COVER PAPER

Building a Large-Scale and Wide-Area Quantum Internet Based on an OSI-Alike Model

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Abstract: The theory and experiment of quantum information have been studied extensively in recent years, and the feasibility of quantum communication has been proved. Although the fundamental technology is not yet mature, research on quantum internet should be conducted. To implement quantum internet, an architecture that describes how quantum nodes are linked to form networks and how protocol functions are vertically composed need to be developed urgently. In this paper, we present a novel design of a cluster-based structure to describe how quantum nodes are interconnected, and how the structure can improve the performance of qubit transmission and reduce the network complexity. The idea of the quantum local area network (QLAN) is proposed as an essential component of the quantum internet. Besides, each quantum repeater links to neighboring repeaters to form a core network, and multiple QLANs are connected through the core network. The core network can be grouped into different hierarchical quantum repeater networks according to needed service requirements. For the sake of interoperability and fast prototyping, we adopt the idea of OSI layering model of the current Internet in the design of quantum internet. Finally, we elaborate on the composition of quantum nodes and the realization of end-to-end communication.

Received: May 09, 2021
Revised: Jul. 01, 2021
Editor: Zhipeng Gao

Keywords: quantum internet; entanglement swapping; quantum repeater; teleportation

I. INTRODUCTION

Quantum information brings new opportunies and challenges to many technical fields, especially in secure communications. In traditional communications, the security of information is guaranteed by encryption algorithms with the hypothesis that they are too complex to be compromised [1]. Unfortunately, the computational security cannot hold for a quantum computer that would crunch current security algorithms in minutes or seconds [2]. The security of quantum communication is based on the physical properties of quantum mechanics. For example, the no-cloning theorem indicates that quantum states cannot be copied during transmission [3], and thus eavesdroppers can be easily detected. Besides, the properties of unitary and entanglement are also conducive to quantum secure communication [4, 5]. Based on these properties, the communication between any two quantum parties can be unconditionally secure.

Quantum communication has been proved to be feasible both theoretically and experimentally [6]. So far, a broad range of fundamental studies have been made in the area of secure communication, from quantum key distribution (QKD)–a protocol to generate random secret keys used to encrypt classical information–to the work of transmitting quantum data in the form of quantum bits (qubits) [7, 8]. However, the existing implementation of quantum communication only focuses on short-distance and small-scale scenarios, and the network topology is relatively simple [9, 10]. The difficulty in scaling up the transmission distance is attributed to that (1) quantum states are susceptible to channel noise, and (2) unlike classical communication, the signal amplification technology cannot be used in quantum communication due to the no-cloning theorem. Physical devices are required to overcome the effects of photon loss and the quantum decoherence inherent to the transmission medium, e.g., optical fiber and free space. Fortunately, the second quantum revolution accelerates the progress of quantum physical devices, particularly quantum memory [11, 12] and quantum repeaters, which brings promise for realizing quantum communication between any two far apart quantum nodes.

Quantum internet is a global network capable of transmitting qubits between any two quantum nodes. However, as the range and scale of quantum communication increases, how to connect thousands of quantum nodes in an effctive and efficient way is a key problem that needs to be solved. We should also design multiplexing protocols to enable efficient communications among multi-pair quantum nodes. Besides, future quantum network services or applications will become more diverse, such as quantum clock synchronization, metrology, and distributed quantum computing [13]. A flexible and inclusive quantum internet is an indispensable infrastructure to support these services. Hence, to implement a large-scale, wide-area, application-aware and inclusive quantum internet, an architecture that describes how quantum nodes are connected and how protocol functions are cohesively composed should be designed.

The design of the quantum internet is rooted in the realization of qubit transmission. Entanglement, i.e., a property of quantum physics that two entangled parties can influence each other no matter how far apart they are, provides possibilities for quantum communication and applications. Teleportation is an entanglement-based qubit transmission technology, which can protect qubits from channel noises in long-distance quantum communications. Besides, entanglement is well suited for applications that require coordination, synchronization, or privacy. Examples of such applications include clock synchronization, leader election, and secure identification. Hence, the quantum Internet architecture should be designed to enable efficient entanglement generation between quantum nodes located anywhere.

To scale up existing small-scale experimental quantum networks to a large-scale, wide-area quantum internet, a hierarchical and scalable network structure and open protocol stacks are urgently needed. In this paper, we discuss the realization of remote qubit transmission and present a communication model to describe the implementation of parallel communications. To improve the performance of qubit transmission and reduce network complexity, we propose a cluster-based structure to describe how a significant number of quantum nodes are interconnected. We consider that the quantum Internet consists of four types of quantum nodes, i.e., end nodes, slave nodes, master nodes, and quantum repeaters. Some slave nodes and a master node are grouped into a cluster called quantum local area network (QLAN), and each quantum repeater links to neighboring repeaters to form a core network. Multiple QLANs are connected through the core network to achieve wide-area quantum communications. Moreover, to provide an universally common and open interfaces for end-to-end quantum communications, we adopt the idea of layering structure inspired by the TCP/IP model in the design of protocol stack for quantum internet. Here, an OSI-alike protocol stack is presented, and each layer hosts various protocols to realize the particular goal of that layer. In what follows, we elaborate on the architecture of the quantum node and how different layers collaborate to implement end-to-end qubit transmission.

