Architecting the Quantum Future: Key Devices and Layers in Quantum Network Design

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***Abstract*—The emergence of quantum networks promises revolutionary advancements in secure communication, computational power, and information processing. This paper provides insights into the essential components and architecture of quantum networks. We systematically examine each layer of the quantum protocol stack, from the physical layer responsible for qubit transmission and entanglement generation to the transport layer ensuring reliable qubit communication, up to the application layer enabling quantum key distribution and quantum computing applications. In this work, we introduce the E-QNet framework, an entanglement-assisted quantum network protocol stack designed to facilitate quantum communication. Key devices such as quantum transceivers, entanglement sources, quantum memories, quantum repeaters, and quantum routers are analyzed in the context of their specific roles and functionalities. We draw parallels with classical network architecture, highlighting both the unique challenges and novel solutions inherent in quantum networking. By elucidating the interplay between hardware devices and protocol layers, this article provides a comprehensive overview of the current state and future directions in quantum network design, offering valuable insights for researchers and engineers in the field. This work aims to contribute to the foundational understanding required for the development and implementation of robust quantum networks.**

***Index Terms*—Quantum Network, Quantum Internet Protocol Stack, Quantum Devices, Layered Network Design, Entanglement-based Quantum Network (E-QNet).**

I. Introduction

As the world stands on the brink of the quantum era, the importance of abstract models in defining network functionalities cannot be overstated. In classical networking, the Open Systems Interconnection (OSI) and Transmission Control Protocol/Internet Protocol (TCP/IP) stacks have provided foundational frameworks for organizing protocols and devices across various layers, ensuring efficient communication, error handling, and data management [1]. These models enable the systematic development of network infrastructure, allowing classical bits—units of information that can be either 0 or 1—to be transmitted reliably [2]. However, the advent of quantum networks introduces new paradigms, necessitating a reimagined protocol stack that accommodates the unique properties of quantum information, such as qubits, superposition, and entanglement [3], [4].

Classical bits, the fundamental units of classical information, exist in a definite state of either 0 or 1. In contrast, qubits, the basic units of quantum information, can exist simultaneously in a superposition of states, embodying both 0 and 1 to varying degrees, as shown in Fig. 1. This property allows quantum systems to perform multiple computations in parallel, a capability unattainable with classical bits [5]. Additionally, qubits can become entangled—a phenomenon where the state of one qubit is intrinsically linked to the state of another, regardless of the distance separating them [6]. This entanglement enables instantaneous state correlation, a key feature for secure communication protocols such as Quantum Key Distribution (QKD) [7], [8].

Superposition and entanglement are cornerstone features that distinguish quantum computing and communication from their classical counterparts. Superposition allows quantum algorithms to explore multiple solutions simultaneously, significantly accelerating problem-solving capabilities. For instance, Shor's algorithm leverages superposition to factorize large integers exponentially faster than the best-known classical algorithms, posing a potential threat to classical encryption methods [9], [10]. Similarly, Grover's algorithm uses superposition to search unsorted databases quadratically faster than classical algorithms [11]. Entanglement, on the other hand, enables quantum teleportation and secure communication [3]. In QKD, for example, entangled qubits generate a shared secret key between two parties, ensuring that any eavesdropping attempt disturbs the system and can be detected [6]. This makes QKD an invaluable tool for future secure communications, promising an unprecedented level of security [12]. Thus, superposition enables efficient information processing, while entanglement ensures the security and integrity of transmitted data [13]. These properties allow quantum computers to perform specific tasks or calculations faster and more effectively than classical computers, a phenomenon known as *quantum supremacy* [2], [3].

