Distributed wireless quantum communication networks with partially entangled pairs*

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Wireless quantum communication networks transfer quantum state by teleportation. Existing research focuses on maximal entangled pairs. In this paper, we analyse the distributed wireless quantum communication networks with partially entangled pairs. A quantum routing scheme with multi-hop teleportation is proposed. With the proposed scheme, is not necessary for the quantum path to be consistent with the classical path. The quantum path and its associated classical path are established in a distributed way. Direct multi-hop teleportation is conducted on the selected path to transfer a quantum state from the source to the destination. Based on the feature of multi-hop teleportation using partially entangled pairs, if the node number of the quantum path is even, the destination node will add another teleportation at itself. We simulated the performance of distributed wireless quantum communication networks with a partially entangled state. The probability of transferring the quantum state successfully is statistically analyzed. Our work shows that multi-hop teleportation on distributed wireless quantum networks with partially entangled pairs is feasible.

Keywords: distributed wireless quantum communication networks, partially entangled pairs, routing, multi-hop teleportation

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1. Introduction

Quantum communication provides high security for information transmission.[1–3] It has potential applications in distributed wireless networks. There are two methods to transfer an unknown quantum state between two nodes: (i) transmitting directly from one node to another; (ii) transmitting by quantum teleportation.[3] Considering the inevitable interactivity of quantum states with the environment and the loss of flying qubits, the direct transmission in the wireless environment may corrupt the quantum states easily and is practicable for only short distance point to point transmission. For quantum teleportation, the two nodes transport an unknown quantum state via shared entangled particle pairs, which does not need to transmit the quantum state directly and is suitable for wireless transmission over any distance. Therefore, in this paper, we choose quantum teleportation to transfer quantum states in wireless quantum communication networks. When one particle of a entangled pair changes its state, the state of the other particle on the distant node changes accordingly. By transmitting local measurement results at one node to another using classical communication, information can be transmitted in a secure way due to the unknown states of the particles.[4,5]

For a faithful teleportation with d-state qudit, the protocols using entangled pairs are extensively studied.[6–16] Existing work on quantum communication by teleportation mainly focuses on point-to-point or simple network topology. There are a few works studying the complicated wireless quantum communication network;[17–21] these are all based on the noiseless maximally entangled states. However, in a practical situation, the quality of the maximally entangled state is usually degraded with decoherence and noise. Generally, the maximally entangled state may become a partially entangled state or a mixed state.[9,22] For becoming a partially entangled state, the entanglement pairs with maximally entangled state $|\phi^+\rangle_{12} = (|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2)/\sqrt{2}$ may degrade to

$$|\phi\rangle_{12} = \alpha|H\rangle_1|H\rangle_2 + \beta|V\rangle_1|V\rangle_2, \tag{1}$$

where α and β are non-negative real numbers and $|\alpha|^2 + |\beta|^2 = 1$, $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarizations, respectively.

How to transfer a quantum state in wireless quantum communication networks with partially entangled pairs is still an open problem. In this paper, we study the distributed wireless quantum communication networks (DWQCN)[21] with the partially entangled state and propose a quantum routing scheme with multi-hop teleportation. The routing scheme sets up routes on links with both quantum and classical channels, so that it performs efficiently. In this paper, we also extend this work to consider the cases where the quantum and the classical paths are not aligned and propose a new routing scheme for DWQCN. Better transmission paths can be found using the proposed scheme. The trade-off of is the increased overhead. After route selection, the quantum states are teleported by the

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proposed teleportation scheme. The performance of DWQCN with partially entangled states is simulated.

The remainder of this paper is organized as follows. Section 2 describes the system model. Section 3 proposes a quantum routing scheme to find a quantum route between two nodes. Section 4 proposes a teleportation scheme with the partially entangled pairs and gives the simulation results. Finally, a conclusion is given in Section 5.