The rest of this paper is organized as follows. In Section II, we discuss the implementation of remote quantum communication and show a quantum communication model. Next we present the architecture of the quantum internet based on entanglement, i.e., cluster-based structure, and protocol stack in Section III. After that, the implementation of qubit transmission under our proposed architecture is described in Section IV. Finally, we conclude with a summary of our work and take an outlook of the quantum internet in Section V.

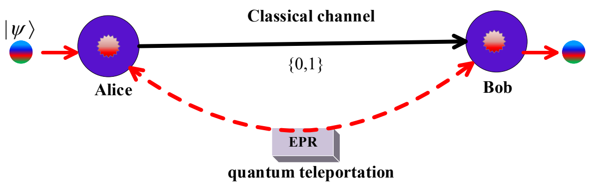

Figure 1. *Teleportation. The local measurement operations and classical communication (LOCC) are performed between two communicating parties to teleport qubit.*

II. REMOTE QUANTUM COMMUNICATION

Remote quantum communication provides a promising building block for quantum internet. However, qubit, the basic unit of quantum information, follows the principle of no-cloning theorem, which leads to the fact that a standard technology of signal amplification cannot be used in quantum communication. Hence, the challenge of how to implement remote quantum communication needs to be overcome first before designing quantum internet architecture.

Remote end-to-end quantum communication cannot be achieved by means of hop-by-hop forwarding. In classic networks, the transmission of packet is generally realized by the store-and-forward scheme [14], which means that packets sent from the source host are stored and processed by all router nodes on the transmission path till they reach the destination host. The most intuitive method of implementing long-distance end-to-end quantum communication is direct hop-by-hop forwarding. In this way, qubits sent from the sender are stored and forwarded down the link toward a neighboring quantum node till the end of the connection (i.e., destination). Note that the drawback of hop-by-hop forwarding is that this method places the valuable qubit at the inevitable risk of signal loss since multiple transport and access operations in quantum memory increase the probability that quantum state drifts from its assigned value. Therefore, a direct hop-by-hop forwarding way is not an ideal choice for remote end-to-end qubit transmission.

The properties of quantum mechanics provide new solutions to the transmission of qubit. Remote quantum communication is limited by the effects of photon loss and decoherence inherent in transport media. However, the phenomena in quantum physics,

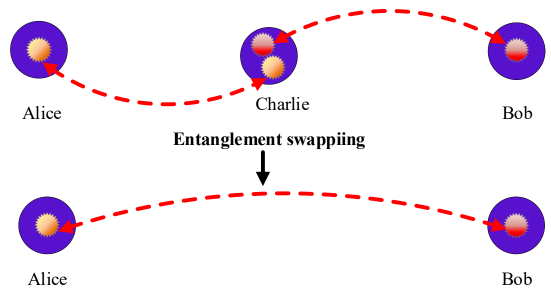

Figure 2. *Entanglement swapping. Two short-distance entanglements can be extended to a remote entanglement between Alice and Bob by performing the LOCC operation on two un-entangled states that Charlie stores.*

with no counterpart in classic networks, compel researchers to seek innovative ways to transmit qubits. Teleportation [15]–a typical entanglement-based qubit transmission technology that can make qubits free from channel noise–is shown in Figure 1. Alice and Bob share a pair of entangled states, i.e., they are entangled. First, Alice jointly measures the qubit to be transmitted and the entangled state that she owns, and then Alice informs Bob the measurement result through a classical channel. According to the result, Bob performs unitary operations to obtain the qubit. Therefore, an improved method compared with hop-by-hop forwarding is to establish entanglement over each quantum link and teleport qubit hop-by-hop. However, considering the attenuation of quantum fidelity per hop, hop-by-hop teleportation still leads to a high bit error rate.

An alternative to the hop-by-hop transmission of qubit is end-to-end teleportation, and it can effectively reduce the influence of channel and memory noise on the qubit. The precondition of end-to-end teleportation is that two communicating parties are entangled. However, two distant nodes cannot directly share a pair of entangled states distributed by the same light source due to photon loss. As a result, the challenge of end-to-end teleportation is how to convert link-level entanglements into long-distance end-to-end entanglement. Quantum repeaters play an important role in overcoming the challenge by performing entanglement swapping on the link-level entanglements [16–19]. As shown in Figure 2, Alice and Bob pre-share a pair of entangled states with Charlie respectively. And a joint measurement is performed on the two entangled states that Charlie stores. As a result, Alice and Bob established

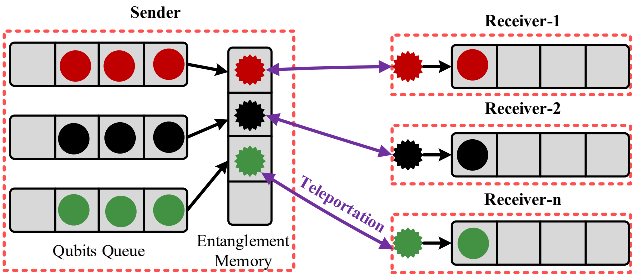

Figure 3. *Quantum communication model. The entangled states shared by communicating parties are store in entanglement memory, and the qubits stored in different quantum queue can be teleported concurrently by performing the LOCC operations.*

a new entanglement system. Hence, any pair of quantum end nodes that are non-entangled can establish entanglement via hop-by-hop entanglement swapping, and then end-to-end teleportation can be performed to teleport qubits.