Quantum computing harnesses the power of superposition,

This work was supported in part by the Quantum Engineering Program, Singapore under grant NRF2021-QEP2-01-P04.

entanglement, and interference to tackle problems far more swiftly than classical computing, thanks to groundbreaking algorithms developed by researchers like Shor and Grover [10], [11]. Leading tech companies, including Google, Toshiba, Rigetti, IDQ, IBM, and Xanadu, have showcased quantum computational advantages. Notably, Toshiba researchers successfully transmitted quantum information using QKD over an impressive 600-kilometer optical fiber network [14]. ID Quantique made strides with a quantum random number generation (QRNG) chip [15], and in 2016, China made history by launching the world's first quantum communication satellite, "Micius" [16]. This satellite established a secure, unhackable communication channel between Beijing and Vienna using QKD. Additionally, Quantum Xchange plans to deploy approximately 500 miles of fiber optic cable to create "Phio," the first commercial QKD network in the U.S [17]. China Telecom has also explored quantum-encrypted VoIP calls using specialized SIM cards [16]. In 2020, Samsung and SK Telecom introduced the Samsung Galaxy A Quantum, the first 5G smartphone featuring quantum encryption, marking a significant milestone in consumer quantum technology [18].

Hence, it is crucial to establish an abstract model for quantum networks to comprehend the framework of protocols and device functionality at each level. To summarize, the key contributions of this paper include:

i. *Detailed Quantum Network Architecture:* A comprehensive exploration of the quantum protocol stack, detailing the functions and devices at each layer, such as quantum transceivers, repeaters, routers, and memories.
ii. *Comparison with Classical Models:* A comparison of each layer of the TCP/IP model with the proposed quantum protocol stacks, which are based on bipartite and multipartite entanglement. It highlights the distinct features and necessary adaptations for quantum networks.
iii. *Introduction of E-QNet:* A proposed entanglement-assisted prototype designed to facilitate quantum communication through a layered quantum network framework.
iv. *Identification of Key Quantum Devices:* Explanation of the roles, functionalities, and challenges associated with crucial quantum devices within the network.

This paper is organized as follows: Section II compares the standard classical TCP/IP stack with the quantum protocol stack by analyzing each layer. Section III provides a detailed overview and breakdown of our proposed quantum network model, along with the roles and functionality of each device and element within the quantum network architecture. Finally, Section IV concludes the paper.

II. Key Quantum Protocol Stack Models

The concept of *quantum supremacy* refers to the capacity of quantum computers to solve problems that are beyond the reach of classical computers. Achieving quantum supremacy necessitates a sophisticated quantum network architecture that enables high-fidelity qubit transmission, reliable entanglement distribution, and the execution of complex quantum algorithms [19], [20]. To support these functionalities, multiple quantum protocol stack models have been developed, analogous to the classical OSI (conceptual model) and TCP/IP (practical implementation) models. A major distinction between the quantum Internet protocol stack and the TCP/IP model is the focus of the lower layers. In the quantum Internet, the layers below the transport layer are dedicated to establishing end-to-end entangled states in preparation for data transmission, which is ultimately accomplished via quantum teleportation. In contrast, classical Internet protocols manage data transmission as early as the link layer. Though a unified quantum Internet protocol stack has yet to be fully established, several independent models have been proposed. Noteworthy among these are the models proposed by Van Meter *et al.* [21], Wehner *et al.* [22], [23], Lie *et al.* [24], and Dür *et al.* [25], each offering a distinct approach to organizing quantum communication and computation layers, as summarized in Fig. 2.

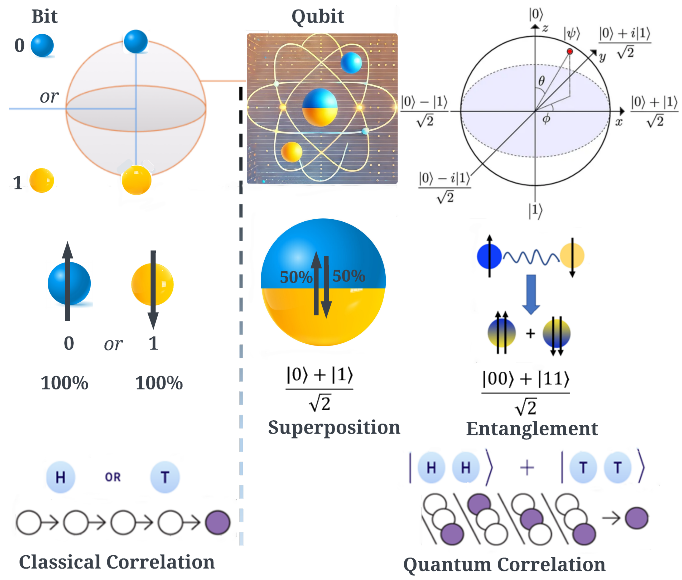

Fig. 1: A diagrammatic portrayal comparing the design of a classical bit and a quantum bit (qubit).

