

From Quantum Communication to the Quantum Internet: A Comprehensive Survey

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Abstract

The transition from quantum communication to the quantum internet represents one of the most significant developments in modern information and communication technologies. By exploiting the principles of quantum mechanics, including superposition, entanglement, and quantum measurement, quantum networks offer capabilities that extend beyond those of conventional communication systems. These capabilities include fundamentally secure information exchange, distributed quantum computing, high-precision sensing, and reliable transmission of quantum information across geographically separated nodes. As research progresses from theoretical concepts to practical implementations, understanding the technologies, challenges, and future directions of the quantum internet has become increasingly important.

This review presents a comprehensive overview of the evolution from quantum communication to the quantum internet, emphasizing its underlying architectures, enabling technologies, experimental progress, open challenges, and emerging applications. It begins by discussing the fundamental principles of quantum communication and the role of quantum bits, entanglement distribution, quantum teleportation, and quantum key distribution in establishing secure and efficient communication networks. The review then examines the major technological building blocks, including quantum repeaters, quantum memories, photonic communication systems, satellite-based quantum links, and network protocols that support scalable quantum networking.

Recent experimental demonstrations and prototype quantum networks developed by leading research institutions are analysed to highlight the current state of the field and the progress toward large-scale deployment. The paper also discusses key technical challenges such as decoherence, transmission losses, error correction, synchronization, interoperability, and scalability, which remain significant obstacles to realizing a global quantum internet. Finally, emerging applications in secure communications, distributed quantum computing, cloud-based quantum services, precision sensing, and future smart infrastructure are explored. By bringing together recent advances and ongoing research efforts, this review provides researchers, engineers, and students with a clear understanding of the current landscape and future prospects of quantum internet technologies while identifying important research directions for the next generation of quantum communication systems.

Keywords: Quantum Communication, Quantum Internet, Quantum Networks, Quantum Key Distribution, Quantum Teleportation, Quantum Repeaters.

I. Introduction

The rapid growth of digital communication has transformed the way information is exchanged across the world. However, the increasing dependence on conventional communication networks has also raised serious concerns regarding data security, privacy, scalability, and computational efficiency. Classical cryptographic techniques, although widely used, are becoming increasingly vulnerable with the emergence of quantum computers capable of solving complex mathematical problems that underpin current encryption methods. These challenges have motivated researchers to explore communication technologies that provide fundamentally secure and future-proof solutions.

Quantum communication has emerged as a promising approach by exploiting the unique properties of quantum mechanics, such as superposition, entanglement, and the no-cloning principle. Unlike classical communication systems, quantum communication enables information to be transmitted with security guaranteed by the laws of physics rather than computational complexity. Technologies such as quantum key distribution and quantum teleportation have demonstrated the potential to establish secure communication channels and enable reliable transmission of quantum information over long distances.

As research advances, the vision of a quantum internet has gained significant attention. A quantum internet aims to interconnect quantum devices through large-scale quantum networks capable of distributing entanglement and supporting applications that cannot be achieved using classical networks alone. Such an infrastructure is expected to play a vital role in secure global communication, distributed quantum computing, networked quantum sensing, and future intelligent communication systems. Recent progress in quantum repeaters, quantum memories, integrated photonics, satellite-based communication, and quantum networking protocols has accelerated the transition from laboratory demonstrations to practical implementations.

Despite these advancements, several scientific and engineering challenges remain, including decoherence, transmission losses, quantum error correction, network synchronization, interoperability among heterogeneous quantum devices, and scalability to global networks. Addressing these challenges requires continued collaboration across physics, computer science, electronics, and communication engineering.

This review presents a comprehensive study of the evolution from quantum communication to the quantum internet by examining its architectures, enabling technologies, experimental progress, major challenges, and emerging applications. It also highlights current research trends and identifies future directions that will contribute to the realization of secure, scalable, and efficient quantum communication networks.

II. Evolution from Quantum Communication to the Quantum Internet

The development of quantum communication has marked a major shift in the way information can be transmitted and protected. Conventional communication technologies have evolved continuously over several decades, providing faster data transmission, greater connectivity, and improved network performance. However, the increasing demand for secure communication and the emergence of quantum computing have exposed the limitations of classical communication systems. These challenges have motivated the scientific community to explore communication methods based on the principles of quantum mechanics. As a result, quantum communication has progressed from a theoretical concept to an active area of research, ultimately leading to the vision of a global quantum internet.