A quantum internet needs to support both long-distance and parallel quantum communication, and quantum memory [20, 21] is an indispensable part to achieve these goals. For remote quantum communication, a pair of entangled states cannot be reused after the LOCC operation and can only be used to teleport one qubit. Hence, a sender generally needs to establish sufficient entanglements with a receiver to teleport numerous qubits. Quantum memory can realize the storage of quantum states. With the help of quantum memory, therefore, long-distance and parallel quantum communication can be realized. In general, the quantum communication model describing long-distance and parallel end-to-end qubit transmission is shown in Figure 3. Each quantum node can equip with two types of quantum memory, i.e., entanglement memory and qubits queue. Each pair of entangled states distributed by light source can be used directly or stored in entanglement memory, and entangled states are used to implement entanglement swapping or teleportation. Besides, the qubits waiting to be transmitted are stored in the queue. If there is a pair of shared entangled states in entanglement memory between the sender and receiver (end-to-end entanglement has been established), the qubit can be teleported from the sender to the receiver by performing teleportation.

III. QUANTUM INTERNET

Long-distance quantum communication can be realized by entanglement-based technologies, and it is significantly different from classical communications. The implementation of the quantum internet requires full consideration of entanglement-based technologies. Hence, the architecture of quantum internet also needs to be a novel design. In this section, we present the architecture of the quantum internet based on quantum entanglement, i.e., cluster-based structure and protocol stack.

3.1 Cluster-based Structure

Before elaborating on the structure of the quantum internet, here are some preconditions. First, in addition to configuring a quantum system, we assume that each quantum node is also capable of processing classical information since classical information is inseparable from quantum communication [22, 23]. Quantum nodes are linked by quantum channels, and there is always a path in classical networks to realize classical communication between any two quantum nodes. Second, note that quantum states are unknown to quantum nodes during transmission. Hence, an identification label is necessary to distinguish quantum states from each other, especially the different pairs of entangled states. Besides, a pair of entangled states can only transmit one qubit. Two communicating parties need to establish sufficient slave-to-slave entanglement with the help of entanglement memory. We assume that quantum repeaters and master nodes try to distribute entangled pairs when link-level entanglement is consumed. Hence, entangled states can be supplemented to provide services for entanglement swapping or teleportation to improve the performance of qubit transmission.

The quantum internet can be characterized by four types of quantum nodes, i.e., end nodes, slave nodes, master nodes, and quantum repeaters. An end node is a terminal device on which quantum applications are run. Slave nodes are configured with a quantum system that can store, forward quantum states, and process entangled states locally by using quantum gates [24] to implement teleportation. Master nodes and quantum repeaters are configured with entangled source to implement link-level entanglement genera-

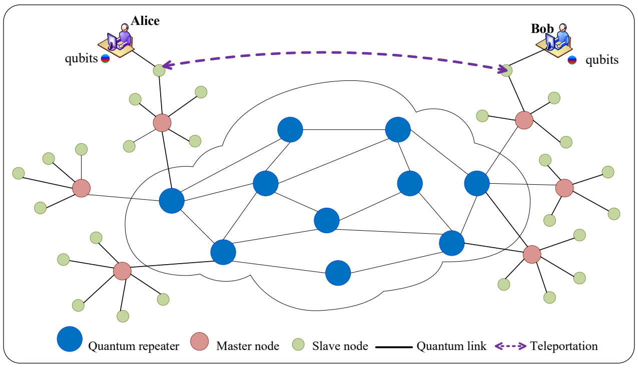

Figure 4. *The structure of the quantum internet topology. The quantum internet is composed of a number of QLANs and the core network. QLANs adopt the master-slave structure, and each quantum repeater links to neighboring repeaters to form the core network.*

