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Distributed wireless quantum communication networks*

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The distributed wireless quantum communication network (DWQCN) has a distributed network topology and transmits information by quantum states. In this paper, we present the concept of the DWQCN and propose a system scheme to transfer quantum states in the DWQCN. The system scheme for transmitting information between any two nodes in the DWQCN includes a routing protocol and a scheme for transferring quantum states. The routing protocol is on-demand and the routing metric is selected based on the number of entangled particle pairs. After setting up a route, quantum teleportation and entanglement swapping are used for transferring quantum states. Entanglement swapping is achieved along with the process of routing set up and the acknowledgment packet transmission. The measurement results of each entanglement swapping are piggybacked with route reply packets or acknowledgment packets. After entanglement swapping, a direct quantum link between source and destination is set up and quantum states are transferred by quantum teleportation. Adopting this scheme, the measurement results of entanglement swapping do not need to be transmitted specially, which decreases the wireless transmission cost and transmission delay.

Keywords: distributed wireless networks, quantum communication networks, quantum teleportation, routing protocol

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1. Introduction

The distributed wireless network is an architecture with distributed nodes and without a central control node, such as the ad hoc network and mesh network.[1,2] All nodes make decisions based on their own local information. It has attracted great interest for its flexibility and has wide applications in the wireless area. However, due to the lack of a fixed infrastructure and all nodes sharing the open wireless channel, the distributed wireless network can be easily attacked.[3,4] Security is an important issue for the distributed wireless network.

Since the 1980s, the combination of quantum physics with information technology has created a fundamentally new mode of communication, which guarantees absolutely secure communication and can improve the capacity of networks.[5–9] Quantum entanglement is an important characteristic of quantum physics. Based on quantum entanglement, teleportation, and swapping, a quantum communication network can be constructed and the information can be carried by quantum states.[10–12] Recently, the research of quantum entanglement has made great progresses. Pan *et al.* created an eight-photon entanglement[13] and carried out the experiment of topological error correction with eight-photon cluster states.[14] The quantum teleportation and entanglement distribution over 100-km free-space channels have also achieved.[15] These technologies offer the possibility to construct large scale and complex wireless quantum communication networks.

Currently, most works focus on a simple network contracture,[16–18] and there are few studies on wireless quantum communication networks with a complex infrastructure. Cheng *et al.* first investigated mobile wireless networks in the quantum domain.[19] They proposed a quantum routing mechanism in a hierarchical network architecture to teleport a quantum state from source to destination even though they do not share Einstein–Podolsky–Rosen (EPR) pairs mutually. Tan *et al.* proposed two heuristic algorithms to generate a constant fidelity entanglement flow in quantum communication networks.[20] Zhou *et al.* proposed an automatic retransmission quantum synchronous communication protocol based on quantum entanglement and solved the two-army problem with EPR pairs and teleportation.[21,22] Yu *et al.* proposed a routing protocol for a wireless ad hoc quantum communication network (WAQCN).[23] In this paper, we integrate the distributed wireless network with quantum physics to guarantee the security of the network, named the distributed wireless quantum communication network (DWQCN). We give the definition of DWQCN and present a system scheme, including a routing protocol and a special quantum information transfer scheme. The system scheme of a DWQCN is adaptable to all wireless quantum communication networks with distributed infrastructures, such as ad hoc infrastructures, mesh infrastructures, and distributed cellular infrastructures. Therefore, compared with

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the WAQCN, the DWQCN has wider applicability.

This paper is organized as follows. In Section 2, the network model and characteristics of the DWQCN are presented. In Section 3, a routing protocol to transfer information between any two nodes of the DWQCN by quantum states is presented. In Section 4, based on the routing protocol, a method to set up a quantum channel is given. In Section 5, the performance of the DWQCN is evaluated. Finally, we give the conclusion of this paper.

2. Model of DWQCN

The distributed wireless quantum communication network (DWQCN) is defined as follows. It has a distributed topology, the network nodes are mobile quantum devices with wireless communication capability; the nodes transmit information mainly through a quantum channel with the classic wireless channel as a supplementary one. In the DWQCN, the information can be carried by quantum states through quantum coding.

