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Perfect Quantum Teleportation via Bell States

Xiaoqing Tan[1, *], Xiaochun Li[1] and Pei Yang[1]

Abstract: Quantum mechanics shows superiority than classical mechanics in many aspects and quantum entanglement plays an essential role in information processing and some computational tasks such as quantum teleportation (QT). QT was proposed to transmit the unknown states, in which EPR pairs, the entangled states, can be used as quantum channels. In this paper, we present two simple schemes for teleporting a product state of two arbitrary single-particle and an arbitrary two-particle pure entangled state respectively. Alice and Bob have shared an entangle state. Two Bell states are used as quantum channels. Then after Alice measuring her qubits and informing Bob her measurement results, Bob can perfectly reconstruct the original state by performing corresponding unitary operators on his qubits. It shown that a product state of two arbitrary single-particle and an arbitrary two-particle pure entangled state can be teleported perfectly, i.e. the success probabilities of our schemes are both 1.

Keywords: Quantum teleportation, Bell states, product state, pure entangled state.

1 Introduction

Quantum, first proposed by German physicist Max Planck in 1900, has shown a great deal of advantage than classical physics in many aspects. Quantum entanglement [Einstein, Podolsky and Rosen (1935); Pan (2001); Muralidharan and Panigrahi (2007)], recognized as a spooky action of quantum mechanics, plays an crucial role in quantum information processing and certain computational tasks like quantum teleportation (QT) [Bennett, Brassard, Crepeau et al. (1993)], quantum dense coding [Nie, Li, Wang et al. (2013)], quantum secure direct communication [Wang and Lu (2013)], quantum cryptography [Ekert (1991)], quantum information splitting [Zheng (2006); Muralidharan and Panigrahi (2008); Wang, Xia, Wang et al. (2009)] and so on, which is a critical element for quantum computation networks [Bouwmeester, Pan and Mattle (1997)].

EPR pairs having the property that it cannot be written as a product of states of its component systems, is entangled states. Suppose there are two parties, usually called Alice and Bob, met long ago and they generated an EPR pair. When they separated each of them took one qubit of the EPR pair. Now they keep far apart and Bob is in hiding. Alice wants to deliver a qubit $|\Psi\rangle$ to Bob. She does not know the state of the qubit, and moreover can only send classical information to Bob. QT can help Alice accomplish this mission. It is such a process that a sender (Alice) transmits an unknown state to a receiver

[1] Department of Mathematics, School of Information Science and Technology, Jinan University, Guangzhou, 510632, China.

[*] Corresponding Author: Xiaoqing Tan. Email: ttanxq@jnu.edu.cn.

(Bob) via a quantum channel with the help of some classical information [Nielson and Chuang (2000)].

In 1993, Bennett et al. [Bennett, Brassard, Crepeau et al. (1993)] first presented quantum teleportation protocol, which is the transmission of an unknown single-particle state by using a maximally entangled two-particle state. Subsequently, various quantum teleportation schemes for an unknown single-particle state or an arbitrary two-particle state are proposed. In 1998, Karlsson et al. [Karlsson and Bourennane (1998)] researched to teleport a quantum state by using three-particle entanglement and shown the similarities between the process and a quantum nondemolition measurement. Lu et al. [Lu and Guo (2000)] raised Teleportation of a two-particle entangled state through entanglement swapping and put forward that the success probability of teleportation is based on the smallest superposition coefficient if the particles are not-maximally entangled. In 2002, Shi et al. [Shi and Tomita (2002)] proposed a scheme for probabilistically teleporting an unknown state by W state while Argrawal et al. [Argrawal and Pati (2006)] shown that a class of W states can be utilized for perfect teleportation and superdense coding in 2006. Later, Yang et al. [Yang, Huang, Yang et al. (2009)] proposed a teleportation scheme via GHZ-like states, and they analyzed the fidelity of the state if the control party is dishonest. In 2014, Zhu [Zhu (2014)] proposed a perfect protocol for quantum teleportation of an arbitrary two-qubit state via GHZ-like states.