2. System model

A DWQCN consists of n nodes distributed randomly. A node communicates with other nodes through one or multi-hop wireless paths. A wireless path is also called a classical path. The nodes are also quantum devices. If two nodes have entangled pairs, such as Einstein–Podolsky–Rosen (EPR) pairs,[23] they can transfer quantum states through quantum teleportation. Entangled pairs in DWQCN can be obtained by entanglement generation (EG)[24] or a third mediating system that is not entangled with either of them.[25,26] Entangled pairs can be regarded as a uniquely quantum resource, because they will be consumed in the process of teleportation. There exists a quantum channel between two nodes if they share entangled pairs. If node A can transmit to node B through one-hop wireless transmission, we say B is A's neighbor in the classical sense. If two nodes have entangled pairs, then they are neighbors in the quantum sense. An example DWQCN is shown in Fig. 1, where solid arrows and dashed lines represent neighborhood in the classical sense and neighborhood in the quantum sense, respectively. For example, the solid arrow from A to B indicates that B is A's neighbor in the classical sense; the dashed line between A and C indicates that B and C are neighbors in the quantum sense. Numbers associated with dashed lines represent the number of available partially entangled particles.

Assume that there is a source node in the DWQCN, which wants to send security information to a destination node in the same network. Security transmission is achieved by quantum teleportation between the two nodes. A classical path from the source to the destination is also needed to send the Bell-state measurement results, so that the transmitted information can be recovered at the destination. The classical path from the source to the destination can be setup and maintained using existing routing mechanisms for wireless networks.[27,28] If the source and destination nodes are not neighbors in the quantum sense, a quantum path has to be setup between them. Neighboring nodes on this quantum path should be neighbors in the quantum sense. A classical path from this node to at least one of its neighbors on the quantum path is also needed to transmit the Bell-state measurement results, so that the quantum teleportation can be performed continuously and finally, make the quantum states transfer from source to destination.

For example, in Fig. 1, node S wants to send security information to node D through quantum teleportation. However, S and D are not neighbors in the quantum sense. The wireless path and quantum path between them are needed. In Section 3, we propose a quantum routing scheme to find quantum paths between S and D, through which quantum states can be transferred from S to D. There are several quantum paths between S and D, such as S–A–B–C–D and S–H–D. Classical routes exist between any neighboring nodes on the paths. For example, classical paths $B \to E \to C$ and $C \to E \to B$ exist between B and C, which are neighbors on the quantum path.

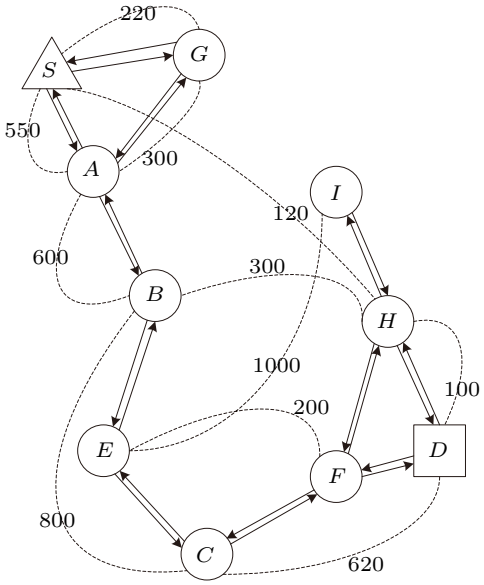


Fig. 1. An example of DWQCN.

3. Quantum routing scheme

In this section, we propose a quantum routing scheme to find quantum paths between two nodes in the DWQCN. We assume one of these two nodes is the source node (we call this node S in the following sections) and the other is the destination node (we call this node D in the following sections). A classical wireless transmission path has already been setup by using existing wireless routing protocols. Each node in the DWQCN has the knowledge of its neighbors in the quantum sense, as well as the number of available entangled particles it shares with its neighbors.

When node S wants to setup a quantum path to node D, it first checks whether D is its neighbor in the quantum sense. If so, the quantum path has already been found and the process ends. If not, S sends a quantum route setup (QRS) packet to D through the classical path, which starts the route discovery process. The QRS packet contains S's ID and the requirement to setup the quantum path.

When receiving the QRS packet, D sends quantum route find (QRF) packets to all its neighbors in the quantum sense. The QRF packets contain the ID of S. It also has a route record field (RRF), which records the quantum route it passes through. When sent from D, the RRF contains D's ID. Note that a neighbor of D in the quantum sense may not be the

neighbor of D in the classical sense. In this case, existing wireless routing protocols can be used to find a classical path from D to this neighbor.

