

ORIGINAL RESEARCH

Optimisation of the routing protocol for quantum wireless Ad Hoc network

Ling Zhang¹  | Qin Liu²
¹Institute of Technology, Dianchi College of Yunnan University, Kunming, China²School of electronic information, Chengdu Jincheng College, Chengdu, China**Correspondence**

Ling Zhang, Institute of Technology, Dianchi College of Yunnan University, Kunming, 650228, China.

Email: 48470480@qq.com

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Abstract

This study addresses the optimisation of on-demand routing protocols for quantum wireless Ad Hoc network. The study improves the route discovery protocol by proposing a 'reverse synchronisation method', which means after the route request is completed, the quantum channel establishment process can be carried out simultaneously with the route reply process. This method is better than the general method which builds quantum channels after the forward path establishment, reduces the time and the number of messages for quantum channel establishment, thus improving the efficiency. Accordingly, this study elaborates the specific methods, procedures and related upgrading message formats involved in quantum route discovery, quantum channel establishment and qubit information transmission of on-demand routing protocol for quantum wireless Ad Hoc network.

KEYWORDS

quantum communication, quantum wireless Ad Hoc network, quantum wireless routing protocol

1 | INTRODUCTION

Quantum communication is a new way of communication, in which information takes the quantum state as the carrier and uses quantum properties. Quantum communication has broken through the limits of classical communication technology in security performance. It has become a new trend in the field of communication and information and has great application value in the field of network technology and information security.

Quantum communication schemes are mainly classified into two categories: quantum key distribution and quantum teleportation [1]. When using quantum teleportation to transmit quantum bits (qubits), the current general method is to first establish a classical channel on the classical communication network, then establish a quantum channel on the path node of the classical channel by using EPR (named after Einstein, Podolsky, and Rosen) pairs and finally transmit qubits through quantum measurement and recovery. In the classical channel,

the tasks of routing, establishing quantum channel, transmitting Bell measurement information and transmitting classical information can be accomplished. In the theory of quantum communication, the quantum entanglement swapping technology [2–6] can expand the information transmission range of the quantum communication network and reduce the amount of calculation of qubits recovery.

Wireless Ad Hoc Network is a kind of mainstream wireless network, which has been widely used. Nodes can construct the network by themselves with high flexibility. Security is a major problem faced by wireless Ad Hoc networks. The application of the quantum teleportation technology to wireless Ad Hoc networks can not only solve the security problem but also improve the network capacity (one qubit can be used to send two classical bits). [7, 8] Quantum wireless Ad Hoc network is a new quantum wireless communication transmission network, and it is the extension of the quantum network in the wireless field. It has a great research value and broad application prospect. Although the research of the quantum wireless Ad

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Hoc network is still in its infancy, it will play an important role in the construction of an information security communication network in the future. Routing protocol is one of the key technologies of a network, hence we study it.

The routing protocols of classic wireless Ad Hoc networks are divided into table driven routing protocol and on-demand routing protocol [9, 10]. Since there are both quantum channels and classical wireless channels in the quantum wireless Ad Hoc network, and the quantum channels vary with the number of EPR pairs, the network topology is easy to change. The nodes using the on-demand driven routing protocol initiate the route discovery process when they need to find a route and do not need to exchange routing information periodically. So, it is suitable for the network whose topology often changes. Therefore, the quantum wireless Ad Hoc network adopts the on-demand routing protocol in our study.

This study addresses the optimisation of the on-demand routing protocol for the quantum wireless Ad Hoc network, and improves the route discovery protocol by proposing a 'reverse synchronisation method'. Accordingly, this study elaborates the procedures of the method in detail. Related upgrading message formats are also listed. We also illustrate the protocol with a specific network example combined with the derivation of the quantum communication process. The advantage of the method in reducing the time and the number of messages for the quantum channel establishment is verified through the analysis of protocol performance.