1) **Van Meter *et al.***: In 2009, Van Meter *et al.* introduced a quantum Internet protocol stack model specifically tailored for quantum repeater networks. This model is characterized by its comprehensive layering structure, designed to handle the intricacies of first-generation quantum repeater schemes utilizing bipartite entanglement [26]. Key components include heralded entanglement generation (HEG) and heralded entanglement purification (HEP), both essential for mitigating loss errors and ensuring the integrity of quantum communication [27]. The model places significant emphasis on the physical and link layers, similar to the data link and physical layers in classical networks, focusing on establishing reliable quantum links and implementing robust error correction mechanisms.

The model is structured into distinct layers, each with specialized functions. At the lowest layer, physical entanglement (PE) layer, operations such as photon emission

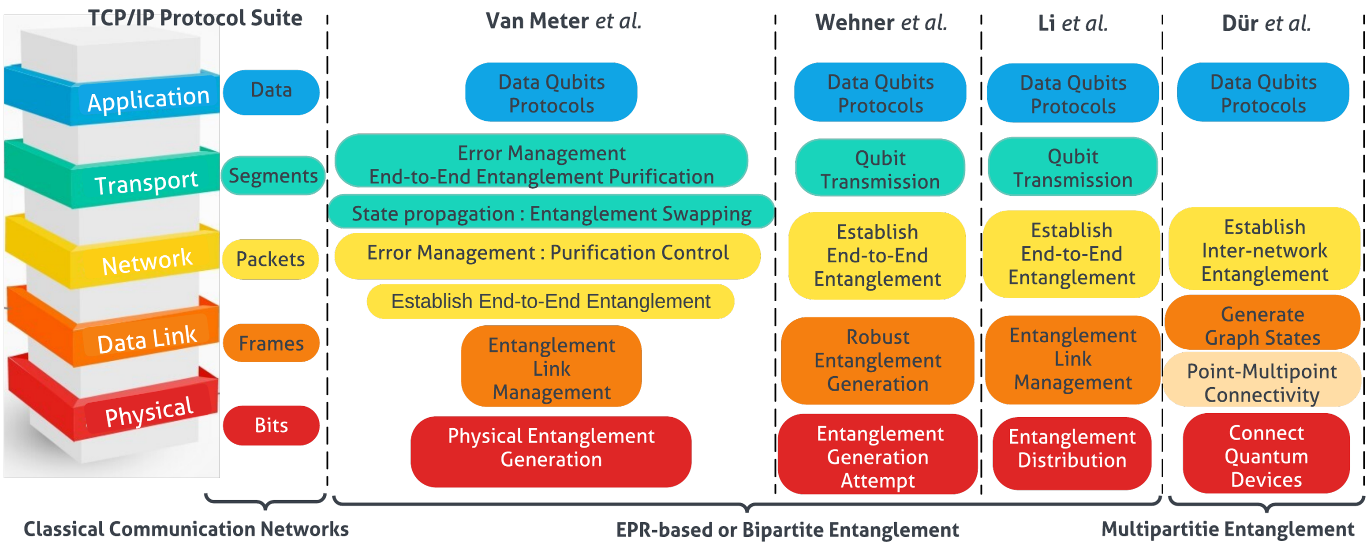

Fig. 2: A comparative illustration of the classical network model alongside various quantum protocol stacks developed for entanglement-assisted quantum networks. All four quantum models recognize entanglement as a fundamental resource within these networks.

and transmission, qubit encoding, and Bell-State Measurements (BSM) are critical for HEG between adjacent nodes. Entanglement in this layer is generated via laser pulses containing multiple photons, which interact directly with qubits at physically connected repeaters to establish the necessary entangled states. The link-level entanglement layer or entanglement control (EC) layer then measures the properties of the laser pulses to determine the success of the entanglement generation attempt [28]. The PE and EC layers operate recursively over single-hop links until an EPR pair is successfully established between directly connected repeaters, ensuring consistent entanglement quality.

