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A Multicast Scheme Based on Fidelity Metrics in Quantum Networks

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ABSTRACT A multicast scheme based on fidelity metrics in quantum networks is proposed in this paper. First of all, according to the fidelity of copies in an asymmetric mechanism of $1 \rightarrow 1 + 1 + 1 + 1$ which is derived, the way of information transmission in the quantum networks is defined: one is one-to-one transmission based on the teleportation and the other is one-to-many lossy transmission based on quantum cloning mechanism. Second, in a specified quantum network which is a connected graph, a source node can randomly assign multicast group members. Then, with constraints of the number of replicas and the maximum number of hops of the shortest path, an optimal multicast tree is constructed to obtain maximum fidelity. Finally, the simulation results show that the proposed scheme can select the optimal path from the source node to the multicast members for the specified quantum network. With the increase of multicast group members, the average value of information fidelity obtained by all members decreases. Compared with the multicast tree constructed by the KMB algorithm, which is used to construct the Steiner tree in classical communication, the proposed schemes make the information fidelity obtained by multicast group members improve significantly.

INDEX TERMS Multicast tree, quantum cloning mechanism, fidelity, multicast group, quantum networks.

I. INTRODUCTION

With the rapid development of the Internet, the multimedia applications that use multicast communications are increasing, such as video on demand, media push, video conferencing, event notification, and status monitoring. In order to support multicast group communication, the most important aspect is to construct an efficient multicast tree and determine the communication routing of participants according to the underlying topology.

There are many multicast routing schemes in traditional networks [1]–[3]. The tree-based multicast routing scheme shares links as much as possible in the process of transmitting information, thus they can save network resources and reduce the burden of the source. The forwarding method based on a spanning tree is to construct a multicast routing tree covering the source and the destinations. The source only needs to send the data once and forward it through the multicast tree. The data is copied at the bifurcation of the tree until each destination. Finally, an optimal multicast tree from the source node to destination nodes is determined according to the objectives and constraints.

Recently, there are still many scholars studying the issue of multicast routing in the context of specific networks and applications [4]–[7]. In 2018, Ren *et al.* [4] presented a Rooted Delay-Constrained Minimum Spanning Tree (RDCMST) construction framework based on dynamic algorithm in tactile Internet. Huang *et al.* [5] proposed an algorithm which leveraged an entropy based process to aggregate all weights into a comprehensive metric, and then used it to search a multicast tree on the basis of the shortest path tree. In 2017, Jiang *et al.* [6] proposed an energy-efficient multicast routing approach to multi-hop wireless networks for smart medical applications. They made use of topology control and sleeping mechanism to obtain the optimal routing strategy with maximum network energy efficiency. Chen *et al.* [7] proposed a multicast routing protocol that constructed multiple multicast trees and employed network coding for lossy MANETs, where each multicast tree can satisfy a predefined percentage of the bandwidth requirement.

The researches of multicast technology [8]–[13] are enough to prove the importance of multicast communication.

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In recent years, with the development of quantum communication technology, the application of point-to-point quantum communication is becoming more and more mature. Quantum communication has gradually changes from theory to practice with the trends of networking and globalization [14]–[17]. Large-scale network communication is an inevitable trend of quantum communication [18]–[22]. Quantum network communication is a great challenge to quantum communication technology. Multicast communication between multiple users is an important part of quantum communication network application, and it is one of the problems that must be studied in the construction and application of large-scale quantum communication networks. This paper studies one of the most common form of multicast application in the quantum domain, namely the quantum information transmission problem between a sender and multiple receivers. Therefore, this paper can provide a theoretical basis for constructing a practical quantum communication network.

There are some researches on quantum network multicast technology. In 2006, Shi and Soljanin [23] considered quantum multicast networks, and quantum states which generated by multiple sources have to be simultaneously delivered to multiple destinations. In fact, it must be under the condition that the source node can generate many copies of quantum states. In 2011, Kobayashi *et al.* [24] considered quantum communication between multiple parties that are connected through a network of quantum channels. They perfectly transferred an unknown quantum state from a source subsystem to a target subsystem, where both source and target are formed by ordered node sets. In 2015, Xu *et al.* [25] investigated network coding for quantum cooperative multicast over the classic butterfly network. They designed a protocol over the butterfly network in which the two source nodes cooperatively transmitted their quantum information to the two target nodes. This work does not adapt to all network types and success probability is not 1. In summary, the current researches on quantum network multicast technology are mainly based on network coding to implement random multicast and cooperative multicast. Their schemes are based on multicast communication problems between multiple source nodes and multiple destination nodes, most of which take the butterfly network as an example. They are concerned with the feasibility of such a scheme and the boundary of the transmission rate, and do not care about the fidelity of the information obtained by all destination nodes.

This paper focuses on point-to-multipoint multicast communication which is one of the most common forms of multicast applications. There are one source and multiple destinations in this scheme. In the traditional network, it is very easy to duplicate the original information and distribute it to every receiver. However, in quantum theory, Wootters and Zurek proposed the non-cloning theorem [26], which was applied in quantum communication networks in 1982. In this theorem, the possibility of accurate replication of unknown quantum states is negated on the basis of the linear properties of quantum mechanics. Therefore, accurate copying cannot be achieved, but many scholars have proposed the approximate cloning and probability cloning of quantum states. In the past few years, the great progress has been achieved in the study of quantum cloning machines applications and implementation both in theory and experiment. Researchers try to clone a quantum state with optimal fidelity, or clone it perfectly with the greatest probability. Some well-known quantum cloning machines [27]–[34] include universal quantum cloning machines, phase change cloning machines, asymmetric quantum cloning machines, and probabilistic quantum cloning machines.

In the scheme of this paper, a single source node can transmit information to multiple destinations at the same time in a randomly generated quantum network by using universal quantum cloning mechanism [28]. A multicast solution in a quantum network is implemented.

The rest of this paper is organized as follows. In Section II, quantum cloning machines are reviewed and the fidelity of copies in an asymmetric mechanism of $1 \rightarrow 1 + 1 + 1 + 1$ is derived. Then, the ways of information transmission in the quantum network are defined and quantum communication network model is introduced in Section III. The routing scheme based on fidelity metrics is described in detail in Section IV. Simulation results are shown in Section V. Finally, conclusions are drawn in Section VI.

II. QUANTUM CLONING MECHANISM

Under the universal quantum cloning mechanism (UQCM), any input quantum state can be cloned with a certain quality. If all of the output single particle states have the same degree of approximation as the input states, it is called symmetric universal quantum clone machine, otherwise it is called asymmetric quantum clone machine. That is, the input of the cloning machine is the original information from the sender, and its output states are different receivers. Each receiver obtains lossy original information.