In this paper, quantum teleportation[10] is used to transfer a quantum state from one node to another via entangled particles, such as EPR pairs.[11] The EPR pairs can be distributed in advance and shared by nodes that are far apart. If there are no direct EPR pairs between the source and the destination, entanglement swapping[12,13] can be technology used to form EPR pairs between the source and the destination. Because of the quantum state transferred following the EPR pair being consumed, the EPR pair can be seen as a quantum link to transfer the quantum state. So we define the quantum link as follows. In the DWQCN, there exists a quantum link between two nodes if and only if they share EPR pairs. The network model is shown in Fig. 1. The dashed line presents the quantum link and the real line expresses the wireless link. The number between two nodes is the number of EPR pairs shared by them. For two nodes, if there exist quantum and wireless links simultaneously between them, they are neighbor nodes, such as node A and node B. The topology of the DWQCN is changed not only for the node joining or leaving, but also for the change of the quantum links. Once the EPR pairs owned by two nodes are exhausted, the topology of the DWQCN is also changed.

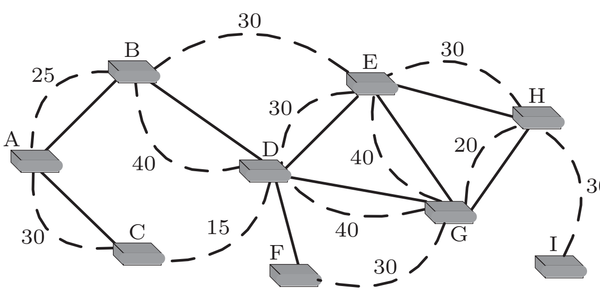

Fig. 1. Network model for DWQCN.

Teleportation and entanglement swapping need a classical channel to transmit measurement results. Therefore, in Fig. 1, two nodes can transfer information by quantum states if and only if there exist a hop-by-hop quantum channel and a wireless channel simultaneously between them. The quantum channel composes the quantum route and the wireless channel composes the wireless route. The nodes in the quantum route and those in the wireless route can be different. For example, node D wants to communicate with node F. The quantum route can be composed by routes DG and FG and the wireless route can be composed by routes DG and DF. In this paper, to simplify the route protocol, we select the route with the same quantum route and wireless route.

3. Routing protocol for DWQCN

As in a traditional network, a routing protocol in the DWQCN is used to set up and maintain routes between nodes. The routing protocols for the traditional wireless distributed networks can be divided into two main categories: table-driven and on-demand.[4] The on-demand routing protocols initiate a route discovery procedure only when a node needs a route to a destination and the procedure is adapt to the changing networks. Therefore, the routing protocol for the DWQCN is proposed as an on-demand protocol.

In the DWQCN, information is carried by quantum states, therefore a route in the DWQCN includes not only a wireless route but also a quantum route. The wireless route is comprised by the nodes making up a hop-by-hop wireless path from the source to the destination. The quantum route is comprised with the nodes sharing EPR pairs hop-by-hop from the source to the destination. Because the wireless and quantum links are all needed in quantum teleportation, the routing protocol in the DWQCN needs to find a route in which every hop owns wireless and quantum links simultaneously. As defined in Section 1, two nodes are considered as neighbor nodes in the DWQCN if and only if there exist quantum and wireless channels simultaneously. Therefore for the DWQCN, we can choose a set of neighbor nodes to set up a route. For example, in Fig. 1, route A→B→D→E→H can be selected as the route from A to H, however route A→B→E→H cannot be selected because nodes B and E are not neighbor nodes.

The routing protocol usually consists of three parts: (i) route request, (ii) route set-up, and (iii) route maintenance. The route request and route set-up constitute a route discovery process to establish a route from the source to the destination. Each node maintains a route table. Route table entries contain the destination address, next hop address, route cost, sequence number for destination, and expiration time for the entry. The sequence number is used for loop prevention and as the route freshness criteria in ad hoc on-demand distance vector AODV[24] routing. For every reachable node, there is only a single route in the table to reduce the difficulty of management.