Recently, schemes of controlled Bidirectional teleportation via seven-qubit entangled State has been proposed, which showed how multiple useful the quantum channel is [Li, Li and Sang (2013)]. Horiuchi [Horiuchi (2015)] demonstrated long-distance quantum teleportation in 2005. Another scheme, using a five-qubit entangled state as a quantum channel, is presented to implement bidirectional controlled quantum teleportation and it shows the quantum channel multi-role [Wu, Zha and Yang (2018)].

Besides, there are many quantum teleportation via cluster states. For example, two schemes for perfectly teleporting an unknown two-particle entangled state via a four-particle entangled cluster state were proposed in 2007 [Li and Cao (2007)]. Li et al. [Li, Ye and Yang (2012)] presented two schemes to teleport a product state via a four-particle entangled cluster state in 2012. Liu et al. [Liu and Zhou (2014)] used five-qubit cluster state as the quantum channel for teleporting a special three-qubit state. In 2016, Tan et al. [Tan, Zhang and Fang (2016)] proposed a perfect quantum teleportation scheme for an unknown single-particle pure state and an arbitrary two-particle pure entangled state by four-particle cluster state. In 2018, Zhao et al. [Zhao, Li, Chen et al. (2018)] let Alice operates four controlled-NOT operators and a six-qubit von-Neumann projective measurement, and then Bob can reconstruct the original state to show the scheme of eight-qubit States via six-qubit Cluster State. Although the cluster states have two basic properties maximum connectedness and a high persistency of entanglement, the difficulty of Alice's measurement increases with the increase of the number of particles in the quantum teleportation. In our paper, we consider two simple schemes that transmit a product state of two arbitrary single-particle states and an arbitrary two-particle pure entangled state respectively by using Bell states which are the product state of two-particle maximally entangled states. In this paper, we propose two teleportation schemes. Quantum teleportation of a product state of two arbitrary single-particle and an arbitrary two particle pure entangled state can be achieved via Bell states. The successful possibilities of these two schemes can be 1.

The rest of this paper is organized as follows. We present the quantum teleportation of a product state of two arbitrary single-particle in Section 2 and for an arbitrary two-particle pure entangled state in Section 3 in detail. Then, we make a brief conclusion in Section 4.

2 Quantum teleportation of a product state of two arbitrary single-particle states

Suppose Alice has a product state of two arbitrary single-particle, which is

$$|\Phi\rangle_{AB} = |\Phi\rangle_A \otimes |\Phi\rangle_B \tag{1}$$

where $|\Phi\rangle_A = a|0\rangle + b|1\rangle, |\Phi\rangle_B = c|0\rangle + d|1\rangle$ in which a, b, c and d are any complex numbers and need satisfying the conditions that $|a|^2 + |b|^2 = 1$ and $|c|^2 + |d|^2 = 1$. Bell states are used as quantum channel between Alice and Bob, which are in the following states

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

We choose $|\Phi^+\rangle$ as quantum channel, shown as follows

$$|\Phi^+\rangle_{12} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \ , \quad |\Phi^+\rangle_{34} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \ . \tag{3}$$

Particles A, B, 1, and 3 belong to Alice, particles 2 and 4 belong to Bob. Initially, the state of the joint system can be written as