In this paper, we use fidelity to measure the quality of the copies. For the simplest case, if you clone a quantum state and get two copies, the two copies are the same. But they are different from the original input state. In particular, the original input state is destroyed and becomes one of the output copies.

Buzek and Hillery [27] showed that there were a universal quantum-copying machine which copied quantum states approximately. The quality of its output did not depend on the input. They also examined the machine which combined unitary transformation and a selective measurement to produce good copies of states in the neighborhood of a particular state in 1996. Gisin and Massar [28] then generalized the cloning machine to $N \rightarrow M$ case, that is M copies were created from N identical qubits. In 1998, the complete proof of the optimality was given by Bruss *et al.* [30]. In their paper, the relationship between optimal quantum cloning and optimal state estimation was established. The upper bound of N to M UQCM was found. In the following, a brief description of the unitary transformation of the cloning machine is given, and the fidelity of the asymmetric quantum cloning mechanism of $1 \rightarrow 1+1+1+1$ is derived in a relatively simple way.

The unitary transformation of the 2-dimensional optimal symmetric $1 \rightarrow M$ universal quantum cloning machine can be described as:

$$|\phi\rangle_X = a|0\rangle_X + b|1\rangle_X \tag{1}$$

$$U_{1M} = (|\phi\rangle_X \otimes |0\cdots0\rangle_A |0\cdots0\rangle_B) = a|\phi_0\rangle_{AC} + b|\phi_1\rangle_{AC} \tag{2}$$

where,

$$\begin{aligned}|\phi_0\rangle_{AC} &= U_{1M}|0\rangle_X|0\cdots0\rangle_A|0\cdots0\rangle_B \\ &= \sum_{j=0}^{M-1}\alpha_j\left|A_j\right\rangle_A \otimes |\{0, M-j\}, \{1, j\}\rangle_C \end{aligned}\tag{3}$$

$$\begin{aligned}|\phi_1\rangle_{AC} &= U_{1M}|1\rangle_X|0\cdots0\rangle_A|0\cdots0\rangle_B \\ &= \sum_{j=0}^{M-1}\alpha_j\left|A_{M-1-j}\right\rangle_A \otimes |\{0, j\}, \{1, M-j\}\rangle_C \end{aligned}\tag{4}$$

$$\alpha_j = \sqrt{\frac{2(M-j)}{M(M+1)}} \tag{5}$$

where, C represents the copy of M qubits which are composed of qubits stored by the original X and B. $\left|A_j\right\rangle_A$ is M orthogonal normalized auxiliary states. $|\{0, M-j\}, \{1, j\}\rangle$ represents symmetric and normalized states of M qubits, among which $M-j$ qubits are in the state $|0\rangle$ and j qubits are in the state $|1\rangle$. For example, if $M = 3$, $j = 1$, then $|\{0, 2\}, \{1, 1\}\rangle = 1\big/\sqrt{3}(|001\rangle + |010\rangle + |100\rangle)$. We note that even if the minimum value of the auxiliary quantity required to support the M-level $\left|A_j\right\rangle_A$ is $\log_2 M$, these can be simply expressed as the symmetry of the composition of the M-1 qubits: $\left|A_j\right\rangle_A = |\{0, M-1-j\}, \{1, j\}\rangle_A$.

Then the optimal copy fidelity is:

$$F_{1\rightarrow M} = \sum_{j=0}^{M-1}\frac{M-j}{M}\alpha_j^2 = \frac{2M+1}{3M} \tag{6}$$

The number of auxiliary particles in the cloning machine increases with the number of copies. In addition, considering that the more copies, the lower fidelity of copies, this paper only considers the cloning machine of $M \leq 4$.

Next, the asymmetric quantum cloning mechanism is taken into consideration. The output states of the asymmetric quantum clone are not exactly the same, and they have different levels of proximity to the input state. The first $1 \rightarrow 1+1$ optimal asymmetric quantum clone machine was proposed by Niu and Griffiths in 1998 [31]. Later, Cerf [32] presented the same result independently using the algebraic method. The optimal asymmetric $1 \rightarrow 1+1+1$ universal quantum cloning machine in d-dimension [33] were presented in 2005. Based on the proposed derivation method of the fidelity of the asymmetric quantum cloning mechanism in [34], we try to obtain the fidelity of the asymmetric quantum cloning mechanism of $1 \rightarrow 1+1+1+1$.

According to (1-5), when $M = 4$, under the unitary transformations, single particle can be represented as

$$\begin{aligned}
&U_{1,4}\,|0\rangle \otimes R \rightarrow \sum_{j=0}^{3}\alpha_j\left|A_j\right\rangle_A \otimes |\{0, 4-j\}, \{1, j\}\rangle_C \\
&= c_0^1|000\rangle_A \otimes |0000\rangle_C + (|001\rangle_A + |010\rangle_A + |100\rangle_A) \\
&\quad \otimes (c_1^1|0001\rangle_C + c_1^2|0010\rangle_C + c_1^3|0100\rangle_C + c_1^4|1000\rangle_C) \\
&\quad + (|110\rangle_A + |101\rangle_A + |011\rangle_A) \\
&\quad \otimes (c_2^1|0011\rangle_C + c_2^2|0101\rangle_C + c_2^3|0110\rangle_C + c_2^4|1100\rangle_C \\
&\quad + c_2^5|1010\rangle_C + c_2^6|1001\rangle_C) \\
&\quad + |111\rangle_A \otimes (c_3^1|0111\rangle_C + c_3^2|1011\rangle_C + c_3^3|1101\rangle_C \\
&\quad + c_3^4|1110\rangle_C) \\
&\quad \times U_{1,4}\,|1\rangle \otimes R \rightarrow \sum_{j=0}^{3}\alpha_j\left|A_{3-j}\right\rangle_A \otimes |\{0, j\}, \{1, 4-j\}\rangle_C \\
&= c_0^1|111\rangle_A \otimes |1111\rangle_C + (|110\rangle_A + |101\rangle_A + |011\rangle_A) \\
&\quad \otimes (c_1^1|1110\rangle_C + c_1^2|1101\rangle_C + c_1^3|1011\rangle_C + c_1^4|0111\rangle_C) \\
&\quad + (|001\rangle_A + |010\rangle_A + |100\rangle_A) \\
&\quad \otimes (c_2^1|1100\rangle_C + c_2^2|1010\rangle_C + c_2^3|1001\rangle_C + c_2^4|0011\rangle_C \\
&\quad + c_2^5|0101\rangle_C + c_2^6|0110\rangle_C) \\
&\quad + |000\rangle_A \otimes (c_3^1|1000\rangle_C + c_3^2|0100\rangle_C + c_3^3|0010\rangle_C \\
&\quad + c_3^4|0001\rangle_C)
\end{aligned}\tag{7}$$