Following this, the error management layer, utilizing the purification control (PC) protocol, supervises the purification process of entangled states. The model progresses to the remote state composition layer, responsible for generating end-to-end entangled states using entanglement swapping control (ESC) protocol. The ESC, along with the PC layer, functions iteratively over multi-hop links, a structure later termed by the author as Quantum Recursive Network Architecture (QRNA). This multi-hop approach is crucial for distributing high-fidelity entangled states across the network. The primary objective is to develop stable, error-corrected quantum channels, facilitated by entanglement swapping and a specific purification protocol known as banded purification. At the application layer, the quantum socket manages how applications access the services provided by the quantum network, ensuring seamless integration and utilization of quantum network capabilities.

2) **Wehner *et al.*** proposed a quantum Internet protocol stack utilizing bipartite entanglement, similar to Van Meter *et al.*'s approach. However, they retained the classical Internet stack's layer names but redefined each layer's functions to suit quantum networking. Unlike Van Meter *et al.*, Wehner *et al.*'s model does not designate error correction as a separate layer. Instead, it focuses on the physical and link layers, with the link layer responsible for robust entanglement generation via the quantum entanglement generation protocol (QEGP).
Two notable features of this model are the establishment of end-to-end entanglement on demand and the introduction of the hardware abstraction layer (HAL) within the link layer, which decouples network protocols from specific physical hardware, enabling interoperability across different technologies. Additionally, a transport layer is included to manage the deterministic transmission of data qubits. This model represents a significant shift from purely physical experiments to comprehensive quantum communication systems. It has been experimentally validated, demonstrating a trade-off between latency and the fidelity of generated entangled states. The emphasis on hardware abstraction enables the protocol stack to operate independently of specific physical implementations, a feature not prominently addressed in Van Meter et al.'s model. Moreover, Wehner *et al.*'s framework includes mechanisms for managing hardware heterogeneity and enhancing the scalability of quantum networks.

3) **Li *et al.*** proposed a layered model for a quantum Internet protocol stack based on bipartite entanglement, sharing similarities with the model proposed by Wehner *et al.* However, a key distinction lies in their approach to entanglement generation. While Wehner *et al.*'s model assumes that entangled states are generated on demand. Li *et al.*'s model is designed for a quantum Internet that pre-establishes entangled states. This difference significantly affects the functionality of the link layer in the protocol stack, which is tailored to maintain control over pre-established entangled states, ensuring they are ready for