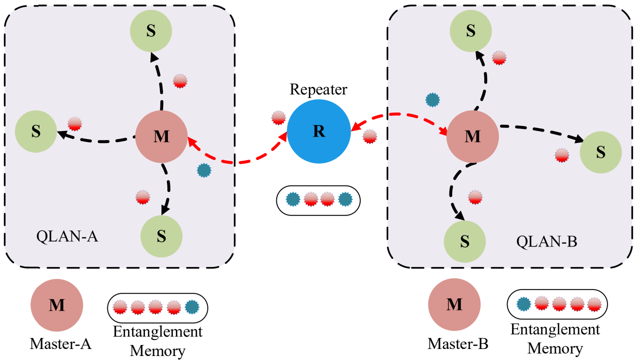

Figure 5. *The establishment of slave-to-slave entanglement. Slave nodes in the same QLAN are entangled in pairs. And slave nodes in different QLANs establish entanglement by performing entanglement swapping on a quantum repeater chain.*

tion. Besides, quantum repeaters are also responsible for the function of routing and extending the distance of quantum communication. Here, we present an innovative scheme of grouping some slave nodes and a master node into an area-based cluster, and we call the cluster "quantum local area network (QLAN)". A master-slave structure is adopted in QLANs–slave nodes link to a master node, and the master node is mainly responsible for establishing intra-cluster entanglement, i.e., any pair of slave nodes are entangled in a QLAN, and any two slave nodes perform teleportation to teleport qubits. Besides, each quantum repeater links to neighboring repeaters to form a core network. Multiple QLANs are connected through the core network to implement wide-area quantum communication. Generally, we can divide the core network into different hierarchical quantum repeater networks according to different service requirements. Small-scale repeater networks provide service for QLANs in its area, and different repeater networks can be connected through a wide-area repeater network. The structure of the quantum internet topology is shown in Figure 4.

The rate of remote slave-to-slave entanglement establishment has a significant influence on the performance of qubit teleportation. A naive way to improve the rate of slave-to-slave entanglement generation is to make the entangled pairs shared by any pair of slave nodes come from the same entanglement source as close as possible to reduce the number of entanglement swappings. In some existing studies on quantum networks, it is assumed that an entanglement source is deployed between any pair of adjacent quantum nodes to realize link-level entanglement distribution [25, 26]. In such a normal chain structure, the establishment of long-distance entanglement requires more entanglement swappings to be performed compared to the master-slave structure in our design. As a result, more entangled states need to be prepared, distributed, stored and measured.

The master-slave structure design can improve the performance of qubit transmission by reducing the number of entanglement swappings. In our master-slave design, slave nodes in the same QLAN are entangled with each other by sharing a pair of entangled states distributed by the master node. Entanglement between two slave nodes in different QLANs is established by performing entanglement swapping on a quantum repeater chain in the core network. When quantum communication occurs between two end nodes in the same QLAN, there is no need to perform entanglement swapping. When quantum communication happens between different QLANs, the number of entanglement swapping performed is equal to the number of quantum repeaters spanned between two QLANs, and the number of swapping is two less than the normal structure that entanglement source is deployed between any two quantum nodes. For example, two different QLANs are connected by a repeater, and the master nodes can distribute entangled states to quantum repeaters (Figure 5). Only one entanglement swapping is needed between two slave nodes because they share a pair of entangled states with the middle repeater. For a normal chain structure, however, more than three entanglement sources need to be deployed, and entanglement swapping needs to be performed four times in this scenario. Hence, the master-slave structure can effectively reduce the number of entanglement swapping compared to the normal chain structure to improve the performance of qubit transmission and reduce the complexity of quantum networks.

The process of end-to-end quantum communication is determined by the location relationship between any pair of end nodes. In our design, there are three scenarios of quantum communication between two end nodes (referred to as Alice and Bob), i.e., Alice and Bob connect to the same slave node, Alice and Bob connect to different slave nodes in the same QLAN, and Alice and Bob are in different QLANs (Figure 6). Besides, both teleportation and direct transmission are adopted, and the implementation of qubit transmission in the three scenarios is different.

In the first scenario, there is only one hop, i.e., a slave node, between Alice and Bob, and they are usually close to the common slave node. Most notably, the implementation of teleportation requires entanglement distribution and Bell state measurement. Besides, a pair of entangled states can be used to teleport one qubit. In the case of one hop, teleportation incurs more overhead and delay than direct transmission. Hence, the qubits are transmitted directly from Alice to the slave node in our design, and the slave node forwards the received qubits to Bob in this scenario, which is simpler and more efficient than performing teleportation between Alice and Bob. In the second scenario, the two slave nodes connected by Alice and Bob are entangled as they share a pair of entangled states distributed by the master node in QLAN, and we can perform teleportation directly to teleport qubit between two slave nodes. Accordingly, the qubit can be forwarded from slave nodes to end nodes like in the first scenario.

In the third scenario, entanglement is the pre-requisite of teleportation. To establish slave-to-slave entanglement, a path from Alice to Bob needs to be pre-determined according to an entanglement routing algorithm, and then quantum repeaters on the path try to perform entanglement swapping to establish entanglement between the two slave nodes

