Laying the Foundations for Quantum Networks: An Overview of Principles, Progress, and Prospects

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Abstract

Driven by quantum superposition and entanglement, the swift advancement of quantum computing has highlighted the limitations of classical computation. As a solution, Quantum Networks (QNs) have emerged, offering high-quality entanglement connections and reliable quantum state transmission, enabling a range of applications that exceed the limitations of classical data networks, including quantum communication and distributed quantum computing (DQC).

This article delves into key components and concepts such as quantum entanglement, quantum decoherence and entanglement distribution. It then explores quantum remote secure communication technologies, including quantum teleportation, quantum key distribution (QKD), quantum dense coding, quantum repeater technology, and quantum satellite communication. We also provide a detailed introduction to quantum remote entanglement distribution and quantum entanglement routing design, including current research progress and a discussion on the challenges and existing solutions for constructing large-scale QNs.

The aim of this article is to provide readers with a fundamental understanding of QNs, an assessment of current research, and insights into the main challenges and solutions in this emerging field. Through these discussions, we hope to help readers better understand the potential and future direction of QNs.

Keywords: Quantum network, Entanglement routing, Entanglement distribution protocols, Quantum key distribution

1 Introduction

As information technology continues to advance rapidly, the demand for data processing is ever-increasing, posing significant challenges to classical computers. However, due to the limitations of physical processes, the computing power of classical computers cannot be infinitely enhanced. Quantum computing, operated on the foundational concepts of quantum superposition and entanglement [1], has demonstrated the potential for exponential acceleration and can solve problems that are difficult for classical computation. Although some simple quantum algorithms have been realized [2-4], current quantum computers are limited in scale and far from meeting the needs of large-scale computation. For instance, IBM's quantum processor only has 1121 superconducting qubits [5], and the scalability of qubits still faces significant challenges.

To address this issue, the concept of DQC [6-8] has emerged. DQC achieves more efficient computation by coordinating multiple quantum computers with a smaller number of qubits. In this process, high-quality entanglement connections and reliable quantum state transmission are crucial. QNs [9] are proposed as a key strategy to significantly expand the long-distance communication capabilities of qubits and classical information.

QNs, as the integration of quantum communication and computation, can not only connect quantum computers with other quantum devices but also lay the foundation for applications in quantum communication, computation, and metrology [10-12]. After more than 20 years of development, quantum network technologies have become a reality, and countries around the world, including the United States, the European Union, and China, are actively researching and investing heavily. Recent milestones include the SECOQC Vienna QKD network, the Tokyo QKD network, and China's satellite quantum network. These experimental works have proven the feasibility of QNs and demonstrated their potential in secure communication and other applications. Recently, [13] further explored the communication capability in quantum entangled networks, demonstrating the quantum communication capability with local operations and classical communication assistance through von Neumann entropy, providing preliminary insights for the use of QNs in higher-level communication protocols.

The basic architecture of QNs, as shown in Figure 1 [14], utilizes the combination of classical and quantum channels, transmitting not only classical information but also quantum states, providing a platform for the realization of quantum cloud computing, quantum secure communication, and quantum relays. Existing

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research has made significant progress in entanglement generation, quantum state transmission, and quantum network routing. However, building large-scale QNs still faces many challenges, such as secure long-distance quantum communication and QNs design. Transmitting quantum bits over long distances presents a significant challenge, and ongoing research into satellite-based quantum communication is aimed at fostering the growth of a worldwide Quantum Internet [15]. The evolution of the quantum internet relies on the combination of secure classical repeaters and the principles of quantum secure direct communication, which allows for the direct transmission of information through quantum channels [16].

In summary, establishing a secure and efficient global QN has become a common goal for academia and industry. The distinctive attributes of QNs, including quantum entanglement and superposition, set them apart markedly from their classical counterparts. In Table 1, we provide a comparative analysis of these two types of networks.