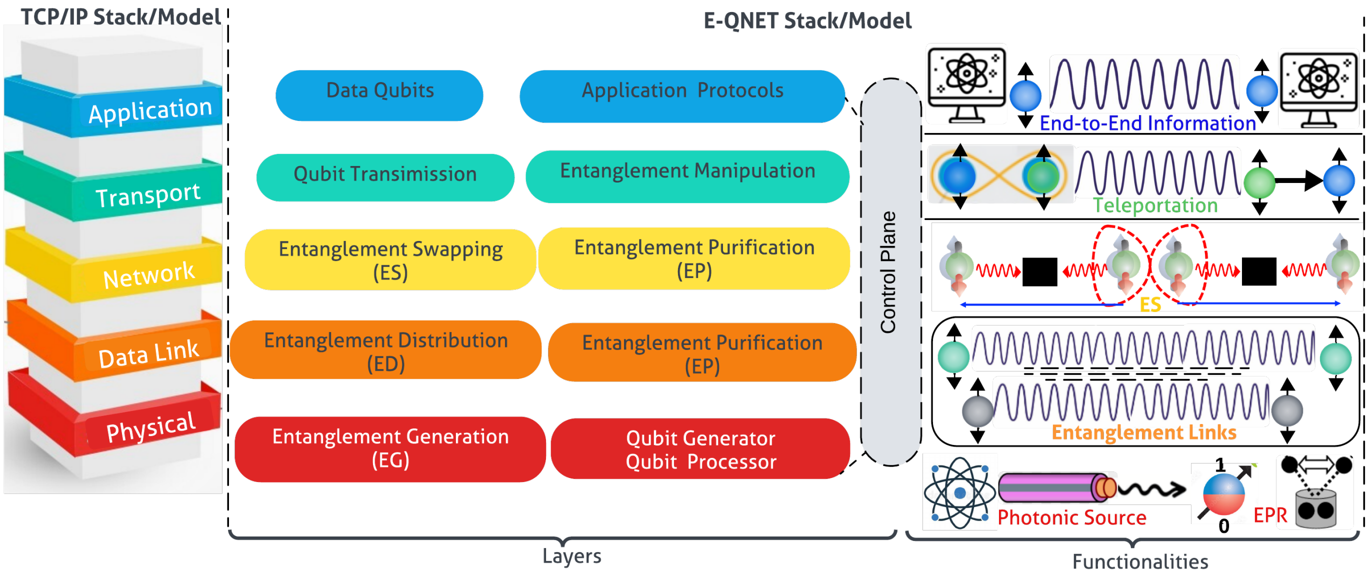

Fig. 3: Comparative representation of the reference TCP/IP layered model and the proposed E-QNet stack, illustrating the respective layers and key functionalities within the E-QNet framework.

use when needed for data transmission. This contrasts with the classical Internet, where the link layer is involved in the direct transmission of data.
The structure of the quantum Internet protocol stack proposed by Li *et al.*, while resembling the OSI model, diverges in its focus. In the quantum Internet, the layers below the transport layer aim to establish end-to-end entangled states, which are then used for data transmission via quantum teleportation. In classical networks, data transmission occurs even at the link layer, highlighting a fundamental difference in the handling of data. In Li *et al.*'s model, the link layer is specifically responsible for managing link-level entanglement and handling feedback from the network layer. Drawing from classical network hierarchy, the quantum local area network (QLAN) is proposed to establish the quantum core network.

4) **Dür *et al.*** propose a protocol stack that incorporates a unique connectivity layer for establishing multipartite entanglement across the network before communication requests are made. This layer enables long-distance entanglement via quantum repeaters. The key distinction from Wehner *et al.*'s model is that Dür's link layer continuously establishes entanglement links, storing them in quantum memory as network resources rather than generating entanglement upon request. Moreover, contrary to Van Meter *et al.*'s approach, the physical layer of this model does not apply error correction or entanglement distillation mechanisms during the initial distribution of quantum particles. Instead, it focuses on the direct transmission of quantum information. Each layer above the physical one can access auxiliary protocols for entanglement distillation, entanglement swapping, and monitoring the network's internal state. The link layer provides varied services depending on the network phase. During the dynamic phase, it generates multipartite entangled states across the network. In the adaptive phase, it generates intra-network arbitrary graph states upon request. At the top, the network layer manages inter-network entanglement, enabling connections between nodes in different quantum networks using quantum routers.

In summary, while the classical OSI and TCP/IP models are well-defined and standardized, the quantum protocol stack must adapt to the probabilistic nature of quantum mechanics, as illustrated in Fig. 1. The key distinctions lie in how data (classical bits vs. qubits) is handled and the critical role of quantum-specific phenomena such as entanglement and superposition. In conclusion, while classical and quantum networks share a conceptual framework in terms of layered architecture, the fundamental differences in data units and transmission methods necessitate a distinct approach. Building upon the above quantum stack/models, this manuscript explores the proposed E-QNet quantum network's architectural layers and the specific devices required at each level, providing critical insights into the construction of a functional and secure prospective quantum Internet.

III. Proposed E-QNet Framework: Layers and Devices Functionality

The proposed E-QNet framework, as illustrated in Fig. 3, showcases the distinct layers and functionalities required to facilitate entanglement-assisted quantum communication. Designed specifically for quantum communication, the E-QNet stack introduces a quantum network architecture driven by entanglement-based functionality. While drawing from the classical TCP/IP network model, it is tailored to address the unique challenges of quantum networks, such as entanglement distribution, quantum error correction, and qubit transmission.