Our key research contributions are

- (i) We improve the route discovery protocol of the quantum wireless Ad Hoc network's on-demand routing protocol by proposing a 'reverse synchronisation method'. It means that, after the route request is completed, the quantum channel establishment process can be carried out simultaneously with the route reply process. We propose the 'reverse synchronisation method' and explain the process of the method in detail.
- (ii) In the 'reverse synchronisation method', we design the specific packet message formats of the route request-quantum (RREQ-Q) and quantum route reply (RREP-Q). With the help of these two control messages, route discovery and the 'reverse synchronisation method' can be realised.
- (iii) Because the quantum channel is set up synchronously when the route reply message is sent, the 'reverse synchronisation method' reduces the time for quantum channel establishment.
- (iv) Since the 'quantum channel request (QCR)' message is carried (piggybacked) in the route reply message, the number of messages in our method is reduced as compared with **the general method** (see Section 2), which sends the QCR alone.

The rest of this study is organised as follows. Section 2 presents the related work of quantum wireless routing protocols and our research motivation. Section 3 introduces the background knowledge involved in this study. We illustrate the

content of the improved protocol and the workflow of the 'reverse synchronisation method' in Section 4. The protocol performance analyses are shown in Section 5. Finally, we conclude this work in Section 6.

2 | RELATED WORK AND MOTIVATION

At present, the quantum wireless routing protocol research is still in the initial stage, and the corresponding research results are few. The feasibility of quantum information transmission in free space has been proved by experiments [11, 12]. The quantum routing algorithm of the quantum wireless wide-area communication network [13] is to study the transmission of quantum states after routing has been established. This is the first study of the wireless communication network using quantum teleportation and entanglement swapping in the quantum field. The structure of the studied network is the hierarchical network structure, and the problems of routing selection and establishment are not involved. A preliminary study on the structure and routing of the multi-point quantum communication network [14, 15] points out that finding the best routing in the quantum network based on the entangled state is a difficult problem that needs further research. A quantum routing protocol based on the quantum relay mechanism is proposed in the mesh structure [16]. Cai et al. studied the routing protocol in the Ad Hoc quantum communication network based on teleportation [17], which adopts the on-demand routing protocol. The optimal path is chosen by the source node from the route reply message. After the optimal path is selected, the quantum channel is established. After the quantum channel is established, qubits communication is carried out through quantum relay or EPR-Pair Bridging. Yu et al. study the routing protocol in distributed wireless quantum communication networks based on the partially entangled state [18]. A quantum routing scheme with multi-hop teleportation is proposed for the distributed wireless quantum communication network with partially entangled pairs. A quantum path does not have to be the same as a classical path. However, the quantum channel is still established after the quantum path is selected.

On the basis of the above research studies and taking into account the characteristics of the Ad Hoc quantum communication on-demand routing protocol, we improve the general method, which first completes routing and then builds the quantum channel (the way adopted by the literature listed in the previous paragraph). Next, we will briefly explain and compare the general method and the 'reverse synchronisation method' proposed to show the motivation of our research.

In a quantum wireless Ad Hoc network, when a source node needs to deliver qubits to a destination node, **the general method** of the on-demand routing algorithm is briefly described as follows: The source node broadcasts route request messages to the neighbouring nodes. The *Route Request message* contains the source address, destination address, nodes' order recorded along the broadcast path, and

routing metric of the path etc. The destination node may receive multiple route discovery messages from different paths. The destination node chooses an optimal path (nodes order) based on the routing metrics recorded in the received messages. The destination node then sends a *Route Reply message* back to the source node along the reverse path. The reverse path is the reverse order of the nodes recorded in the *Route Request message*. After receiving the *Route Reply message*, the source node records the path in its routing table. The routing is created. Then the source node sends the 'QCR' message along the forward path to establish the quantum entanglement. After the establishment of the quantum channel, qubits can be transferred by an entanglement swap.