If the input state is the same as in (1), then the output state is:

$$\begin{aligned}
&|\varphi_{out}\rangle \\
&= a\begin{bmatrix}
c_0^1|0000000\rangle_{AC} \\
+(|001\rangle + |010\rangle + |100\rangle)_A \otimes \\
(c_1^1\,|0001\rangle + c_1^2\,|0010\rangle + c_1^3\,|0100\rangle + c_1^4\,|1000\rangle)_C \\
+(|110\rangle + |101\rangle + |011\rangle)_A \otimes \\
(c_2^1\,|0011\rangle + c_2^2\,|0101\rangle + c_2^3\,|0110\rangle + \\
c_2^4\,|1100\rangle + c_2^5\,|1010\rangle + c_2^6\,|1001\rangle)_C \\
+|111\rangle_A \otimes \\
(c_3^1\,|0111\rangle + c_3^2\,|1011\rangle + c_3^3\,|1101\rangle + c_3^4\,|1110\rangle)_C
\end{bmatrix} \\
&\quad + b\begin{bmatrix}
c_0^1|1111111\rangle_{AC} \\
+(|110\rangle + |101\rangle + |011\rangle)_A \otimes \\
(c_1^1\,|1110\rangle + c_1^2\,|1101\rangle + c_1^3\,|1011\rangle + c_1^4\,|0111\rangle)_C \\
+(|001\rangle + |010\rangle + |100\rangle)_A \otimes \\
(c_2^1\,|1100\rangle + c_2^2\,|1010\rangle + c_2^3\,|1001\rangle + \\
c_2^4\,|0011\rangle + c_2^5\,|0101\rangle + c_2^6\,|0110\rangle)_C \\
+|000\rangle_A \otimes \\
(c_3^1\,|1000\rangle + c_3^2\,|0100\rangle + c_3^3\,|0010\rangle + c_3^4\,|0001\rangle)_C
\end{bmatrix}
\end{aligned}\tag{8}$$

where the constraint condition of the coefficient is:

$$\begin{aligned}
&\left(c_0^1\right)^2 + 3\left[\left(c_1^1\right)^2 + \left(c_1^2\right)^2 + \left(c_1^3\right)^2 + \left(c_1^4\right)^2\right] \\
&+ 3\left[\left(c_2^1\right)^2 + \left(c_2^2\right)^2 + \left(c_2^3\right)^2 + \left(c_2^4\right)^2 + \left(c_2^5\right)^2 + \left(c_2^6\right)^2\right] \\
&+ \left(c_3^1\right)^2 + \left(c_3^2\right)^2 + \left(c_3^3\right)^2 + \left(c_3^4\right)^2 = 1
\end{aligned}\tag{9}$$

Therefore, the density matrix of the output particles can be obtained according to $\rho_C = Tr_A |\varphi_{out}\rangle\langle\varphi_{out}|$. The density matrix of single particle in the output state can be obtained through $\rho_x = Tr_{C-x}(\rho_C)$. The fidelity of each copy can be derived by $F_x = \langle\varphi^{in}|\,\rho_x\,|\varphi^{in}\rangle$ as follow:

$$\begin{aligned} F_{1\to4-1} &= \frac{1}{2} + c_0^1 c_3^1 + 3(c_1^1 c_2^3 + c_1^2 c_2^2 + c_1^3 c_2^1) \\ F_{1\to4-2} &= \frac{1}{2} + c_0^1 c_3^2 + 3(c_1^1 c_2^5 + c_1^2 c_2^6 + c_1^4 c_2^1) \\ F_{1\to4-3} &= \frac{1}{2} + c_0^1 c_3^3 + 3(c_1^1 c_2^4 + c_1^3 c_2^6 + c_1^4 c_2^2) \\ F_{1\to4-4} &= \frac{1}{2} + c_0^1 c_3^4 + 3(c_1^2 c_2^4 + c_1^3 c_2^5 + c_1^4 c_2^3) \end{aligned} \tag{10}$$

Moreover, if the input state is unknown, we get the simplified form of $1 \to 1+1+1+1$ quantum cloning mechanism similarly to the literature [34]. This result is consistent with the literature [29].

$$\begin{aligned} F_{1\to4-1} &= 1 - \frac{1}{2}\left[\beta_2^2 + \beta_3^2 + \beta_4^2 + \frac{2}{3}(\beta_2\beta_3 + \beta_2\beta_4 + \beta_3\beta_4)\right] \\ F_{1\to4-2} &= 1 - \frac{1}{2}\left[\beta_1^2 + \beta_3^2 + \beta_4^2 + \frac{2}{3}(\beta_1\beta_3 + \beta_1\beta_4 + \beta_3\beta_4)\right] \\ F_{1\to4-3} &= 1 - \frac{1}{2}\left[\beta_1^2 + \beta_2^2 + \beta_4^2 + \frac{2}{3}(\beta_1\beta_2 + \beta_1\beta_4 + \beta_2\beta_4)\right] \\ F_{1\to4-4} &= 1 - \frac{1}{2}\left[\beta_1^2 + \beta_2^2 + \beta_3^2 + \frac{2}{3}(\beta_2\beta_3 + \beta_1\beta_2 + \beta_1\beta_3)\right] \end{aligned} \tag{11}$$

where, $\beta_1^2+\beta_2^2+\beta_3^2+\beta_4^2+\beta_1\beta_2+\beta_1\beta_3+\beta_1\beta_4+\beta_2\beta_3+\beta_2\beta_4+\beta_3\beta_4 = 1$. From (11) with the equal parameters, we find $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 1\big/\sqrt{10}$, so the optimal fidelities can be found to be $F_{1\to4-1} = F_{1\to4-2} = F_{1\to4-3} = F_{1\to4-4} = 3\big/4$. Therefore, we can recover the symmetric optimal cloning machine from our asymmetric one. Using this method, the relationship of the fidelities of M copies can be continued to derive. The most important thing is to find a constraint relationship between the coefficients similar to (9).