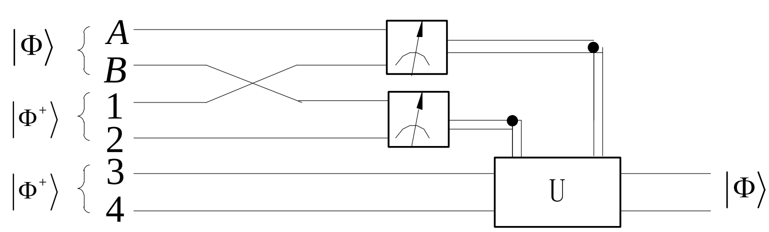

Figure 1: The schematic diagram of this quantum teleportation

$$
\begin{aligned}
&|\Psi\rangle_{AB1234} = |\Phi\rangle_{AB} \otimes |\Phi^+\rangle_{12} \otimes |\Phi^+\rangle_{34} \\
&= \tfrac{1}{2}(a|0\rangle + b|1\rangle)_A \otimes (c|0\rangle + d|1\rangle)_B \otimes (|0000\rangle + |0011\rangle + |1100\rangle + |1111\rangle)_{1234} \\
&= \tfrac{1}{2}(ac|000000\rangle + ac|000011\rangle + ac|001100\rangle + ac|001111\rangle \\
&+ ad|010000\rangle + ad|010011\rangle + ad|011100\rangle + ad|011111\rangle \\
&+ bc|100000\rangle + bc|100011\rangle + bc|101100\rangle + bc|101111\rangle \\
&+ bd|110000\rangle + bd|110011\rangle + bd|111100\rangle + bd|111111\rangle)_{AB1234} \\
&= \tfrac{1}{4}[|\Phi^+\rangle_{A1}|\Phi^+\rangle_{B3}(ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle)_{24} \\
&+ |\Phi^+\rangle_{A1}|\Phi^-\rangle_{B3}(ac|00\rangle - ad|01\rangle + bc|10\rangle - bd|11\rangle)_{24} \\
&+ |\Phi^-\rangle_{A1}|\Phi^+\rangle_{B3}(ac|00\rangle + ad|01\rangle - bc|10\rangle - bd|11\rangle)_{24} \\
&+ |\Phi^-\rangle_{A1}|\Phi^-\rangle_{B3}(ac|00\rangle - ad|01\rangle - bc|10\rangle + bd|11\rangle)_{24} \\
&+ |\Phi^+\rangle_{A1}|\Psi^+\rangle_{B3}(ac|01\rangle + ad|00\rangle + bc|11\rangle + bd|10\rangle)_{24} \\
&+ |\Phi^+\rangle_{A1}|\Psi^-\rangle_{B3}(ac|01\rangle - ad|00\rangle + bc|11\rangle - bd|10\rangle)_{24} \\
&+ |\Phi^-\rangle_{A1}|\Psi^+\rangle_{B3}(ac|01\rangle + ad|00\rangle - bc|11\rangle - bd|10\rangle)_{24} \\
&+ |\Phi^-\rangle_{A1}|\Psi^-\rangle_{B3}(ac|01\rangle - ad|00\rangle - bc|11\rangle + bd|10\rangle)_{24} \\
&+ |\Psi^+\rangle_{A1}|\Phi^+\rangle_{B3}(ac|10\rangle + ad|11\rangle + bc|00\rangle + bd|01\rangle)_{24} \\
&+ |\Psi^+\rangle_{A1}|\Phi^-\rangle_{B3}(ac|10\rangle - ad|11\rangle + bc|00\rangle - bd|01\rangle)_{24} \\
&+ |\Psi^-\rangle_{A1}|\Phi^+\rangle_{B3}(ac|10\rangle + ad|11\rangle - bc|00\rangle - bd|01\rangle)_{24} \\
&+ |\Psi^-\rangle_{A1}|\Phi^-\rangle_{B3}(ac|10\rangle - ad|11\rangle - bc|00\rangle + bd|01\rangle)_{24} \\
&+ |\Psi^+\rangle_{A1}|\Psi^+\rangle_{B3}(ac|11\rangle + ad|10\rangle + bc|01\rangle + bd|00\rangle)_{24} \\
&+ |\Psi^+\rangle_{A1}|\Psi^-\rangle_{B3}(ac|11\rangle - ad|10\rangle + bc|01\rangle - bd|00\rangle)_{24} \\
&+ |\Psi^-\rangle_{A1}|\Psi^+\rangle_{B3}(ac|11\rangle + ad|10\rangle - bc|01\rangle - bd|00\rangle)_{24} \\
&+ |\Psi^-\rangle_{A1}|\Psi^-\rangle_{B3}(ac|11\rangle - ad|10\rangle - bc|01\rangle + bd|00\rangle)_{24}] \ .
\end{aligned}
\tag{4}
$$

Alice measures particles (A, 1) and (B, 3) by using Bell basis respectively. The measurement result of Alice and the final collapsed state are reflected in Eq. (4). After measuring, Alice tells Bob her measurement results via a classical channel. Then, Bob can reconstruct the initial state on particles 2 and 4 by performing appropriate unitary transformations.