If the EPR pairs between two neighbor nodes are exhausted, the quantum link between them will break. Therefore the EPR pairs are the resource for transferring quantum states. Different from a traditional wireless network using minimum hop-count as the route metric, the DWQCN can use the number of EPR pairs between neighbors as the route metric. The routing metric used in the proposed protocol is

$$M = \max(N_j), \quad 1 \le j \le m, \tag{1}$$

where m is the number of selectable routes, N_j is the minimal number of EPR pairs between nodes in the j-th selectable route. In the following, the basic procedure to set up and maintain the route from node A to node H in Fig. 1 is described in detail to propose the basic mechanisms of our protocol.

3.1. Route request

In Fig. 1, once node A wants to send information to node H, first it will check the route table for a fresh route to node H. If there does not exist an available route to node H, a route discovery process is initiated by node A. Node A broadcasts a route request (RREQ) packet to its neighbors via the wireless channel. The RREQ packet includes the addresses of source and destination, sequence numbers of source and destination, the address of the previous node, the value of routing cost, and the request ID. The source sequence number adds 1 before being added to the RREQ. The initial value of the routing cost is set to 0. The intermediate node receiving the RREQ will check whether it has received the same RREQ. If received, the RREQ is discarded; otherwise, the node will take the following actions.

(i) Update the route cost in the RREQ. The number of EPR pairs between the sending and the receiving nodes in the RREQ is denoted as $N_{\rm e}$ and the value of routing cost in the RREQ is denoted as $C_{\rm r}$. If $N_{\rm e}$ is zero, indicating that there does not exist any wireless or quantum link, the RREQ is discarded. Otherwise the node updates $C_{\rm r}$, if $C_{\rm r} > N_{\rm e}$ or $C_{\rm r} = 0$, set $C_{\rm r}$ to $N_{\rm e}$; if $C_{\rm r} \le N_{\rm e}$, $C_{\rm r}$ is not changed.

(ii) Update the route table to set up a reverse route to the source node. If there exists a fresh route to the source node, the route cost in the route table is compared to $C_{\rm r}$. If the route cost in the route table is smaller, then the route entry to the source is updated, and the cost is set to $C_{\rm r}$. The next hop address to the source is replaced by the previous node address in the RREQ.

(iii) Update the previous node address in the RREQ with the current node address and broadcast the RREQ. At last, the destination node may receive more than one RREQ from its neighbors with different routes and will initiate a route set-up procedure.

3.2. Route set-up

The route set-up procedure is initiated only by the destination node. A direct quantum link between the source and the destination is also set up following the route set-up procedure. The destination node selects an optimal route from the available routes according to the route cost and adds the selected route to the route table. Assume there are two available routes, one is A→B→D→E→H, and the other is A→C→F→G→H. The route costs for the two routes are 25 and 20, respectively. Based on the routing metric, destination node H selects A→B→D→E→H as the route from node A to node H. Node H unicasts a route reply (RREP) packet to node E. The RREP packet includes the addresses of source and destination, destination sequence number, the address of the previous node, and the route cost to the destination. The initial value of the route cost is zero. After receiving the RREP, node E will take the following actions.

(i) Update the route cost in the RREP. The number of EPR pairs between the sending and the receiving nodes in the RREP is denoted by $N'_{\rm e}$, and the route cost in the RREP is denoted by $C'_{\rm r}$. The process of updating the route cost in every intermediate node is as follows. If $C'_{\rm r} > N'_{\rm e}$ or $C'_{\rm r}=0$, set $C'_{\rm r}$ to $N'_{\rm e}$; if $C'_{\rm r} \le N'_{\rm e}$, $C'_{\rm r}$ is not changed. For node E, the route cost in the RREP is updated to $N'_{\rm e}$.

(ii) Update the route table to set up the route to the destination node with the selected route. The route cost of the route entry to the destination node is set to $C'_{\rm r}$ and the next hop to node H is set to the previous node in the RREP. In this example, the previous node of node E is node H.