We also use the fidelity of the asymmetric quantum cloning mechanism $1 \to 1+1$:

$$\begin{aligned} F_{1\to2-1} &= 1 + p^2\Big/1 + p^2 + q^2 \\ F_{1\to2-2} &= 1 + q^2\Big/1 + p^2 + q^2 \end{aligned} \tag{12}$$

where $p + q = 1$. The fidelity of the asymmetric quantum cloning mechanism $1 \to 1+1+1$:

$$\begin{aligned} F_{1\to3-1} &= 1 - 1\big/2(\beta^2 + \gamma^2 + 2\big/3\beta\gamma) \\ F_{1\to3-2} &= 1 - 1\big/2(\alpha^2 + \gamma^2 + 2\big/3\alpha\gamma) \\ F_{1\to3-3} &= 1 - 1\big/2(\alpha^2 + \beta^2 + 2\big/3\alpha\beta) \end{aligned} \tag{13}$$

where $\alpha^2+\beta^2+\gamma^2+\alpha\beta+\alpha\gamma+\beta\gamma = 1$. Similarly, when the parameters are equal, the asymmetric clone can be reduced to a symmetric quantum clone. The schematic diagram of the cloning mechanism can be shown in the Fig.1.

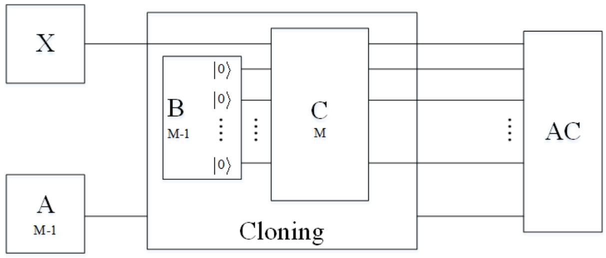

FIGURE 1. Quantum cloning machine schematic diagram. The original single qubit X is subjected to a unitary transformation to obtain the copies of its approximate. System B is a blank particle system with M-1 bits, and System A is an auxiliary particle system with M-1 bits. System C is a copy system, contains M copies. In the output system, system C and A are in direct accumulation state. It is worth noting that the copy system C contains the original particle X, and all the copies are entangled.

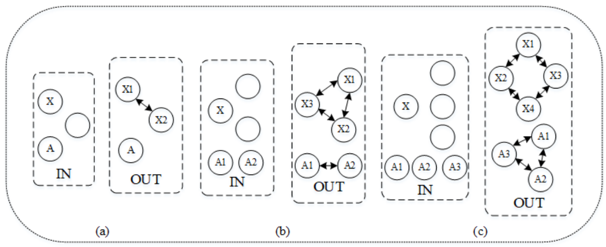

FIGURE 2. Quantum information transmission mode. The subgraph (a), (b), and (c) respectively represents the $1 \to 2/1+1$ cloning mechanism, the $1 \to 3/1+1+1$ cloning mechanism, and the $1 \to 4/1+1+1+1$ cloning mechanism in the one-to-many transmission mode. The input states include single qubit X, the auxiliary particles system A, the blank particles system, and the output states include all of the replica particles and all particles in the auxiliary particle system A.

III. DEFINITION OF QUANTUM INFORMATION TRANSMISSION AND QUANTUM COMMUNICATION NETWORK MODEL

Definition 1: The sender transmits the original quantum information to the receiver with a fidelity of one. This type of transmission is defined as one-to-one transmission in this paper.

In quantum communication network, there are two ways to transfer information between two nodes. The first one can transmit quantum information which carried by carrier, such as a photon, directly to the receiver. The second can adopt quantum teleportation [35] to realize information transmission between two nodes through a quantum channel established by entangled particles. Both of these methods allow the sender to transmit the original quantum information to the receiver with a fidelity of one.

Definition 2: Quantum information is transmitted in a form with fidelity less than one by using quantum cloning mechanisms. This transmission mode is defined as one-to-many transmission in this paper.

In this paper, we consider the most mature universal quantum cloning machine to achieve point-to-multipoint information transmission. The universal quantum cloning mechanism can be used to obtain a number of copies which approximate to original state, and fidelity $F < 1$. This quantum information mode is shown in Fig.2.

In the quantum network, there are three conditions for the transmission from the sending node to receiving nodes:

(1) One-to-one transmission, and the sending node is not a member of the multicast group

The transmission is lossless transmission, that is, the receiving nodes receive information that fidelity is 1;

(2) One-to-many transmission, and the sending node is not a member of the multicast group

The transmission is duplicated and lossy transmission. The cloning mechanism $1 \rightarrow 2/1+1$, $1 \rightarrow 3/1+1+1$, $1 \rightarrow 4/1+1+1+1$ respectively represents that the sender transmits information to two receivers, three receivers, and four receivers by cloning machine.

(3) One-to-many transmission, and the sending node is a multicast group member

Assume that we need x copies and choose $1 \rightarrow x$ quantum machine. Because the sending node is also a member of the multicast group, one copy needs to be retained. In this case, $1 \rightarrow x+1$ cloning machine should be used to achieve that x receivers can obtain information.

According to the different number of copies, the sending node performs different operations. The fidelity obtained by the receiving nodes can be calculated according to Section II. In order to realize the information transmission from point to multi-point in quantum network, the most mature universal quantum cloning machine is adopted in this paper.

Assume that the network consists of n nodes which are randomly distributed in a square area. Each node is assigned a unique identifier to distinguish it from other nodes. We set a threshold for information transmission in order to realize the connectivity of the quantum communication network. For all nodes, if the Euclidean distance between any two nodes exceeds this threshold, the two nodes cannot directly transmit quantum information.

Definition 3: If two nodes satisfy the constraint of direct communication, that is the Euclidean distance of the two nodes does not exceed the threshold, the two nodes are adjacent.

The multicast quantum communication network discussed in this paper has the following characteristics as shown in Fig.3:

(1) All nodes have the same functions and can transmit information in specific ways which are defined in Definition 1 and Definition 2.

(2) Except the source node, other nodes in the routes can serve as intermediate nodes.

(3) All nodes can communicate directly with their adjacent nodes, and can also communicate with nonadjacent nodes through intermediate nodes.

(4) The multicast group contains m members, and one source node needs to transmit the quantum state carrying the message to the multicast group containing m nodes.

(5) When a source node has no connection with a member of the multicast group, it needs to forward the information by intermediate nodes. A multi-hop transmission from the source node to all multicast group nodes forms tree routing.

