Future Quantum Communications and Networking: A Review and Vision

Peiying Zhang, Ning Chen, Shigen Shen, Shui Yu, Sheng Wu, and Neeraj Kumar

Abstract

Based on quantum mechanics, quantum communications have clock synchronization properties and unbreakable security. Recently, related technologies of quantum communications have made breakthroughs one after another, and it has also realized functions and applications that are difficult to achieve in traditional networks. In this era of the rise of quantum networks similar to the eve of the birth of the classical Internet "Arpanet," researchers are full of longing for the blueprint of the future quantum network. In this work, we summarize, analyze and look forward to quantum communications and networking compared with the traditional Internet. Specifically, the related fundamentals, related technological developments, and existing challenges of quantum networks are firstly analyzed. On this basis, we look ahead and propose a prototype of the future quantum network architectures. Finally, we sort out and analyze the paradigm, principle, and properties of quantum communications. To the best of our knowledge, this is the first review and vision work on quantum communications and networking.

Introduction

In recent years, quantum networks, as a future emerging architecture, have attracted extensive attention from researchers. The interconnection between network entities through quantum routers will achieve quantum-level bit transmission, which will significantly promote seamless global coverage of the network. Ground-based Internet of Things, drones, satellites, and other related technologies, especially the space-air-ground integrated network, will also usher in breakthrough development [1]. Since it takes quantum mechanics as the starting point, the security of communications is guaranteed, even "unbreakable." Not only that, but the quantum network will also provide technical support for network computing and storage, and so on. Specifically, due to the unclonable characteristic of the quantum, it is impossible for an unknown quantum state to be exactly replicated. Moreover, it can also support cloud-based computing, which will shine in many fields, such as medical, defense, transportation, communications, and so on. In addition, combined with ground and space sensing, quantum networks can accurately predict the environment and natural resources, such as earthquakes and oil. In summary, the development of quantum networks will have a profound impact on human life.

In 2018, Wehner *et al.* [2] imagined the blueprint of the quantum network and pointed out that it is not a replacement for the existing network, but an upgrade to it. It is composed of massively distributed quantum nodes and quantum channels and is propagated over long distances based on quantum communications protocols through quantum repeaters. The organic combination of the three is employed for enhanced communication and computing between quantum nodes. Similar to the transmission, storage, and computing of the traditional Internet, quantum networks perform similar processing on quantum information. Moreover, quantum networks can be understood as a new type of network that supports quantum communications, which is an extension and supplement of traditional Internet functions. However, it is not and cannot replace the traditional Internet. Specifically, the traditional Internet transmits traditional bits carried by electrical signals, while the quantum network transmits quantum bits (Qubits) carried by quantum states. Due to the fundamental difference between quantum states and conventional electrical signals, it poses challenges for precise manipulation at the quantum scale. This in turn brings a series of technical bottlenecks to be solved for quantum networks, such as architecture design, protocol execution, quantum routers and memory, and so on.

In 2021, Pompili *et al.* [3] built the first quantum network entanglement based on multiple quantum nodes (qubits are nitrogen-vacancy centers in diamond). In addition to Qubits, quantum entanglement is also the main resource of quantum networks. However, the transmission of quantum information (photon form) inevitably suffers from attenuation and loss. Specifically, as traveling long distances, their intensity will decays, especially where quantum devices connect. Therefore, quantum repeaters become essential components, which are dedicated to extending the long-distance transmission capabilities of quantum links. A favorable quantum repeater can minimize the loss and convert photons efficiently. Theoretically, to facilitate the interconnection of large-scale quantum networks in the future, Li *et al.* [4] presented a novel design of a

