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基于六粒子最大纠缠态的双向控制隐形传态方案

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摘　要：提出了一个利用六粒子最大纠缠态作为纠缠资源的双向量子控制隐形传态方案．该理论方案中，六粒子最大纠缠态作为量子通道来连系着合法的三方——通信双方和控制方，通信双方既是发送方同时也是接收方．传输过程中，Alice 传输一个任意单粒子态 a 给 Bob 的同时 Bob 也传输一个任意的单粒子态 b 给 Alice；由控制方 Charlie 来控制和协助通信双方完成最终的量子态的交换；Bob 先对自己手中的粒子作一个幺正操作，用户双方再各自对自己手中的粒子执行 Bell 基测量，测量完成后通过经典信道将自己的测量结果公开宣布，用户双方根据对方所公布的测量结果做相应的幺正操作，从而成功地实现双向量子控制隐形传态．

关键词：量子信息；双向量子控制隐形传态；六粒子最大纠缠态；幺正操作；Bell 基测量
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A Scheme of Bidirectional Quantum Controlled Teleportation via Six-qubit Maximally Entangled State

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Abstract: A bidirectional quantum controlled teleportation scheme using the entanglement property of six-qubit maximally entangled state was presented. In the theoretical scheme, the six-qubit maximally entangled state was employed as the quantum channel linking three legitimate participants. Users were both sender and receiver. Alice transmitted an arbitrary single qubit state of qubit a to Bob and Bob transmitted an arbitrary single qubit state of qubit b to Alice via the control of the supervisor Charlie. Users carried out the Bell state measurements on their own particles and publicly announced their measurement results via a classical channel. Then they operated proper unitary transformation on their own particles, respectively. The bidirectional quantum controlled teleportation was successfully realized.

Key words: Quantum information; Bidirectional quantum controlled teleportation; Six-qubit maximally entangled state; Unitary transformation; Bell-state measurements

0 Introduction

Quantum teleportation is a prime example of a quantum information processing task, where an unknown state can be perfectly transported from one place to another by using previously shared entanglement and classical communication between the sender and the receiver. Since the first creation of quantum teleportation protocol by Bennett[1], research on quantum teleportation has attracted much attention both in theoretical and experimental aspects in recent years due to its important applications in quantum calculation and quantum communication. Several experimental

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implementations of teleportation have been reported[2-3] and some schemes of quantum teleportation have also been presented[4-14]. However, the success of these protocols relies largely on the quality of the shared entanglement as well as the performance of clean projective measurements, and for real circumstance, the considered system unavoidably interacts with its surroundings and therefore induce decoherence and degradation of entanglement, for which fidelity of quantum teleportation may be reduced, see, e. g. , Refs[15-20] for several typical works along this line of research.

In this paper, we presented a scheme of bidirectional quantum controlled teleportation in which a six-qubit maximally entangled state quantum channel initially shared by the sender (receiver) Alice, Bob and supervisor Charlie. Suppose that Alice has a particle in an unknown state, she wants to transmit the state of particle a to Bob; at the same time, Bob has particle b in an unknown state, he wants to transmit the state of particle b to Alice. We showed that the original state of each qubit can be restored by the receiver as long as sender Alice (Bob) makes a C-not measurement and Bell-state measurements on the sender's side and operates an appropriate unitary transformation on the receiver's side with the cooperation of the supervisor Charlie.

1 Bidirectional quantum controlled teleportation

Assume that the quantum channel of the proposed bidirectional quantum controlled teleportation can be denoted as follow

$$|\varphi\rangle_{123456}=\frac{1}{4}(|000000\rangle+|000111\rangle-|001001\rangle+|001110\rangle+|010100-|010011\rangle+|011010\rangle+|011101\rangle+|100101\rangle-|100010\rangle-|101011\rangle-|101100\rangle+|110001\rangle+|110110+|111000\rangle-|111111\rangle)_{123456} \quad (1)$$

Now we consider that Alice, Bob and Charlie hold qubits (1, 2); (3, 4); (5, 6), respectively. Thus the entangled channel can also be written

$$|\varphi\rangle_{A_1A_2B_1B_2C_1C_2}=\frac{1}{4}(|000000\rangle+|000111\rangle-|001001\rangle+|001110\rangle+|010100\rangle-|010011\rangle+|011010\rangle+|011101\rangle+|100101\rangle-|100010\rangle-|101011\rangle-|101100\rangle+|110001\rangle+|110110\rangle+|111000\rangle-|111111\rangle)_{A_1A_2B_1B_2C_1C_2} \quad (2)$$

