Deterministic quantum teleportation and information splitting via a peculiar W-class state*

Mei Feng(梅 锋), Yu Ya-Fei(於亚飞)†, and Zhang Zhi-Ming(张智明)

Laboratory of Photonic Information Technology, School for Information and Optoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, *China*

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In the paper (*Phys. Rev.* 2006 A **74** 062320) Agrawal *et al.* have introduced a kind of W-class state which can be used for the quantum teleportation of single-particle state via a three-particle von Neumann measurement, and they thought that the state could not be used to teleport an unknown state by making two-particle and one-particle measurements. Here we reconsider the features of the W-class state and the quantum teleportation process via the W-class state. We show that, by introducing a unitary operation, the quantum teleportation can be achieved deterministically by making two-particle and one-particle measurements. In addition, our protocol is extended to the process of teleporting two-particle state and splitting information.

Keywords: W-class state, quantum teleportation, quantum information splitting
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1. Introduction

Quantum entanglement has rightly been a hot subject of many studies in recent years as a potential resource for quantum communication and quantum information processing.[1−3] Bipartite entanglement states are the simplest entangled states which have been well understood in many aspects. Interest is now focused on the multiparticle entangled states. Dealing with multiparticle entangled states is not always easy. In the case of tripartite entangled states, it is well known that there are two inequivalent classes, the Greenberger–Home–Zeilinger (GHZ)-class and the W-class.[4] Both of them cannot be converted to each other under stochastic local operation and classical communication (SLOCC). Moreover, the W-class states are robust against the loss of particles (i.e., if we trace out any one particle, there is some genuine entanglement between the remaining two) while the GHZ-class states are not. Therefore, in contrast to the GHZ-class state, the W-class state seems more attractive as an entanglement resource.

Recently, the W-class states have attracted much attention. Quantum teleportation[3,5] and information splitting[6] have been studied by using the W-class states.[7−12] However, their teleportation protocols work probabilistically, not deterministically. Agrawal *et al.*[13] have shown a kind of W-class state which can be used for the quantum teleportation of single-particle state with a three-particle measurement,[14] but they stated that the W-class state could not be used to teleport an unknown state by making two-particle and one-particle measurements, which means that it cannot be used for quantum state sharing.[15]

In the present paper, we show that a peculiar three-particle W-class state has some interesting entanglement properties which combine the attractive features of the Bell state, GHZ state and W state. Its usefulness in quantum teleportation of single and two-particle unknown states and information splitting is investigated. Compared with the previous protocols, our teleportation protocol can achieve the teleportation of an unknown single-particle and two-particle state with unit probability and unit fidelity, including the teleportation of an unknown single-particle state by making two-particle and one-particle measurements. Moreover, the teleportation protocol can also be utilized to complete quantum state sharing.

The rest of this paper is organized as follows. In Section 2 we characterize further a class of W states and discover a peculiar three-particle W-class state. In Section 3 we present a deterministic protocol of quantum teleportation for single and two-particle unknown states. The protocol is extended to split information

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†Corresponding author. E-mail: yfyuks@hotmail.com
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in Section 4. Finally, the conclusions are drawn from the present study in Section 5.

2. Character of a peculiar W-class state

In Ref. [13], Agrawal *et al.* have discovered that a W-class state can be used as an entanglement resource, which is given by

$$|W_n\rangle_{123} = \frac{1}{\sqrt{2(n+1)}}(|100\rangle_{123} + \sqrt{n}\,\mathrm{e}^{\mathrm{i}\,\gamma}|010\rangle_{123} + \sqrt{n+1}\,\mathrm{e}^{\mathrm{i}\,\delta}|001\rangle_{123}), \quad (1)$$

where n is a real number and γ, δ are phases. In particular, if we take $n = 1$ for simplicity and set phases to be zero, then we have the following peculiar W-class state:

$$|W\rangle_{123} = \frac{1}{2}(|100\rangle_{123} + |010\rangle_{123} + \sqrt{2}|001\rangle_{123}). \quad (2)$$