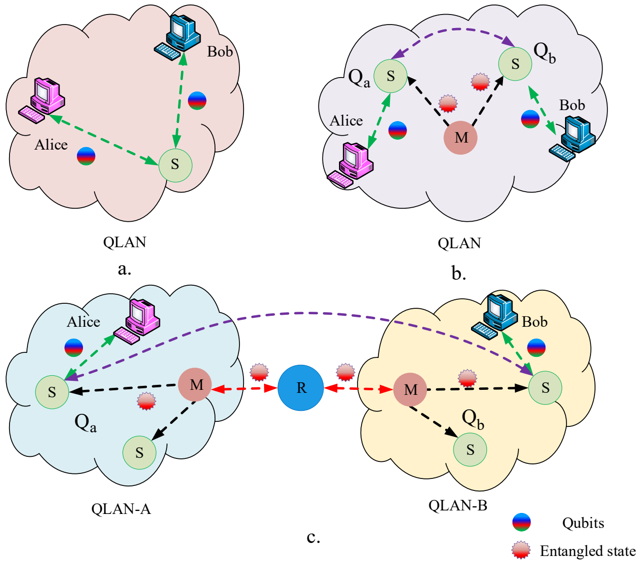

Figure 6. *Three scenarios of end-to-end quantum communication. Quantum communication is realized by the schemes of direct transmission and teleportation in the quantum internet.*

connected by Alice and Bob. When slave-to-slave entanglement is established, slave nodes can perform teleportation and forward the qubit to the end nodes. In the process, entanglement routing is an interseting research topic worth studying. Most notably, quantum states cannot be measured during transmission. Therefore, entanglement routing is mainly completed by classical communication over a classical network. In the implementation of entanglement routing, quantum repeaters can only represent the relevant characteristics of their quantum system, e.g., the fidelity of quantum memory, the rate of entanglement distribution, and the success rate of entanglement swapping. Classical information is responsible for collecting the characteristics to form a routing table. In general, there are two types of entanglement routing algorithms, i.e., centralized and distributed. We will focus on the design of entanglement routing in our next work.

The fidelity attenuation of a quantum system cannot be ignored in each of the three scenarios. The fidelity–an index for tracking the quality of quantum states–decreases gradually during communication due to decoherence [27, 28] and noise. Quantum decoherence is one of the key obstacles in the applications of quantum information, and it will result in a high error rate. Hence, we should employ related techniques for managing bit errors. Here are some schemes that have been developed [29, 30], some based on classical error correction, and others are realized based on quantum technologies. In general, we need to improve the fidelity of quantum states by performing purification or distillation.

3.2 Protocol Stack

To simplify the complex problem of end-to-end quantum communication and meet the increasingly complex requirements of quantum applications to support the iterative development of quantum internet, an overarching stack and related protocols must be developed. The stack describes how protocol functions are vertically composed to realize quantum communication. Before developing the stack, we must first understand the process of entanglement-based end-to-end quantum communication. In general, the processes associated with entanglement in long-distance quantum communication are divided into the following parts:

- **entanglement preparation.** Each master and quantum repeater generates entangled pairs used for establishing entanglement between any two slave nodes or performing teleportation to teleport qubits. Entangled pairs will be stored in entanglement memory or distributed directly.
- **entanglement distribution.** The masters and quantum repeaters distribute entangled states through quantum channels, such as optical fiber and free space, to neighboring quantum nodes to establish link-level entanglement.
- **entanglement establishment.** An entanglement path from the source slave node to the destination composed of multiple quantum repeaters is selected according to the routing algorithm, and entanglement swapping is iteratively performed on the repeaters chain. As a result, the link-level entanglement is converted into a remote slave-to-slave entanglement.
- **quantum teleportation.** After slave-to-slave entanglement is established, teleportation is realized by performing LOCC in both the source and the destination slave node to transmit qubit.

We propose a protocol stack for quantum internet inspired by the layering idea of the TCP/IP protocol architecture. In the TCP/IP architecture, the processes of classical end-to-end communication are divided into five layers, and the functions of each layer are specified. Layers are independent of each other. Each layer only needs to provide an interface for its adjacent layers, and each interface defines what information and services a layer must provide for the layer above it. Besides, each layer does not need to know the implementation details of other layers. The design of the stack simplifies the complex design problem of end-to-end communication and network interconnection. Most notably, the steps involved in achieving quantum communication between any pair of end nodes are independent. The end-to-end quantum communication processes can be divided into five layers, and the design is shown in Figure 7. Note that the tasks of each layer on the quantum internet are significantly different from those of each layer on the traditional Internet. What follows are some new issues that need to be addressed in each layer.

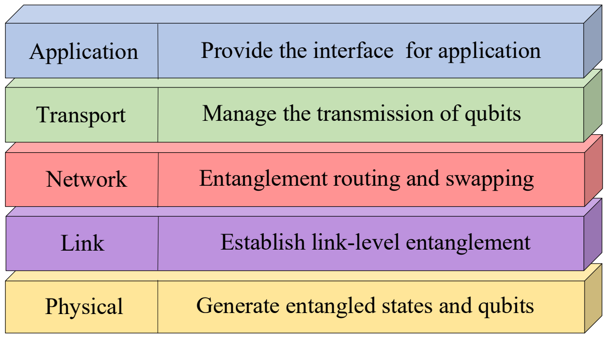

Figure 7. *A protocol stack for quantum Internet. The protocol stack contains the physical layer, link layer, network layer, transport layer and application layer with different functions.*

3.2.1 Physical layer

The physical layer is responsible for solving the problems caused by the difference of quantum physical devices and the processing of quantum information. In the traditional Internet, the physical layer should shield the difference between the physical device and the transmission medium to enable the upper layer to be oblivious of the channel. In the quantum internet, the physical layer needs to realize the similar functionality. First, this layer is responsible for converting quantum information in different forms between quantum memory and quantum channel to the form of each other. In quantum networks, each quantum node will be connected to others by different quantum channels, such as optical fiber or free space. Note that qubits normally are stored in quantum memory for a certain time before being measured and transmitted. A quantum device may store qubit in ion-trap [31] or NV-center [32, 33], but the transmission of qubit is achieved by optical setup [34]. Therefore, the physical layer in quantum internet must shield the difference between the physical device and the transmission medium as well.