Fig. 1 shows the schematic diagram of this quantum teleportation that Alice measures her qubits and informs Bob her measurement results, and then Bob perform some certain operators on his own particles according to the receiving classical information. At last, Bob will get the unknown state $|\Phi\rangle_{AB}$.

We discuss the operations in detail. Without loss of generality, assume Alice's measurement results are $|\Psi^-\rangle_{A1}$ and $|\Phi^-\rangle_{B3}$ respectively, the particle pair (2, 4) should be collapsed into the state

$$\frac{1}{4}(ac|10\rangle - ad|11\rangle - bc|00\rangle + bd|01\rangle) = \frac{1}{4}(a|1\rangle - b|0\rangle) \otimes (c|0\rangle - d|1\rangle) \ . \tag{5}$$

Bob need to perform $i\sigma_y^2 \otimes \sigma_z^4$ on the particle pair (2,4) to reconstruct the original state. And the probability of success is $(\frac{1}{4})^2 = \frac{1}{16}$. The others possible cases are list in Tab. 1. There are 16 possible cases and then we get $16 \times (\frac{1}{4})^2 = 1$, i.e. the successful probability of this scheme can reach 1.

Table 1: Bob's unitary operations corresponding to Alice's measurement results

Alice's results	Bob's operations	Alice's results	Bob's operations
$\|\Phi^+\rangle_{A1}\|\Phi^+\rangle_{B3}$	$I^2 \otimes I^4$	$\|\Psi^+\rangle_{A1}\|\Phi^+\rangle_{B3}$	$\sigma_x^2 \otimes I^4$
$\|\Phi^+\rangle_{A1}\|\Phi^-\rangle_{B3}$	$I^2 \otimes \sigma_z^4$	$\|\Psi^+\rangle_{A1}\|\Phi^-\rangle_{B3}$	$\sigma_x^2 \otimes \sigma_z^4$
$\|\Phi^-\rangle_{A1}\|\Phi^+\rangle_{B3}$	$\sigma_z^2 \otimes I^4$	$\|\Psi^-\rangle_{A1}\|\Phi^+\rangle_{B3}$	$i\sigma_y^2 \otimes I^4$
$\|\Phi^-\rangle_{A1}\|\Phi^-\rangle_{B3}$	$\sigma_z^2 \otimes \sigma_z^4$	$\|\Psi^-\rangle_{A1}\|\Phi^-\rangle_{B3}$	$i\sigma_y^2 \otimes \sigma_z^4$
$\|\Phi^+\rangle_{A1}\|\Psi^+\rangle_{B3}$	$I^2 \otimes \sigma_x^4$	$\|\Psi^+\rangle_{A1}\|\Psi^+\rangle_{B3}$	$\sigma_x^2 \otimes \sigma_x^4$
$\|\Phi^+\rangle_{A1}\|\Psi^-\rangle_{B3}$	$I^2 \otimes i\sigma_y^4$	$\|\Psi^+\rangle_{A1}\|\Psi^-\rangle_{B3}$	$\sigma_x^2 \otimes i\sigma_y^4$
$\|\Phi^-\rangle_{A1}\|\Psi^+\rangle_{B3}$	$\sigma_z^2 \otimes \sigma_x^4$	$\|\Psi^-\rangle_{A1}\|\Psi^+\rangle_{B3}$	$i\sigma_y^2 \otimes \sigma_x^4$
$\|\Phi^-\rangle_{A1}\|\Psi^-\rangle_{B3}$	$\sigma_z^2 \otimes i\sigma_y^4$	$\|\Psi^-\rangle_{A1}\|\Psi^-\rangle_{B3}$	$i\sigma_y^2 \otimes i\sigma_y^4$

