

Partially entangled states bridge in quantum teleportation

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The traditional method for information transfer in a quantum communication system using partially entangled state resource is quantum distillation or direct teleportation. In order to reduce the waiting time cost in hop-by-hop transmission and execute independently in each node, we propose a quantum bridging method with partially entangled states to teleport quantum states from source node to destination node. We also prove that the designed specific quantum bridging circuit is feasible for partially entangled states teleportation across multiple intermediate nodes. Compared to two traditional ways, our partially entanglement quantum bridging method uses simpler logic gates, has better security, and can be used in less quantum resource situation.

Keywords partially entangled states, quantum bridge, quantum teleportation, quantum logic gate

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1 Introduction

In quantum mechanics, there is a kind of entangled relationship between two microscopic particles from same source. No matter how far away they are separated from each other, the state of a particle would immediately change according to the change of the other, a process called quantum entanglement [1]. When these entangled states are used as communication resource, quantum teleportation is adapted for both its security and transmission efficiency.

Different quantum communication methods have been proposed. For maximally entangled states, quantum circuits and routing protocols have been designed for Einstein–Podolsky–Rosen (EPR) pair quantum channels [2–7]. However, perfect entanglement is difficult to preserve. Maximally entangled states usually degrade to partially entangled ones [8]. There are two traditional methods to teleport a qubit for partially entangled states. One method is to execute entanglement distillation process, the other is to perform quantum communication directly.

The entanglement distillation is of great importance in quantum communication. The purpose of a distillation method is to get the maximally entangled states and then communicate with maximally entanglement resource. Many important works are contributed to the

study of entanglement concentration and purification [9–14]. It is often realized by local operations and classical communication [15–25]. Entanglement swapping can be used to realize entanglement purifying. Using partial entanglement for entanglement swapping was first discussed by Bose *et al.* [18]. Then, Guo proposed another distillation protocol [19]. If an unitary transformation is introduced locally when the less entangled states are obtained, then a maximally entangled state can be obtained. Conventional entanglement distillation protocols utilize at less 2 partial entangled states. The Schmidt projective method is used to distillate maximally entangled states through collective measurement of partially entanglement states. To get a higher success probability, some distillation processes can be repeated for several rounds and are already feasible with current experiment [20, 21]. As for the quantum network, it has been proved that arbitrary nodes can be connected in networks when there are sufficient partially entangled states in a particular form [22].

When there are not enough resources to finish the distillation process, direct communication of partially entanglement methods are taken. To teleport an d -state particle through an n -state particle partially entanglement channel, the condition $n > d$ is necessary. The scheme proposed by Gilad costs less classical communication resources than distillation teleportation methods [26]. Generally, performing teleportation based on direct

quantum communication with partially entangled states needs fewer resources. Partially entangled states teleportation methods are combinations of three basic strategies, including: interaction of the entanglement, and an ancilla as assistance to determine whether the teleportation is successful, generalized Bell measurements to realize a probabilistic teleportation and repetition of protocols to increase utilization efficiency [27]. The protocols combined with these strategies suit in many different situations to improve the performance [27–39]. For example, when there are sufficient partially entanglement resource, to keep applying the third strategy will finally reach a balanced number of qubit states to recover the initial information [27, 38]. For another example, when generalized Bell measurements match the channel states, a protocol combined with both the second and third strategy will achieve the same efficiency, using half times of teleportation [27, 39].

However, the methods above transfer quantum states based on quantum relay. It means quantum teleportation in these methods occurs in adjacent nodes in one hop. Teleportation of quantum states in wireless quantum communication networks was also analyzed [40]. Compared to hop-by-hop mechanism, quantum bridging mechanism can be executed independently in each node, then time for logic operations and classical information transmissions can be saved.