(iii) With receiving RREP, node E triggers an entanglement swapping and a quantum link between node H and node D is set up. The measurement results of entanglement swapping are piggybacked onto the RREP.

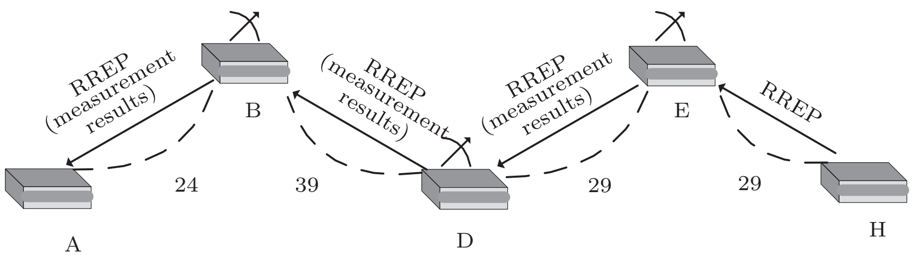

Fig. 2. Selected route in the example.

(iv) Node E sends the RREP to node D.

After receiving the RREP, node D conducts the same procedure as node E. By this way, the RREP is received eventually by node A and a quantum link from node A to node H is set up simultaneously. Node A adds the route entry to destination H. After the route discovery, the numbers of EPR pairs shared between neighbors in the selected route are shown in Fig. 2. Compared with the status shown in Fig. 1, the number of EPR pairs in the selected route decreases by 1 because of the entanglement swapping.

3.3. Route maintenance

The same as the route maintenance in AODV, each node in an active route needs to monitor the connectivity to the next hop. This connection includes wireless and quantum links. For the wireless link, each node broadcasts a HELLO message to its neighbors periodically. If a node does not receive the HELLO message from a neighbor for a certain time, it considers that the wireless link between them is broken. For the quantum link, if the EPR pairs between two nodes are exhausted, it considers that the quantum link between them is broken. When a node detects that a wireless or quantum link to the next hop in an active route is broken, it informs the source node with a route error (RERR) packet. All unreachable destinations are listed in the RERR. Every intermediate node deletes the unreachable route and forwards the RERR until it reaches the source node. Then the source node reinitiates a route discovery process to find a new route to the destination node.

4. Quantum information transfer scheme

Using the proposed routing protocol, entanglement swapping is operated following the transmission of the RREP. When the RREP reaches the source node, one particle of the source has been entangled with that of the destination. For the selected route A→B→D→E→H, the quantum logic circuit for quantum teleportation and entanglement swapping is shown in Fig. 3. Assume x is the particle carrying information, its state can be expressed as

$$|x\rangle = \alpha|H\rangle + \beta|V\rangle, \tag{2}$$

where α and β are complex numbers and $\|\alpha\|^2 + \|\beta\|^2 = 1$, $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization sates of this particle, respectively.

In the following, the transmission process of a quantum state in the DWQCN is described in detail. When the RREP reaches node E from node H, an entanglement swapping is used to generate an EPR pair between nodes H and D. As shown in Fig. 3, particles E_2 and H_1 form an EPR pair, D_2 and E_1 also form an EPR pair. There are four possible Bell states for an EPR pair

$$|\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2),$$
$$|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |H\rangle_1|V\rangle_2). \tag{3}$$

Assume E_2 and H_1 are in state $|\phi^+\rangle_{E_2H_1} = (|H\rangle_{E_2}|H\rangle_{H_1} + |V\rangle_{E_2}|V\rangle_{H_1})/\sqrt{2}$, and D_2 and E_1 are in state $|\phi^+\rangle_{E_2H_1} = (|H\rangle_{E_2}|H\rangle_{H_1} + |V\rangle_{E_2}|V\rangle_{H_1})/\sqrt{2}$, the total four-particle state is

$$\begin{aligned}|\phi\rangle_{D_2E_1E_2H_1} &= \frac{1}{2}(|H\rangle_{D_2}|H\rangle_{E_1} + |V\rangle_{D_2}|V\rangle_{E_1})\\ &\quad\otimes(|H\rangle_{E_2}|H\rangle_{H_1} + |V\rangle_{E_2}|V\rangle_{H_1}).\end{aligned} \tag{4}$$