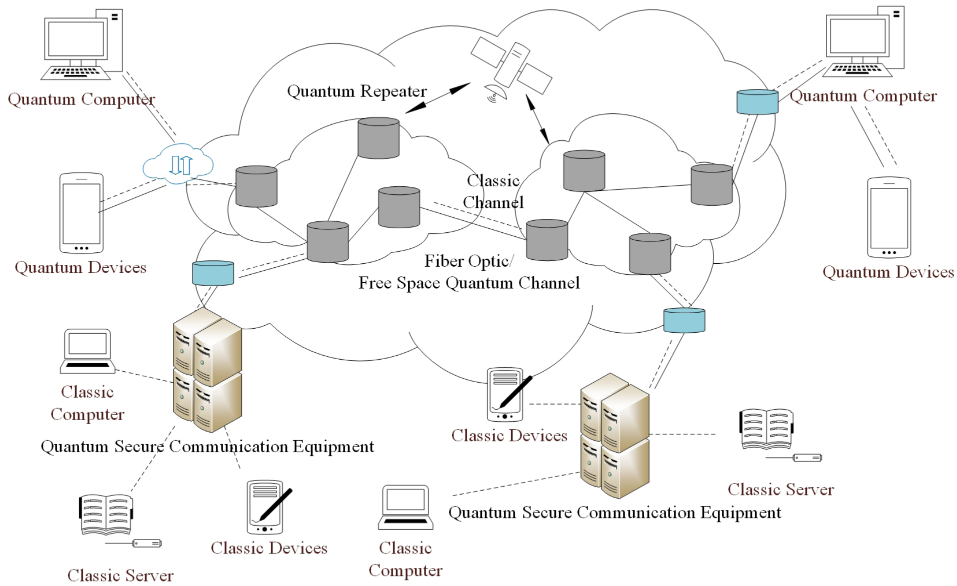

Figure 1. General architecture diagram of QNs

Therefore, it is necessary to delve into the theoretical and practical issues of QNs, especially the design of quantum long-distance secure communication and quantum entanglement routing. This article aims to:

1. Provide readers with an understanding of the basic concepts and knowledge of building QNs.
2. Recognize the current state of research in QNs, especially in the areas of quantum long-distance secure communication and quantum entanglement routing design.
3. Familiarize readers with the main challenges and existing solutions for the realization of QNs.

The structure of this paper is as follows. Section 2 introduces the basic concepts and background of QNs. In Section 3, we discuss quantum teleportation and quantum long-distance secure communication. Section 4 elaborates on the current state of research and achievements in quantum network design. In Section 5, we analyze the challenges and current state of research in QNs. Conclusions are drawn in Section 6.

Table 1. Comparison QN between classical network

Feature	Classical network	QN
Information Carrier	Electromagnetic waves, electrons	Qubits
Unit of Information	Bits	Qubits
State Representation	0 or 1	Superposition of 0 and 1
Transmission Mechanism	Fiber optics, cables, radio waves	Quantum entanglement, quantum tunneling
Transmission Medium	Electrical signals, optical signals	Quantum states (e.g. Photons,electrons)
Encryption Method	Algorithmic encryption (e.g. RSA, AES)	Quantum encryption (e.g. QKD)
Security	Based on computational complexity, prone to being cracked	Based on quantum mechanics principles,
Error Detection and Correction	Error-detecting codes, error-correcting codes (e.g. CRC, Hamming code)	Quantum error-correcting codes (e.g. Shor code, Steane code)
Parallel Computing Capability	Limited, depends on hardware parallelism	Highly parallel, utilizing superposition entanglement

2 Preliminaries

In this section, we will cover fundamental concepts and background necessary for constructing QNs. This includes topics such as quantum entanglement [10], quantum decoherence. Additionally, we will discuss entanglement distribution [17], entanglement purification [18], and entanglement swapping. These three steps facilitate the creation of virtual links, allowing quantum information to be transmitted between nodes within the QNs [19].

2.1 Quantum Entanglement

Quantum entanglement is a distinctive phenomenon in quantum mechanics that characterizes the non-classical correlation between two or more quantum systems [20]. In an entangled state, any alteration in one system's state will immediately affect the state of the other, irrespective of the distance between them [21], and without any classical communication or interaction .This non-classical correlation surpasses the principle of locality in classical physics and offers many potential applications for quantum communication and quantum computing, such as quantum entanglement distribution protocols, quantum teleportation.

2.2 Quantum Decoherence

In quantum mechanics, coherence is a property that describes the interference and phase relationships between different states in a quantum system. When a quantum system is in a coherent state, there is a specific phase relationship between its different states, allowing them to interfere and exhibit quantum characteristics. The main causes of decoherence include environmental interference, measurement processes, and internal system coupling [22].

2.3 Quantum Entanglement Distribution

The purpose of quantum entanglement distribution is to establish the entanglement relationship of quantum bits between different nodes in a QN, in order to achieve remote quantum communication and quantum computing. This is usually achieved by generating entangled photon pairs through dedicated entanglement sources, and then distributing them to various nodes in the network using physical transmission methods. The location of the entanglement source installation has a significant impact on the entanglement quality and requires careful design to ensure entanglement fidelity for long-distance transmission [23-24].