In addition, quantum network devices may employ different communication technologies and strategies. For example, quantum nodes use different pulse frequencies in an optical setup to generate and transmit qubit, and two quantum nodes employ different encoding methods to convert quantum information into qubit. Hence, a converter should be adopted to translate between those different communication technologies and transmission strategies in the quantum internet. Note that the quantum information represented by a quantum state cannot be obtained before measuring the quantum state, and the physical layer thus needs to implement the measurement of quantum states. In general, quantum states exist in the form of photons, and the preparation of qubits and entangled photons is also realized at the physical layer.

3.2.2 Link layer

The main function of the link layer is to establish entanglement between adjacent quantum nodes. To achieve end-to-end quantum communication, two slave nodes must first establish long-distance entanglement by performing entanglement swapping. In this process, the physical layer is responsible for generating link-level entanglements, and the responsibility of the network layer is to choose an entanglement path used to establish long-distance entanglement. Therefore, the main work of the link layer is to realize the distribution of entangled states to establish short-link entanglements in the quantum internet.

In our design, there are master nodes, one in each QLAN, and quantum repeaters to fulfill the work. With the help of quantum memory, entangled states can be stored in an entanglement memory and consumed when entanglement swapping or teleportation is required. And it is also worth noting that each entanglement swapping consumes one entangled pair that can not be reused after measurement. Neighboring nodes should keep being entangled to provide service for other communication tasks. Hence, the link layer should design protocols for controlling entanglement distribution and process feedback from the network layer to keep entanglement between two neighboring repeaters. Besides, direct forwarding is adopted to transmit qubit between end nodes and slave nodes in our design. Therefore, this layer is also responsible for forwarding qubits between end nodes and slave nodes. Whether it is entanglement distribution or transmitting qubit, the obligation of the link layer in each quantum node is to forward quantum states to neighbors. Most notably, quantum decoherence results in the attenuation of entanglement fidelity, and entanglement purification is required to improve fidelity. Entanglement purification is implemented at the cost of the reduced number of link-level entanglements, i.e., entanglement purification is usually performed at the link layer. Hence, the link layer is also responsible for implementing entanglement purification for two entangled nodes, which can ensure that long-distance slave-to-slave entanglement has a sufficiently high-fidelity.

3.2.3 Network layer

This layer is responsible for establishing long-distance slave-to-slave entanglement. The network layer consists of two important parts, i.e., entanglement routing and entanglement swapping [35]. Entanglement routing aims to pre-define communication paths from the source slave node to the destination slave node. Entanglement swapping is responsible for patching multiple link-level entanglements together into a remote slave-to-slave entanglement. Hence, the main work of the network layer is to pre-define a communication path and perform entanglement swapping on the path. Here, we focus on the problem of entanglement routing. In general, multiple paths can be selected for establishing entanglement between the two distant slave nodes. However, path selection has a significant impact on the entanglement resource consumption and the performance of end-to-end quantum communication. The network layer is supposed to choose a good path to perform entanglement swapping.

In traditional Internet, there have been many well-known routing algorithms, such as the Dijkstra algorithm and Bellman-Ford algorithm [36, 37]. Their commonality is to apply a cost function to evaluate the path. The cost function needs to consider many indicators including latency and hop count. However, the routing algorithms in the quantum internet need to be redesigned due to the properties of quantum physics. Some papers have proposed some routing algorithms [38, 39], but these designs simply apply the classical routing algorithms to quantum internet without adaptation to the uniqueness of quantum properties. At the network layer, entanglement routing is mainly completed by classical communication over a classical network, and quantum repeaters can only represent the relevant characteristics of their quantum system. Classical information is responsible for collecting the characteristics to form a routing table. Here, we briefly discuss the metrics that need to be considered for the cost function of entanglement routing.

There are several metrics that we consider in this process. First, the distance of the quantum channel is a momentous metric due to the fact that quantum states are susceptible to channel noise. The distance of the channel affects the success rate of entanglement distribution, the fidelity of quantum states, and the success rate of entanglement swapping. Second, since entanglement plays an important role in quantum communication, we also take entangled source (entanglement memory size) into account. In our design, entangled states are stored in memory to provide service before performing entanglement swapping. Entangled source affects the rate of establishing slave-to-slave entanglement and teleportation. Besides, hop count must also be considered. Fewer hops can reduce the latency of long-distance entanglement establishment and improve the fidelity of slave-to-slave entanglement. Quantum states can only be stored in quantum memory for a short period of time. The life-time of quantum states is also an important factor. There is a trade-off between the above metrics, and routing requires comprehensive consideration of them. We will only discuss entanglement routing briefly here, and the design of cost function by integrating these metrics will be our future work.