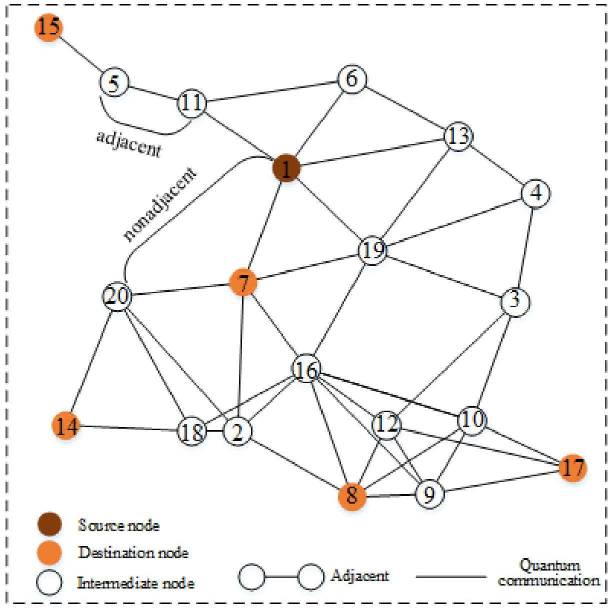

FIGURE 3. Quantum communication network model.

We model the network as an undirected graph $G = (V, E)$ where V is the set of nodes and E is the set of edges. Let $Z \subseteq V$ be the set of destination nodes. $T = (V_T, E_T)$ is a multicast tree whose all leaf nodes form the set of destination nodes in the multicast group, where $V_T \subseteq V$ and $E_T \subseteq E$. Each edge $(u, v) \in E$ connects nodes u and v.

IV. A ROUTING SCHEME BASED ON FIDELITY MEASURES

According to the quantum network model established in the Section III, our optimization goal is to construct the best fidelity path from the source node S to the m destination nodes, namely the tree structure T. To maximize the sum of the fidelity of the information obtained by the m destination nodes from the source node.

$$\max F(T) = \sum_{v_i \in Z} f(v_i) \tag{14}$$

where Z represents the set of destination nodes. For all the destination nodes $v_i \in Z, i = 1, 2, \cdots, m, f(v_i)$ represents the fidelity of the information finally obtained by the destination node v_i.

The constraints are as follows in this paper:

(1) In the final determined path, that is, the source node in the multicast tree is as the root node, the copy operation of any node is $1 \rightarrow 4/1+1+1+1$ at most;

(2) In the final determined path, the hop counts from the source node to any destination node must be less than or equal to the maximum hop counts of the shortest path from the source node to any destination node;

$$hop(v_i) \leq \max hop_{dijkstra}(v_l) \tag{15}$$

where $hop(v_i)$ represents the hop counts from the source node to the destination node v_i in the constructed multicast tree, $hop_{dijkstra}(v_l)$ represents the hop counts of the shortest path from the source node to the destination node v_l, $v_l \in Z$, $l = 1, 2, \cdots, m$.

The reason why hop count is a constraint is that there is no chain tree in the final tree routing. The classical shortest path algorithm Dijkstra can be used to obtain the hop counts of the shortest path from the source node to the destination nodes.

Because of the transmission patterns in quantum networks, we find that some multicast routing schemes in traditional networks cannot be used directly in the quantum network modeled in this paper. In a quantum multicast network, if two destination nodes can directly connect to each other in the final tree routing, the last hop destination must use a $1 \rightarrow 2/1+1$ quantum cloning machine to transmit the information to the next hop destination. The fidelity of the information obtained by the last-hop node will decline because of using the cloning machine again. In this case, there is no bifurcation structure of branches, but in order to ensure both destination nodes can obtain information, quantum cloning machine must be used to achieve the goal instead of the one-to-one transmission pattern. Otherwise, not all members of the multicast group can receive the information sent by the source node. Therefore, this is the biggest difference between a multicast scheme in a quantum network and a traditional multicast routing protocol.

This paper proposes a multicast scheme based on fidelity metrics. It can construct a suitable multicast tree in the specific quantum network. The steps are as follows:

Step 1, the quantum network connectivity graph is initialized, the position coordinates of every node and the adjacency matrix of the graph are obtained.

Step 2, Dijkstra algorithm is used to obtain the maximum value h of the hop counts of the shortest path from the source node to all destination nodes.

Step 3, consider all the shortest paths between the source node and each destination node. According to the Top-k-shortest paths (KSP) algorithm [36], the path which does not exceed h hops from the source node to any destination node are obtained.

Step 4, according to the path obtained in last step, a set R of path graph from source node to all the destination nodes is generated.

Step 5, choose the path graph which meets the requirement of tree from the set R. A temporary tree set T_0 composed of the source node, all the destination nodes and some intermediate nodes is obtained.

Step 6, the tree routing in which the number of child nodes of non-destination nodes exceeds 4 or the number of child nodes of the destination node exceeds 3 in the temporary tree set is not selected. Then, the spanning tree set T is obtained.

Step 7, we calculate the sum of the fidelity obtained by all the destination nodes of every tree in the spanning tree set T. All the tree structures with the greatest sum of fidelity of the destination nodes are obtained finally.

The KSP in Step 3 is already a very mature algorithm. For solving the K shortest path problem, the earliest deviation path algorithm was adopted by Yen [36] in 1971. The Yen algorithm firstly used the standard shortest path algorithm (such as Dijkstra algorithm) to find the shortest path from the source node S to the destination node, and put it as P_1 and in the result list A. After obtaining the first k paths $\{P_1, P_2 \cdots, P_k\}$, the process of calculating P_{k+1} is as follows:

(1) Take every node v_i except the destination nodes in P_k as a possible deflected node, and calculate the shortest path from v_i to the destination node. The following two conditions need to be met: First, the path cannot pass through any node between S and v_i on the current shortest path P_k to ensure there are no rings in the tree; Second, in order to avoid duplication with previous paths, the edges that branch from node v_i cannot be the same as the edges from v_i which were found on the shortest paths $P_1, P_2 \cdots, P_k$.

(2) After finding the shortest path between v_i and the destination node that satisfies the above two conditions, the shortest path and the path from S to v_i on the current path P_k are stitched together to form a candidate path of P_{k+1}, and it is stored in the candidate path list B.

(3) Select the shortest one from the candidate path list B as P_{k+1}, and place it in the result list A. The above process is repeated until K paths are obtained.

The algorithm in Step 5 is to use depth-first search algorithm to traverse every graph in the path graph set R. If the number of vertices and edges which can be accessed when traversing a graph is n vertices and $n-1$ edges, the graph is a tree.

In Step 6, if the sum of elements in the row of the destination nodes in the tree's adjacency matrix is not greater than 4, or the sum of elements in the row of intermediate nodes is not greater than 5, the tree is added to the spanning tree set, otherwise it is not added.

The fidelity of the copies is obtained by the universal cloning mechanism in the Section II. The symmetrical mechanism is used as an example to describe the algorithm to calculate the sum of the fidelity of the destination nodes of each tree in the set of spanning trees. The asymmetric mechanism is the same to it.