2.4 Quantum Purification

During the entanglement distribution process, due to environmental noise, operational errors, and imperfections in communication channels, the entangled states may be damaged or degraded, resulting in a reduction of quantum fidelity. The core idea of quantum entanglement purification is to introduce an additional Bell pair to test whether the existing entanglement link is in the expected ideal state. If the verification fails, the Bell pair is discarded, and a new Bell pair is generated for testing; if the verification succeeds, the entanglement link is retained, and its fidelity is enhanced. Specifically, two Bell pairs are used: the first pair serves as the entanglement link to be purified, and the second pair is used to test whether the entanglement link is in the ideal state (i.e., $|\beta_{00}\rangle$). Through the application of a Controlled-NOT (CNOT) gate, Alice and Bob compare the measurement outcomes of the quantum bits of the second Bell pair. If the measurements are consistent, it indicates that the entanglement link is in the expected state; if the measurements are inconsistent, it implies that the entanglement link is defective, and the Bell pair is discarded. The final fidelity after purification can be calculated based on the following formula [25]:

$$f(x_1, x_2) = \frac{x_1 x_2}{x_1 x_2 + (1 - x_1)(1 - x_2)} \quad (1)$$

x_1, x_2 are the fidelity of Bell pairs involved in purification. It is typically assumed that the fidelity is the same across all links in a given network, though different links may have different fidelities (i.e., $x_1 = x_2$). In iterative purification, multiple sacrificial pairs can be used to purify the same Bell pair multiple times.

2.5 Quantum Swapping

Swapping quantum entanglement is a pivotal technique for establishing quantum links between local quantum nodes. As shown in Figure 2, Alice and Bob initially do not share entanglement, but they each share an entangled pair with a repeater. The repeater performs a Bell state measurement (BSM) [26] on one quantum state from each of the two entangled pairs, and then, based on the measurement results, applies corresponding quantum operations to the remaining two quantum states, ultimately achieving entanglement between the remote nodes Alice and Bob.

Nowadays, researchers have also developed entanglement swapping methods that do not require measurement [27].

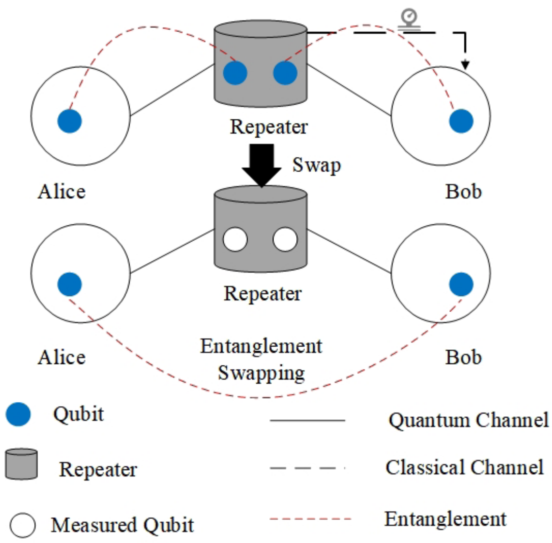

Figure 2. Entanglement swapping

3 Quantum Long-Distance Secure Communication

The construction of QNs requires the interconnection of multiple quantum nodes, with quantum secure transmission being crucial in this process. Since QNs, operating under the principles of quantum mechanics, encounter distinctive hurdles. These include the no-cloning theorem, the intricacies of quantum measurement, and the phenomenon of entanglement. These factors introduce complex constraints in the architecture of QNs. This section will explore several key technologies in quantum long-distance secure communication and compare the advantages and application scenarios of these technologies.

3.1 Quantum Teleportation

Quantum teleportation is a method of transferring the quantum state of a particle to another particle without physically transferring the particle itself. This technique achieves secure communication in QNs [28], as it can transmit unknown quantum states between different quantum computers without violating the principles of quantum mechanics. The specific process is shown in Figure 3: Alice and Bob share a pair of entangled qubits that are in an entangled state, such that a measurement on one qubit, no matter the distance, will instantaneously affect the other. Alice wishes to teleport an unknown quantum state to Bob. She performs a joint measurement on her entangled qubit and the unknown quantum state, a process that collapses the original state but encodes the information into the measurement outcomes. Alice then sends these outcomes to Bob via a classical communication channel. Upon receiving the measurement results, Bob performs an appropriate quantum operation on his entangled qubit, based on the information provided, which transforms his qubit into the same state as the quantum state Alice intended to teleport, thus completing the teleportation of the quantum state [27].