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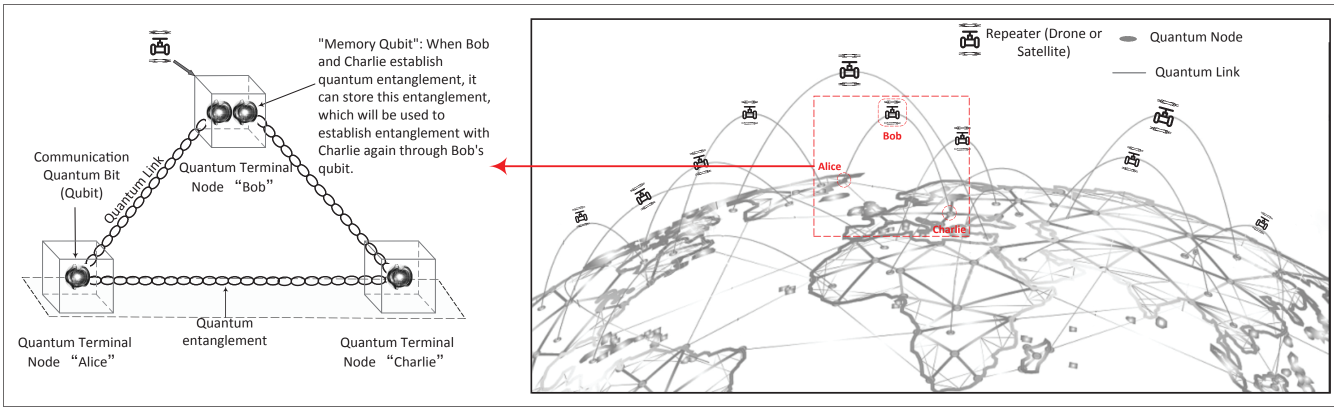

FIGURE 1. Multi-node quantum communications network (QCN) with drones and satellites as repeaters, which is used for wide-area communications expansion. The left shows the connection of multiple quantum nodes, see [3] for details.

cluster-based structure and OSI-alike protocol stack, which can not only reduce the network complexity but also benefit fast prototyping. Meanwhile, Liu *et al.* [5] presented the first prototype for quantum entanglement forwarding by mobile devices. Specifically, it successfully realizes the transmission of entangled qubits with drones as repeaters, which will enable drones to serve as flexible and scalable nodes in quantum networks. In addition, Yin *et al.* [6] used the "Micius" quantum communications satellite as a trusted relay to achieve a 1200-kilometer quantum key distribution (QKD) based on entangled qubits. It should be noted that QKD is the main means of quantum communications, which we will analyze in the follow-up content.

Inspired by them, we conduct related research on a wide-area multi-node quantum communications network (QCN) as a prototype, where drones, satellites, and so on, are the repeaters for wide-area communication expansion. QCN is illustrated in Fig.1. In addition, in QCN, each domain has its unique properties as well as defects. For example, quantum devices in the terrestrial domain have better storage capacity and lower communication latency. However, their effective deployment has always been a challenge.

Due to its flexible and high-speed characteristics, the aerial quantum repeater can well act as a "bridge" for quantum communications, making up for the weaknesses of the ground network. Especially in the needs of regional emergency monitoring, remote sensing, emergency or temporary coverage, and so on, aerial quantum repeater plays an important role. It can assist terrestrial quantum devices in wide-area coverage communication to realize real-time long-distance quantum communications services [7]. However, due to the high maneuverability of them, it makes QCN time-variant and heterogeneous. In addition, the booming artificial intelligence (AI) technologies have been successfully employed in the field of networking and communications, which promote the development of related technologies and significantly enhance the perception, adaptability, and decision-making capabilities. At that time, AI will be widely applied in quantum networks to improve the intelligence of various applications. Therefore, the deployment of quantum networks in the future has many challenges in terms of hardware and software. It is also necessary to have a clear understanding of the relevant problems at this stage and the difficulties to be solved. Moreover, the development of a series of studies by researchers related to quantum communications is also inseparable from a unified structural prototype and communications principle for future quantum networks.

In this work, based on the comparison with the traditional Internet, we conduct a related analysis of quantum communications and networking. Specifically, we analyze and summarize the fundamentals, technical challenges, related developments, and properties of future quantum network communications. Next, we present a prototype of a future quantum network architecture. Then, we sort out and analyze the core and principles. Finally, we summarize the work done and give an outlook on future work.