The number of nodes in the spanning tree T is n, the destination nodes set Z, adjacency matrix $Aij[n][n]$, the maximum number h of the shortest path hop counts from the source node to each destination nodes. In the beginning, the fidelity of arbitrary node $f(v_t) = 1, v_t \in V, t = 1, 2, \cdots, n$. Get the sum of the elements of each row in the adjacency matrix Aij: $sum\_r[n]$. Traversing the tree by sequence traversal method, we obtain the node's layer number set $x[n]$, the number of nodes in each layer $num[h]$. According to the node number which obtained by sequence traversal, the number of its child node is $j, j+1, \cdots, j + sum\_r[t] - 2$. where,

$$\begin{aligned} j = t &+ sum\_r[t - \sum\nolimits_{y=1}^{x[t]} num[y]] - 1 \\ &+ sum\_r[t - \sum\nolimits_{y=1}^{x[t]} num[y] + 1] - 1 + \cdots \\ &+ \sum\_r[t-1] - 1 \end{aligned}$$

The specific calculation method is shown in Algorithm 1.

Algorithm 1 Calculate the Sum of the Fidelity of All Destination Nodes Based on the Spanning Tree Structure

Input: The number of nodes in the spanning tree T is n, the first number of each node's child node is j, the sum of the elements of each row in the adjacency matrix Aij: $sum\_r[n]$.
Output: The sum of fidelity $F(T)$ obtained by the destination nodes from the source node.
for each $t = 1$: n **do**
  if Node t does not belong to the destination node set **then**
    $F[j] = F_{1\to sum\_r[t]-1}F[t]$;
    $F[j+1] = F_{1\to sum\_r[t]-1}F[t]$;
    $\vdots$
    $F[j+sum\_r[t]-2] = F_{1\to sum\_r[t]-1}F[t]$;
    $F[t] = 0$;
  else
    $F[j] = F_{1\to sum\_r[t]}F[t]$;
    $F[j+1] = F_{1\to sum\_r[t]}F[t]$;
    $\vdots$
    $F[j+sum\_r[t]-2] = F_{1\to sum\_r[t]}F[t]$;
    $F[t] = F_{1\to sum\_r[t]}F[t]$;
  end if
end for
return $F[T] = \sum_{t=1}^{n} F[t]$

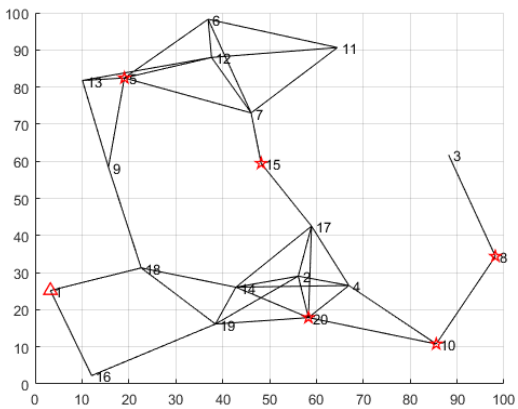

FIGURE 4. Quantum network connectivity graph with 20 nodes.

We provide an illustrative example of the execution of our multicast scheme. The number of all nodes n is 20. Figure 4 is the initialized quantum network connectivity graph. The source node is node 1, and randomly selects five destination nodes which are nodes 5, 8, 10, 15, 20 respectively. According to the shortest path algorithm, the number of hops for the shortest path from node 1 to node 5, 8, 10, 15, 20 is: 3, 5, 4, 4, and 3, so $h = 5$.

According to the proposed multicast solution, the spanning tree set T of the Fig.4 is obtained, and the set includes six tree routings, which are respectively shown in the subgraphs (1)-(6) of the Fig.5.

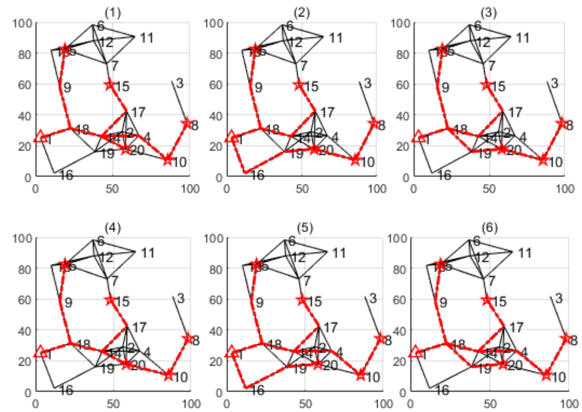

FIGURE 5. Spanning tree structure of 20 nodes.

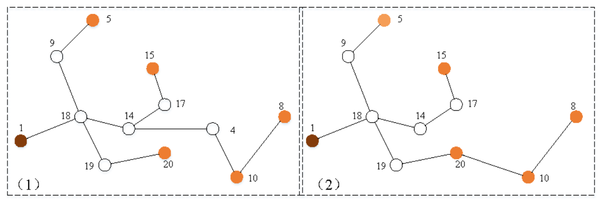

FIGURE 6. The optimal spanning tree structure of 20 nodes based on symmetric cloning machine.

According to the algorithm of calculating the fidelity, through the tree routing (1)-(6) in Fig.5 to transmit information. The fidelity of the information obtained by the destination nodes are calculated by using the simplest symmetric clone mechanism as follow:

(1): $F_{1\to 2} + 2F_{1\to 2} \times F_{1\to 3} + 2F_{1\to 2}^2 \times F_{1\to 3} = 260/81 \approx 3.21$.

(2): $3F_{1\to 2}^2 + 2F_{1\to 3}^2 = 175/54 \approx 3.24$.

(3) and (6): $2F_{1\to 3} + F_{1\to 2} \times F_{1\to 3} + 2F_{1\to 2}^2 \times F_{1\to 3} = 266/81 \approx 3.28$.

(4) and (5): $F_{1\to 2} + F_{1\to 2}^2 + F_{1\to 2}^3 + 2F_{1\to 2}^4 = 995/324 \approx 3.07$.

In conclusion, in the quantum network connectivity graph of Fig.4, the source node 1 transmits quantum information to multicast group, and the maximum sum of the fidelity of the information finally obtained by the multicast group is: 3.28. The source node can select the path as shown in Fig.6 for multicast communication so that the multicast group members obtain the largest fidelity of the information. The two multicast trees in Fig 6 are different in structure, but they can achieve the same effect.