The method in this study optimises the general method above. The optimisation is as follows: When the destination node sends the route reply message to the source node, it carries (called as piggyback) the 'QCR' in the message, and a quantum entanglement is initiated synchronously on the reverse path nodes to establish the quantum channel. The improved method is based on the fact that the destination node already knows the routing path after selecting the optimal path, and it is not necessary to wait until the source node receives the route reply message to initiate the quantum channel establishment process. This method is called as the '**reverse synchronisation method**'.

3 | BACKGROUND

3.1 | Quantum wireless Ad Hoc network

The schematic diagram of the quantum wireless Ad Hoc network is shown in Figure 1. Based on the ordinary Ad Hoc network, this network assumes that each node has quantum communication functions including the capacity of holding and manipulating EPR pairs, and they support classical communication at the same time. The dotted line represents the quantum channel. The solid line represents the classic wireless channel. The number marked in the dotted line is the remaining number of EPR pairs between the two nodes.

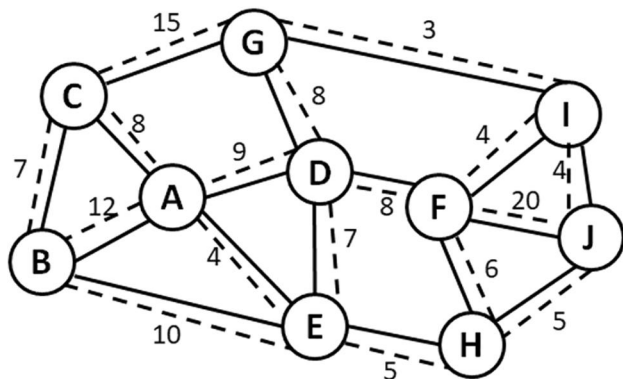


FIGURE 1 Schematic diagram of the quantum wireless Ad Hoc network

3.2 | Quantum routing metric

The quantum routing metric refers to the factors to be considered when establishing the optimal path of the quantum channel in the process of route discovery, which ensures that the path is the best path suitable for quantum communication.

However, routing in quantum networks is more complicated because it must compute the paths not only based on the path length, cost, and throughput, but it must also take into account the desired end-to-end fidelity [19]. Quantum network routing algorithms are an emerging field of study and recent research studies emerge one after another. For example, the multi-path routing algorithm in diamond topology [20], quantum routing protocol based on the quantum relay mechanism of the mesh structure [16], quantum network routing algorithm based on ring or sphere topology [21], entanglement routing algorithm in different special topologies [22], optimal routing problem in a chain of repeaters [23], entanglement routing solutions in grid networks [24], virtual-path based greedy routing in ring and grid networks [25], and the universal entanglement routing algorithm for arbitrary network topologies [26].

Since this work studies the improvement of process steps in the routing protocol, the routing metric algorithm is not discussed here. The routing metric is mentioned here because it is a field in the route request and route reply message formats discussed later. However, the specific calculation of this field is not studied in this work.

4 | IMPROVED PROTOCOL

The main function of the routing protocol in the quantum wireless Ad Hoc network is to establish and maintain routing, exchange routing information, monitor the change of network topology, and forward the quantum state carrying information according to routing. In the quantum wireless Ad Hoc network, we adopt the on-demand routing protocol. It is composed of route discovery and route maintenance.

4.1 | Route discovery

When a source node in the network needs to send the quantum state carrying information to a destination node, and there is no valid quantum routing table entry to the destination node, the route discovery process will be initiated. The source node creates a quantum route request (RREQ-Q) packet message in the format shown in Table 1. Then the source node broadcasts RREQ-Q to its neighbours.

The node receiving RREQ-Q checks whether it is the destination node. **If not**, it judges whether the received RREQ-Q is a repeated message according to the quantum route request ID. If repeated, the message will be discarded and the operation will end. If not repeated, the current node will update the quantum routing metric value, set its address as the 'Last hop address', and add its address to the end of the

TABLE 1 Route Request-Quantum (RREQ-Q) packet message format

Command frame identifier	Quantum route request ID	Source address	Destination address	Last hop address	Quantum routing metric	Quantum routing record (QRR)
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TABLE 2 Quantum Route Reply (RREP-Q) packet message format

Command frame identifier	Quantum route request ID	Source address	Destination address	Quantum routing metric	Flagged Quantum routing record (QRR-F)	Quantum Channel Request (QCR)
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quantum routing record (QRR). After that the current node will continue to broadcast the updated RREQ-Q message to the surrounding nodes and repeat the above operation. **If yes**, follow the procedure below.