2.1 Historical Timeline

Quantum communication emerged in the early 1980s when researchers explored the use of quantum mechanics to achieve secure information exchange. A major breakthrough came in 1984 with the introduction of the BB84 Quantum Key Distribution (QKD) protocol by Bennett and Brassard, demonstrating that cryptographic keys could be shared with security guaranteed by the laws of quantum physics. During the 1990s, advances in quantum entanglement and quantum teleportation established the theoretical and experimental foundations of quantum information transfer. In the 2000s, research focused on extending communication distances through optical fibers, free-space optical links, quantum repeaters, and quantum memories. A significant milestone was reached in 2016 with the launch of the Micius quantum satellite, enabling satellite-based QKD and long-distance quantum teleportation. Today, the development of metropolitan quantum networks and quantum internet testbeds is accelerating the transition toward global-scale quantum networking.

2.2 Major Milestones and Development Phases

The evolution of quantum communication can be divided into four phases. The first phase established the theoretical foundations of quantum cryptography and quantum information. The second phase validated these concepts through experimental demonstrations of quantum teleportation, entanglement distribution, and QKD. The third phase focused on practical implementation by developing quantum repeaters, quantum memories, integrated photonic devices, and long-distance communication systems. The current phase aims to build scalable quantum networks through advanced network architectures, communication protocols, and integration with existing communication infrastructure, ultimately leading to the realization of the quantum internet.

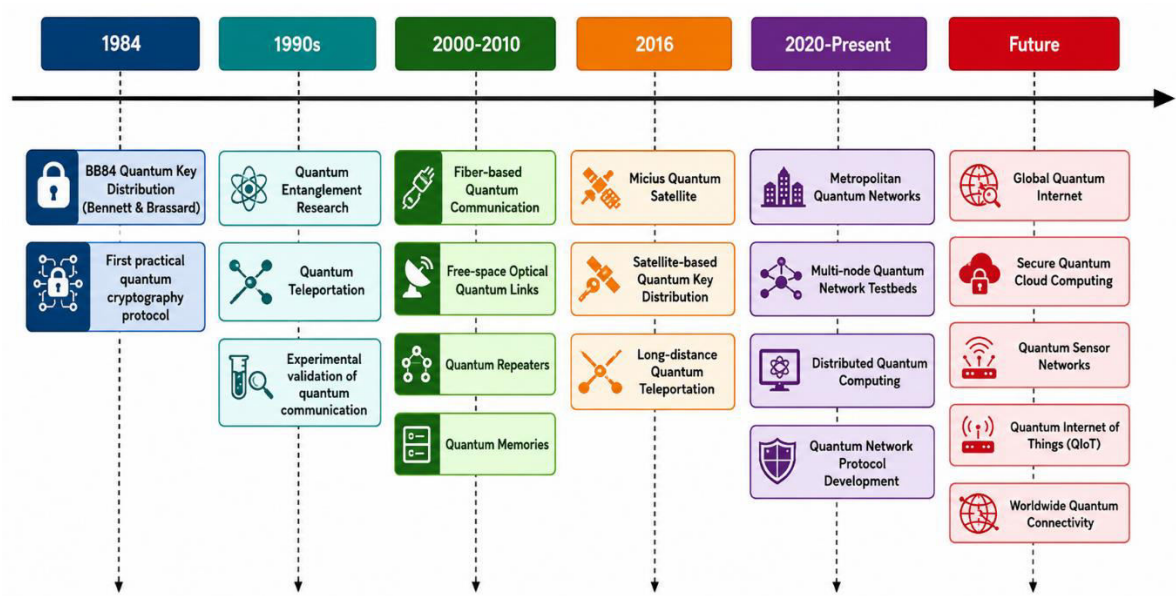


Figure: Evolution from Quantum Communication to the Quantum Internet

2.3 Vision of the Quantum Internet

The quantum internet represents the next generation of communication networks, enabling the transmission of quantum information and entanglement between geographically distributed quantum devices. Beyond secure communication, it will support distributed quantum computing, quantum cloud services, networked quantum sensing, and precision timing applications. Rather than replacing the classical internet, the quantum internet is expected to complement existing communication systems by providing capabilities that are impossible with classical technologies.