Under the limitation of the symmetric cloning mechanism, the fidelity of the output states after one cloning is equal. However, in quantum communication network, if the constructed multicast tree routing has more multicast group members on one branch, and other branches have only a few multicast group members, the asymmetric cloning mechanism may perform better. Because the cloning mechanism is lossy transmission, when the fidelity of all the multicast group members can obtain the maximum information, the parent node with more child nodes can allocate different fidelity output states to different child nodes as needed.

Calculate the sum of the fidelity of the information obtained by the members of the multicast group based on the asymmetric cloning mechanism for each tree routing in Fig.5. In this way, each tree needs to build an optimization goal. For each asymmetric cloning, we need to choose the appropriate parameters to achieve the ultimate goal. Therefore, this problem can be converted to a nonlinear programming problem.

In order to describe the multicast routing scheme based on the asymmetric cloning mechanism, we choose to the optimal tree routing based on the symmetric mechanism as shown in Fig.6 (2). According to this spanning tree structure, asymmetric cloning needs to be performed three times. The optimal value of the fidelity obtained by the members of the multicast group can be expressed as:

$$\begin{aligned} F_{asymmetric} &= F_{1\to 3\text{–}1} + F_{1\to 3\text{–}2} + F_{1\to 3\text{–}3} \\ &\quad \times \left(F_{1\to 2\text{–}1} + F_{1\to 2\text{–}2} \times \left(F_{1\to 2\text{–}1'} + F_{1\to 2\text{–}2'}\right)\right) \end{aligned} \tag{16}$$

where, $F_{1\to 3\text{–}1}, F_{1\to 3\text{–}2}, F_{1\to 3\text{–}3}$ are the fidelity of the output state of the $1 \to 1+1+1$ asymmetric cloning mechanism. $F_{1\to 2\text{–}1}, F_{1\to 2\text{–}2}$ is the fidelity of the output state of the first $1 \to 1+1$ asymmetric mechanism. $F_{1\to 2\text{–}1'}, F_{1\to 2\text{–}2'}$ is the fidelity of the output state of the second $1 \to 1+1$ asymmetric cloning mechanism. Therefore, the optimization objective and constraints are as follows:

$$\begin{aligned} &Max F_{asymmetric} \\ &= F_{1\to 3\text{–}1} + F_{1\to 3\text{–}2} \\ &\quad + F_{1\to 3\text{–}3} \times \left(F_{1\to 2\text{–}1} + F_{1\to 2\text{–}2} \times \left(F_{1\to 2\text{–}1'} + F_{1\to 2\text{–}2'}\right)\right) \\ &= 1 - 1/2(\beta^2 + \gamma^2 + 2/3\beta\gamma) + 1 - 1/2(\alpha^2 + \gamma^2 + 2/3\alpha\gamma) \\ &\quad + \left(1 - 1/2(\alpha^2 + \beta^2 + 2/3\alpha\beta)\right) \\ &\quad \times \left\{1 - \frac{1}{2}a^2 + \left(1 - \frac{1}{2}b^2\right) \times \left[2 - \frac{1}{2}\left(a'^2 + b'^2\right)\right]\right\} \\ &\quad s.t. \begin{cases} \alpha^2 + \beta^2 + \gamma^2 + \alpha\beta + \alpha\gamma + \beta\gamma - 1 = 0 \\ a'^2 + b'^2 + a'b' - 1 = 0 \\ a^2 + b^2 + ab - 1 = 0 \end{cases} \end{aligned} \tag{17}$$

Fmincon function or optimtool toolbox of MATLAB can be used to obtain an approximate optimal solution. When $a = 0.3624, b = 0.7682, a' = 0.5774, b' = 0.5774, \alpha = 0.2346, \beta = 0.2346, \gamma = 0.7088, F_{asymmetric} = 3.4279$. This result is superior to the optimal fidelity obtained through symmetric cloning mechanism. Similarly, the sum of the fidelity of multicast members obtained by other tree structures as shown in Fig.5 (1), (2) and (4) in set T are calculated: $F_{asymmetric-1} = 3.4396$, $F_{asymmetric-2} = 3.2964$, $F_{asymmetric-4} = 3.3811$.

The structure with the optimal fidelity is shown in Figure 7, which is the optimal multicast tree routing based on the asymmetric cloning mechanism.

Compared with the multicast routing scheme based on symmetric cloning machine, it can be found that: First, in the multicast tree routing set T, the tree routing with the highest fidelity based on the asymmetric cloning machine may be inconsistent with the symmetric cloning machine; Second, the different tree routings that obtain the same fidelity based on the symmetric cloning machine are still the same in the asymmetric cloning machine; Third, for the same tree routing, the scheme based on the asymmetric mechanism may make the sum of the information fidelity better than the scheme based on the symmetric mechanism.

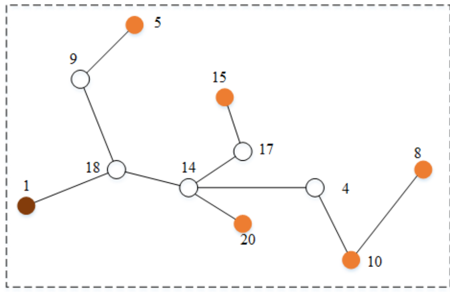

FIGURE 7. The optimal spanning tree structure of 20 nodes based on asymmetric cloning machine.

V. SIMULATION RESULT AND ANALYSIS

This paper uses MATLAB R2018a as simulation tool, and the simulation environment is Windows 10. In the simulation, all the nodes in the quantum network connectivity graph are randomly distributed within a 100 km × 100 km rectangular area. The communication range of each node is 30 km. It is defined whether the nodes can directly communicate with another node by this threshold. In this simulation, considering the proposed symmetric and asymmetric mechanisms and the KMB algorithm, the fidelity is calculated and analyzed.

Because there were few researches on the issues that we focus on in this paper, the proposed multicast scheme is compared with the classical KMB algorithm [37] of constructing the Steiner tree. The KMB algorithm is used to solve the multicast tree construction problem in classical networks. This algorithm was the first algorithm proposed to solve this type of problem. Some other algorithms are based on its improvements, adding different constraints for different simulation environments. However, the constraints considered by some algorithms are different from the focus of this paper. Therefore, the proposed algorithm is compared with the classical algorithm of KMB. The information fidelity obtained by multicast group members is used as the metrics to evaluate the performance of the proposed scheme. Analyze the advantages and disadvantages of the two methods. But because the fidelity of the multicast tree in the quantum network must be considered, there are up to four copies. Therefore, a multicast tree constructed by the KMB algorithm may not enable all multicast group members to obtain information. In this simulation, we consider the case where the multicast tree constructed by the KMB algorithm can make all multicast group members obtain the information sent by the source node. If the multicast tree constructed cannot guarantee all

