "teleported" to Bob's qubit, ($|\psi_B\rangle = \alpha\,|E\rangle + \beta\,|L\rangle$), without direct physical transmission to Bob.

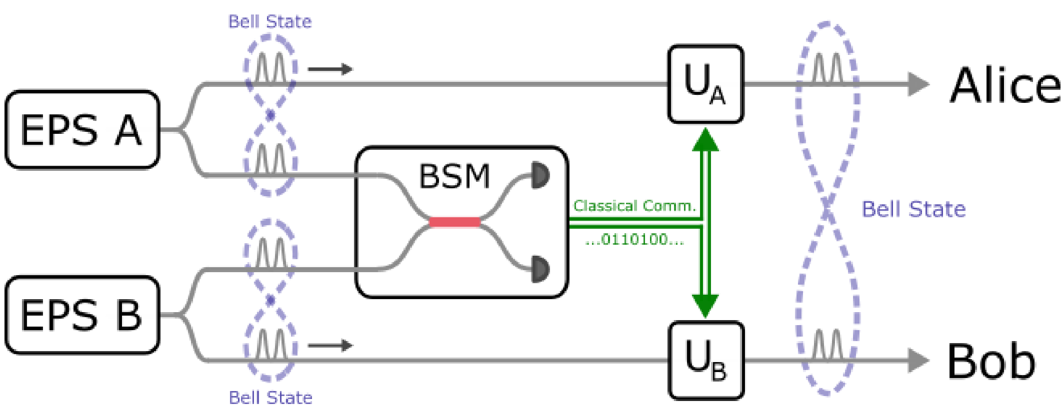

Figure 7.4: Entanglement swapping, i.e., "teleportation of entanglement," with time-bin qubits. Alice and Bob want to share a pair of entangled qubits. Alice and Bob each locally prepare a Bell pair using entangled photon pair source (EPS) A and B, respectively. One member of each pair is sent to a Bell state measurement (BSM) node. The outcome of the BSM is classically communicated to Alice and Bob. Alice and Bob each apply a unitary (U_A and U_B, respectively) to their remaining qubit conditioned on the BSM outcome. As a result, the entanglement is "swapped" between the original Bell pairs, such that the remaining qubits at Alice and Bob are entangled.

strating high-fidelity swapping of time-bin qubits with visibilities up to 92 ± 3.8%, corresponding to a Bell violation exceeding five standard deviations (Chapter 10). To support field deployment and physically separated nodes, precise synchronization of a universal clock reference is required across all network nodes. To this end, we developed a clock synchronization system capable of co-distributing entangled qubits and classical optical clock signals over the same fiber, achieving picosecond-level synchronization using SNSPDs. Following successful demonstrations at Caltech, we deployed the system over a metropolitan-scale fiber network and demonstrated entanglement distribution between nodes at Fermilab and Argonne National Laboratory with 2 ps synchronization precision (Chapter 11). This body of work provides a scalable blueprint for constructing regional quantum networks for the quantum internet.

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