2.4 Comparison with the Classical Internet

While both the classical and quantum internet aim to connect users and exchange information, they differ fundamentally in their operating principles. Classical networks transmit information using binary bits and rely on computationally secure encryption algorithms. In contrast, the quantum internet uses qubits that exploit superposition and entanglement, with security ensured by the laws of quantum mechanics. Unlike classical information, quantum information cannot be copied due to the no-cloning theorem. Consequently, the quantum internet offers unique capabilities such as provably secure communication, distributed quantum computing, quantum cloud services, and advanced quantum sensing, making it a transformative technology for future communication systems.

III. Quantum Internet Architecture

The quantum internet is envisioned as a next-generation communication infrastructure that enables the transmission of quantum information between geographically distributed quantum devices. Unlike the classical internet, which transfers digital bits through electrical or optical signals, the quantum internet relies on quantum bits (qubits) and quantum entanglement to exchange information securely and efficiently. Its architecture integrates specialized network layers and quantum hardware components that work together to establish, distribute, and manage quantum states across the network. A well-defined architecture is essential for ensuring reliable communication, scalability, interoperability, and fault tolerance in future quantum networks.

Network Layers

The quantum internet adopts a layered architecture similar in concept to the classical networking model, but each layer performs operations specifically designed for quantum information.

Physical Layer

The physical layer forms the foundation of the quantum internet. It is responsible for generating, transmitting, detecting, and storing qubits using physical media such as optical fibers, free-space optical links, and satellite communication channels. Quantum devices including single-photon sources, photon detectors, quantum memories, and entangled photon generators operate at this layer. The physical layer must minimize decoherence and transmission losses to preserve quantum states during communication.

Link Layer

The link layer establishes reliable quantum connections between directly connected quantum nodes. It performs entanglement generation, purification, synchronization, and error detection to improve the quality of shared quantum states. Since quantum information cannot be copied because of the no-cloning theorem, this layer focuses on maintaining high-fidelity entanglement rather than retransmitting lost data.

Network Layer

The network layer manages end-to-end communication across multiple quantum nodes. Its primary functions include routing entangled states, selecting optimal communication paths, resource allocation, and managing quantum repeaters. Efficient routing algorithms are required because quantum resources are limited and highly sensitive to environmental disturbances.