If a node in the DWQCN receives a QRF packet, it appends its own ID to the end of RRF. After that, it forwards the QRF to its neighbors in the quantum sense, except node S (if S is its neighbor) and those neighbors whose IDs have already been listed in the RRF. As a result, loops in the QRF forwarding can be avoided. The node also checks whether S is its neighbor in the quantum sense. If so, it sends back a quantum route discovered (QRD) packet through the classical path to the node with its ID listed at the end of the RRF in the received QRF packet. The QRD packet contains a route metric field (RMF), which records the metric of the route, such as the number of available entangled pairs (as routing metrics) with each quantum link on the path. When the QRD packet is created, the node sets the RMF by copying the RRF, appending its own ID at the end of it and associating the number of available entangled pairs between S and itself to its own ID. Metrics with other IDs in the RMF are set to zero.

If a node in the DWQCN receives a QRD packet, it checks the RMF in the packet. If its own ID does not match the last ID with zero metric in the RMF, it discards this packet. Otherwise, it associates the number of available entangled particles between its upstream node and itself with its own ID in the RMF. The upstream node's ID is next to its own ID in the RMF. After that, the node forwards the QRD packet to its downstream neighbor according to the ID list in the RMF.

An example is shown in Fig. 2. Figure 2(a) shows the distribution of QRF packets from D. Each intermediate nodes appends its own ID to the RRF and forwards the received packets. Node B receives two packets from C and H. It appends its ID and forwards the packets separately. Node A finds that S is its neighbor in the quantum sense. It sends back QRD packets as shown in Fig. 2(b) and still forwards the QRF packets to G. G has two neighbors: S and A. Since A appears in the QRF packets, G will not forward the received QRF packets. Since S is G's neighbor, G sends back QRD packets. Figure 2(b) shows the distribution of QRD packets. To make the figure clear, only QRD packets sent from A are plotted. G and H, which are S's neighbors in the quantum sense, also initiate QRD packets, which are not plotted. As plotted in the figure, D receives two QRD packets from A, which indicates two available paths: one is S–A–B–C–D and the other is S–A–B–H–D. Other packets not shown carry information on others routes, such as S–G–A–B–C–D, S–G–A–B–H–D, S–H–D and S–H–B–C–D.

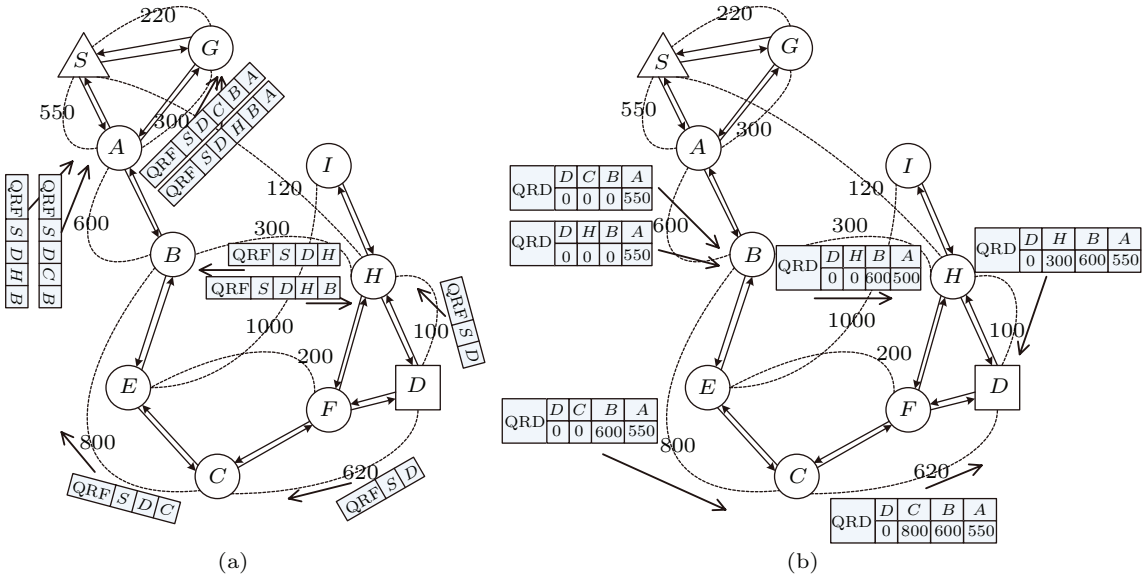


Fig. 2. Illustration of route discovery, (a) shows the distribution of QRF packets and (b) shows parts of the distribution of QRD packets.