Suppose that Alice has particle a in an unknown state

$$|\chi\rangle_a=(a_0|0\rangle+a_1|1\rangle)_a$$

And that Bob has particle b in an unknown state

$$|\chi\rangle_b=(b_0|0\rangle+b_1|1\rangle)_b$$

Alice wants to transmit the state of particle a to Bob, at the same time, Bob wants to transmit the state of particle b to Alice. Hence, the joint state of the whole system can be expressed as

$$|\psi\rangle_s=|\chi\rangle_a\otimes|\chi\rangle_b\otimes|\varphi\rangle_{A_1A_2B_1B_2C_1C_2}=(a_0|0\rangle+a_1|1\rangle)_a(b_0|0\rangle+b_1|1\rangle)_b\otimes\frac{1}{4}(|000000\rangle+|000111\rangle-|001001\rangle+|001110\rangle+|010100\rangle-|010011\rangle+|011010\rangle+|011101\rangle+|100101\rangle-|100010\rangle-|101011\rangle-|101100\rangle+|110001\rangle+|110110\rangle+|111000\rangle-|111111\rangle)_{A_1A_2B_1B_2C_1C_2} \quad (3)$$

To achieve the purpose of bidirectional controlled teleportation task, firstly, Bob needs to perform a unitary transformation $U_{B_1B_2}$ on particles B_1B_2 which can be expressed as the following matrix

$$\boldsymbol{U}_{B_1B_2}=\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&-1\\0&0&1&0\end{pmatrix} \quad (4)$$

Then, we have

$$|\psi'\rangle_s=U_{B_1B_2}|\psi\rangle_s=|\chi\rangle_a\otimes|\chi\rangle_b\otimes U_{B_1B_2}|\varphi\rangle_{A_1A_2B_1B_2C_1C_2}=(a_0|0\rangle+a_1|1\rangle)_a(b_0|0\rangle+b_1|1\rangle)_b\otimes\frac{1}{4}(|000000\rangle+|000111\rangle-|001101\rangle-|001010\rangle+|010100\rangle-|010011\rangle+|011110\rangle-|011001\rangle+|100101\rangle-|100010\rangle-|101111\rangle+|101000\rangle+|110001\rangle+|110110\rangle+|111100\rangle+|111011\rangle)_{A_1A_2B_1B_2C_1C_2}=$$

$$\frac{1}{4}[a_0b_0(|00000000\rangle+|00000111\rangle-|00010101\rangle-|00010010\rangle+|00100100\rangle-|00100011\rangle+|00110110\rangle-|00110001\rangle+|01000101\rangle-|01000010\rangle-|01010111\rangle+|01010000\rangle+|01100001\rangle+|01100110\rangle+|01110100\rangle+|01110011\rangle)_{aA_1A_2B_1bB_2C_1C_2}+a_0b_1(|00001000\rangle+|00001111\rangle-|00011101\rangle-|00011010\rangle+|00101100\rangle-|00101011\rangle+|00111110\rangle-|00111001\rangle+|01001101\rangle-|01001010\rangle-|01011111\rangle+|01011000\rangle+|01101001\rangle+|01101110\rangle+|01111100\rangle+|01111011\rangle)_{aA_1A_2B_1bB_2C_1C_2}+a_1b_0(|10000000\rangle+|10000111\rangle-|10010101\rangle-|10010010\rangle+|10100100\rangle-|10100011\rangle+|10110110\rangle-|10110001\rangle+|11000101\rangle-|11000010\rangle-|11010111\rangle+|11010000\rangle+|11100001\rangle+|11100110\rangle+|11110100\rangle+|11110011\rangle)_{aA_1A_2B_1bB_2C_1C_2}+a_1b_1(|10001000\rangle+|10001111\rangle-$$

$$|10011101\rangle-|10011010\rangle+|10101100\rangle-|10101011\rangle+|10111110\rangle-|10111001\rangle+|11001101-|11001010\rangle-|11011111\rangle+|\rangle|11011000\rangle+|11101001\rangle+|11101110\rangle+|11111100\rangle+|11111011\rangle)_{aA_1A_2B_1bB_2C_1C_2}] \tag{5}$$

Secondly, Alice has to perform Bell state measurements on her qubit pairs (a, A_1), where $|\varphi^i_{aA_1}\rangle (i=1,2,3,4)$ are Bell states

$$|\varphi^1_{aA_1}\rangle=\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$$

$$|\varphi^2_{aA_1}\rangle=\frac{1}{\sqrt{2}}(|00\rangle-|11\rangle)$$

$$|\varphi^3_{aA_1}\rangle=\frac{1}{\sqrt{2}}(|01\rangle+|10\rangle)$$

$$|\varphi^4_{aA_1}\rangle=\frac{1}{\sqrt{2}}(|01\rangle-|10\rangle)$$

Then she will inform Bob and Charlie of the result of the measurement by the classical channel. Without loss of generality, we assume that the outcome of Alice′s measurement is $|\varphi^1_{aA_1}\rangle$, the state of $A_2B_1bB_2C_1C_2$ will collapse into Eq. (6)