Quantum Network: A Future Full of Opportunities and Challenges

Quantum entanglement, with its peculiar effects, was called "spooky behavior at a distance" by Einstein. It enables the quantum network as a carrier to provide an extremely secure, highly private, and computationally powerful environment for quantum communications. This magnificent vision of quantum networks has prompted a wave of related research, and some applications will also have epoch-making significance. At the same time, there have also been some phased results in related research on quantum network components. In this section, we review the fundamentals of quantum networks and sort out the challenges and developments of related technologies.

Fundamentals of Quantum Networks: What is Quantum Entanglement?

In the field of quantum mechanics, the individual properties of each interacting quantum are integrated into the overall properties. At this time, the properties of a single quantum cannot be described, but only the properties of the whole can be described. This phenomenon is called quantum entanglement. Furthermore, the properties (states or information) of an entangled system as a whole are called quantum states. Various properties of particles in entangled states are fully correlated, such as position, spin, momentum, and so on.

Generally speaking, as illustrated in Fig. 2, if the state of one quantum in a pair of mutually entangled states changes, the other quantum will also change at the same time. Without decoherence phenomena such as quantum decay, quantum entanglement is not theoretically limited by distance. Furthermore, communications based on quantum entanglement are known as an "unconditional secure" technology. The "quantum entanglement key" based on quantum mechanics enables both ends of the entanglement to share a stable quantum state. At this time, if there is an "eavesdropper" in the quantum link of entangled communication, the quantum states of the sender and receiver will collapse at the same time. At this point, both parties in the quantum communications will know the existence of the "eavesdropper," and the "eavesdropper" cannot obtain the communication information either. Thus, "sensitive" quantum states enable quantum communications in a highly secure environment.

Challenges of Quantum Networks

We document essential differences between the traditional network and quantum network in Table 1. Specifically, the challenges faced by the practical deployment of quantum networks and the differences from traditional networks can be divided into the following aspects:

Stable Quantum Repeater: As demands continue to increase, researchers are beginning to experiment with quantum teleportation over long distances. However, quantum states cannot be replicated as easily as conventional information. Moreover, the transmission of quantum signals in optical fibers is susceptible to the interference of quantum noise, which leads to the decoherence phenomenon of Qubit, that is, the problem of exponential attenuation. Therefore, to solve the above problems, quantum repeaters are required to extend the quantum link to any communication distance.

A traditional repeater, usually as an "amplifier," is used to restore the energy of the communication signal. It restores the transmission characteristics of the signal on the one hand and the bits of the information on the other hand. However, the quantum repeater is fundamentally different from it, which requires quantum entanglement distribution and exchange technology to realize the relay function. In addition, quantum properties make the core of transmission and detection, not energy but the quantum state. Therefore, a quantum repeater should have the function:

- Complement the energy of quantum signals for stable transmission.
- Guarantee that the Qubit carried by the quantum signal will not change.

Reliable Quantum Memory: As the core components of quantum devices such as quantum computers and quantum repeaters, quantum memory needs to store Qubit in a short time. Furthermore, like conventional devices, quantum devices require quantum memory support to enable complex computations. According to different business requirements, quantum memory needs to store different quantum information. Here, we take linear optical quantum computing as an example. As a basic computing resource, multi-photon has a very low probability of being directly generated. Fortunately, quantum memory can turn this into a deterministic source of photons.

Existing related research only studies the storage of Qubit with the same substance [7]. However, depending on the actual mission requirements, such as quantum computing or quantum sensing, different nodes of the quantum network may use different materials. Therefore, how to design a reliable quantum memory that can store Qubits from different types of materials promptly, and then perform stable quantum entanglement, is a technical difficulty to be overcome. In addition, the quantum repeater segments the quantum link, that is, the long-range quantum entanglement is decomposed into multiple short-range entanglements, and long-range entanglement is established by entanglement exchange. However, the entanglement establishment times of different segments are often not synchronized. For example, the first segment takes 0.1s and the second segment takes 0.05s. Therefore, high-performance quantum memory also needs to solve the problem of entanglement synchronization.

In addition, traditional memory storage units are bits, that is, one storage unit stores one bit, and the overall storage capacity can reach the TeraByte level today. The quantum memory storage unit is Qubit, and one storage unit can store multiple Qubits.