The destination node receives the RREQ-Q message. If more than one RREQ-Q message reaches the destination node within a certain cutoff time, the destination node compares the route values in each message to select the best path. Then this path (recorded in QRR) is saved for subsequent route reply.

Then, a ‘reverse synchronisation method’ will be used to synchronously establish the quantum channel during the route reply process. When the optimal path is selected, the destination node will send a unicast route reply message to the source node along the reverse path (the path of the destination node to the source node). When the intermediate nodes on the path receive the route reply message, they will know that they are selected as the routing nodes and update their routing tables. When the route reply message reaches the source node, the source node updates its routing table according to the path and initiates the communication. In the above process, since the destination node already knows the route path after choosing the optimal route, the destination node can synchronously initiate the quantum channel establishment process while returning route reply.

The specific method is that the destination node creates and unicasts an RREP-Q message along the reverse path. The message format is shown in Table 2. The ‘QCR’ message field is used to initiate the entangled quantum channel establishment by the requesting node. The ‘Flagged Quantum routing record (QRR-F)’ records a flagged path that is alternately marked 0 or 1 on the nodes of the path recorded by QRR. The principle of flagging is that the destination node is always 0 and then the nodes along the reverse path are 1, 0, 1... The purpose of flagging is that the nodes receiving the RREP-Q message on the reverse path can decide whether to read the QCR field according to the flagged value of 0 or 1. If the flagged value is 0, the QCR field will be effective and read; if it is 1, it will be invalid and ignored. A node receiving the QCR message will reply to a QCR reply message, and a node receiving the QCR reply message will generate EPR pairs and distribute them.

In the ‘reverse synchronisation method’, the node in the reverse path, after receiving the RREP-Q message, will know that it is already a node in the selected path and will immediately conduct the quantum channel establishment process. The establishment of the quantum channel does not wait until the reply message reaches the source node and the forward route is completed. This serves the purpose of increasing efficiency.

4.2 | Example of the ‘reverse synchronisation method’

4.2.1 | Quantum channel establishment

In the following, the ‘reverse synchronisation method’ is analysed in detail by taking the network shown in Figure 2 as an example. If node B in the network needs to conduct quantum communication with node J, and if the destination node J chooses the best path of B-A-D-F-J after receiving the RREQ-Q messages, node J will send route reply along the reverse path of J-F-D-A-B and establish the quantum channel process simultaneously. The specific process is as follows:

- (i) Node J generates a RREP-Q message based on the content of the RREQ-Q, where the QRR-F field formed after flagging QRR is B(0)-A(1)-D(0)-F(1)-J(0).
- (ii) Node J→F sends the RREP-Q message. After receiving the RREP-Q message, node F checks that the flagged value corresponding to its address in the QRR-F field is 1, so the QCR field is invalid. And node F does not reply to a QCR Reply message, but sends a QCR message to node J. At the same time, node F continues to forward the RREP-Q message to node D along the reverse path. After receiving the RREP-Q message, D checks that the flagged value corresponding to its address in the QRR-F field is 0, so the QCR field takes effect. Then node D replies to a QCR Reply message and continues to forward the RREP-Q message to node A along the reverse path. Node J also replies to a QCR Reply message after receiving the QCR message.
- (iii) Node F generates EPR pair 1 and 1', then assigns them to nodes J and D with the state as $|\varphi\rangle_{11'} = \frac{1}{\sqrt{2}}(|01\rangle_{11'} + |10\rangle_{11'})$, and J and D will confirm when they receive the particles, otherwise they will resend the QCR message.
- (iv) After receiving the RREP-Q message, node A checks that the flagged value corresponding to its address in the QRR-F field is 1, so the QCR field is invalid. And node A does not reply to a QCR Reply message but sends a QCR message to node D. At the same time, node A continues to forward the RREP-Q message to node B along the reverse path. Node D replies to a QCR Reply message after receiving the QCR message.
- (v) After receiving the RREP-Q message, node B checks that the flagged value corresponding to its address in the QRR-F field is 0, so the QCR field takes effect; then node B replies to a QCR Reply message.