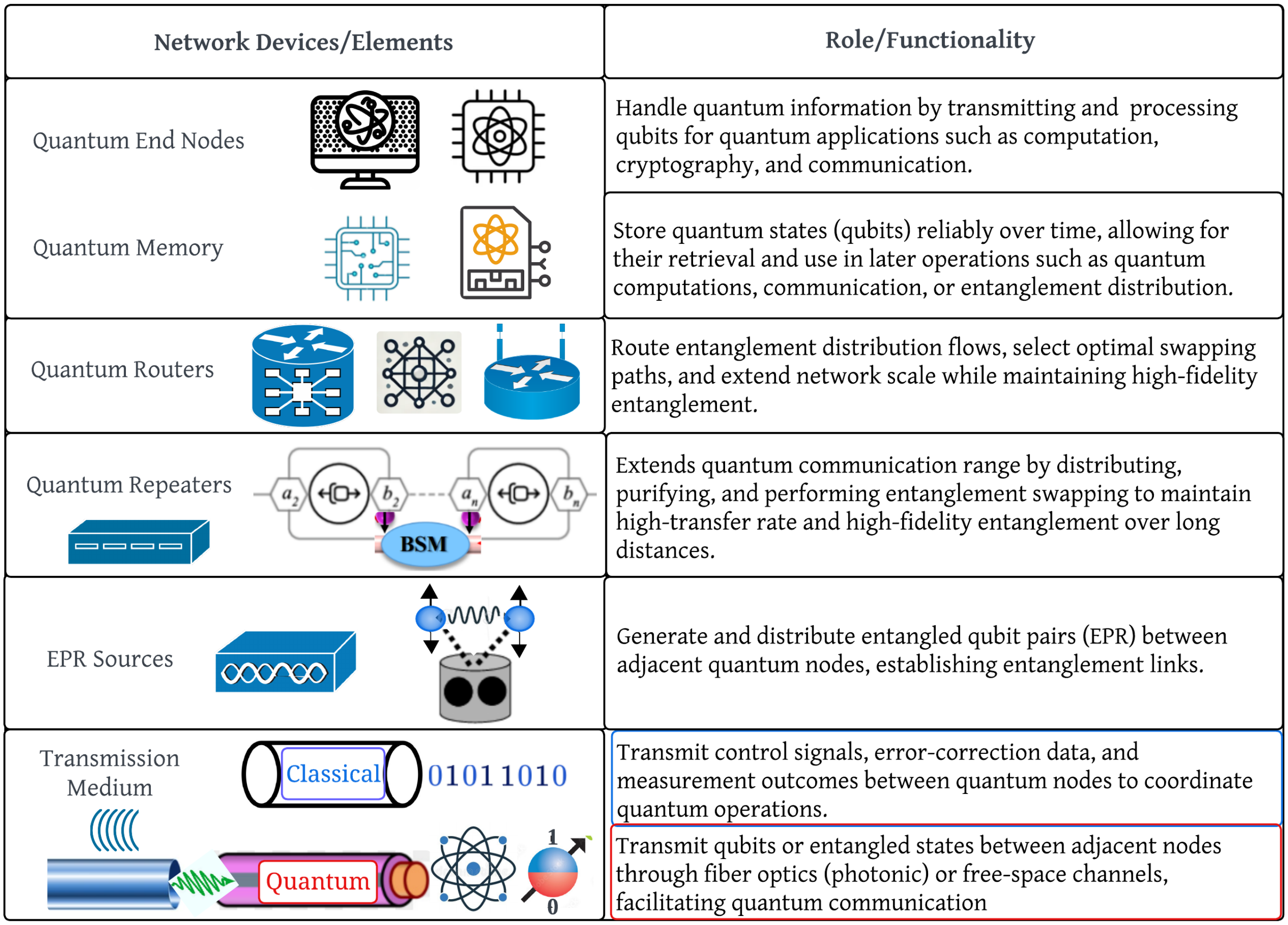

Fig. 4: Overview of network devices/elements and their roles/functionalities in a quantum network protocol stack.