Flexible Quantum Communications Protocol: To meet the communication needs of multiple quantum nodes, quantum communications protocols are essential to network components. Specifically, it represents a predetermined set of rules to be followed to complete communication between quantum devices. Among them, the most representative one is an encryption protocol, namely quantum key distribution (QKD). As a secure communication technology, it can support the secure sharing of random keys between quantum devices. In addition, the classic protocols are BB84, B92, E91, and so on [8]. However, in quantum networks, quantum communications protocols still have many technical difficulties. For example, lossless conversion of quantum and optical signal carriers, reduction of transmission signal-to-noise ratio, and so on. Therefore, a flexible quantum communications protocol is crucial. In addition, Yu *et al.* [9] proposed

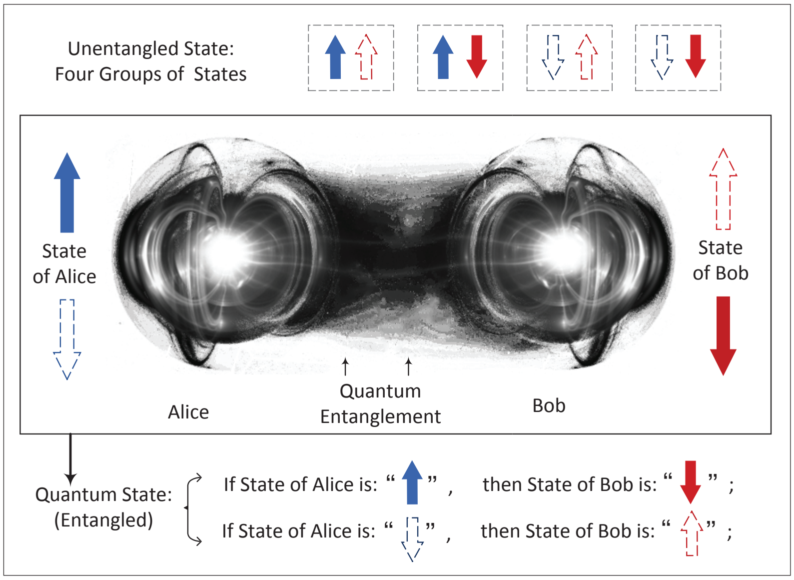

FIGURE 2. Quantum entanglement obtains an interconnected overall quantum state, where the state of one quantum can be inferred from the state of the other quantum, even if they are far apart.

Difference	Traditional Network	Quantum Network
Repeater	Core: energy. Purpose: (1) Restore the transmission characteristics; (2) Restore the bit.	Core: quantum state. Purpose: (1) Complement the quantum energy for stable transmission; (2) Guarantee the Qubit will not change.
Memory	Storage unit: bit. One storage unit stores one bit.	Storage unit: Qubit. One storage unit can store multiple qubits.
Protocol	Function: Electrical signal communication. Representative protocols: TCP/IP, IPX/SPX, NetBEUI.	Function: Optical signal communication. Representative protocols: QKD, BB84, B92, E91.
Coverage	Current goal: Global seamless coverage of the air-space-ground integrated network.	Current goal: Achieve wider-area quantum network coverage through quantum repeaters and optical fibers.

TABLE 1. Traditional network vs. quantum network.

Properties	Traditional Communications	Quantum Communications
Security	Rely on complex encryption algorithms.	Derive from quantum undetectability. Unconditional security.
Extensive application	Related to the transmission medium.	Regardless of the transmission medium. Wider application.
Anti-interference	The communication information passes through the traditional channel, and the anti-interference is weak.	The communication information does not pass through the traditional channel, and the anti-interference is strong.
Concealment	Have electromagnetic radiation.	Undetectable, no electromagnetic radiation.

TABLE 2. Traditional communications vs. quantum communications.

a packet intercommunication protocol for future quantum networks. Especially for the possible packet loss problem, a quantum retransmission protocol is proposed to improve the efficiency and reliability of quantum communication.