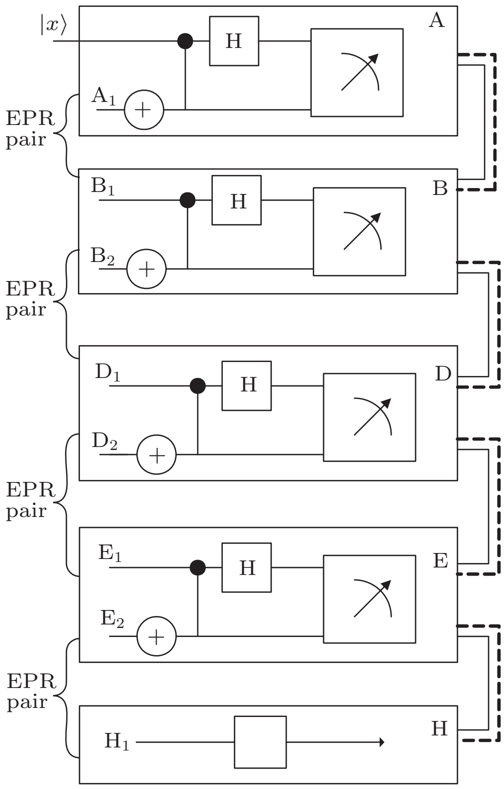

Fig. 3. The quantum logic circuit.

At node E, using the Bell-sate measurement to E_1 and E_2 will make them entangled. Consequently, H_1 and D_2 will also become entangled and the entanglement swapping is achieved. The quantum logical circuit of entanglement swapping is composed by a CNOT gate and a Hadamard gate as shown in Fig. 3. By using the CNOT gate to E_1 and E_2, the four-particle state becomes

$$\begin{aligned}|\phi\rangle_{D_2E_1E_2H_1} &= \frac{1}{2}\big[|H\rangle_{D_2}|H\rangle_{E_1}(|H\rangle_{E_2}|H\rangle_{H_1} + |V\rangle_{E_2}|V\rangle_{H_1})\\ &\quad + |V\rangle_{D_2}|V\rangle_{E_1}(|V\rangle_{E_2}|H\rangle_{H_1} + |H\rangle_{E_2}|V\rangle_{H_1})\big].\end{aligned} \tag{5}$$

After applying the Hadamard gate to E_1, we have

$$\begin{aligned}&|\phi\rangle_{D_2E_1E_2H_1}\\ &= \frac{1}{2\sqrt{2}}\big[|H\rangle_{D_2}(|H\rangle_{E_1} + |V\rangle_{E_1})(|H\rangle_{E_2}|H\rangle_{H_1} + |V\rangle_{E_2}|V\rangle_{H_1})\end{aligned}$$

$$+|V\rangle_{\mathrm{D}_2}(|H\rangle_{\mathrm{E}_1}-|V\rangle_{\mathrm{E}_1})(|V\rangle_{\mathrm{E}_2}|H\rangle_{\mathrm{H}_1}+|H\rangle_{\mathrm{E}_2}|V\rangle_{\mathrm{H}_1})]. \quad (6)$$