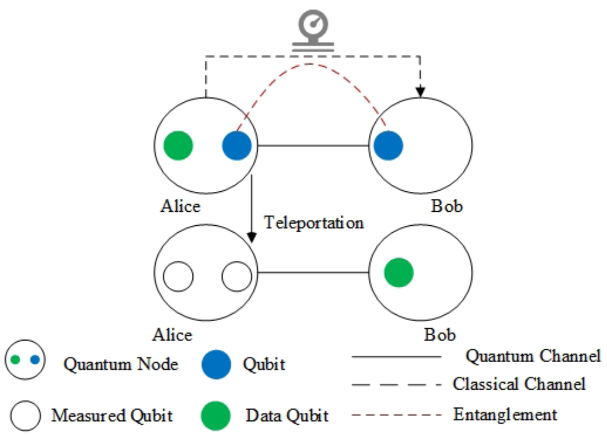

Figure 3. Quantum teleportation

3.2 Quantum Key Distribution

Unlike quantum teleportation, the core of QKD lies in generating and distributing a secret key known only to the communicating parties. This key is used to encrypt and decrypt messages, ensuring the security of information during transmission [29].

QKD leverages the core principles of quantum mechanics to generate a key between communicating parties [30]. The BB84 protocol is the most famous QKD protocol, proposed by Bennett and Brassard in 1984 [31]. Later, researchers developed several other QKD protocols, such as B92, six state protocol, etc., to meet different needs. However, in the real world, due to device and technological limitations, QKD systems may pose security risks, and attackers may exploit these vulnerabilities for eavesdropping. To address this issue, researchers have proposed new protocols such as DI-QKD and MDI-QKD [32].

3.3 Quantum Dense Encoding

Researchers have explored an innovative technology in QNs - quantum dense coding [33], which utilizes quantum entanglement to transmit information between two classical bits by transmitting a single quantum bit, achieving efficient transmission of information. Thus, the future research direction may be to develop interfaces and protocols that can seamlessly process quantum and classical information, in order to achieve collaborative work between the two networks [34]. The process of quantum dense encoding begins with Alice and Bob sharing a pair of entangled qubits. Alice operates on her qubits based on the two classical bit information she wants to transmit, and then sends it to Bob. Bob decodes the two classical bits transmitted by Alice through Bell state measurement. Dutta et al. [35] developed a distributed dense coding method to achieve absolute secure quantum communication between multiple parties.

3.4 Quantum Repeater Technology

Quantum repeater technology is proposed to overcome the transmission distance limitations in quantum communication [36]. Owing to the sensitivity of quantum states to noise and loss, traditional quantum communication faces signal attenuation and distortion problems over longer distances. Quantum repeaters enhance the reach of quantum communication by strategically placing nodes along the transmission path, leveraging the principles of quantum entanglement and non-demolition measurements to ensure the efficient propagation of quantum states.

As shown in Figure 4, Alice and Bob are geographically far apart and not directly connected by a channel, but they are interconnected through several other quantum computers or quantum repeaters. When Alice and Bob are both connected to the same node [37], entanglement between Alice and Bob can be achieved through a process called quantum swapping on the intermediate quantum nodes.

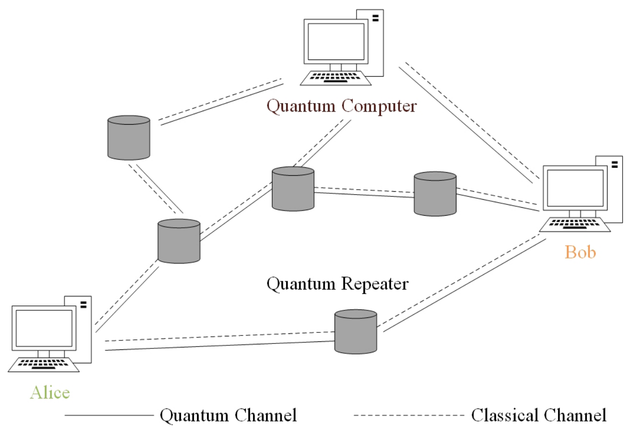

Figure 4. quantum swapping

3.5 Quantum Satellite Communication

In addition to quantum repeater and swapping technologies that enable the secure transmission of quantum information over long distances, quantum communication can also be achieved globally through satellite transmission in free space. This approach overcomes the limitations of traditional fiber-optic communication, which is restricted by geographical distance, offering the advantages of global reach and security [38]. For instance, the "Mozi" quantum science experimental satellite utilizes the satellite as a source of quantum entanglement, directly distributing entanglement between two distant locations through free-space channels, thus providing a feasible path for the realization of entanglement-based quantum secure communication under current technological conditions. Quantum communication based on satellite platforms is a viable means of constructing a global quantum communication network.Table 2 compares the advantages and application scenarios of different communication technologies.