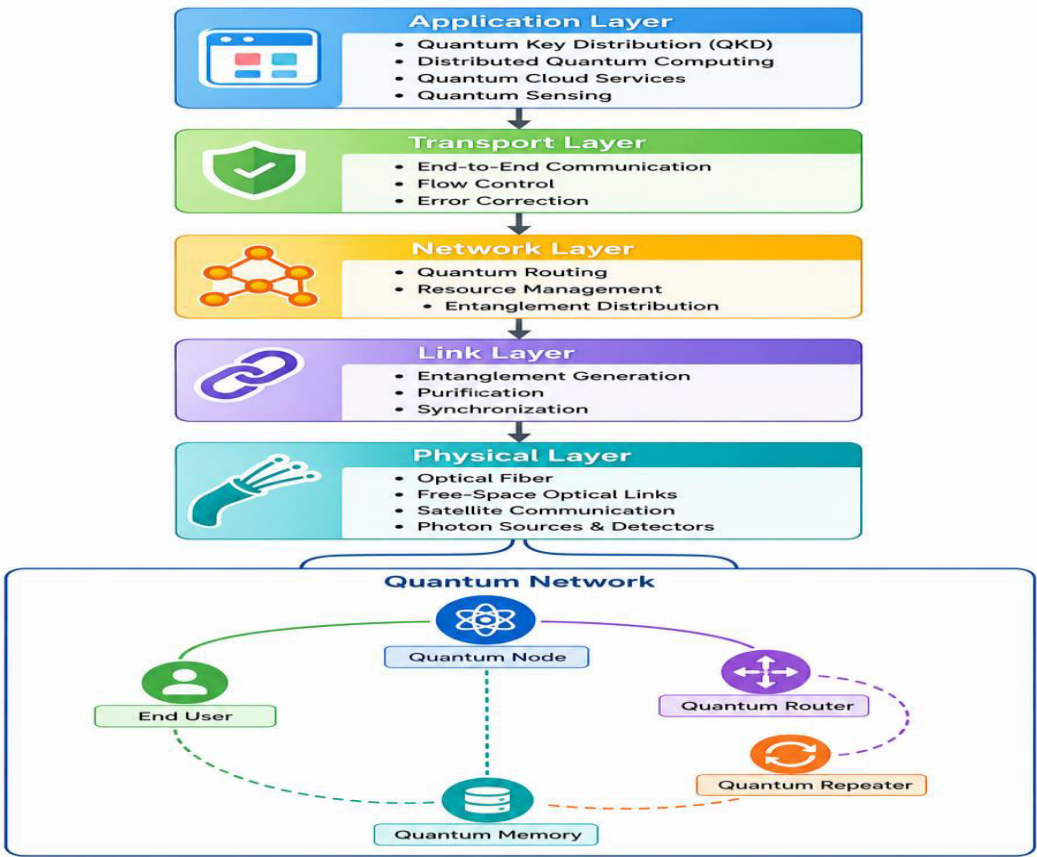


Figure: Architecture of Quantum Internet

Transport Layer

The transport layer ensures reliable delivery of quantum information between distant users. It coordinates end-to-end entanglement establishment, maintains communication sessions, controls data flow, and supports quantum error correction mechanisms. This layer also works closely with classical communication channels that exchange control information required for quantum operations such as teleportation and entanglement swapping.

Application Layer

The application layer provides services that directly support end users and quantum-enabled applications. These include quantum key distribution (QKD), distributed quantum computing, secure cloud quantum computing, quantum sensing, quantum voting, quantum financial transactions, and quantum-enhanced scientific collaboration. This layer acts as the interface between users and the underlying quantum network infrastructure.

Network Components

The successful operation of the quantum internet depends on several specialized hardware components that perform distinct networking functions.

Quantum Nodes

Quantum nodes are the fundamental processing units of the network. They generate, process, store, and measure quantum information while communicating with other nodes through quantum channels. These nodes may consist of quantum computers, quantum processors, sensors, or communication terminals.

Quantum Routers

Quantum routers determine the most efficient path for distributing entangled qubits across the network. Unlike classical routers that forward packets, quantum routers coordinate entanglement distribution and manage quantum resources without directly copying quantum information.

Quantum Repeaters

Quantum repeaters extend the communication distance by overcoming photon loss and decoherence. They divide long communication links into shorter segments, perform entanglement swapping and purification, and significantly improve the reliability of long-distance quantum communication.

Quantum Memories

Quantum memories temporarily store fragile quantum states until communication or computation can continue. High-efficiency quantum memories are essential for synchronization, buffering, and large-scale quantum networking because they allow entangled states to be preserved with minimal loss.

End Users

End users represent individuals, organizations, research laboratories, industries, government agencies, and cloud service providers that access quantum internet services. Through quantum-enabled applications, users can perform secure communication, distributed quantum computation, confidential financial transactions, and high-precision sensing while benefiting from the unique capabilities of quantum mechanics.

III. Enabling Technologies

The realization of the quantum internet depends on a collection of advanced technologies that enable the generation, transmission, storage, and processing of quantum information. These technologies work together to establish secure, scalable, and reliable quantum communication networks capable of supporting future applications beyond the capabilities of classical communication systems.

Quantum Key Distribution (QKD) is the cornerstone of secure quantum communication. It enables two parties to generate a shared secret encryption key while ensuring that any eavesdropping attempt can be detected through the principles of quantum mechanics. The BB84 protocol, introduced by Bennett and Brassard in 1984, is the first and most widely adopted QKD protocol, using non-orthogonal photon polarization states for secure key exchange. The E91 protocol, proposed by Ekert in 1991, employs quantum entanglement to establish cryptographic keys and provides additional security through Bell inequality verification. To overcome vulnerabilities caused by multi-photon emissions, the Decoy State QKD protocol introduces randomly varying photon intensities, significantly improving security over long distances. Continuous Variable QKD (CV-QKD) uses the amplitude and phase of coherent light instead of single photons, allowing compatibility with existing optical communication infrastructure and offering practical advantages for metropolitan quantum networks.