This equation can be rewritten in the basis of Bell states of E_1 and E_2

$$\begin{aligned}
&|\phi\rangle_{\mathrm{D}_2\mathrm{E}_1\mathrm{E}_2\mathrm{H}_1}\\
&= \frac{1}{2\sqrt{2}}[|H\rangle_{\mathrm{E}_1}|H\rangle_{\mathrm{E}_2}(|H\rangle_{\mathrm{D}_2}|H\rangle_{\mathrm{H}_1}+|V\rangle_{\mathrm{D}_2}|V\rangle_{\mathrm{H}_1})\\
&\quad +|H\rangle_{\mathrm{E}_1}|V\rangle_{\mathrm{E}_2}(|H\rangle_{\mathrm{D}_2}|V\rangle_{\mathrm{H}_1}+|V\rangle_{\mathrm{D}_2}|H\rangle_{\mathrm{H}_1})\\
&\quad +|V\rangle_{\mathrm{E}_1}|H\rangle_{\mathrm{E}_2}(|H\rangle_{\mathrm{D}_2}|H\rangle_{\mathrm{H}_1}-|V\rangle_{\mathrm{D}_2}|V\rangle_{\mathrm{H}_1})\\
&\quad +|V\rangle_{\mathrm{E}_1}|V\rangle_{\mathrm{E}_2}(|H\rangle_{\mathrm{D}_2}|V\rangle_{\mathrm{H}_1}-|V\rangle_{\mathrm{D}_2}|H\rangle_{\mathrm{H}_1})]. \qquad (7)
\end{aligned}$$

Note that after the entanglement swapping, particles D_2 and H_1 are entangled. The Bell state of D_2 and H_1 depends on the states of the two particles held by node E. For example, if the measurement result of E_1 and E_2 is $|HH\rangle_{\mathrm{E}_1\mathrm{E}_2}$, the state of D_2 and H_1 must be $(|H\rangle_{\mathrm{D}_2}|H\rangle_{\mathrm{H}_1}+|V\rangle_{\mathrm{D}_2}|V\rangle_{\mathrm{H}_1})/\sqrt{2}$. The measurement results, represented by 2 bits of classical information, are piggybacked with the RREP to node D. Node D obtains the Bell state of D_2 and H_1 by the measurement results and will do entanglement swapping as node E. Every intermediate node operates in the same way as node E. At last, particle A_1 at node A and particle H_1 at node H form an EPR pair and the measurement results of B_1 and B_2 are sent from node B to node A. Node A obtains the Bell state of A_1 and H_1 by the measurement results. A direct quantum link from the source to the destination is set up. After that, node A transfers the state of x by quantum teleportation. Assume the Bell state of A_1 and H_1 is $(|H\rangle_{A_1}|V\rangle_{\mathrm{H}_1}-|H\rangle_{\mathrm{A}_1}|V\rangle_{\mathrm{H}_1})/\sqrt{2}$, node A makes a joint Bell-state measurement on particles x and A_1. The quantum logical circuit of measurement is shown in Fig. 3. The entire system can be written as state $|x\rangle_{\mathrm{x}}\otimes|\psi^-\rangle_{\mathrm{A}_1\mathrm{H}_1}$. After applying the CNOT and Hadamard gates, the state can be written as

$$\begin{aligned}
&|\psi\rangle_{\mathrm{xA}_1\mathrm{H}_1}\\
&= (\alpha/2)(|H\rangle_{\mathrm{x}}+|V\rangle_{\mathrm{x}})(|H\rangle_{\mathrm{A}_1}|V\rangle_{\mathrm{H}_1}-|V\rangle_{\mathrm{A}_1}|H\rangle_{\mathrm{H}_1})\\
&\quad +(\beta/2)(|H\rangle_{\mathrm{x}}-|V\rangle_{\mathrm{x}})(|V\rangle_{\mathrm{A}_1}|V\rangle_{\mathrm{H}_1}-|H\rangle_{\mathrm{A}_1}|H\rangle_{\mathrm{H}_1}). \quad (8)
\end{aligned}$$