Table 2. Technology comparison and application scenarios

Technology	Principle	Advantages	Application scenarios
Quantum Teleportation	Quantum state transfer without transmitting the particle itself	Achieves remote quantum state transfer, high security	DQC, Global QNs
QKD	Generation and distribution of a secret key	Information-theoretic security eavesdropping detection	High-security communication, military, finance
Quantum Dense Encoding	Transmit two classical bits by sending one qubit	Increases information transmission efficiency	Efficient information transmission, quantum communication
Quantum Repeater Technology	leverage the principles of quantum entanglement and non-demolition measurements	Extends quantum communication distance	Large-scale QNs
Quantum Satellite Communication	Free-space quantum communication via satellites	Global coverage, high security	Global quantum communication, cross-border networks

4 Quantum Network Protocols

For large-scale quantum networks, effective resource use and routing are crucial. Quantum entanglement distribution protocols [39], which manage entanglement resources and employ purification and relay techniques, are fundamental. Quantum routing selects optimal paths for entangled state transmission, maximizing efficiency and fidelity, essential for complex quantum computing tasks. This section discusses advancements in these protocols and algorithms.

4.1 Quantum Entanglement Distribution

A range of approaches have been suggested to achieve efficient entanglement distribution within QNs: In 2010, [40] developed a fault-tolerant protocol for quantum entanglement distribution over long distances using linear optical elements without the need for quantum CNOT gates. In the same year, Sheng et al. [41] also introduced an effective method for quantum entanglement distribution across different collective noise environments, achieving a 100% success rate by converting frequency entanglement to polarization entanglement.

In 2013, Qi et al. [42] have presented a capture and tracking mechanism for an experiment involving the distribution of quantum entanglement over a distance of 100 kilometers. They highlight the potential of optical free space as a viable conduit for extensive quantum communication networks. In 2015, [43] analyzed the distribution of quantum entanglement in next-generation wireless communication systems, highlighting the potential for integrating quantum entanglement distribution directly into wireless networks beyond 5G.

In 2018, Piparo et al. [44] presented a scheme for entangling multiple remote quantum memories with a single photon pulse. In 2020, Dai et al. [45] proposed maximizing the entanglement distribution rate by introducing the concept of electron negativity in the network, achieving an optimal remote entanglement distribution protocol. Liu et al. [46] focused on fully utilizing quantum discord resources in QNs coding to achieve efficient entanglement distribution. Coopmans et al. [47] have furnished enhanced analytical estimates for the durations of long-distance entanglement transfers, considering the success rates of the network's individual components. Wang et al. [48] proposed a decentralized, asynchronous model for entanglement distribution designed to address the uncertainty associated with entanglement swapping. This model is capable of fulfilling multiple requests for entanglement generation concurrently. The model avoids exchange conflicts through a weighted maximum matching algorithm and signal interaction mechanism, as shown in the following Figure 5. Table 3 summizes some articles on quantum entanglement distribution studies.

Table 3. Summary of quantum entanglement distribution studies

Year	Authors	Method description
2010	Salemian et al.	developed a fault-tolerant protocol.
2010	Sheng et al.	reached a 100% success rate across various noise levels.
2013	Qi et al.	proposed a mechanism for 100 km entanglement distribution.
2015	Hosseidehaj et al.	analyzed entanglement in next-gen wireless systems.
2018	Piparo et al.	presented a scheme for entangling multiple remote quantum memories.
2020	Dai et al.	Introduced using electron negativity to maximize entanglement rate.
2020	Liu et al.	utilized quantum discord resources.
2020	Coopmans et al.	provided enhanced estimates for long-distance entanglement transfer durations.
2020	Wang et al.	proposed a decentralized, asynchronous model.
2022	Li et al.	suggested connection-oriented and connectionless strategies.
2022	Lago-Rivera et al.	discussed telecommunication-predicted for quantum repeaters.
2022	Chen et al.	proposed a heuristic algorithm for quantum paths with limited memory.
2023	Mylvarapu et al.	studied concurrency of entangled states in one-dimensional networks.
2023	Das et al.	emphasized the importance of efficient entanglement distribution.
2024	Qin et al.	reported a high-visibility entanglement system on a low-loss silicon platform.
2024	Chen et al.	introduced a decentralized and reliable protocol.