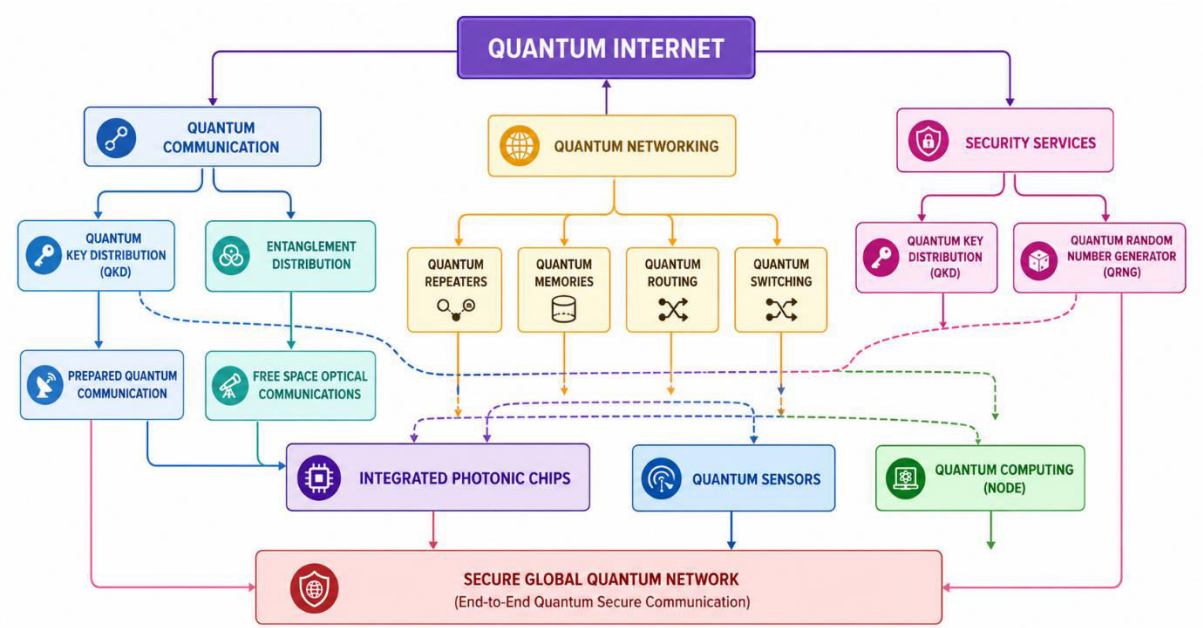


Figure: Architecture of Enabling Technologies for the Quantum Internet

Another fundamental technology is quantum teleportation, which enables the transfer of an unknown quantum state between distant nodes without physically transmitting the quantum particle itself. This process relies on previously shared entanglement and classical communication and forms the basis for distributed quantum computing and long-distance quantum networking.

Entanglement distribution is equally essential, as it establishes correlated quantum states between remote nodes. Reliable distribution of high-quality entanglement enables secure communication, quantum sensing, and teleportation across large-scale quantum networks.

Since quantum signals cannot be amplified using conventional repeaters, quantum repeaters are employed to extend communication distances. These devices combine entanglement swapping, purification, and quantum memory techniques to overcome photon losses and maintain quantum coherence over hundreds or even thousands of kilometers.

Quantum memories provide temporary storage of quantum states while preserving coherence. They synchronize quantum operations between distant network nodes and are indispensable for entanglement distribution, quantum repeaters, and network scalability.

Recent advances in integrated photonics have significantly accelerated the development of compact quantum communication devices. Photonic integrated circuits combine photon generation, manipulation, and detection on a single chip, reducing system complexity while improving stability and scalability.

To achieve global quantum connectivity, satellite quantum communication has emerged as a promising solution. By transmitting entangled photons and quantum keys between satellites and ground stations, satellite-based systems overcome the distance limitations of terrestrial fiber networks and enable secure intercontinental communication.

For short- and medium-range communication, free-space optical (FSO) quantum communication provides flexible links through the atmosphere without requiring physical fiber infrastructure. Although atmospheric turbulence introduces challenges, FSO systems are particularly suitable for ground-to-satellite and airborne quantum communication.

In metropolitan and backbone networks, fiber-based quantum communication remains the most mature transmission technology. Optical fibers provide low-loss transmission over moderate distances and integrate well with existing telecommunication infrastructure, making them ideal for early quantum internet deployments.

Another critical component is the Quantum Random Number Generator (QRNG), which exploits inherently unpredictable quantum phenomena to generate truly random numbers. Unlike algorithm-based classical random number generators, QRNGs provide genuine randomness, strengthening cryptographic protocols and enhancing the overall security of quantum communication systems.

Together, these enabling technologies form the technological foundation of the quantum internet. Continued advances in hardware integration, error correction, and network protocols will further improve their performance and accelerate the realization of secure, scalable, and globally interconnected quantum communication networks.

IV. Quantum Networking Protocols

Quantum networking protocols provide the foundation for reliable communication between quantum devices by enabling the efficient transmission, processing, and management of quantum information across distributed networks. Unlike classical protocols, they must preserve fragile quantum states while minimizing the effects of noise and decoherence.