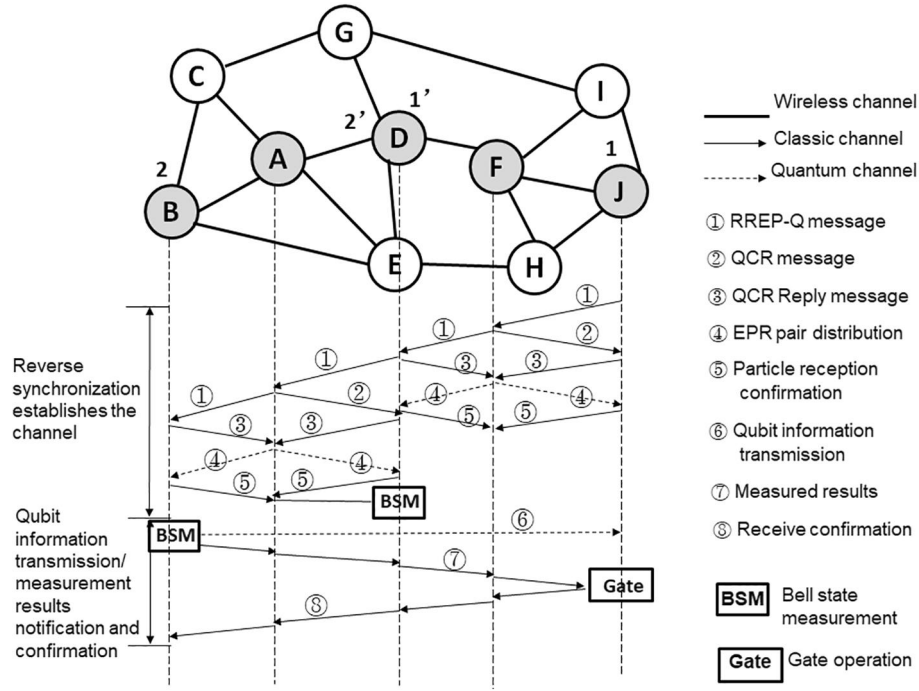


FIGURE 2 Schematic diagram of the quantum channel establishment and transmission analysis in the quantum wireless Ad Hoc network

- (vi) Node A generates EPR pair 2 and 2', then assigns them to nodes B and D with the state as $|\varphi\rangle_{22'} = \frac{1}{\sqrt{2}}(|10\rangle_{22'} - |01\rangle_{22'})$, and B and D will confirm when they receive the particles, otherwise they will resend the QCR message.

$$|\varphi\rangle_{11'} \otimes |\varphi\rangle_{22'} = [|\psi\rangle_{12}^- |\psi\rangle_{1'2'}^+ - |\psi\rangle_{12}^+ |\psi\rangle_{1'2'}^- + |\varphi\rangle_{12}^+ |\varphi\rangle_{1'2'}^- - |\varphi\rangle_{12}^- |\varphi\rangle_{1'2'}^+] \quad (1)$$

According to the entanglement swapping [5] and derivation process [27], the system composed of particles 1, 1' and 2, 2' is expressed by $|\varphi\rangle_{11'} \otimes |\varphi\rangle_{22'}$. Node D performs Bell state measurements on particles 1' and 2' (expression of the Bell basis is $|\varphi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$, $|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$). The system is expressed as

Assuming that $|\psi\rangle_{1'2'}^-$ is selected, the state of particles 1, 2 is $|\psi\rangle_{12}^+$ after measurement and the entanglement is realised. An entangled quantum channel is successfully established between nodes B and J.

