Chapter 1

INTRODUCTION

Over the past several decades, advances in information processing have driven unprecedented developments in science and technology. Information technologies, such as personal computers, mobile phones, and precision sensors, continue to transform the modern world. The recent rise of large-data processing and artificial intelligence is further accelerating global demand for computational power, communication bandwidth, and sensing capabilities. In response, new technological paradigms are being explored to overcome current limitations in information processing capabilities. One of the most exciting directions emerging from this challenge is the development of quantum information technologies, which leverage the consequences of quantum physics to unlock new ways of sensing, processing, and transmitting information.

Quantum technologies are often grouped into three pillars: quantum sensing, quantum computing, and quantum communication. Of the three pillars, quantum sensing is the most mature and widely adopted. Quantum sensors exploit features of quantum mechanical systems such as coherence, entanglement, and quantum interference to surpass precision limits of conventional sensors. Established examples include atomic clocks, which define the international time standard, and superconducting quantum interference devices, used for ultra-sensitive magnetic field detection in both research and medical imaging. More recent developments include squeezed-light interferometry, matter-wave interferometry, quantum gas microscopes, and molecular spin qubits, offering paths toward Heisenberg-limited sensitivity in applications ranging from biological imaging to gravitational wave detection.

Quantum computing represents a new paradigm for computation based on manipulating quantum bits of information. Unlike classical computers, which operate on bits that are either 0 or 1, quantum computers operate on qubits, or states of a two-level quantum system, which can exist in a superposition of both states. This allows quantum algorithms to explore exponentially large solution spaces in ways that are inaccessible to classical computers, promising exponential speedups for specific classes of problems. A notable example is Shor's algorithm, which can factor large numbers exponentially faster than classical algorithms, posing a threat to modern encryption systems. The discovery of Shor's algorithm catalyzed widespread interest in quantum computing and launched a global effort to build quantum processors capable of efficiently performing tasks that could are intractable in classical supercomputers. Recent milestones in quantum hardware have sparked a global race to build large-scale, fault-tolerant quantum computers that have transformative potential for simulating complex quantum systems, solving hard optimization problems, and advancing fields from biochemistry to artifical intelligence.

The threat posed by quantum computers to current cryptographic systems has also driven progress in quantum cryptography. Unlike classical cryptographic schemes, whose security depends on computational hardness assumptions, quantum cryptographic protocols such as quantum key distribution (QKD) offer information-theoretic security guaranteed by the no-cloning theorem and the irreversible nature of quantum measurement. Quantum communication systems enable these protocols by transmitting and interfering quantum states between distant locations, allowing for secure key exchange, teleportation of quantum states, and coordination of spatially separated quantum systems. By interconnecting quantum devices, such as quantum sensors and computers, at remote locations, quantum communication channels form the basis of distributed quantum networks. These quantum networks enable functionalities beyond the reach of any isolated system, including secure multiparty communication, distributed quantum sensing, and teleportation-based quantum state transfer. The long-term vision is the development of a quantum internet: a world-wide network of quantum technologies that are interconnected by quantum communication channels across the globe. Just as the classical internet revolutionized the sharing of digital information, the quantum internet will allow for the distribution of entanglement and quantum states over vast distances and unlock the full potential of quantum technologies.

Alongside the accelerating development of quantum networks, distribution of entanglement has emerged as a key thread connecting information science to the deepest questions in fundamental physics. Quantum networks capable of high-fidelity entanglement distribution have served as a platform for experimental tests of the foundations of quantum mechanics, including Bell tests that probe the validity of locality and realism. These experiments, which culminated in the 2022 Nobel Prize in Physics, confirmed that quantum correlations cannot be explained by any local hidden variable theory. More recently, connections between quantum information and gravity have sparked a new line of inquiry. Quantum teleportation protocols, for instance, have been shown to admit a dual interpretation in gravitational theories as the transmission of information through traversable wormholes. This insight is part of a broader effort to understand the emergence of spacetime from entanglement, exemplified by the ER=EPR conjecture, which posits a deep equivalence between entangled quantum states and gravitational wormholes. Such developments suggest that quantum communication may not only be a technological tool, but also a powerful probe of the causal and geometric structure of spacetime itself.

In this thesis, I present some of the latest advances in quantum communication devices, channels, and networks, both at a technological and fundamental level. The thesis is divided into three parts. Part I focuses on quantum sources and detectors, which form the foundational building blocks of quantum networks. I begin by introducing the principles behind photon-pair sources and single-photon detectors (Chapter 2) and highlight key challenges in the current state-of-the-art. I then present progress in cutting-edge sources and detectors: photon-number-resolving superconducting nanowire detectors and their first application to improving heralded single-photon sources (Chapter 3) and high-rate photon-number discrimination (Chapter 4); a high-rate entangled photon-pair source for quantum key distribution (Chapter 5); and high-bandwidth on-chip balanced homodyne detectors (BHDs), enabling continuous-variable quantum key distribution and squeezed-light detection (Chapters 2 and 6). I also introduce the concept of a novel quantum sensor, which we call the "quantum phased array" (QPA), and present a proof-of-concept demonstration of a QPA receiver implemented in a large-scale silicon photonic-electronic platform (Chapter 6). This system integrates a directional free-space-to-chip interface for quantum light and features the first on-chip detection of squeezed light using a quantum-limited BHD array. Using this architecture, we demonstrate coherent multipixel imaging and beamforming of squeezed light, illustrating key functionalities envisioned for future wireless quantum sensors and communication systems.

Part II of this thesis describes the development of quantum network testbeds at Caltech and Fermi National Accelerator Laboratory, with a focus on designing scalable architectures for quantum networks toward the quantum internet (Chapter 7). A defining feature of quantum networks is the ability to distribute entanglement between remote nodes, which is essential for numerous quantum communication protocols including teleportation, entanglement swapping, and quantum repeaters.

We construct systems capable of high-fidelity quantum teleportation (Chapter 8) and entanglement swapping (Chapter 10) over long distances. We achieve state-of-the-art teleportation fidelities over 45 km of optical fiber and entanglement swapping visibilities with time-bin qubits. To support the development of these systems, I describe theoretical models for the experiments (Chapter 9) that guide system design and optimization. Finally, I detail our efforts to extend these capabilities to real-world metropolitan environments, and present experimental demonstrations of entanglement distribution to remote nodes at FNAL and Argonne National Laboratory with picosecond-level clock synchronization (Chapter 11). These systems are envisioned to form the backbone of a prototype quantum internet connecting the seventeen national labs of the United States.

Part III of this thesis explores the intersection of quantum communication and fundamental physics (Chapter 12). I begin by describing the experimental generation of multipartite entanglement, specifically GHZ states, in our quantum network testbeds (Chapter 13). GHZ states serve as valuable resources for foundational tests of quantum mechanics, including more stringent Bell inequalities and nonlocality tests, as well as for distributed quantum sensing protocols. Our demonstration is a first step towards establishing a field-deployed quantum sensing network at Fermilab designed to perform precision measurements for high energy physics. I then present the first experimental realization of a traversable wormhole teleportation protocol implemented on quantum computer (Chapter 14). We observe characteristic features of traversable wormhole dynamics, such as time-ordered signal propagation, the preservation of input information, and sensitivity to coupling strength, consistent with expectations from semiclassical gravity.

Finally, I conclude with an outlook on future directions and opportunities for the devices, networks, and experiments presented in this thesis (Chapter 15). I propose a new line of inquiry at the intersection of all these research domains: Bell inequalities for quantum gravity. Specifically, I formulate a concrete Bell inequality tailored for holographic systems with a wormhole dual.