3.2.4 Transport layer

The responsibility of the transport layer is to realize the reliable transmission of qubits. In the traditional Internet, the information to be transmitted will be divided into a certain number of packets, and these packets are transmitted by packet switching means. In general, the reliable transmission of classical communication is mainly to solve the problem of out-of-order packets, packet loss, and network congestion. However, quantum information exists in the form of qubits, and qubits transmission is mainly implemented by teleportation between two distant end nodes, which is fundamentally different from the transmission of classical information. How to realize the reliable transmission of qubit needs to be reconsidered at the transport layer.

The transmission of qubits in our design is divided into two ways: direct forwarding and teleportation. The method of reliable transmission adopted in the traditional network is suitable for direct forwarding. For teleportation, however, one teleportation can only transmit one qubit, and the order that the qubits arrive at the receiver can well correspond to the order in which they are sent, i.e., there is no problem with out-of-order qubits. Hence, the reliability we discuss mainly includes the processing of qubit loss, error correction, and network congestion. Those problems are mainly caused by the characteristics of quantum communication. First, quantum state is the smallest unit of physics, and qubits are susceptible to channel noise. As a result, photon loss in the quantum channel seriously affects the performance of quantum communication. Second, quantum decoherence results in the attenuation of quantum state, i.e., there are high error codes in quantum communication. Last, each quantum node is equipped with limited quantum memory, which means that the number of link-level entanglements established between adjacent nodes is finite. Network congestion will exist when concurrent quantum communication tasks compete with link-level entanglements. Therefore, the responsibility of the transport layer is to solve the problem of qubit loss, error correction, and network congestion.

New protocols are highly expected to be developed to realize the reliable transmission of qubits at the transport layer. Various schemes for handling errors have been proposed. For example, the purpose of purification operation is to maintain the state. Besides, using classical information to control transmission can deal with qubit loss and congestion. Loss in the channel generally forces a return classical message to be used acknowledging success or failure, then the sender deals with the loss situations. An entanglement resource allocation scheme is required to solve network congestion, which will be addressed in our future work. In general, there is desperate need to develop new technologies to guarantee reliable transmission at the transport layer of a quantum internet.

3.2.5 Application layer

The application layer is actually a quantum application entity. It is the highest layer of the quantum internet architecture, which directly provides services for the application process. The function of the application layer is to realize multiple quantum system application processes to communicate with each other and complete a series of services needed for business processing. The service elements provided by the application layer consist of several Specific Application Service Elements (SASE) and one or more Common Application Service Elements (CASE). Each SASE is responsible for providing specific application services, e.g., quantum key distribution and clock synchronization. And CASE provides a set of common application services such as the basic control mechanisms for application process. In general, the role of the application layer is to provide a series of services required for different quantum applications. Similar to the traditional Internet, the specific design of the application layer is determined by the quantum application.

IV. IMPLEMENTATION

4.1 The Architecture of Quantum Node

According to the quantum communication model and processes of long-distance end-to-end communication, we summarize the components needed to be realized by quantum nodes (Figure 8). First, the preparation of entangled states and qubits is usually realized by the light source. Second, qubits or entangled states will be used directly or stored in memory, and we need to configure a quantum memory

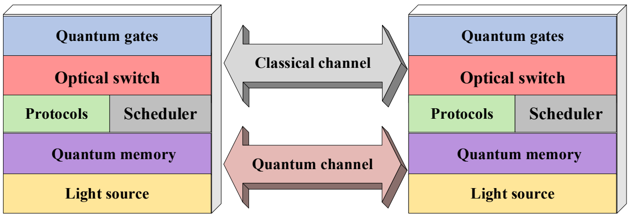

Figure 8. *The quantum node. Quantum nodes should have the capacity to generate, store, forward, and process qubits or entangled states. Protocols and scheduler are required to manage each process in quantum communication.*

to store them. Third, we need to deploy quantum gates to manipulate qubits and entangled states. Besides, the complex problems of long-distance communication are simplified into several simple steps, and they require the close coordination of different rules to complete qubit transmission. Hence, the protocols also need to be configured in a quantum node, and the process scheduling is implemented by the scheduler with the help of protocols. To implement end-to-end communication, quantum nodes also need to configure an optical switch to select the next hop and link port.