Seamless Global Coverage: The goal of quantum networks is to connect to intercontinental networks and even networks with seamless global coverage through repeaters. Today, the technologies related to quantum entanglement generated by small-scale quantum relay modules are relatively mature. However, as the key to large-scale quantum communications, how to store small-scale quantum relay modules through quantum memory and establish efficient connections with adjacent relay modules to achieve wider-area quantum communications, thereby expanding the distribution of quantum networks in the spatial dimension, has been being a critical issue to be resolved. Among them, quantum repeaters will play a role in the wide-area expansion of quantum signals. Drones, quantum communications satellites, and so on. will serve as important repeater equipment. At present, Chen *et al.* [10] have realized an air-to-ground quantum communications network that can span more than 4,600 kilometers through optical fibers and quantum repeaters (satellites), promoting the globalization of quantum networks.

Developments of Quantum Networks

In the previous section, we have introduced some related advances [2–6, 9, 10] with quantum networks. In this section, we will complement the corresponding cutting-edge work.

In 2020, a quantum network prototype, an eight-user city-scale quantum network is proposed. Deployed over fiber in Bristol, the network works without trusted nodes and active switching [11]. Recently, Pu *et al.* [12] have proposed and realized the on-demand efficient entanglement connection of different relay modules through quantum storage for the first time. It realizes the asynchronous preparation of adjacent quantum relay modules. And through the entanglement exchange between relay modules, an efficient entanglement connection is achieved. This has greatly improved the connection efficiency of the quantum repeater, and the practical application of the quantum network has taken another key step. Liu *et al.* [13] first proposed and developed an on-demand read-on-demand solid-state quantum memory with a storage fidelity of 99.3 ± 0.2 percent. This is of great significance for the wide-area quantum network, large-capacity quantum storage, and the development of quantum intelligence applications. In addition, Li *et al.* [14, 15] firstly proposed connection-oriented and connectionless remote entanglement distribution strategies and designed a novel fidelity-guaranteed entanglement routing scheme by leveraging entanglement purification, which pave the road for the implementation of large-scale quantum networks from the perspective of networking protocols.

Moving toward a fully operational quantum network is full of difficult challenges, and its implementation still has a long way to go, which requires the concerted efforts and hard work of many researchers.

Properties of Quantum Communications

After the above analysis, compared with traditional communications, we summarize the unique characteristics of quantum communications, which are recorded in Table 2 Specifically:

- Unconditional security: The key to quantum communications is non-reproducible and absolutely secure. Once eavesdropped, the communication information will be terminated immediately and the two communicating parties will be informed, even if the attacker has infinite computing resources and any means of eavesdropping.
- Efficiency: Based on the superposition and entanglement properties of quantum states, quantum communications will surpass the efficiency of traditional communications in transmitting and processing information.

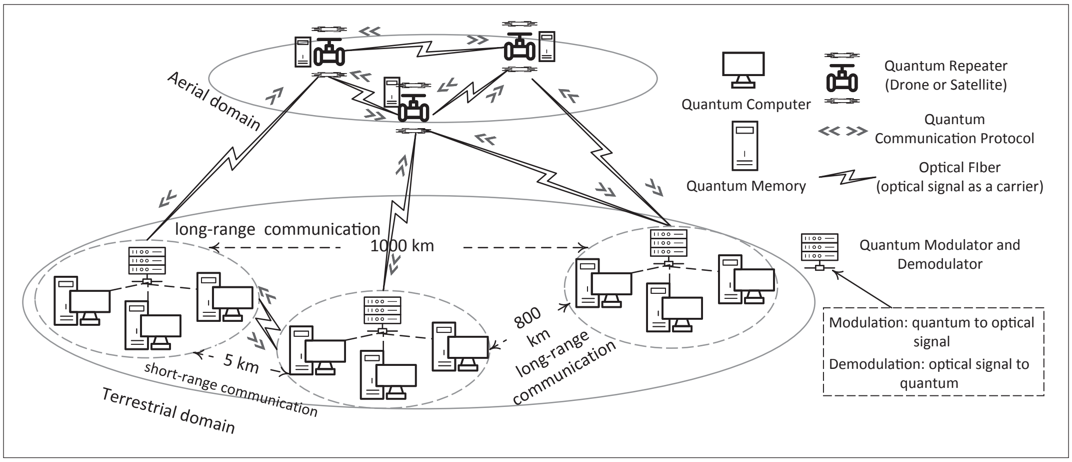

FIGURE 3. Details of future quantum communications network (QCN) architectures.