Finally, the QRD packets will arrive at node D. From RMF in the QRD packets, D obtains information on all available quantum paths between S and itself. The information includes ID's of the nodes on the paths and the metric on the paths, such as the number of available entangled particles with each link on the paths. Considering the features of quantum teleportation, D may select one or more paths based on some criteria, such as minimal consumption of entangled particles, maximizing network lifetime of DWQCN, or maximizing the probability of successful transmission.

If we want to minimize consumption of entangled particles, then the criterion of selecting the path is

$$C_{\mathrm{r}} = \min h_i (1 \leq i \leq m), \tag{2}$$

where m is the number of candidate paths and h_i is the number of hops at the i-th path. Therefore, the path S–H–D is selected.

If we want to maximize the network lifetime of DWDCN, then, the criterion of selecting the path is

$$C_{\mathrm{r}} = \max E_i (1 \leq i \leq m), \tag{3}$$

where E_i is the minimal number of EPR pairs between nodes in the i-th candidate path. Adopting this criterion, the partition of DWQCN due to disconnection of quantum channels will be avoided and the network lifetime is maximized. Therefore, the path *S*–*A*–*B*–*C*–*D* is selected. The minimal entangled particle number is 550 on this path.

If we want to maximize the probability of successful transmission, for DWQCN with impartially entangled pairs, the path with minimum hops will be selected if the teleportation scheme in Section 4 is adopted. Using this scheme, the probability of successful transmission decreases with the increase of the number of hops. Therefore, the path *S*–*H*–*D* is selected.

For large-scale DWQCN, the amount of calculation needed to find the optimal route between the source and destination nodes is huge. We can use a quantum counting algorithm to solve this problem.[29]

4. Multi-hop teleportation scheme via partially entangled pairs for the quantum path

After the quantum path is selected, teleportation is performed to transfer quantum states from *S* to *D*. Generally, there may not exist partially entangled pairs between *S* and *D* directly. They share an entangled state with intermediate nodes on the quantum path. In this section, a teleportation scheme is proposed to transfer the quantum state.

Recently, the scheme of quantum teleportation via partially entangled pairs has been extensively studied.[30–34] Generally, two solutions can be used to transfer quantum states for quantum teleportation via partially entangled pairs. One is converting partially entangled pairs to maximally entangled pairs. The other uses partially entangled pairs directly. Converting the partially entangled pairs into maximally entangled pairs can be used to achieve fidelity teleportation. Many entanglement distillation schemes are developed to obtain maximally entangled states.[35–39] However, the distillation schemes without ancilla particle usually need a large number of partially entangled pairs to obtain a small number of maximally entangled pairs. Compared with distillation schemes, the single-photon-assisted scheme can get maximally entangled pairs with less cost. However, additional operations are still needed for each teleportation.[39] Therefore, we consider a teleportation scheme using partially entangled pairs directly. In Refs. [31]–[33], a feature of multiple teleportation via partially entangled pairs is shown that the errors introduced in the previous teleportation can be corrected by the errors introduced in the following teleportation. Considering that there are usually several nodes in a selected route of DWQCN, this feature is suitable for direct teleportation on a selected path with multi-hops.

For direct teleportation, assume that *S* wants to teleport a quantum state $|\phi\rangle_1$ of particle 1 to *D*

$$|\phi\rangle_1 = a|0\rangle + b|1\rangle, \tag{4}$$

where $|a|^2 + |b|^2 = 1$.

Assume the partially entangled pairs in the DWQCN are in the same state

$$|\Phi\rangle = \alpha|0\rangle|0\rangle + \beta|1\rangle|1\rangle, \tag{5}$$

where $|\alpha|^2 + |\beta|^2 = 1$.

The standard Bell basis are used for the Bell state measurements as follows:

$$\begin{aligned} |\Phi^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle), \\ |\Psi^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle). \end{aligned} \tag{6}$$