The equation can be rewritten as

$$\begin{aligned}
&|\psi\rangle_{\mathrm{xA}_1\mathrm{H}_1}\\
&= \frac{1}{2}[(|H\rangle_{\mathrm{x}}|H\rangle_{\mathrm{A}_1}+|V\rangle_{\mathrm{x}}|V\rangle_{\mathrm{A}_1})(\alpha|V\rangle_{\mathrm{H}_1}-\beta|H\rangle_{\mathrm{H}_1})\\
&\quad +(|H\rangle_{\mathrm{x}}|H\rangle_{\mathrm{A}_1}-|V\rangle_{\mathrm{x}}|V\rangle_{\mathrm{A}_1})(\alpha|V\rangle_{\mathrm{H}_1}+\beta|H\rangle_{\mathrm{H}_1})\\
&\quad +(|H\rangle_{\mathrm{x}}|V\rangle_{\mathrm{A}_1}+|V\rangle_{\mathrm{x}}|H\rangle_{\mathrm{A}_1})(-\alpha|H\rangle_{\mathrm{H}_1}+\beta|V\rangle_{\mathrm{H}_1})\\
&\quad +(|H\rangle_{\mathrm{x}}|V\rangle_{\mathrm{A}_1}-|V\rangle_{\mathrm{x}}|H\rangle_{\mathrm{A}_1})(-\alpha|H\rangle_{\mathrm{H}_1}-\beta|V\rangle_{\mathrm{H}_1})]. \quad (9)
\end{aligned}$$

Clearly, particles x and A_1 are projected into an EPR pair with one of the four Bell states and H_1 is projected into a state which is uniquely related to the original state of x. At node A, the measurement results of the state of x and A_1 (2 bits of classical information) are sent to node H by a wireless channel. The packet is called a quantum teleportation measurement results (QTMR) packet. It includes the addresses of source and destination, the measurement results, and a flag to indicate whether the information transmission from node A to node H is finished. From the QTMR, node H gets the state of x and A_1 and performs a corresponding linear unitary operation on particle H_1 to obtain an exact replica of the state of x.

After obtaining the information, node H sends an acknowledgement (ACK) packet to node A. The flag in the QTMR is copied into the ACK packet. The intermediate node receiving the ACK checks the flag. If the information transmission is not finished, the node does entanglement swapping to set up a new quantum link from the source to the destination. The measurement results of entanglement swapping are piggybacked with the ACK hop by hop. Node A receiving the ACK gets the state of a new EPR pair between A and H and uses quantum teleportation to transmit new information. The process is repeated until the information transmission is finished (flag=0).

During all information transmission processes, every intermediate node performs entanglement swapping following the routing set-up or acknowledgment process. During the information transmission processes, the messages transmitted on the wireless channels are shown in Fig. 4. The measurement results of entanglement swapping are transmitted piggybacked with control messages and do not consume additional wireless resources.

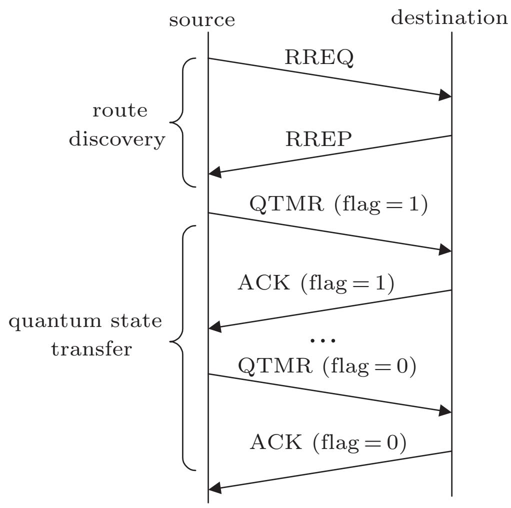

Fig. 4. Messages transmitted on wireless channels.

5. Performance evaluation

For the traditional on-demand routing protocols in wireless networks, if an intermediate node has a valid route to the destination, it will reply to the source with an RREP and the route is selected by the source. For the routing protocol in the DWQCN, the intermediate node dose not send an RREP even if it has the valid route to the destination and the route is selected by the destination. These special characteristics are more adapted to the DWQCN, because the valid state for a route in the route table will remain for some time but the number of EPR pairs are changing constantly with quantum state transferring. The destination node chooses a route and the route metric is decided by the number of EPR pairs, which is more suitable for the current status of network.

In our scheme, the measurement results of entanglement swapping are piggybacked with the control message and do not need to be transmitted separately. Compared with the quantum information transmission scheme in Ref. [23], which needs to transmit the measurement results separately, the information transmission scheme in this paper decreases the transmission cost and delay.