Quantum communications take the quantum state as the information carrier and realize quantum information or classical information transmission technology through the transmission of the quantum state.

- Wide range of applications: Quantum communications are not limited by the transmission medium. It can communicate all in the air, under the sea, and in media such as optical fibers.
- Strong anti-interference: The transmission of entangled qubits in quantum communications does not pass through traditional channels, so it has a better anti-interference ability.
- Good concealment: The third party cannot monitor or detect, and there is no electromagnetic radiation.

Future Quantum Network Architecture: A Vision

Now, we are in the initial stage of preparation for the development of quantum networks, that is, the research, development, deployment, and testing of related infrastructures (quantum memories, quantum repeaters, quantum computers, quantum communications protocols, etc.), short-range, medium-range and long-range quantum communications. Excitingly, this is similar to the "eve" of the birth of Arpanet, and we are in an era of massive change in the Internet. At that time, the development of traditional computers encountered a setback, and the first Internet message was forwarded through only four nodes. However, after the hard work of researchers, the traditional computer and the Internet were born. This is exceedingly similar to the trajectory of quantum networks today, we are in the golden age of both opportunities and challenges for the development of quantum networks.

In this section, based on the quantum network QCN with drones and satellites as repeaters proposed in Fig. 1 (Drones and satellites as flexible quantum repeaters expansion nodes to achieve global wide-area coverage), and based on existing fundamentals, we have fully anticipated the details of the future quantum network architecture manifested in Fig. 3. Specifically, quantum computers, as the general term for quantum devices with computing capabilities, realize logical operations through the laws of quantum mechanics and will support the development of AI applications in quantum networks. Quantum modulators and demodulators are used to convert quantum signals and optical signals to connect quantum computers located in different places. Due to the decoherence phenomenon of quantum entanglement, it is necessary to use optical fibers for the transmission of optical signals of quantum information carriers. Meanwhile, the quantum repeater is utilized for extended communications over arbitrary distances. Quantum memory is employed to store and forward the Qubit of quantum devices. The quantum communication protocol is exploited to constrain the communication process of the quantum entities of both parties, that is, to comply with the pre-established regulations, so that they can work together in an orderly manner to achieve information exchange and resource sharing.

Quantum Network Communication: Working Principle

In the proposed future quantum network prototype, how to carry out information transfer and communication between entangled particles located in different places becomes the next problem we are concerned about.

Core Directions

Quantum communications take the quantum state as the information carrier and realize quantum information or classical information transmission technology through the transmission of the quantum state. It is an emerging research field that combines quantum theory and information theory developed in recent years. Moreover, it includes a variety of protocols and applications, such as Quantum Key Distribution (QKD), Quantum Teleportation (QT), quantum dense coding, and so on. Recently, this discipline has gradually moved from theory to experiment and developed toward practicality [14]. Based on the basic principles of quantum mechanics, it has become an international research hotspot in quantum physics and information science.

QKD is a method in which both parties of the communication can jointly generate a set of random numbers (which can be used as symmetric keys) by transmitting quantum states [6]. Furthermore, QKD and QT are two fundamental research directions. QKD allows spatially separated users to share unbreakable keys, so it has always been an essential direction for quantum communications and is the quantum communications technology with the highest degree of practicality and engineering, which has long been agreed upon internationally.