Assume that particle 2 in *S* is entangled with particle 3 in the next node of the selected quantum path from *S* to *D*. The three particles state can be written as

$$\begin{aligned} |\Psi\rangle_{123} &= (a|H\rangle_1 + b|V\rangle_1) \otimes (\alpha|H\rangle_2|H\rangle_3 + \beta|V\rangle_2|V\rangle_3) \\ &= \sqrt{\frac{\alpha^2|a|^2 + \beta^2|b|^2}{2}}|\Phi^+\rangle_{12}\frac{\alpha a|0\rangle_3 + \beta b|1\rangle_3}{\sqrt{\alpha^2|a|^2 + \beta^2|b|^2}} \\ &\quad + \sqrt{\frac{\alpha^2|a|^2 + \beta^2|b|^2}{2}}|\Phi^-\rangle_{12}\frac{\alpha a|0\rangle_3 - \beta b|1\rangle_3}{\sqrt{\alpha^2|a|^2 + \beta^2|b|^2}} \\ &\quad + \sqrt{\frac{\beta^2|a|^2 + \alpha^2|b|^2}{2}}|\Psi^+\rangle_{12}\frac{\alpha b|0\rangle_3 + \beta a|1\rangle_3}{\sqrt{\beta^2|a|^2 + \alpha^2|b|^2}} \\ &\quad + \sqrt{\frac{\beta^2|a|^2 + \alpha^2|b|^2}{2}}|\Psi^-\rangle_{12}\frac{\beta a|1\rangle_3 - \alpha b|0\rangle_3}{\sqrt{\beta^2|a|^2 + \alpha^2|b|^2}}. \end{aligned} \tag{7}$$

After the measurement at node *S*, the unitary operation at the next node should do as in Table 1. After the unitary operation is performed, the according states of the entangled particle in the next node are also shown in Table 1.

From Table 1, utility fidelity teleportation occurs only if α is equal to β, which means the according entanglement state is the maximal entangled state. For partially entangled pairs, α is not equal to β, P_i is used to denote the success probability of i-th teleportation. From Table 1, we can obtain after the first teleportation, P_1=0. Assuming that the measurement results of *S* is $|\Phi^+\rangle$, for the second teleportation at the next node, the quantum state to transfer is

$$|\phi\rangle = a_1|H\rangle + b_1|V\rangle, \tag{8}$$

where

$$a_1 = \frac{\alpha a}{\sqrt{\alpha^2|a|^2 + \beta^2|b|^2}}, \quad b_1 = \frac{\beta b}{\sqrt{\alpha^2|a|^2 + \beta^2|b|^2}}.$$

Table 1. Relationship of measurement results and operations at the first teleportation.

Measurement results	Operations	According states
$\|\Phi^+\rangle$	1	$\frac{\alpha a\|0\rangle_3+\beta b\|1\rangle_3}{\sqrt{\alpha^2\|a\|^2+\beta^2\|b\|^2}}$
$\|\Phi^-\rangle$	Z-GATE	$\frac{\alpha a\|0\rangle_3+\beta b\|1\rangle_3}{\sqrt{\alpha^2\|a\|^2+\beta^2\|b\|^2}}$
$\|\Psi^+\rangle$	X-GATE	$\frac{\beta a\|0\rangle_3+\alpha b\|1\rangle_3}{\sqrt{\beta^2\|a\|^2+\alpha^2\|b\|^2}}$
$\|\Psi^-\rangle$	$Y(ZX)$-GATE	$\frac{\beta a\|0\rangle_3+\alpha b\|1\rangle_3}{\sqrt{\beta^2\|a\|^2+\alpha^2\|b\|^2}}$

Based on Eqs. (2)–(5) and Table 1, after the second teleportation, the unitary operation and the according states of entangled particles at the third node on the path are shown in Table 2.

From Table 2, it is obviously that if the measurement results are $|\Psi^{\pm}\rangle$, the teleportation succeeds. Using the same method, we can conclude that the second teleportation is successful if the two measurements satisfy the following conditions: the first measurement results are $|\Phi^{\pm}\rangle(|\Psi^{\pm}\rangle)$, the second measurement results are $|\Psi^{\pm}\rangle(|\Phi^{\pm}\rangle)$. This is consistent with the conclusion of protocol 2 in Ref. [32] that the quantum state may be transferred successfully only if a balanced sequence of $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$ is obtained. Assume that the number of nodes on the selected quantum route is N. If N is odd, the quantum state may be transferred successfully by teleportation hop by hop. If N is even, we cannot obtain a balanced sequence of $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$ by teleportation hop by hop. Therefore, as N is even, the destination node D will add another teleportation at itself. The process of the teleportation scheme on the selected via partially entangle pairs route is shown in Fig. 3.

Table 2. Relationship of measurement results and operations at the second teleportation.