In 2022, Li et al. [49], suggested both connection-oriented and connectionless strategies for end-to-end entanglement distribution, drawing inspiration from the design principles of classical communication systems, pointing out the advantages and disadvantages of both strategies. In addition, Lago-Rivera et al. [50] discussed the telecommunication-predicted entanglement distribution between remote solid-state quantum memories to achieve quantum repeaters. Chen et al. [51] proposed a heuristic algorithm for quantum paths with limited memory, effectively generating short-distance entanglement using dynamic programming.

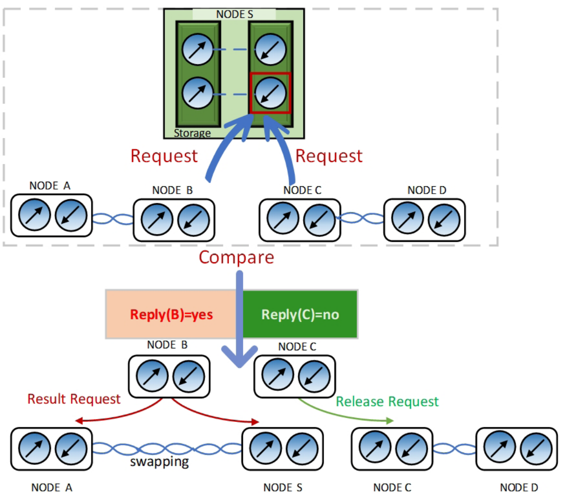

Figure 5. A decentralized asynchronous entanglement distribution model [48]

In 2023, [52] studied the concurrency of entangled states in one-dimensional networks with repeaters, emphasizing the future application of entanglement and teleportation in sending quantum information between remote quantum processors. Das et al. [53] emphasized the importance of efficient entanglement distribution between network nodes, discussing various entanglement distribution methods based on fidelity, network topology, and active distribution factors.

In 2024, Qin et al. [54] reported a high-visibility entanglement system implemented on a low-loss silicon integrated platform, demonstrating the robustness of entangled pairs for long-distance quantum entanglement distribution. Chen et al. [55] introduced a decentralized and reliable protocol for entanglement distribution that is well-suited for large-scale network implementations, operating in a forward-backward propagation manner, reaching consensus hop by hop and propagating it to all nodes on the path.

In summary, the literature on quantum entanglement distribution covers a range of topics, including fault-tolerant protocols, effective distribution methods, experimental setups, integration into wireless communication systems, and optimal distribution using specific types of entanglement.

4.2 Entanglement Routing Strategy

Early QN research mostly focused on specific network topologies, including diamond [56], ring [57], and star structures [58]. Significant contributions include Pirandola [56] analyzed multipath routing in diamond topology. Schoute et al. [57] introduced a framework intended for the analysis of quantum network routing. Nonetheless, their discourse was confined to ring-shaped or spherical network topologies. Vardoyan et al. [58] investigated quantum entanglement switches within a star topology. The aforementioned studies were restricted to analyzing conventional routing algorithms in particular network topologies to improve entanglement routing. However, this may be an oversimplification. The topology of actual QNs may be an arbitrary graph. Chen et al. [59] considered the above issues and studied an entanglement routing model suitable for arbitrary network topologies.

In recent research, considering the physical properties of QNs, Pirandola [56] and Vardoyan et al. [58] have developed routing protocols and theoretically analyzed end-to-end capacity and expected stored quantum bit counts. In addition, Caleffi et al. [60] also explored how to achieve communication beyond the limits of Shannon's theory through quantum paths, allowing information to propagate on paths without a clear causal order, and established upper and lower bounds for quantum capacity achieved through quantum paths. Chen et al. [61] considered the impact of multiple rounds of entanglement purification operations on fidelity and proposed optimal link-level purification scheduling algorithms and joint entanglement purification scheduling and routing algorithms to establish end-to-end entanglement with optimal throughput and fidelity guarantee in QNs. Addressing the issue of routing in the face of quantum memory failures, Shi et al. [62] suggested an effective adaptive routing technique grounded on the foundational graph. In the event of failures that may disrupt certain entanglement links, the network can maintain uninterrupted transmission. The shortest alternative route can be identified through the use of adaptive routing. Li et al. [63] proposed an entanglement routing design to address congestion in QNs. It is based on the concept of 'recycling' idle link-level entanglement resources from abundant links to bottleneck links through entanglement swapping, thereby enhancing resource utilization and network throughput. To bolster fault tolerance, some methods [25, 64-65] have incorporated redundant candidate paths in their routing strategies. This redundancy ensures that alternative routes are available in the event of link failures, thus increasing the robustness of QNs.