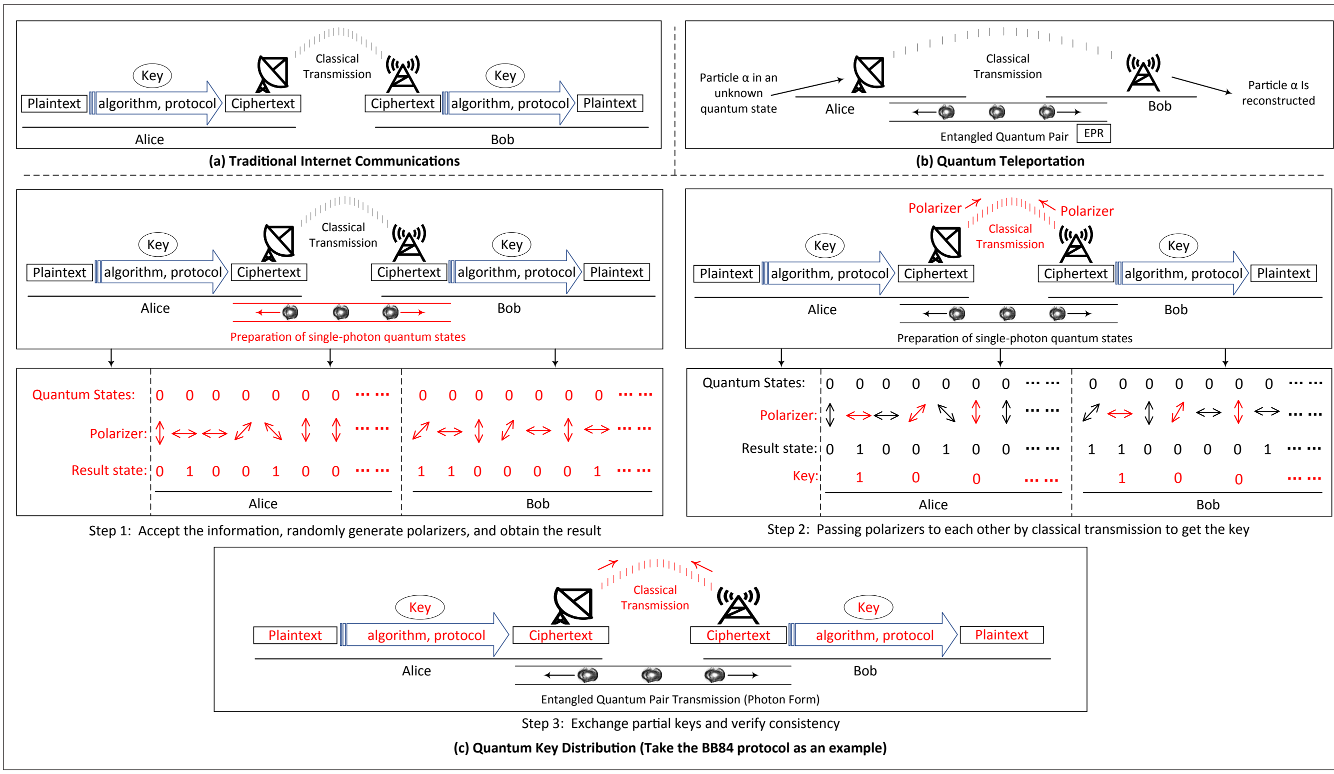

FIGURE 4. Comparison of traditional communication, quantum teleportation, and quantum key distribution processes. In the QKD process, the red part represents the work that the current step responds to.

Traditional Internet Communications

In information communications, the security of information is mainly: confidentiality, authenticity, integrity, and non-repudiation. Confidentiality refers to the inability of third parties to eavesdrop. Authenticity means that the identities of both parties in the communication are true and reliable. Integrity means that the communication information has not been tampered with. Non-repudiation means that the communication information cannot be denied. The mainstream means of ensuring information security is modern cryptography, which mainly includes three parts: algorithm, protocol, and key. Except for the key, the other two parts are public. Therefore, the essential point to guarantee communication security is to ensure the security of key distribution. Traditional Internet encrypted communication is shown in Fig. 4a, where the key is only known by both parties Alice and Bob, and the encryption algorithm and protocol are public. Using the key, Alice encrypts the communication plaintext into ciphertext and sends it to Bob. Bob receives the information and uses the key to decrypt the ciphertext into plaintext. However, it is easy to be eavesdropped on and cracked in the process of ciphertext transmission, which makes the communication in an unsafe environment.

Principles of Quantum Communications

After development, the BB84 protocol is the most widely used one with mature security demonstrations. The optical fiber QKD equipment based on this protocol has been partially commercialized. In addition, the B92 protocol simplifies the four polarizers into two, but due to the high bit error rate, its coding efficiency is also halved, the security is lower than that of BB84, and the requirements for communication lines are higher. The E91 protocol is based on quantum entanglement, but since it is equivalent to the BB84 protocol using single photons, entangled photons are more difficult to prepare than single photons. Therefore, we take BB84 as an example to analyze the principle and characteristics of QKD. Specifically, its flowchart is shown in Fig. 4c, and the specific process is as follows.