4.2.2 | Qubits transmission

After the quantum channel is established, qubits can be transmitted. As shown in Figure 2, if node B needs to send a qubit $|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$ and loads it onto the established quantum channel. A Bell state measurement of particles $|\varphi\rangle$ and 2 is performed at node B. This can be expressed by formula (2).

$$|\varphi\rangle |\psi^+\rangle_{12} = \alpha/\sqrt{2}(|001\rangle + |010\rangle) + \beta/\sqrt{2}(|101\rangle + |110\rangle) \quad (2)$$

Particles $|\varphi\rangle$ and 2 are sent into the controlled-not gate, and Equation (2) becomes the following Equation (3).

$$\begin{aligned} |\varphi\rangle |\varphi^+\rangle &= \alpha/\sqrt{2}(|001\rangle + |010\rangle) + \beta/\sqrt{2}(|111\rangle + |100\rangle) \\ &= \alpha/\sqrt{2}|0\rangle(|01\rangle + |10\rangle) + \beta/\sqrt{2}|1\rangle(|11\rangle + |00\rangle) \end{aligned} \quad (3)$$

Then the first particle passes through the Hadamard Gate, and Equation (3) becomes the following Equation (4).

$$\begin{aligned} |\varphi\rangle |\varphi^+\rangle &= \alpha/2(|0\rangle + |1\rangle)(|01\rangle + |10\rangle) \\ &\quad + \beta/2(|0\rangle - |1\rangle)(|11\rangle + |00\rangle) \\ &= \frac{1}{2}|00\rangle(\alpha|1\rangle + \beta|0\rangle) + \frac{1}{2}|01\rangle(\alpha|0\rangle + \beta|1\rangle) \\ &\quad + \frac{1}{2}|10\rangle(\alpha|1\rangle - \beta|0\rangle) + \frac{1}{2}|11\rangle(\alpha|0\rangle - \beta|1\rangle) \end{aligned} \quad (4)$$

If node B measures its own two particles ($|\varphi\rangle$ and particle 2), there may be four states $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$ with the probability of one-fourth each. According to Appendix A, node B encodes its measurement states and tells node J through the classical channel. J performs the appropriate gate operation on its particle 1. This can recover the quantum state and realise the transmission of qubits.

Node J receives and confirms the qubit transmission through the classical channel. So far, node B completes the qubit transmission.

4.3 | Route maintenance

In quantum wireless Ad Hoc communication networks, on the one hand, node movement and EPR pairs' consumption may lead to changes in the network topology, interruption of selected paths and failure of information transmission. On the other hand, the unknown quantum state cannot be copied and retransmitted due to the principle of quantum non-cloning. Before the source node starts to transmit the quantum state, it needs to determine whether the nodes on the current path are still valid for this transmission. Therefore, the route maintenance process can be carried out in the way of prior quantum path check [28]. That is, when the source node has quantum communication demand, if there is a quantum path to the destination node in the routing table, it will send a path verification request to the destination node along the path through the classical wireless channel to verify whether the path is effective. If it works, communication can occur. If it fails, the quantum path needs to be re-established, that is, the process of initiating route discovery as described in part A of Section 4 above.

5 | PROTOCOL ANALYSIS

Section 4 above describes the route discovery process of the quantum wireless ad hoc communication network routing protocol and explains the 'reverse synchronisation method' with an example. In the above example, the number of intermediate nodes on the path is odd. If it is even, then the node next to the source node generates EPR pairs and allocates EPR pairs to itself and the source node. For example, if node A needs to communicate with node J in Figure 2, the selected path is A-D-F-J and the reverse path is J-F-D-A. Then the nodes that generate and distribute the EPR pairs are as follows: F to D and J, D to itself and A. When the number of selected path nodes is odd or even, the analysis of the 'reverse synchronisation method' is shown in Table 3. As can be seen from the table, no matter whether the total number of nodes on the path is odd or even, the nodes responsible for generating and distributing the EPR pairs are always the nodes that receive the QCR Reply messages, and the number of these nodes is only related to the total number of nodes on the path. If the total number of nodes on the path is odd, the number of these nodes is (Total nodes-1)/2, and if the number is even, it is Total nodes/2. It shows that