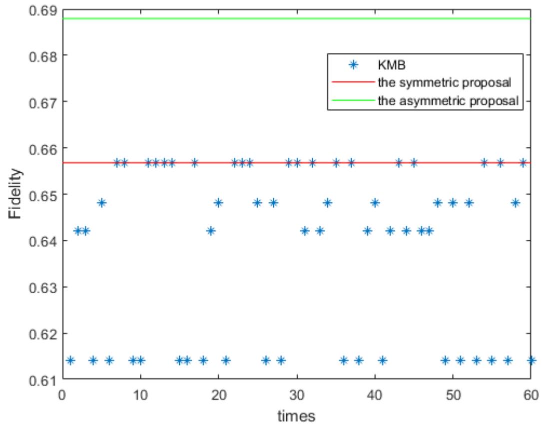

FIGURE 8. **The information fidelity obtained by destination nodes of three methods.**

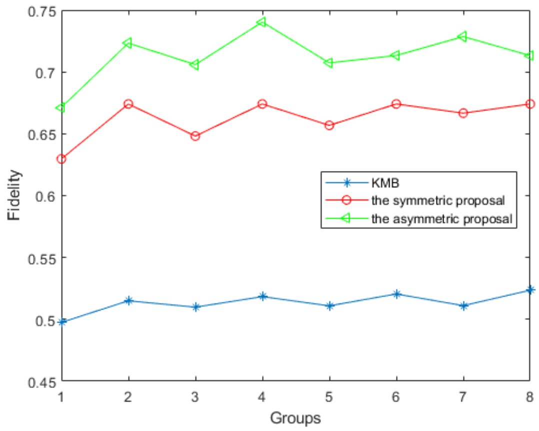

FIGURE 9. **Comparison of information fidelity obtained by destination nodes of different multicast groups.**

the multicast group members to obtain information, then the quantum information transmitting through the tree fails, and the fidelity is denoted as 0.

In the simulation, the number of nodes in the network n is set to 20. One source node and five multicast group members are selected randomly. These member nodes are fixed and do not change during the simulation. The result of running 60 times is shown in Fig.8. The multicast tree constructed by our proposed scheme obtains the optimal fidelity of the multicast group members, and $F_{opt-symmetric} = 0.657$, $F_{opt-\mathrm{asymmetric}} = 0.68792$. The multicast tree constructed by the KMB algorithm makes the maximum fidelity obtained by multicast group members reach the optimal value with a certain probability, in most cases it is lower than the optimal level.

For a quantum communication network with 20 nodes, different multicast group members are randomly selected. Each multicast group with fixed multicast group members runs the multicast schemes respectively several times to construct the multicast tree, and the sum of the fidelities of the information obtained by the multicast group members is calculated. Then the average value of fidelity is calculated and compared with the proposed scheme. The results are shown in the Fig.9. The multicast tree constructed by multicast scheme based on asymmetric mechanism makes the fidelity of the multicast group members better than the scheme based on symmetric mechanism, but both of them exceed the fidelity obtained by the multicast tree constructed by the KMB algorithm.

The variation trend of the fidelity of the information obtained by different numbers multicast group members in the fixed quantum network is analyzed. In this simulation, the number of nodes in the fixed quantum network is set to 40, and the multicast group members are 4, 5, 6, 8, 9 and 10, respectively. Three schemes are used to construct multicast tree for different multicast group. Then, the fidelity of information obtained by multicast group members is calculated. Since the members are randomly assigned by the source node, by running the algorithm several times and calculating the average value of fidelities, the normalized fidelities of different multicast group are obtained as shown in the Fig.10.

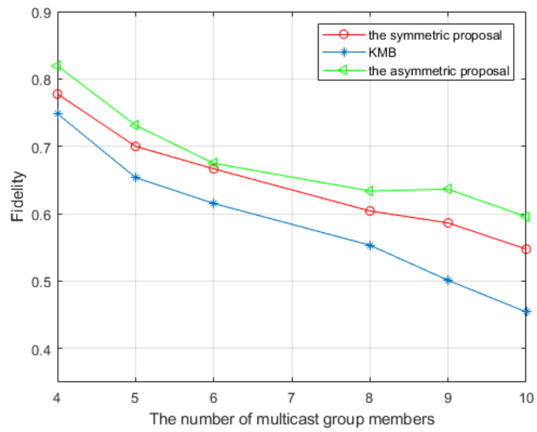

FIGURE 10. **Comparison of fidelity of information obtained by different number of multicast groups.**

It can be found that, when the number of multicast group members increases, the normalized fidelity shows a downward trend. The proposed scheme based on symmetric mechanism is better in fidelity than KMB algorithm, and the ratios of improvement are: 3.91%, 7.08%, 8.34%, 9.19%, 17.00% and 20.51%, respectively. The proposed scheme based on asymmetric mechanism performs better than the symmetric mechanism in fidelity. Compared with the KMB algorithm, the ratios of improvement are: 9.48%, 11.85%, 9.69%, 14.54%, 26.98% and 31.04%, respectively. The proposed scheme performs better when the number of the multicast group members is relatively large. Because, when the number of child nodes increases, the multicast tree constructed by the KMB algorithm cannot make all multicast group members get information, that is, multicast communication fails.

VI. CONCLUSION

This paper proposes a multicast scheme based on fidelity metrics in quantum networks. Firstly, the fidelity of the asymmetric quantum cloning mechanism is analyzed and derived.

The way of information transmission in the quantum network is defined: one-to-one transmission based on teleportation, and one-to-many lossy transmission based on the quantum cloning mechanism. Among them, one-to-many transmission is divided into two specific patterns according to whether a node is a member of the multicast group. The quantum network model is established. Then, the scheme to obtain the optimal path fidelity of multicast communication for a given quantum network connectivity graph is proposed. There is only one source node and it can randomly assign multicast group members. The maximum fidelity of the information obtained by all multicast members is the optimization goal. The number of copies of the quantum cloning mechanism and the maximum number of hops of the shortest path from the source node to all destination nodes are the two constraint conditions and an optimal multicast tree is constructed. The two mechanisms of symmetric cloning mechanism and asymmetric cloning mechanism are used to solve the fidelity of the multicast tree. Finally, using MATLAB software to simulate, the results show that the proposed scheme can construct the best fidelity path from the source node to multicast members for a random quantum network to multicast communication. With the increase of the number of multicast group members, the average value of information fidelity which all members receiving decreases. Compared with the multicast tree constructed by the KMB algorithm, the proposed scheme has better performance. At the same time, the performance of the scheme based on the asymmetric mechanism is better than the symmetric mechanism.

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