3 Quantum teleportation of an arbitrary two-particle pure entangled state

Suppose Alice has an arbitrary two-particle pure entangled state, which is

$$|\varphi\rangle_{ab} = \alpha|00\rangle_{ab} + \beta|01\rangle_{ab} + \gamma|10\rangle_{ab} + \delta|11\rangle_{ab} \ , \tag{6}$$

where $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$. $|\Phi^+\rangle_{12}$ and $|\Phi^+\rangle_{34}$ are also utilized as quantum channel. Particles a, b, 1, and 3 belong to Alice, particles 2 and 4 belong to Bob. Initially, the state of the joint system can be written as

$$\begin{aligned}
&|\Psi\rangle_{ab1234} \\
&= |\varphi\rangle_{ab} \otimes |\Phi^+\rangle_{12} \otimes |\Phi^+\rangle_{34} \\
&= \tfrac{1}{2}(\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle)_{ab} \otimes (|00\rangle + |11\rangle)_{12} \otimes (|00\rangle + |11\rangle)_{34} \\
&= \tfrac{1}{2}(\alpha|000000\rangle + \alpha|000011\rangle + \alpha|001100\rangle + \alpha|001111\rangle \\
&+ \beta|010000\rangle + \beta|010011\rangle + \beta|011100\rangle + \beta|011111\rangle \\
&+ \gamma|100000\rangle + \gamma|100011\rangle + \gamma|101100\rangle + \gamma|101111\rangle \\
&+ \delta|110000\rangle + \delta|110011\rangle + \delta|111100\rangle + \delta|111111\rangle)_{ab1234} \ .
\end{aligned} \tag{7}$$

Alice measures particles (a, 1) and (b, 3) by using Bell basis respectively. It causes particles (2, 4) collapsed into one of the following states

$$
\begin{aligned}
|\Psi^{(1)}\rangle_{24} &= \frac{1}{4}(\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle) \ , \\
|\Psi^{(2)}\rangle_{24} &= \frac{1}{4}(\alpha|00\rangle - \beta|01\rangle + \gamma|10\rangle - \delta|11\rangle) \ , \\
|\Psi^{(3)}\rangle_{24} &= \frac{1}{4}(\alpha|00\rangle + \beta|01\rangle - \gamma|10\rangle - \delta|11\rangle) \ , \\
|\Psi^{(4)}\rangle_{24} &= \frac{1}{4}(\alpha|00\rangle - \beta|01\rangle - \gamma|10\rangle + \delta|11\rangle) \ , \\
|\Psi^{(5)}\rangle_{24} &= \frac{1}{4}(\alpha|01\rangle + \beta|00\rangle + \gamma|11\rangle + \delta|10\rangle) \ , \\
|\Psi^{(6)}\rangle_{24} &= \frac{1}{4}(\alpha|01\rangle - \beta|00\rangle + \gamma|11\rangle - \delta|10\rangle) \ , \\
|\Psi^{(7)}\rangle_{24} &= \frac{1}{4}(\alpha|01\rangle + \beta|00\rangle - \gamma|11\rangle - \delta|10\rangle) \ , \\
|\Psi^{(8)}\rangle_{24} &= \frac{1}{4}(\alpha|01\rangle - \beta|00\rangle - \gamma|11\rangle + \delta|10\rangle) \ , \\
|\Psi^{(9)}\rangle_{24} &= \frac{1}{4}(\alpha|10\rangle + \beta|11\rangle + \gamma|00\rangle + \delta|01\rangle) \ , \\
|\Psi^{(10)}\rangle_{24} &= \frac{1}{4}(\alpha|10\rangle - \beta|11\rangle + \gamma|00\rangle - \delta|01\rangle) \ , \\
|\Psi^{(11)}\rangle_{24} &= \frac{1}{4}(\alpha|10\rangle + \beta|11\rangle - \gamma|00\rangle - \delta|01\rangle) \ , \\
|\Psi^{(12)}\rangle_{24} &= \frac{1}{4}(\alpha|10\rangle - \beta|11\rangle - \gamma|00\rangle + \delta|01\rangle) \ , \\
|\Psi^{(13)}\rangle_{24} &= \frac{1}{4}(\alpha|11\rangle + \beta|10\rangle + \gamma|01\rangle + \delta|00\rangle) \ , \\
|\Psi^{(14)}\rangle_{24} &= \frac{1}{4}(\alpha|11\rangle - \beta|10\rangle + \gamma|01\rangle - \delta|00\rangle) \ , \\
|\Psi^{(15)}\rangle_{24} &= \frac{1}{4}(\alpha|11\rangle + \beta|10\rangle - \gamma|01\rangle - \delta|00\rangle) \ , \\
|\Psi^{(16)}\rangle_{24} &= \frac{1}{4}(\alpha|11\rangle - \beta|10\rangle - \gamma|01\rangle + \delta|00\rangle) \ .
\end{aligned} \tag{8}
$$