TABLE 3 Odd or even nodes analysis

Number of intermediate nodes on the path	Total nodes on the path	Nodes responsible for generating and distributing EPR pairs	Number of nodes that generate and distribute EPR pairs
Odd: O	O + 2	Nodes receiving the QCR reply message	$[(O + 2) - 1]/2$
Even: E	E + 2		$(E + 2)/2$

Abbreviations: EPR, Einstein, Podolsky, and Rosen; QCR, Quantum Channel Request.

the rules described by the 'reverse synchronisation method' have universal applicability. Whether the QCR Reply message is received or not, it can be used as the judging condition to control the node to generate and distribute the EPR pairs.

In the following, the number of messages needed to be sent on the classical channel and the time (mainly refers to propagation delay) taken to establish the channel are analysed in the process of the 'reverse synchronisation method' for the quantum channel establishment. Compared with the general method [13, 16–18], literature [17] also studies the quantum wireless ad hoc network, so we select it for comparative analysis. Assuming that the total number of nodes on the path is N, the classical wireless message transmission time between two adjacent nodes is equal, which is calculated as one time unit, then the calculation starts from the destination node sending the route reply. In the general method, the time units T required to establish the quantum channel is expressed by Equation (7), and the number of messages A required to establish the quantum channel is shown in Equation (8).

$$T = \begin{cases} 3N - 1, N \geq 3 \text{ even number} \\ 3N - 2, N \geq 3 \text{ odd number} \end{cases} \quad (7)$$

$$A = 4N - 4, N \geq 3 \quad (8)$$

Using the 'reverse synchronisation method' in this study, the time units T required to establish the quantum channel is expressed by Equation (9) and the number of messages A required to establish the quantum channel is shown in Equation (10).

$$T = \begin{cases} N + 3, N \geq 3 \text{ even number} \\ N + 2, N \geq 3 \text{ odd number} \end{cases} \quad (9)$$

$$A = \begin{cases} (7N - 6)/2, N \geq 3 \text{ even number} \\ (7N - 7)/2, N \geq 3 \text{ odd number} \end{cases} \quad (10)$$

The comparison of the time required to establish the quantum channel of the two methods is shown in Figure 3. It can be seen that with the increase in the number of path nodes, the 'reverse synchronisation method' saves more time than the general method. The comparison of the number of messages required to establish the quantum channel of the two protocols is shown in Figure 4. It can be seen that with the increase in the number of path nodes, the number of messages required by the 'reverse synchronisation method' is less than that of the general method, and it is more significant with the increase in the number of nodes.

6 | CONCLUSION

This study addresses the optimisation of the on-demand routing protocol for the quantum wireless Ad Hoc network. It improves the route discovery protocol by proposing a 'reverse synchronisation method'. We design the RREQ-Q and RREP-Q messages to assist in the implementation of this optimisation protocol. We illustrate the protocol with a