Several studies have considered the quality assessment of entanglement connections as a key metric for entanglement routing [25, 66]. Caleffi et al. [66] crafted a stochastic framework that takes into account various physical phenomena, including decoherence time, the creation of atom-photon and photon-photon entanglement, as well as entanglement swapping. They formulated a precise expression for the end-to-end entanglement rate across any given path and devised an effective algorithm to compute these entanglement rates. Zhao et al. [25] quantified the end-to-end fidelity of entanglement connections and proposed an algorithm for determining a set of candidate entanglement path purification schemes to maximize network throughput. Li et al. [39] introduced an entanglement routing design that supports purification, providing fidelity guarantees for multiple SDs within QNs. Additionally, new path selection metrics have emerged in other studies, including minimum entanglement cost pairs, minimum hop counts, minimum path length sums, and generation rates. Wang et al. [67], recognizing that entanglement swapping and purification are capable of extending the reach of entanglement and enhancing the fidelity of entangled pairs, have proposed a method for concurrent swapping applicable to paths of any length. This approach yields higher allocation rates and reduced resource expenditure, with particularly pronounced benefits when the path involves numerous intermediary nodes.

In subsequent research, scholars have considered general QN setups involving multiple SD pairs requiring remote connections. Creating multi-hop quantum entanglement links for various SD pairs with the aid of quantum repeaters requires a robust solution for entanglement routing. The primary goal of these studies is to maximize the expected network throughput, despite performance guarantees. Ramiro et al. [68] introduced a clustering algorithm to identify clusters of connections with given required functionalities within the network, essentially the network topology structure needed for an entanglement-based network, along with a merging algorithm. This algorithm constructs multi-partite entanglement resource states, reducing memory requirements to meet all necessary network requests. Zeng et al. [69] have encapsulated the process of routing entanglement among multiple pairs of quantum users into two phases. They have structured this as a conventional linear programming issue, from which they have extracted viable solutions. [62, 70] examined a generic QN for establishing entanglement among several pairs of quantum users. Some studies, aiming to make more efficient use of available quantum resources, have expanded the entanglement routing scenarios in QNs to include slot modes and online modes. [62] and others proposed a four-phase model known as Time slots, and based on this model, they suggested pre-calculated path selection and algorithms for fault recovery based on segmented link failures. Chen et al. [55] devised a decentralized, asynchronous mechanism for entanglement distribution, aimed at mitigating the limitations inherent in models reliant on centralized control. Zhang et al. [70] introduced a novel segment-aware entanglement routing algorithm. Utilizing fault-tolerant entanglement routing, entangled qubits are shared among all paths, and resource contention issues are addressed through a priority connection mechanism.

These studies delve into how to effectively store and retrieve quantum information within QNs. One of the main challenges for QNs is developing quantum storage solutions that maintain quantum coherence across various environmental conditions. Moreover, QNs have also introduced opportunistic strategies [71], which allow for the chance establishment of quantum links and enhance routing flexibility.

The aforementioned studies have been dedicated to addressing intra-domain entanglement routing issues, taking into account a variety of factors, including network topology, the physical properties of QNs, the creation of quantum memories for QNs, the establishment of remote connections for various SDs, as well as routing selection and resource allocation. Table 4 compares these articles. Recently, Liu et al. [72] shifted their focus to the inter-domain scenario, utilizing network benchmark testing transformed into an optimal arm problem to assess the fidelity of quantum links. Based on this, they introduced a quantum border gateway protocol along with an online Top-k path selection algorithm to facilitate entanglement routing in scenarios involving multiple interconnected domains [73].

Table 4. Summary of articles

Articles	Arbitrary network topologies	Multiple requests	Multipath	Resource allocation	Self-adaption	Purification
[56]	×	√	√	√	×	√
[57]	×	√	×	√	√	×
[58]	×	√		√	√	
[59]	√	√	√	√	√	×
[60]	√		√	√	√	√
[61]		√	√	√	√	√
[62]	√	√	√	√	√	
[63]	√	√	√	√	√	×
[64]		√	√	√	√	×
[66]		√	√	×	√	×
[25]	√	√	√	√	×	√
[39]	√	√	√	√	×	√
[67]		√	√	√	√	√
[68]	√	√	×	√		×
[69]	√	√	√	√	√	×
[70]				√		×
[73]	√	√	√	√	√	×

5 Quantum Networks Challenges

In this section, we can speculate that there are potential challenges for QNs. These challenges can be categorized into technical, theoretical, and application challenges.