Measurement results	Operations	According states
$\|\Phi^+\rangle$	1	$\frac{\alpha^2 a\|0\rangle_5+\beta^2 b\|1\rangle_5}{\sqrt{\alpha^4\|a\|^2+\beta^4\|b\|^2}}$
$\|\Phi^-\rangle$	Z-GATE	$\frac{\alpha^2 a\|0\rangle_5+\beta^2 b\|1\rangle_5}{\sqrt{\alpha^4\|a\|^2+\beta^4\|b\|^2}}$
$\|\Psi^+\rangle$	X-GATE	$a\|0\rangle_5+b\|1\rangle_5$
$\|\Psi^-\rangle$	$Y(ZX)$-GATE	$a\|0\rangle_5+b\|1\rangle_5$

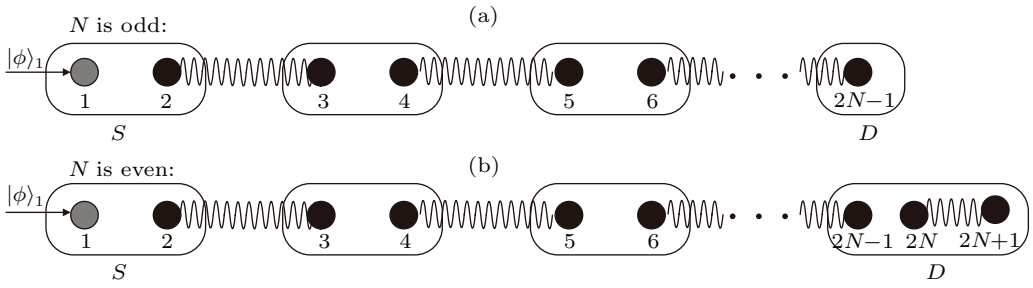


Fig. 3. Process of teleportation scheme via partially entangle pairs: (a) N is odd; (b) N is even.

For the second teleportation, the probability of every possible success is

$$P_2' = \left(\sqrt{\frac{\alpha^2|a|^2+\beta^2|b|^2}{2}}\right)^2\left(\sqrt{\frac{\alpha^2\beta^3}{2(\alpha^2|a|^2+\beta^2|b|^2)}}\right)^2 = \left(\frac{\alpha\beta}{2}\right)^2. \quad (9)$$

There are $C_4^1C_2^1$ cases of possibilities of success. The total possibilities of success is

$$P_2 = 2\alpha^2\beta^2. \quad (10)$$

When N is odd , the number of the teleportation is $N-1$. A successful teleportation is composed by $(N-1)/2$ pairs of $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$. The probability of a successful transfer is

$$P_{N-1}' = \left[\left(\frac{\alpha\beta}{2}\right)^2\right]^{(N-1)/2}. \quad (11)$$

For a balanced sequence of $|\Phi^{\pm}\rangle$ and $|\Psi^{\pm}\rangle$, the number of all possible successes is $C_q^{(N-1)/2}2^{N-1}$. Therefore, the total success probability of the selected route is

$$P = C_{N-1}^{(N-1)/2}(\alpha\beta)^{N-1}. \quad (12)$$

When N is even, the destination node D will do another teleportation by itself, as shown in Fig. 3. The total success probability of the selected route is

$$P = C_N^{N/2}(\alpha\beta)^N. \quad (13)$$

The DWQCN with partially entangled state is simulated and the probability of successful transmission is statistically analyzed. In our simulations, the network area is 1000 m × 1000 m. The nodes are distributed in the network randomly. For the same number of nodes, the connectivity of DWQCN is changed by transmission range R and the probability of any two nodes sharing partially entangled pairs p_e. The transmission range is the separation distance, which allows two nodes to transmit data successfully in a wireless channel. In our simulation, there exists a wireless link between two nodes if and only if the distance between them is within the transmission range. Examples of the wireless topology with 50 nodes

are shown in Figs. 4 and 5, corresponding to the transmission range 200 m and 300 m, respectively. The quantum topology with the same nodes is shown in Figs. 5 and 6, corresponding to $p_e = 0.2$ and 0.5, respectively. As shown in Figs. 4 and 5, increasing the transmission range can increase the connectivity of wireless topology. As shown in Figs. 6 and 7, increasing p_e can increase the connectivity of the quantum topology. All possible source-destination pairs are simulated. Simulation results given in the paper are the averaged values on the results of all the possible pairs. The wireless route is set up based on minimal hops. If there exists a wireless route between S and D, then we set up quantum route. Considering that the success probability decreases with the increase of the number of hops, the metric of the quantum route is also the minimal number of hops. If there exists a wireless route and a quantum route simultaneously between S and D, the directly multiple teleportation via partially entangled pairs is performed and the success probability is obtained by Eqs. (10) and (11). In addition, the quantum state transfer from S to D fails. We change the wireless transmission range and the number of nodes in DWQCN. The probability of successfully transferring quantum states are shown in Figs. 8–10. To avoid the influence of topology, every simulation runs on 100 topologies and the average results are given.