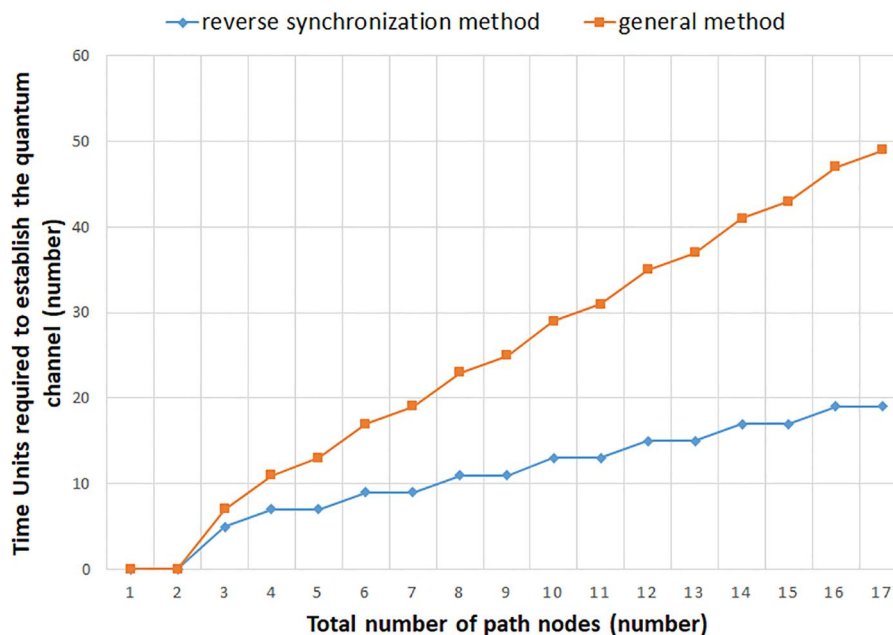


FIGURE 3 Comparison of the time required for the quantum channel establishment

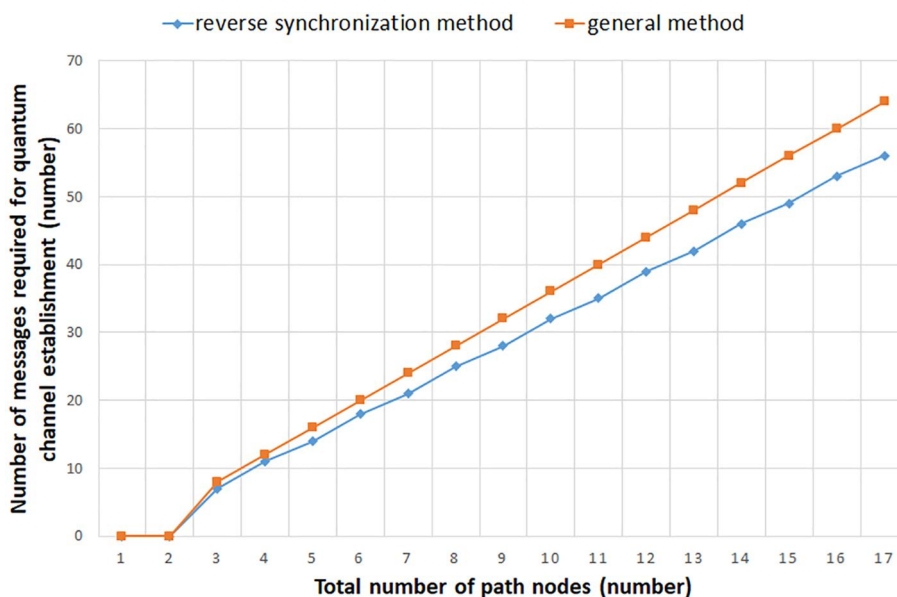


FIGURE 4 Comparison of the number of messages required for the quantum channel establishment

specific network example combined with the derivation of the quantum communication process. The universal applicability of the ‘reverse synchronisation method’ is verified through the protocol performance analysis. Compared with the quantum channel establishment after the forward routing is established, this method reduces the quantum channel establishment time and the number of messages, so it improves the efficiency.

The next step is to model these protocols and evaluate their effectiveness by simulation.

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CONFLICT OF INTEREST

The authors declare no competing non-financial/financial interests.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

None.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Ling Zhang  <https://orcid.org/0000-0001-9523-7171>

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APPENDIX A

A. Reference table for node J to restore the initial quantum state

Measurement states of node B	Messages from B to J	Operations of node J
$ 00\rangle$	00	X gate
$ 01\rangle$	01	Nothing
$ 01\rangle$	10	Both X and Z gate
$ 11\rangle$	11	Z gate