The article first proposes a quantum bridging method to teleport quantum states with partially entangled states, in order to improve the performance in teleportation across three nodes. The bridging mechanism and circuits also work in the multi-intermediate nodes condition. The article is organized as follows: Section 2 proposes a quantum bridging method with partially entangled states to teleport the qubit when there is one intermediate node. Section 3 proves that the designed specific quantum bridging circuit is still feasible for quantum teleportation across multiple intermediate nodes and then calculates the success probability. Finally, conclusion is drawn in Section 4 and some issues are discussed in Section 5.

2 Quantum bridge

Assume that in a quantum network, each node shares at least one partially entangled state with one another. Partially entanglement resources are often represented by $\frac{1}{\sqrt{1+n^2}}(|0\rangle_1|0\rangle_2 + n|1\rangle_1|1\rangle_2)$. When $n = 0$, there is no entanglement and when $n = 1$, it turns to be a maximally entangled state.

The partially entanglement pair can be seen as a bridge

between adjacent nodes, and quantum teleportation can be regarded as transporting a specific qubit by passing it through the bridge [2]. Thus, the sender nodes are able to find a quantum entanglement route to destination nodes. The problem to be solved in this section is how to realize quantum teleportation with partially entanglement states with an intermediate node.

First, the intermediate node shares partially entangled pairs with both quantum source and destination nodes. The quantum circuit is represented as shown in Fig. 1.

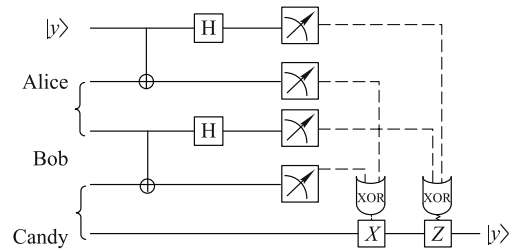


Fig. 1 Quantum circuit for partially entangled states bridging.

The source node (Alice) and intermediate node (Bob) share a declined EPR pair represented as $\frac{1}{\sqrt{1+n^2}}(|0\rangle_A|0\rangle_B + n|1\rangle_A|1\rangle_B)$. Similarly, the intermediate node (Bob) and the destination node (Candy) share a partially entanglement pair that can be expressed as $\frac{1}{\sqrt{1+n^2}}(|0\rangle_B|0\rangle_C + n|1\rangle_B|1\rangle_C)$. Therefore, the entire system of 4 qubits can be expressed as

$$\frac{1}{\sqrt{1+n^2}}(|0\rangle_A|0\rangle_B + n|1\rangle_A|1\rangle_B) \otimes \frac{1}{\sqrt{1+n^2}}(|0\rangle_B|0\rangle_C + n|1\rangle_B|1\rangle_C) \quad (1)$$

The purpose of following steps is to explain how the maximally entanglement of node A and C can be probably generated from the initial two partial entanglements between node A, B and C.

By applying the controlled NOT gate, the second qubit of Bob decides the qubit change of Candy, we then get

$$\frac{1}{1+n^2}(|0\rangle_A|0\rangle_B(|0\rangle_B|0\rangle_C + n|1\rangle_B|1\rangle_C) + \frac{n}{1+n^2}|1\rangle_A|1\rangle_B(|1\rangle_B|0\rangle_C + n|0\rangle_B|1\rangle_C) \quad (2)$$

Then, performing Hadamard gate, which means the qubit state $|1\rangle$ will be projected into $\frac{|0\rangle-|1\rangle}{\sqrt{2}}$, and state $|0\rangle$ will be projected into $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$. We can get

$$\frac{1}{\sqrt{2}(1+n^2)}(|0\rangle_A(|0\rangle_B + |1\rangle_B)(|0\rangle_B|0\rangle_C + n|1\rangle_B|1\rangle_C) + \frac{n}{\sqrt{2}(1+n^2)}|1\rangle_A(|0\rangle_B - |1\rangle_B)(|0\rangle_B|0\rangle_C + n|1\rangle_B|1\rangle_C) \quad (3)$$