Technical Challenges. One of the primary technical challenges lies in the generation and allocation of entangled states [74]. The efficient operation of QNs relies on the reliable generation and distribution of entangled states. However, the generation of Bell states is costly and has a limited rate [75-76]. Efficiently allocating these entangled resources and optimizing the placement of entanglement-producing stations (EPS) under resource constraints represents a key challenge in the design of QNs. Additionally, the short storage time of quantum states and the limited resources of quantum memories pose significant technical hurdles. These issues not only affect the long-term storage of quantum information but also impact the fidelity of quantum states and the success rate of entanglement connections during long-distance transmission. Researchers [77-79] have proposed high-performance quantum memory designs to address these challenges, though their effectiveness in practical applications requires further validation.

Theoretical Challenges. The optimization of quantum entanglement routing and the maintenance of quantum fidelity over long-distance transmissions are critical theoretical challenges [80]. Current quantum routing protocols must consider the susceptibility of quantum states to interference and degradation, requiring the selection of optimal paths to ensure efficient and reliable transmission of information [81]. Additionally, quantum states are prone to decoherence during long-distance transmission, and while quantum purification techniques can partially mitigate this issue, maintaining quantum coherence over long distances remains a key research area.

Application Challenges. In terms of application, the physical architecture of quantum devices imposes limitations on the connectivity of physical qubits, making it challenging to efficiently configure these qubits in large-scale networks [82]. To enhance transmission efficiency, it is necessary to design efficient entanglement routing schemes that can adapt to dynamic networks and real-time requirements [83]. However, integrating quantum technology into existing classical networks to achieve large-scale secure quantum communication presents numerous challenges, including issues of protocol and hardware compatibility and operational complexity.

In addition to the challenges and limitations mentioned above, some studies have also considered increasing quantum bit control and developing software solutions. Despite some progress, further research is still needed to address the unresolved issues and opportunities in the field of QNs.

6 Conclusion and Future Work

Here, we first introduced QNs basic concepts and outlined their general architecture, then discussed quantum entanglement, quantum decoherence and the three main steps for establishing virtual links and transmitting quantum information between nodes in a QN:

entanglement distribution, entanglement purification, and entanglement swapping. Next, we introduced quantum teleportation, which guarantees the secure conveyance of quantum states [79, 84], and quantum dense coding, which achieves the transmission of classical information through quantum states, and listed the main technologies for realizing long-distance secure quantum communication: quantum repeater technology and quantum satellite communication. Subsequently, we reviewed recent research papers on entanglement distribution protocols and quantum routing algorithms and designs, and pointed out the challenges faced in the design of QNs. Finally, we analyzed the broader challenges faced by QNs.

QNs are currently in an active phase of development [85], and have attracted widespread attention. Figure 6 summarizes the characteristics of QNs.

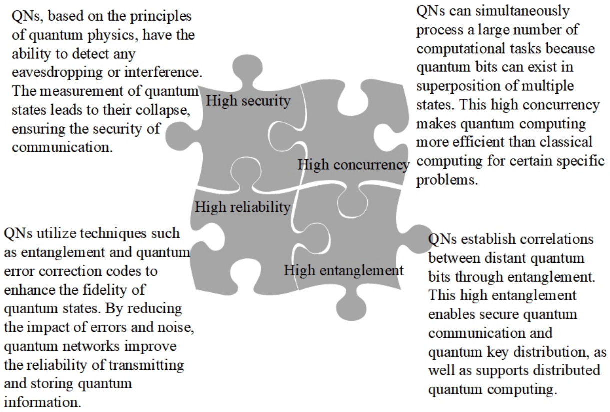

Figure 6. The characteristics of QNs

Looking ahead, research in quantum networks is poised to address a broader and more complex array of scenarios. In addition to the studies and challenges mentioned above, scholars may strive to design cost-effective entanglement purification scheduling algorithms that meet the demands of quantum network routing protocols, as well as joint optimization algorithms for link failure and resource allocation. Furthermore, an indispensable aspect to consider is the integrated decoherence time, which is related to the degradation of entanglement fidelity over time. In tandem with these efforts, the realms of quantum network architecture, entanglement distribution protocols, and quantum network resource allocation are also progressing, all aimed at achieving a more secure and efficient global communication network.

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