Each layer within the E-QNet stack plays a crucial role in ensuring scalable, high-fidelity quantum communication, supporting applications such as QKD and quantum computing.

At the physical layer, E-QNet manages the transmission of qubits and entangled states over photonic or free-space channels. This layer also facilitates entanglement generation (EG) to prepare qubits for subsequent operations. In contrast to the classical TCP/IP link layer, which handles the creation, transmission, and reception of data frames between adjacent nodes, the E-QNet link layer ensures reliable entanglement distribution (ED) and entanglement purification (EP). Moreover, unlike the classical TCP/IP network layer, which provides reliable end-to-end communication by routing packets from host to host, the E-QNet network layer handles entanglement swapping (ES), enabling long-distance quantum communication. This ES can be performed sequentially (host-to-host), in parallel, or nested over a selected route. The transport layer ensures efficient qubit transmission and manages quantum teleportation using established entanglement links. Finally, the application layer supports high-level quantum applications such as quantum cryptography, quantum teleportation, and quantum computing algorithms by performing measurement operations that conclude end-to-end quantum communication.

It is important to note that, functionally, the E-QNet framework's layers differ from the classical TCP/IP layered architecture due to the inherent quantum features of entanglement and superposition. Additionally, the E-QNet protocol suite includes a control plane, similar to the TCP/IP or SS7 telephony signaling control plane, which provides feedback control for all quantum layer operations. This control plane can operate over classical or quantum channels, facilitating the integration of quantum and classical networks. Another key aspect of E-QNet is the distinction between data qubits and communication qubits, which are crucial for network performance. Unlike classical networks, the number of communication qubits at a node directly affects entanglement resources. More communication qubits enable higher entanglement rates, but this reduces the availability of data qubits [29], necessitating optimization for quantum computing operations. Nevertheless, E-QNet aims to optimize entanglement resources and network performance to ensure efficient communication using the control plane.

In entanglement-based networks, network entities are foundational to the quantum network paradigm. Understanding the roles and functionalities of key devices is essential for secure communication and efficient data transmission. These elements form the backbone of the quantum network, as summarized in Fig. 4, making them crucial for developing a robust and scalable quantum infrastructure.

A. Quantum End Nodes

Quantum End Nodes (QENs) play a pivotal role in quantum networks by managing quantum information to enable a wide range of quantum applications. Similar to classical networks, these nodes act as processors responsible for initiating and receiving quantum data, including complex computations, qubit manipulation, quantum cryptography, quantum sensing, and other quantum-based tasks. QENs serve as the interface between the quantum network and end-users or devices, processing quantum information to make it accessible for practical applications. The functionality of QENs is crucial, as they are the primary points where quantum information is input and output, forming the backbone of the quantum Internet's data processing capabilities. In this context, Noisy Intermediate-Scale Quantum (NISQ) computers/processors are currently being developed in their preliminary stages [5].

B. Quantum Memories

Quantum memory devices are responsible for storing and retrieving quantum information. They temporarily hold quantum states, enabling the synchronization of quantum processes and stabilizing quantum states over time [30], [31]. Quantum memory is essential for applications that require time delays, such as quantum repeaters and certain quantum computing tasks. Contrary to classical memory, which stores copyable binary (digital) bits, quantum memories hold fragile qubits constrained by the principles of quantum mechanics, making them crucial for maintaining coherence and efficiency in quantum networks. Although commercial solutions are not yet available [32], quantum memories are vital for storing and synchronizing randomly generated entangled qubits in entanglement-assisted quantum networks.

C. Quantum Routers

Quantum routers enable the routing of entanglement distribution flows between source and destination nodes. They scale the network by aggregating multiple quantum nodes and managing entanglement swapping across quantum repeater chains [33]. Quantum routers go beyond repeaters by not only storing entangled qubits but also using local entanglement to link the entangled qubits of neighboring nodes. Unlike classical routers that manage data packet routing, quantum routers use quantum registers or memory to store qubits and a swapping module to perform BSM for entanglement swapping. The routing process involves selecting an output port via a routing processor, retrieving entangled qubits, and forwarding them to the next hop. Though constrained by current technology, quantum routers are expected to efficiently manage entanglement distribution and significantly enhance the scalability of quantum networks.