The expression above can be written as

$$\begin{aligned} & \frac{1}{\sqrt{2(1+n^2)}}|00\rangle_B(|0\rangle_A|0\rangle_C + n^2|1\rangle_A|1\rangle_C) \\ & + \frac{1}{\sqrt{2(1+n^2)}}|01\rangle_B(n|0\rangle_A|1\rangle_C + n|1\rangle_A|0\rangle_C) \\ & + \frac{1}{\sqrt{2(1+n^2)}}|10\rangle_B(|0\rangle_A|0\rangle_C - n^2|1\rangle_A|1\rangle_C) \\ & + \frac{1}{\sqrt{2(1+n^2)}}|11\rangle_B(n|0\rangle_A|1\rangle_C - n|1\rangle_A|0\rangle_C) \end{aligned} \quad (4)$$

As can be seen, the whole system depends on the two qubit states that Bob held. Therefore, as long as the intermediate node measures its own two qubits, it establishes the maximally entangled quantum channel between the source and destination nodes with a certain probability. when the result of measurement of B is $|01\rangle$ or $|11\rangle$, it is successful. It means the success probability to establish a maximally entangled channel is $\frac{2n^2}{(1+n^2)^2}$. Therefore, the feasibility of establishing a maximally entanglement channel is proved.

Assume the quantum state to be transmitted is $|y\rangle = \alpha|0\rangle + \beta|1\rangle$, the particle of the source and the intermediate node constitute a partially entanglement state, the second qubit of the intermediate node and the destination node constitute another partially entanglement state. Then the entire five-qubit system can be represented as

$$\begin{aligned} & |y\rangle_{A1} \otimes \frac{1}{\sqrt{1+n^2}}(|0\rangle_{A2}|0\rangle_{B1} + n|1\rangle_{A2}|1\rangle_{B1}) \\ & \otimes \frac{1}{\sqrt{1+n^2}}(|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \\ & = (\alpha|0\rangle_{A1} + \beta|1\rangle_{A1}) \\ & \otimes \frac{1}{\sqrt{1+n^2}}(|0\rangle_{A2}|0\rangle_{B1} + n|1\rangle_{A2}|1\rangle_{B1}) \\ & \otimes \frac{1}{\sqrt{1+n^2}}(|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \end{aligned} \quad (5)$$

Performing the following quantum circuit procedures, it shows how the node C recovers the initial quantum information from node A.

When state of Alice and Bob pass through a controlled NOT gate, the whole system becomes

$$\begin{aligned} & \frac{\alpha}{1+n^2}|0\rangle_{A1} \otimes |0\rangle_{A2}|0\rangle_{B1}(|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{n\alpha}{1+n^2}|0\rangle_{A1} \otimes |1\rangle_{A2}|1\rangle_{B1}(|1\rangle_{B2}|0\rangle_{C1} + n|0\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{\beta}{1+n^2}|1\rangle_{A1} \otimes |0\rangle_{A2}|1\rangle_{B1}(|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{n\beta}{1+n^2}|1\rangle_{A1} \otimes |0\rangle_{A2}|1\rangle_{B1}(|1\rangle_{B2}|0\rangle_{C1} + n|0\rangle_{B2}|1\rangle_{C1}) \end{aligned} \quad (6)$$

Then, Alice and Bob send their first quantum bit into Hadamard gate, the system will become

$$\begin{aligned} & \frac{\alpha}{2(1+n^2)}(|0\rangle + |1\rangle)_{A1} \otimes |0\rangle_{A2} \otimes (|0\rangle + |1\rangle)_{B1} \\ & \otimes (|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{n\alpha}{2(1+n^2)}(|0\rangle + |1\rangle)_{A1} \otimes |1\rangle_{A2} \otimes (|0\rangle - |1\rangle)_{B1} \\ & \otimes (|1\rangle_{B2}|0\rangle_{C1} + n|0\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{\beta}{2(1+n^2)}(|0\rangle - |1\rangle)_{A1} \otimes |1\rangle_{A2} \otimes (|0\rangle + |1\rangle)_{B1} \\ & \otimes (|0\rangle_{B2}|0\rangle_{C1} + n|1\rangle_{B2}|1\rangle_{C1}) \\ & + \frac{n\beta}{2(1+n^2)}(|0\rangle - |1\rangle)_{A1} \otimes |0\rangle_{A2} \otimes (|0\rangle - |1\rangle)_{B1} \\ & \otimes (|1\rangle_{B2}|0\rangle_{C1} + n|0\rangle_{B2}|1\rangle_{C1}) \end{aligned} \quad (7)$$