$$|\psi'^{|\varphi^1_{aA_1}\rangle}\rangle_s=\frac{1}{4\sqrt{2}}[a_0b_0(|000000\rangle+|000111\rangle-|010101\rangle-|010010\rangle+|100100\rangle-|100011\rangle+|110110\rangle-|110001\rangle)_{A_2B_1bB_2C_1C_2}+a_0b_1(|001000\rangle+|001111\rangle-|011101\rangle-|011010\rangle+|101100\rangle-|101011\rangle+|111110\rangle-|111001\rangle)_{A_2B_1bB_2C_1C_2}+a_1b_0(|000101\rangle-|000010\rangle-|010111\rangle+|010000\rangle+|100001\rangle+|100110\rangle+|110100\rangle+|110011\rangle)_{A_2B_1bB_2C_1C_2}+a_1b_1(|001101\rangle-|001010\rangle-|011111\rangle+|011000\rangle+|101001\rangle+|101110\rangle+|111100\rangle+|111011\rangle)_{A_2B_1bB_2C_1C_2}] \tag{6}$$

Thirdly, Bob has to perform Bell state measurements on his qubit pairs (b, B_2), where $|\varphi^j_{bB_2}\rangle (j=1,2,3,4)$ are Bell states,

$$|\varphi^1_{bB_2}\rangle=\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$$

$$|\varphi^2_{bB_2}\rangle=\frac{1}{\sqrt{2}}(|00\rangle-|11\rangle)$$

$$|\varphi^3_{bB_2}\rangle=\frac{1}{\sqrt{2}}(|01\rangle+|10\rangle)$$

$$|\varphi^4_{bB_2}\rangle=\frac{1}{\sqrt{2}}(|01\rangle-|10\rangle)$$

We also assume that the outcome of Bob′s measurement is $|\varphi^1_{bB_2}\rangle$, the state of $A_2B_1C_1C_2$ will collapse into Eq. (7)

$$|\psi'^{|\varphi^1_{aA_1}\rangle,|\varphi^1_{bB_2}\rangle}\rangle_s=\frac{1}{8}[a_0b_0(|0000\rangle-|0110\rangle-|1011\rangle-|1101\rangle)_{A_2B_1C_1C_2}+a_0b_1(|0011\rangle-|0101\rangle+|1000\rangle+|1110\rangle)_{A_2B_1C_1C_2}+a_1b_0(-|0010\rangle+|0100\rangle+|1001\rangle+|1111\rangle)_{A_2B_1C_1C_2}+a_1b_1(|0001\rangle-|0111\rangle+|1010\rangle+|1100\rangle)_{A_2B_1C_1C_2}] \tag{7}$$

Subsequently, Charlie performs a Von Neumann measurement on his qubits. if Charlie′s Von Neumann measurement result is $|00\rangle_{C_1C_2}$, the state of A_2B_1 will collapse into Eq. (8)

$$|\psi'^{|\varphi^1_{aA_1}\rangle,|\varphi^1_{bB_2}\rangle,|00\rangle_{C_1C_2}}\rangle_s=\frac{1}{8}(a_0|0\rangle+a_1|1\rangle)_{B_1}(b_0|0\rangle+b_1|1\rangle)_{A_2} \tag{8}$$

Alice and Bob need to carry out the local unitary operation $I_{A_2}\otimes I_{B_1}$. After doing those operations, Bob and Alice can successfully reconstruct the original unknown single qubit state. Thus the bidirectional quantum controlled teleportation is successfully realized.

For the other cases, the relation of measurement results performed by Alice on her qubits (a, A_1) and performed by Bob on his qubits (b, B_2) with the corresponding collapsed state of particle A_2B_1 is summarized in the Table 1, In the meantime, the corresponding transformations performed by Alice and Bob is also given in the Table 1.

According to measurement results by Alice, Bob and Charlie, Alice and Bob operate an appropriate unitary transformation. The

Table 1 The collapse states of particles A_2B_1 and the corresponding transformations performed by Alice and Bob on qubits A_2 and B_1