Similar to the first scheme, all possible recovery operations are list in Tab. 2. It shows that any two-particle pure entangled state can be reconstructed on Bob's side successfully, and the total successful probability of the teleportation is $16 \times (\frac{1}{4})^2 = 1$.

Table 2: Bob's unitary operations corresponding to Alice's measurement results

Alice's results	Bob's operations	Alice's results	Bob's operations
$\lvert\Phi^+\rangle_{a1}\lvert\Phi^+\rangle_{b3}$	$I^2 \otimes I^4$	$\lvert\Psi^+\rangle_{a1}\lvert\Phi^+\rangle_{b3}$	$\sigma_x^2 \otimes I^4$
$\lvert\Phi^+\rangle_{a1}\lvert\Phi^-\rangle_{b3}$	$I^2 \otimes \sigma_z^4$	$\lvert\Psi^+\rangle_{a1}\lvert\Phi^-\rangle_{b3}$	$\sigma_x^2 \otimes \sigma_z^4$
$\lvert\Phi^-\rangle_{a1}\lvert\Phi^+\rangle_{b3}$	$\sigma_z^2 \otimes I^4$	$\lvert\Psi^-\rangle_{a1}\lvert\Phi^+\rangle_{b3}$	$i\sigma_y^2 \otimes I^4$
$\lvert\Phi^-\rangle_{a1}\lvert\Phi^-\rangle_{b3}$	$\sigma_z^2 \otimes \sigma_z^4$	$\lvert\Psi^-\rangle_{a1}\lvert\Phi^-\rangle_{b3}$	$i\sigma_y^2 \otimes \sigma_z^4$
$\lvert\Phi^+\rangle_{a1}\lvert\Psi^+\rangle_{b3}$	$I^2 \otimes \sigma_x^4$	$\lvert\Psi^+\rangle_{a1}\lvert\Psi^+\rangle_{b3}$	$\sigma_x^2 \otimes \sigma_x^4$
$\lvert\Phi^+\rangle_{a1}\lvert\Psi^-\rangle_{b3}$	$I^2 \otimes i\sigma_y^4$	$\lvert\Psi^+\rangle_{a1}\lvert\Psi^-\rangle_{b3}$	$\sigma_x^2 \otimes i\sigma_y^4$
$\lvert\Phi^-\rangle_{a1}\lvert\Psi^+\rangle_{b3}$	$\sigma_z^2 \otimes \sigma_x^4$	$\lvert\Psi^-\rangle_{a1}\lvert\Psi^+\rangle_{b3}$	$i\sigma_y^2 \otimes \sigma_x^4$
$\lvert\Phi^-\rangle_{a1}\lvert\Psi^-\rangle_{b3}$	$\sigma_z^2 \otimes i\sigma_y^4$	$\lvert\Psi^-\rangle_{a1}\lvert\Psi^-\rangle_{b3}$	$i\sigma_y^2 \otimes i\sigma_y^4$

4 Conclusion

In this paper, we propose two quantum teleportation schemes for teleporting a product state of two arbitrary single-particle and an arbitrary two-particle pure entangled state. Here, two Bell states are utilized as the quantum channel. Bob can reconstruct the original state according to the measurement results of Alice. Because the unknown quantum state can be reconstructed perfectly, the successful possibilities of two schemes are both 1.

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