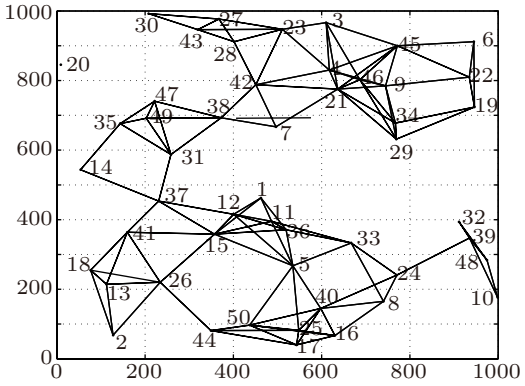


Fig. 4. An example of wireless topology with 50 nodes (R = 200 m).

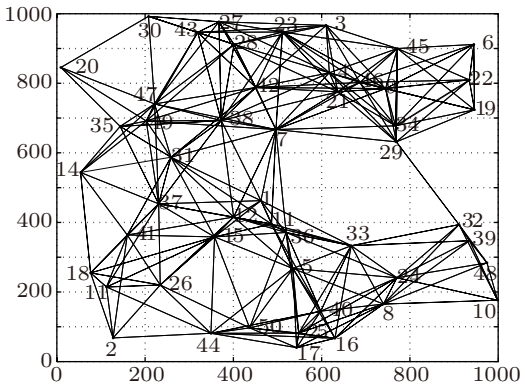


Fig. 5. An example of wireless topology with the same nodes (R = 300 m).

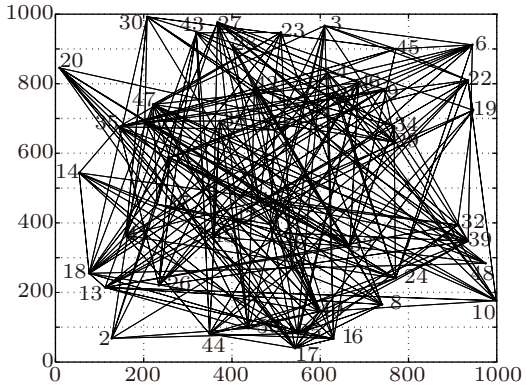


Fig. 6. An example of quantum topology with the same nodes ($p_e = 0.2$).

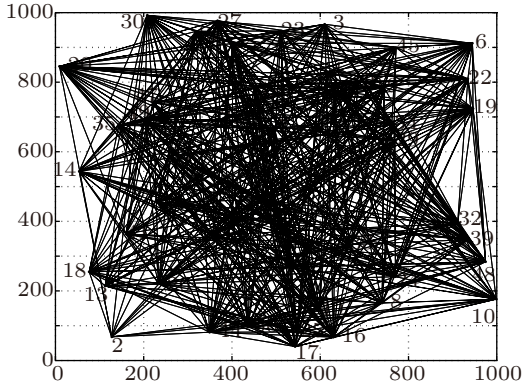


Fig. 7. An example of quantum topology with the same nodes ($p_e = 0.5$).

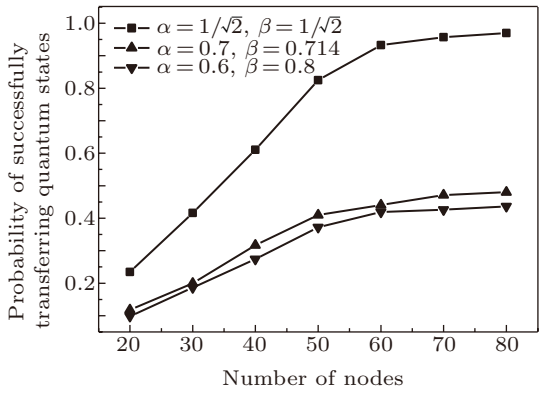


Fig. 8. Probability of successfully transferring quantum states versus the number of nodes ($R = 200$ m, $p_e = 0.5$).