We rewritten it into the following form:

$$\begin{aligned} & \frac{1}{2(1+n^2)}[|0000\rangle_{A1A2B1B2} \otimes (\alpha|0\rangle + n^2\beta|1\rangle)_{C1} \\ & + |0001\rangle_{A1A2B1B2} \otimes (n\alpha|1\rangle + n\beta|0\rangle)_{C1} \\ & + |0010\rangle_{A1A2B1B2} \otimes (\alpha|0\rangle - n^2\beta|1\rangle)_{C1} \\ & + |0011\rangle_{A1A2B1B2} \otimes (n\alpha|1\rangle - n\beta|0\rangle)_{C1} \\ & + |0100\rangle_{A1A2B1B2} \otimes (n^2\alpha|1\rangle + \beta|0\rangle)_{C1} \\ & + |0101\rangle_{A1A2B1B2} \otimes (n\alpha|0\rangle + n\beta|1\rangle)_{C1} \\ & + |0110\rangle_{A1A2B1B2} \otimes (-n^2\alpha|1\rangle + \beta|0\rangle)_{C1} \\ & + |0111\rangle_{A1A2B1B2} \otimes (-n\alpha|0\rangle + n\beta|1\rangle)_{C1} \\ & + |1000\rangle_{A1A2B1B2} \otimes (\alpha|0\rangle - n^2\beta|1\rangle)_{C1} \\ & + |1001\rangle_{A1A2B1B2} \otimes (n\alpha|1\rangle - n\beta|0\rangle)_{C1} \\ & + |1010\rangle_{A1A2B1B2} \otimes (\alpha|0\rangle + n^2\beta|1\rangle)_{C1} \\ & + |1011\rangle_{A1A2B1B2} \otimes (n\alpha|1\rangle + n\beta|0\rangle)_{C1} \\ & + |1100\rangle_{A1A2B1B2} \otimes (n^2\alpha|1\rangle - \beta|0\rangle)_{C1} \\ & + |1101\rangle_{A1A2B1B2} \otimes (n\alpha|0\rangle - n\beta|1\rangle)_{C1} \\ & + |1110\rangle_{A1A2B1B2} \otimes (-n^2\alpha|1\rangle - \beta|0\rangle)_{C1} \\ & + |1111\rangle_{A1A2B1B2} \otimes (-n\alpha|0\rangle - n\beta|1\rangle)_{C1}] \end{aligned} \quad (8)$$

Then we get when $A1A2B1B2$ is $\{1111\}$ or $\{0101\}$ the state of $C1$ is $(\alpha|0\rangle + \beta|1\rangle)_{C1}$, and the according success probability $p1 = \frac{n^2}{2(1+n^2)^2}$. when $A1A2B1B2$ is $\{1101\}$ or $\{0111\}$ the state of $C1$ is $(\alpha|0\rangle - \beta|1\rangle)_{C1}$, and the according success probability $p2 = \frac{n^2}{2(1+n^2)^2}$. when $A1A2B1B2$ is $\{1011\}$ or $\{0001\}$ the state of $C1$ is $(\alpha|1\rangle + \beta|0\rangle)_{C1}$, and the according success probability $p3 = \frac{n^2}{2(1+n^2)^2}$. when $A1A2B1B2$ is $\{1001\}$ or $\{0011\}$ the state of $C1$ is $(\alpha|1\rangle - \beta|0\rangle)_{C1}$, and the according success probability $p4 = \frac{n^2}{2(1+n^2)^2}$.