We simulate the performances of the DWQCN with the proposed scheme using a discrete event driven method. In our simulations, the network area is 600 m$\times$600 m. The nodes are uniformly distributed in a random way and each node selects its destination node randomly. A node shares EPR pairs with nodes within its wireless transmission range. The initial number of EPR pairs between any neighboring nodes is set to a random value between 1000 and 2000. The physical layer has a bi-directional wireless channel and each node has a wireless bandwidth of 11 Mbps. A random way-point model[17] is used as the movement model. In this model, a node selects a location in the specified network area randomly, then moves to that point with a constant speed which is selected randomly within a preset speed range (0, $V_{\max}$), where $V_{\max}$ is the maximal moving speed of nodes. After reaching the objective location, the node stays there for a pause time and then moves again. We change the effective transmission range and the value of $V_{\max}$. The main evaluation measurement in the simulation is the average route discovery time, which is the average time from the source node sending an RREQ to receiving an according RREP from the destination node. The results are shown in Fig. 5.

As shown in Fig. 5, with the same number of nodes, the route discovery time decreases with the increase of the single-hop wireless transmission range. A larger wireless transmission range makes more nodes become neighbors, so the average number of hops between two nodes in the network decreases. When the wireless transmission range is 100, a larger number of nodes will lead to a smaller route discovery time. The reason is that when the transmission range is small, there exist fewer available routes. When the number of nodes increases, the available routes also increase. When the wireless transmission range is 200, a larger number of nodes will lead to a longer route discovery time. The reason is that when the transmission range is larger, there are more available routes. But with the increase of node number, the number of broadcasted route request messages increases rapidly, which leads to more queuing time and confliction. Therefore the route discovery time will also increase.

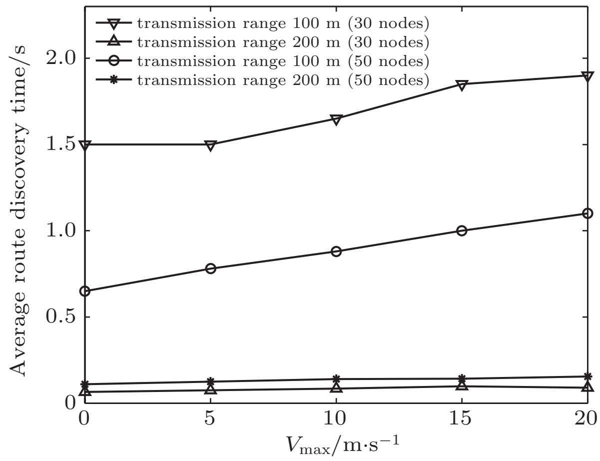

Fig. 5. Average route discovery time.

We then discuss the security of the DWQCN. The following method can be used to improve the security of the DWQCN. Before distributing the entangled particles, a preamble sequence is sent to avoid the replacement or destruction. For the sender and receiver of the entangled particles, the preamble sequence is composed by a serial of particles with known states in a predefined order. For example, the polarization direction of particle 1 is linear and the polarization direction of particle 2 is orthogonal. If an adversary replaces or destroys the particles in the preamble sequence, he cannot send the particle with the same state to the receiver because the state of this particle is unknown. Therefore, if any state of the received particles is not correct, the receiver will know that there exists an adversary. During the process of teleportation and swapping, the measurement results will be transmitted safely by using traditional secret communication methods,[25] such as asymmetric or public key cryptography.

6. Conclusion

In this paper, a system scheme including a routing protocol and a quantum information transfer is proposed to transfer quantum states carrying information between any two nodes in the DWQCN. Because the information is transmitted with quantum states, the number of EPR pairs between neighbors is used as the routing metric. This routing protocol is on-demand. The routing request packets are transmitted by a wireless channel and the selected route is decided by the destination node, which is adapted to the current distribution of EPR pairs in the network. Quantum teleportation is used for transferring quantum states. If the source and the destination nodes do not share EPR pairs mutually, entanglement swapping is used. Entanglement swapping is operated with the process of transmitting RREP or ACK. The measurement results of entanglement swapping are piggybacked with RREP or ACK, which decreases the transmission cost and delay.

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