Step 1: Through the entangled qubits transmission channel, Alice and Bob receive entangled qubits containing information in turn, and obtain the resulting data through a group of randomly generated polarizers.

Step 2: Through the classic transmission channel, Alice and Bob transmit their polarizers to each other, respectively. Data with different polarizers will be discarded and the same will be retained. At this point, Alice and Bob have obtained the same data, which is their common key known only by themselves.

Step 3: Verify the consistency by sending a part of the key to the other party. If they are consistent, both data are valid. Otherwise, the communication is in an insecure environment and will be canceled. After that, the key is encrypted into ciphertext and passed through the classic transmission channel, and the receiver decrypts the ciphertext through the key.

Advantages of QKD: In quantum communications, quantum is non-replicable, that is, it is impossible to accurately replicate an unknown quantum state. Unlike traditional communications, QKD has two transmission channels. One of these channels is employed to transmit classical information. The other channel is used to transmit entangled qubits, which as analyzed earlier usually propagate in the form of optical signals. Therefore, if the entangled qubits are intercepted or listened to in Step 1, this destroys the entangled relationship of the quantum state. Then in Step 3, the inconsistency of the data will be found, and the eavesdropper can be found immediately. Based on the properties of quantum mechanics, QKD can generate and distribute unconditionally secure communications keys.

Limitations of QKD: However, secure quantum communication represented by QKD is also limited by the characteristics and development level of QKD technology, equipment, networking, and network capability provision. Specifically:
- QKD itself cannot provide identity authentication of communication clients. Therefore, an asymmetric cipher or preset key is also required to provide authentication.
- The security of QKD is based on a specific physical layer communication. This requires dedicated fiber optic connections or physically controlled free-space transmitters. Being a hardware system, it may introduce vulnerabilities, lack of security patches and flexibility for system upgrades.
- The need for equipment such as quantum repeaters will increase the cost of construction and the use of security facilities.
- The actual security provided by QKD is more dependent on the limited security provided by hardware and engineering design.
- QKD also increases the risk of Denial of Service (DoS).

Therefore, due to the above problems, it is difficult for QKD to achieve the ideal "absolute security," and there is still a long way for QKD to be fully practical.

Principles of Quantum Teleportation

The role of QKD is to keep secrets, and the role of QT is to transmit Qubit. QT is an important communication method for transferring quantum states. It transfers the quantum information carried by the quantum state with the help of the quantum entanglement effect, the process of which is shown in Fig. 4b.

First, Alice and Bob receive an entangled quantum pair containing information. Second, Alice performs a joint measurement on the particle a in the unknown quantum state, and transmits the result to Bob through the classical channel. Based on the effect of quantum entanglement, the particle held by Bob will change simultaneously with Alice's measurement and become a new quantum state. Bob performs a unitary transformation to reconstruct the particle a. It can be seen that QT still needs to use the classical channel combined with the quantum channel to transmit quantum information.

Conclusion and Future

In this work, we analyze the development of quantum network-related technologies and the bottleneck challenges to be solved. Furthermore, we fully outlook and propose a prototype of a future quantum network architecture with drones and satellites as extended repeaters. Finally, we analyze the principles and properties of quantum communications compared with traditional communications.

The Internet has changed our lives, and quantum mechanics is changing the Internet. In recent years, quantum network-related equipment and technologies have received good news one after another, and the era of quantum networks has arrived. Quantum communications and networking have entered a period of thriving. For some time to come, we should focus on the improvement of quantum network-related infrastructure technologies. Especially the main components like quantum memory, quantum repeaters, and so on. The equipment should be made more stable, cost-effective, and easy to maintain. In addition, building the basic backbone of quantum communications on the existing basis will also be an obligatory key challenge.

The Internet has changed our lives, and quantum mechanics is changing the Internet. In recent years, quantum network-related equipment and technologies have received good news one after another, and the era of quantum networks has arrived.

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