In Figs. 8–10, when the other conditions are the same, the success probabilities increase with the transmission range, the number of nodes in a DWQCN and the probability p_e. The reason is that network connectivity will increase. With the increasing network connectivity, the number of selectable routes increases and the minimal number of hops deceases. The deceasing of the minimal number of hops leads to the success probabilities increasing. The ratio of α to β represents the degree of entanglement. When the ratio is closer to 1, the degree of entanglement is greater. The simulation results also show that the success probabilities also increases with the

increasing of the entanglement degree. For maximal entangled pairs, α is equal to β and the value is $1/\sqrt{2}$. In Figs. 8 and 10, the success probabilities of teleportation via maximal entangled pairs are greater than via partially entangled pairs. For direct teleportation via maximal entangled pairs, because $|\alpha|^2+|\beta|^2=1$, the success probability is always less than 0.5. We can increase the success probability by retransmission.

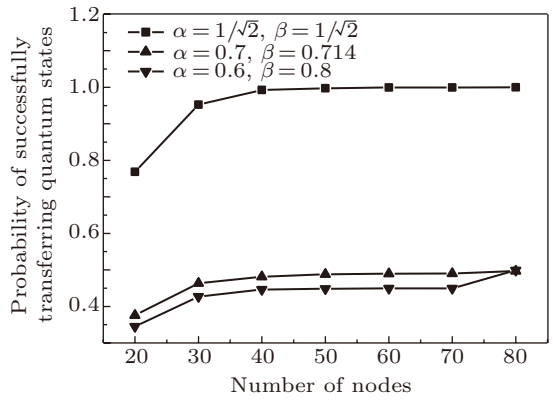


Fig. 9. Probability of successfully transferring quantum states versus the number of nodes ($R=300$ m, $p_e=0.5$).

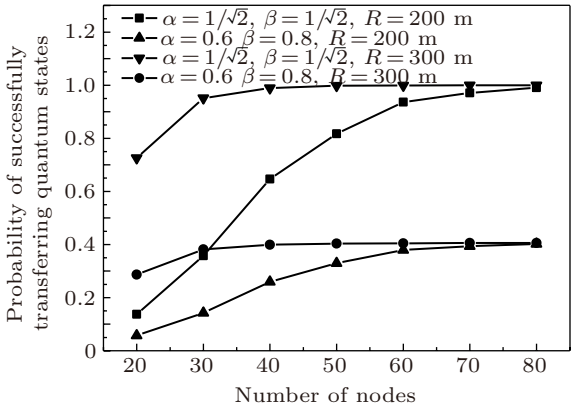


Fig. 10. Probability of successfully transferring quantum states versus the number of nodes ($p_e=0.2$).

5. Conclusions

In this paper, we propose a quantum routing scheme with multi-hop teleportation for DWQCN with partially entangled pairs. We solve the problem that the quantum path and classical path may not coincide. Classical paths can be setup using existing routing protocols for wireless networks. A broadcast process is conducted to find as many quantum paths as possible. The destination node selects one or more paths on which a multiple teleportation is performed. After the wireless path and quantum path are selected, the direct multi-hop teleportation scheme via partially entangled pairs is performed to transfer the quantum state from the source to the destination. When the node number of the quantum path is even, the destination node will add another teleportation at itself to make the transfer successful. The DWQCN with a partially entangled state is simulated. The probability of successfully transferring a quantum state is conducted. The work shows that multi-hop teleportation on distributed wireless quantum networks with partially entangled pairs is feasible.

Although the proposed quantum routing scheme is optimal in the sense of finding all feasible paths, open problems exist. One problem is to reduce the protocol overhead, which can be solved in several ways. One way is to distribute the route selection function to intermediate nodes in the network, so that some routes can be pruned during the route finding process. Another way is to incorporate multicast routing in the route discovery process, which can reduce the overhead with broadcasting. Another problem is with route selection, which is affected by different criteria. Upper layer utilities should be considered. Still a more complicated scenario is the multiple-source and multiple-destination case, where the optimal solution is difficult to find and sub-optimal ones can be investigated. For the selected quantum route, more research is needed to increase the probability of successfully transferring quantum states.

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