For each end node, the qubits it generated will be stored in quantum memory or be sent to neighboring slave nodes, and the qubits it received will be stored in quantum memory or measured directly. For each slave node, the qubits or entangled states it received will be stored in memory. If the destination end node is a neighboring end node, the qubits will be taken out of memory and forwarded to the destination. Otherwise, the slave node first figures out if it stores the entangled states shared by the slave node that is connected by the destination end node. If the two slave nodes are entangled, they can teleport the qubits directly. Otherwise, they send entanglement routing request to establish slave-to-slave entanglement. For each master node, if it receives a request for establishing long-distance entanglement, the master node forwards the request to neighboring repeaters and tries to distribute entangled pairs to the corresponding slave node and repeater. In the core network, any two neighboring quantum repeaters try to perform link-level entanglement distribution to fill the quantum memory initially. When a repeater receives an entanglement routing request, if there are unassigned entangled states, the repeater can accept the request and assign entangled

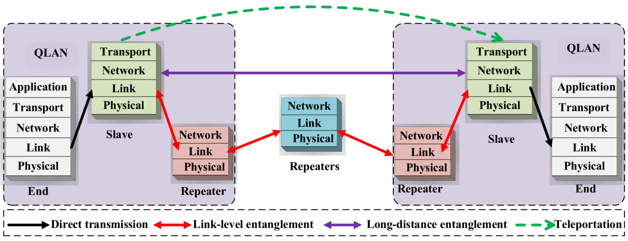

Figure 9. *The implementation of qubit transmission. The slave nodes belonging to different QLANs can establish entanglement by performing entanglement swapping. Then, teleportations are performed to transmit qubits. Last, the direct transmission is adopted between end nodes and slave nodes.*

states to implement entanglement swapping. If the request can not be satisfied, the repeater will forward the request to neighboring repeaters.

4.2 The Process of Qubit Transmission

The process of quantum communication between any two end nodes in the same QLAN is not a complex problem since there is no need to perform entanglement routing and entanglement swapping. Hence, we pay more attention to the process of quantum communication between any two end nodes in different QLANs, and the process can be divided into five steps as follows.

We show the flow of qubits from one end node to another over a long distance in Figure 9. Note that entangled states are continuously supplemented by link-level entanglement distribution to provide services for long-distance entanglement establishment or teleportation. In the first step, one end node generates qubits, which is implemented at the physical layer, and the qubits are forwarded to a slave node at the link layer. In the second step, the slave node in the QLAN receives qubits from Alice and stores them in a quantum memory. Then, the slave node forwards an entanglement routing request to adjacent quantum repeaters. Third, an entanglement path from the source slave node to the destination slave node is selected according to the routing protocol. Entanglement swappings are performed among the path to convert link-level entanglements to a long-distance slave-to-slave entanglement, which is completed at the network layer. Then, teleportations are performed between two entangled slave nodes at the transport layer to teleport qubits stored in quantum memory. Finally, the slave node to which Bob connected obtains qubits and selects the corresponding port to transmit qubits to Bob.

V. CONCLUSION AND OUTLOOK

In this paper, we took some steps towards the implementation of a large-scale, wide-area quantum internet. We proposed how to realize the long-distance qubits transmission and presented a quantum communication model. Based on the process of end-to-end quantum communication, the structure of the quantum internet is designed, which consists of end nodes, slave nodes, master nodes, and quantum repeaters. To improve the performance of qubits transmission and reduce network complexity, we group some slave nodes and a master node into an entangled cluster named QLANs, where the master node is responsible for establishing entanglement in QLANs. Besides, each quantum repeater links to neighboring repeaters to form a core network, and multiple QLANs are connected through the core network to realize remote quantum communication. The core network is divided into different hierarchical quantum repeater networks according to different service requirements. And the end-to-end quantum communication is divided into three scenarios, i.e., Alice and Bob connecting to the same slave node, Alice and Bob connecting to different slave nodes in the same QLAN, and Alice and Bob in different QLANs. Besides, to simplify the complex problem of end-to-end quantum communication and meet the increasingly complex requirements of quantum applications, we present a OSI-alike protocol stack. We illuminated the functions and components of each layer. Finally, we elaborated on the composition of a quantum node and the realization of end-to-end quantum communication.

However, there are still some technology challenges to overcome. First, the selection of communication path is the most important challenge since the special properties of quantum physics. We need to consider both the rate of remote entanglement distribution and the fidelity of remote entanglement. Second, as a key resource of quantum communication, the protocols for the generation and supplement of link-level entanglement need to be designed to improve the performance of qubit transmission. Besides, to improve the quality of quantum communication, i.e., the fidelity of remote entanglement, the scheduling of entanglement swapping and entanglement purification is also a vital problem that needs to be considered. In general, we need to consider not only the transmission rate of qubits but also the qubit error rate. As hardware and software problems are tackled, the quantum internet will provide a wide range of high quality of services in the near future.

ACKNOWLEDGMENT

This work is supported in part by Anhui Initiative in Quantum Information Technologies under grant No. AHY150300 and Youth Innovation Promotion Association Chinese Academy of Sciences (CAS) under grant No. Y202093.

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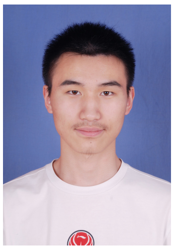

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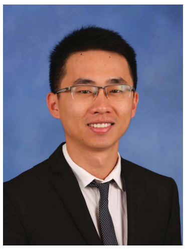

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