i,j	$\lvert\psi'^{\lvert\varphi^i_{aA_1}\rangle,\lvert\varphi^j_{bB_2}\rangle,\lvert 00\rangle_{C_1C_2}}\rangle_s$	Operation of Alice and Bob	$\lvert\psi'^{\lvert\varphi^i_{aA_1}\rangle,\lvert\varphi^j_{bB_2}\rangle,\lvert 11\rangle_{C_1C_2}}\rangle_s$	Operation of Alice and Bob
$i=1,j=1$	$\frac{1}{8}(a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 0\rangle+b_1\lvert 1\rangle)_{A_2}$	$I_{A_2}\otimes I_{B_1}$	$\frac{1}{8}(-a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 1\rangle-b_1\lvert 0\rangle)_{A_2}$	$i\sigma_{A_2y}\otimes\sigma_{B_1z}$
$i=1,j=2$	$\frac{1}{8}(a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 0\rangle-b_1\lvert 1\rangle)_{A_2}$	$\sigma_{A_2z}\otimes I_{B_1}$	$\frac{1}{8}(-a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 1\rangle+b_1\lvert 0\rangle)_{A_2}$	$\sigma_{A_2x}\otimes\sigma_{B_1z}$
$i=1,j=3$	$\frac{1}{8}(a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 1\rangle+b_1\lvert 0\rangle)_{A_2}$	$\sigma_{A_2x}\otimes I_{B_1}$	$\frac{1}{8}(a_0\lvert 0\rangle-a_1\lvert 1\rangle)_{B_1}(b_0\lvert 0\rangle-b_1\lvert 1\rangle)_{A_2}$	$\sigma_{A_2z}\otimes\sigma_{B_1z}$
$i=1,j=4$	$\frac{1}{8}(a_0\lvert 0\rangle+a_1\lvert 1\rangle)_{B_1}(b_0\lvert 1\rangle-b_1\lvert 0\rangle)_{A_2}$	$i\sigma_{A_2y}\otimes I_{B_1}$	$\frac{1}{8}(a_0\lvert 0\rangle-a_1\lvert 1\rangle)_{B_1}(b_0\lvert 0\rangle+b_1\lvert 1\rangle)_{A_2}$	$I_{A_2}\otimes\sigma_{B_1z}$

$i=2,j=1$	$\frac{1}{8}(a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes\sigma_{B_1 z}$	$\frac{1}{8}(-a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes I_{B_1}$
$i=2,j=2$	$\frac{1}{8}(a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes\sigma_{B_1 z}$	$\frac{1}{8}(-a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes I_{B_1}$
$i=2,j=3$	$\frac{1}{8}(a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes\sigma_{B_1 z}$	$\frac{1}{8}(a_0\|0\rangle+a_1\|1\rangle)_{B_1}(b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes I_{B_1}$
$i=2,j=4$	$\frac{1}{8}(a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes\sigma_{B_1 z}$	$\frac{1}{8}(a_0\|0\rangle+a_1\|1\rangle)_{B_1}(b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes I_{B_1}$
$i=3,j=1$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes\sigma_{B_1 x}$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes i\sigma_{B_1 y}$
$i=3,j=2$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes\sigma_{B_1 x}$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes i\sigma_{B_1 y}$
$i=3,j=3$	$\frac{1}{8}(a_0\|0\rangle-a_1\|1\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes\sigma_{B_1 x}$	$\frac{1}{8}(-a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes i\sigma_{B_1 y}$
$i=3,j=4$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes\sigma_{B_1 x}$	$\frac{1}{8}(-a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes i\sigma_{B_1 y}$
$i=4,j=1$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes i\sigma_{B_1 y}$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes\sigma_{B_1 x}$
$i=4,j=2$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes i\sigma_{B_1 y}$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes\sigma_{B_1 x}$
$i=4,j=3$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|1\rangle+b_1\|0\rangle)_{A_2}$	$\sigma_{A_2 x}\otimes i\sigma_{B_1 y}$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(-b_0\|0\rangle+b_1\|1\rangle)_{A_2}$	$\sigma_{A_2 z}\otimes\sigma_{B_1 x}$
$i=4,j=4$	$\frac{1}{8}(a_0\|1\rangle-a_1\|0\rangle)_{B_1}(b_0\|1\rangle-b_1\|0\rangle)_{A_2}$	$i\sigma_{A_2 y}\otimes i\sigma_{B_1 y}$	$\frac{1}{8}(a_0\|1\rangle+a_1\|0\rangle)_{B_1}(-b_0\|0\rangle-b_1\|1\rangle)_{A_2}$	$I_{A_2}\otimes\sigma_{B_1 x}$

Bidirectional quantum controlled teleportation is easily realized.

2 Conclusion

In summary, we presented a theoretical scheme for bidirectional quantum controlled teleportation using the entanglement property of six-qubit maximally entangled state. In the scheme, Alice and Bob are both sender and receiver. If Alice and Bob operate Bell-state measurement and appropriate unitary transformation with the help of Charlie, the two unknown states a and b can be successfully swapped. We hope that such a bidirectional quantum controlled teleportation scheme can be realized experimentally in the future.

As a final remark, we would like to point out here that our proposed teleportation scheme is based on the special structure of the shared quantum channel, and when considering the non-idealistic situation, the expected fidelity of the received state may be reduced due to the detrimental effects of the environments, which will be investigated in our future work.

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