Qubit measurement results are passed to Candy

through classical channels. As can be seen, once Candy was told the states of two qubits (qubits of Alice and Bob), Candy gets the qubit states information that he needs.

Notice that some logic operations of unavailable states do not affect the final results, then we simplify the relationship with Karnaugh maps (Figs. 2 and 3).

A1A2 C1C2	00	01	11	10
	00			
01	0		1	1
11	1	1		0
10				

Fig. 2 Z gate Karnaugh map according to A1A2B1B2 states.

A1A2 C1C2	00	01	11	10
	00			
01	1		0	1
11	1	0		1
10				

Fig. 3 X gate Karnaugh map according to A1A2B1B2 states.

$Z = 0$ corresponds to $\{1111\ 0001\ 1011\ 0101\}$

$Z = 1$ corresponds to $\{0011\ 1101\ 0111\ 1001\}$

$X = 1$ corresponds to $\{0001\ 0101\ 0011\ 0111\}$

$X = 0$ corresponds to $\{1111\ 1011\ 1101\ 1001\}$

Z corresponds to $A1 \otimes B1$ and X corresponds to $A1 \otimes B2$.

Therefore, the bridging mechanism can be executed independently, that is to say, each intermediate node executes quantum gates in parallel, and then delivers the results through classical information channel. Finally, the destination node operates the XOR gate according to the results and recovers the quantum state $|y\rangle = \alpha|0\rangle + \beta|1\rangle$ with a probability.

3 Multi-intermediate nodes bridging

Then we consider the situation of n nodes, to prove the XOR logic relationship in the designed quantum circuit still work.

Assume there is $n - 2$ intermediate nodes. In the following figure, two nodes to be added are represented as node D and node E. D shares two partially entangled states with node C and E (Fig. 4).

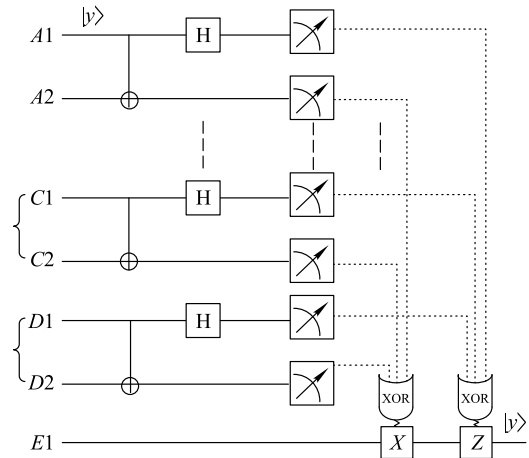


Fig. 4 Quantum circuit for more nodes bridging.

When transported through the former $n - 2$ intermediate nodes, the final system state is

$$\begin{aligned}
 & \overline{(A1 \oplus A2 \oplus \dots \oplus An)} \otimes \overline{(B1 \oplus B2 \oplus \dots \oplus Bn)} \\
 & \otimes (\alpha|0\rangle + \beta|1\rangle)_C \\
 & + \overline{(A1 \oplus A2 \oplus \dots \oplus An)} \otimes (B1 \oplus B2 \oplus \dots \oplus Bn) \\
 & \otimes (\alpha|1\rangle + \beta|0\rangle)_C \\
 & + (A1 \oplus A2 \oplus \dots \oplus An) \otimes \overline{(B1 \oplus B2 \oplus \dots \oplus Bn)} \\
 & \otimes (\alpha|0\rangle - \beta|1\rangle)_C \\
 & + (A1 \oplus A2 \oplus \dots \oplus An) \otimes (B1 \oplus B2 \oplus \dots \oplus Bn) \\
 & \otimes (\alpha|1\rangle - \beta|0\rangle)_C
 \end{aligned} \tag{9}$$