Entanglement routing is a key protocol that establishes and maintains entangled links between distant quantum nodes, allowing secure communication and distributed quantum operations. Quantum routing extends this concept by selecting optimal paths for transmitting

quantum information while considering the availability of entangled resources, channel quality, and network conditions. Since quantum information cannot be copied due to the no-cloning theorem, routing decisions require specialized mechanisms that differ significantly from classical networking.

Quantum error correction plays a vital role in protecting quantum information from errors caused by environmental interactions and imperfect hardware. Various error-correcting codes help maintain data integrity without directly measuring the quantum state. Quantum network coding further improves communication efficiency by optimizing the use of network resources and reducing the number of transmissions required for quantum information exchange.

Efficient resource allocation is essential for managing limited quantum resources such as qubits, quantum memories, and entangled pairs. In addition, accurate synchronization among distributed quantum nodes ensures coordinated operations, particularly during entanglement generation and quantum teleportation. To support interoperability and scalability, researchers are also developing quantum internet protocols that define standardized procedures for communication, resource management, routing, and control, forming the basis for future large-scale quantum networks.

V. Experimental Progress

Significant progress in quantum networking has been achieved over the past decade through large-scale experimental demonstrations across several countries. China has emerged as a global leader by integrating terrestrial fiber-optic quantum networks with satellite-based communication through the *Micius* satellite, enabling quantum key distribution and long-distance quantum teleportation over thousands of kilometers. In the United States, research institutions and technology companies are developing scalable quantum network testbeds, focusing on quantum repeaters, distributed quantum computing, and quantum data center connectivity.

European countries have established collaborative initiatives such as the Quantum Internet Alliance, where researchers are building metropolitan quantum networks and developing standardized networking protocols. Japan has concentrated on high-speed quantum communication using photonic technologies and ultra-low-loss optical fibers, while Canada has made notable contributions in quantum cryptography, quantum memories, and secure communication infrastructure. The Netherlands has become a pioneer in realizing the first prototype quantum internet, successfully demonstrating entanglement distribution between multiple quantum processors through its Quantum Network Explorer project.

Recent experimental efforts have demonstrated reliable fiber-based quantum communication over metropolitan distances and satellite-assisted quantum links spanning several thousand kilometers. Long-distance quantum teleportation experiments have validated the feasibility of transmitting quantum states without physically transferring quantum particles, representing a critical milestone toward global quantum networking. Metropolitan quantum networks deployed in several countries have further demonstrated secure communication among multiple users in urban environments. In parallel, researchers are exploring quantum data centers capable of interconnecting quantum processors through entanglement-based communication, laying the foundation for distributed quantum computing and cloud-based quantum services. Although these achievements confirm the practical potential of the

quantum internet, challenges related to scalability, quantum repeaters, synchronization, and error correction must still be addressed before worldwide deployment becomes a reality.

Table 3. Comparison of Recent Experimental Progress in Quantum Networking

Country/Region	Major Experimental Achievement	Network Type	Key Contribution
China	Micius satellite, long-distance QKD, quantum teleportation	Fiber + Satellite	Global-scale secure quantum communication
USA	Quantum network testbeds, distributed quantum computing	Fiber Networks	Quantum repeaters and quantum data center research
Europe	Quantum Internet Alliance, metropolitan quantum networks	Fiber Networks	Multi-node quantum networking and protocol development
Japan	High-speed photonic quantum communication	Optical Fiber	Low-loss transmission and photonic integration
Canada	Quantum cryptography and quantum memory experiments	Fiber Networks	Secure communication and quantum memory technologies
Netherlands	Prototype quantum internet and entanglement distribution	Metropolitan Quantum Network	First multi-node quantum internet demonstrations

VI. Conclusion

Quantum communication has progressed from a theoretical concept to a rapidly advancing field that is paving the way for the realization of the quantum internet. This review examined the fundamental principles, network architectures, enabling technologies, experimental achievements, key challenges, and emerging applications that define this transition. Although significant progress has been made, challenges related to scalability, quantum repeaters, error correction, interoperability, and reliable long-distance communication remain open research problems. Continued collaboration among researchers, industry, and policymakers will be essential to address these issues. With ongoing technological innovations and global research efforts, the quantum internet is expected to become a transformative communication infrastructure, enabling secure information exchange, distributed quantum computing, and a new generation of intelligent networked applications.

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