D. Quantum Repeaters

Quantum repeaters, acting as intermediate devices, facilitate long-distance, high-fidelity entanglement distribution by overcoming the challenges of signal/photon loss and quantum decoherence in transmission channels. Unlike classical repeaters, they cannot amplify signals due to the no-cloning theorem [2]; instead, they use entanglement swapping to extend the range of quantum communication. Quantum repeaters are categorized into two types: matter-based and all-photonic. Matter-based repeaters rely on quantum memories, while all-photonic repeaters use photonic states and interference techniques [26]. These repeaters often incorporate quantum memory to store entangled qubits, enabling error correction techniques such as entanglement purification and quantum error correction (QEC). For instance, third-generation repeaters utilize QEC codes to suppress both loss and operational errors. These devices are pivotal in the quantum network stack, maintaining qubit integrity and enabling the distribution of entangled qubits between distant nodes, ultimately improving transmission rates over long distances.

E. EPR Sources

EPR sources generate and distribute entangled qubit pairs between adjacent quantum nodes, providing essential link resources for qubit transmission by establishing entanglement links. The functionality of EPR sources is critical, as entanglement is a key resource in quantum networks, enabling secure communication and information sharing. These sources are foundational in creating the entangled states necessary for various quantum protocols, such as BSM for teleportation, entanglement swapping, and QKD [6]. The generation of entangled qubits via EPR sources has been experimentally achieved using techniques such as trapped ions, Rydberg atoms, NV centers in diamond, ultracold molecules, and superconducting circuits [34]. With continuous advancements in physical materials and device technologies, high-quality entangled qubits are now being generated more efficiently, further enhancing the performance of entanglement-assisted quantum networks and ensuring reliable quantum communication.

F. Physical Channels

Physical Channels are the communication links that connect adjacent quantum nodes in quantum networks (Fig. 1). Classical channels are responsible for transmitting control signals and measurement outcomes, while quantum channels are used for the transmission of qubits to enable entanglement distribution [2], [5]. Due to the nature of qubits, quantum channels can only be photonic and are available in two forms: free-space channels and optical fiber channels. Free-space channels offer higher bandwidth, but optical fiber channels exhibit significantly lower photon loss, making them more efficient for long-distance quantum communication. Both channel types have their own advantages, and future quantum networks will likely combine them to optimize bandwidth and minimize loss. Understanding the role and characteristics of physical channels is critical for building a robust and scalable quantum Internet.

Overall, a comprehensive understanding of these layers and devices' functionality provides the foundation for developing a coherent and effective quantum Internet protocol stack.

IV. Conclusion and Future Perspectives

This article introduced the E-QNet framework, an entanglement-assisted quantum network protocol stack designed to facilitate quantum communication. By examining the architectural layers and key devices—such as Quantum End Nodes, Quantum Repeaters, EPR Sources, Quantum Memories, and Quantum Routers—this work provides critical insights into how these components interact to support secure communication and efficient data transmission in quantum networks. Through a comparative analysis of quantum Internet protocol models proposed by Van Meter, Wehner, Li, and Dür, we highlighted the unique challenges and opportunities presented by quantum networks compared to classical networking paradigms. This work not only enhances our understanding of quantum protocol stack architectures but also lays the groundwork for designing a framework for the standard quantum Internet that supports the complex requirements of quantum communication, interfaces, computation, and security, thereby advancing its implementation and adoption.

Looking ahead, the development of a global quantum Internet hinges on overcoming current limitations, such as the lack of commercial quantum memory, robust quantum repeaters, and standardized hardware technologies. However, ongoing international standardization efforts by organizations such as IEEE, ITU, GSMA, and IETF will be critical in ensuring interoperability between quantum networks and existing telecommunications infrastructure. Furthermore, the recent release of quantum-resistant cryptographic standards by NIST in August 2024 underscores the growing importance of secure communication in a post-quantum world. These developments set the stage for realizing a scalable, resilient, and secure quantum Internet protocol suite, paving the way for the standardization of quantum communication infrastructure.

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