When add two intermediate nodes, we get

$$\begin{aligned}
 & \overline{(A1 \oplus A2 \oplus \dots \oplus An)} \otimes \overline{(B1 \oplus B2 \oplus \dots \oplus Bn)} \\
 & \otimes (\alpha|0\rangle + \beta|1\rangle)_C \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_C |0\rangle_D + n|1\rangle_C |1\rangle_D) \\
 & \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_D |0\rangle_E + n|1\rangle_D |1\rangle_E) \\
 & + \overline{(A1 \oplus A2 \oplus \dots \oplus An)} \otimes (B1 \oplus B2 \oplus \dots \oplus Bn) \\
 & \otimes (\alpha|1\rangle + \beta|0\rangle)_C \\
 & \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_C |0\rangle_D + n|1\rangle_C |1\rangle_D)
 \end{aligned}$$

$$\begin{aligned}
& \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_D |0\rangle_E + n|1\rangle_D |1\rangle_E) \\
& + (A1 \oplus A2 \oplus \dots \oplus An) \otimes (\overline{B1 \oplus B2 \oplus \dots \oplus Bn}) \\
& \otimes (\alpha|0\rangle - \beta|1\rangle)_C \\
& \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_C |0\rangle_D + n|1\rangle_C |1\rangle_D) \\
& \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_D |0\rangle_E + n|1\rangle_D |1\rangle_E) \\
& + (A1 \oplus A2 \oplus \dots \oplus An) \otimes (B1 \oplus B2 \oplus \dots \oplus Bn) \\
& \otimes (\alpha|1\rangle - \beta|0\rangle)_C \\
& \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_C |0\rangle_D + n|1\rangle_C |1\rangle_D) \\
& \otimes \frac{1}{\sqrt{1+n^2}} (|0\rangle_D |0\rangle_E + n|1\rangle_D |1\rangle_E) \quad (10)
\end{aligned}$$

Ignore the formula factor $(A1 \oplus A2 \oplus \dots \oplus An) \otimes (B1 \oplus B2 \oplus \dots \oplus Bn)$. Formula (10) has the same form with formula (5), so it equals the derivation process. When add two intermediate nodes in a quantum teleportation process, the same operation of XOR logic to destination node still work.

Then the formula factor turns into

$$\begin{aligned}
& (A1 \oplus A2 \oplus \dots \oplus An \oplus C1 \oplus D1) \\
& \otimes (B1 \oplus B2 \oplus \dots \oplus Bn \oplus C2 \oplus D2)
\end{aligned}$$

It means the successful probability is

$$P_{n+2} = P_n \times \frac{2n^2}{(1+n^2)^2} \quad (11)$$

So when the number of intermediate nodes is odd number, quantum teleportation can be fulfilled with a probability $(\frac{\sqrt{2n}}{1+n^2})^{2m}$, $k = 2m - 1$, k is the number of intermediate nodes. With the increment of intermediate nodes number, the success probability will decrease rapidly.

4 Conclusion

This paper proposes the quantum bridging method to teleport qubits with partially entangled states. Specific quantum bridging circuit can be designed for qubit teleportation across a plurality of intermediate nodes. After the entangled particles are passed through quantum gates, measurement results in each node then are passed independently to the destination node. Destination node then executes XOR operation to obtain information needed for final quantum gates to recover the initial qubit information. In this way, when partially entanglement quantum resource is limited, new scheme can teleport a qubit successfully with a certain probability. The benefit of this scheme is the simpler logic and better security. So

when teleportation occurs across multiple intermediate nodes, quantum bridging method is feasible.

5 Discussion

To explore the usage of partially entangled state in quantum teleportation, and improve the resource efficiency together with success probability, there are still some problems to be solved.

First, when the degrees of entanglement in partially entangled states are not the same, does this mechanism still work? Some methods for detecting or measuring entanglement are developed [41]. The answer helps to reduce the complexity of future quantum channel preparation.

Second, whether auxiliary particle can be introduced into this bridging mechanism to improved the final success probability deserves us a future study, since intermediate nodes number affects the teleportation result seriously. It also helps to decide whether the teleportation is successful.

Third, we hope to improve this bridging mechanism to suit teleporting multiparticle quantum information, so that the resource efficiency can be increased.

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