Firstly, a qualitative analysis on the W-class state from its reduced matrix is given. Partitioning the three particles into two subsystems in a way of 12|3, one can obtain

$$\begin{aligned}
&\rho_3 = \frac{1}{2}|0\rangle\langle 0| + \frac{1}{2}|1\rangle\langle 1|,\\
&\rho_1 = \rho_2 = \frac{3}{4}|0\rangle\langle 0| + \frac{1}{4}|1\rangle\langle 1|,\\
&\rho_{12} = \frac{1}{2}|\psi^+\rangle\langle\psi^+| + \frac{1}{2}|00\rangle\langle 00|,\\
&|\psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle),\\
&\rho_{13} = \rho_{23} = \frac{3}{4}|\psi\rangle\langle\psi| + \frac{1}{4}|00\rangle\langle 00|,\\
&|\psi\rangle = \frac{1}{\sqrt{3}}(\sqrt{2}|01\rangle + |10\rangle). \quad (3)
\end{aligned}$$

The von Neumann entropy[16] and the concurrence[17] between any two subsystems can be calculated as

$$\begin{aligned}
&E_{(12|3)} = 1, \quad E_{1|(23)} = E_{2|(13)} < 1,\\
&C_{12} = \frac{1}{2}, \quad C_{13} = C_{23} = \frac{\sqrt{2}}{2}, \quad C_{(12)|3} = 1. \quad (4)
\end{aligned}$$

It means that the peculiar W-class state in Eq. (2) has some particular properties. (i) In the cut 12|3, the two subsystems {1, 2} and {3} share one ebit of entanglement, so the state can be used to achieve some quantum information tasks instead of the Bell state in some situations. (ii) The entanglement shared by the particles 1 and 3 is quantitatively equal to the one shared by particles 2 and 3, which denotes the W-class state and can be used as a quantum channel with two receivers for splitting information of single-particle unknown state and teleportation of two-particle state, just like the behaviour of the GHZ state. (iii) After tracing out any particle in the W-class state, there still exists some genuine entanglement between the other two. So, the W-class state also has the robustness against decoherence as the genuine W state does.

3. Teleportation via W-class state

3.1. Teleportation of a single particle state

We briefly discussed the quantum teleportation protocol in Ref. [13] by using the peculiar W-class state in Eq. (2) as a quantum channel.

For convenience, the W-class state can be rewritten as follows:

$$|W\rangle_{123} = \frac{|\psi^+\rangle_{12}|0\rangle_3 + |00\rangle_{12}|1\rangle_3}{\sqrt{2}}. \quad (5)$$

We consider a situation in which Alice possesses particles 1 and 2, and particle 3 belongs to Bob. Alice also has another particle a in the following unknown state: $|\psi\rangle_a = \alpha|0\rangle + \beta|1\rangle$. Alice now wants to teleport this state to Bob. The whole state reads

$$\begin{aligned}
|\psi\rangle_a \otimes |W\rangle_{123} &= (\alpha|0\rangle + \beta|1\rangle)_a \otimes \frac{|\psi^+\rangle_{12}|0\rangle_3 + |00\rangle_{12}|1\rangle_3}{\sqrt{2}}\\
&= \frac{1}{2}[|\eta^+\rangle_{a12}(\alpha|0\rangle \pm \beta|1\rangle)_3 + |\varepsilon^+\rangle_{a12}(\beta|0\rangle \pm \alpha|1\rangle)_3], \quad (6)
\end{aligned}$$

where $\{|\eta^\pm\rangle, |\varepsilon^\pm\rangle\}$ is a set of orthogonal states given by

$$\begin{aligned}
|\eta^\pm\rangle &= (|0\rangle_a|\psi^+\rangle_{12} \pm |1\rangle_a|00\rangle_{12})/\sqrt{2}, |\varepsilon^\pm\rangle\\
&= (|1\rangle_a|\psi^+\rangle_{12} \pm |0\rangle_a|00\rangle_{12})/\sqrt{2}. \quad (7)
\end{aligned}$$

Alice makes a von Neumann measurement in the basis $\{|\eta^\pm\rangle, |\varepsilon^\pm\rangle\}$ on the three particles $a12$ and conveys two bits of classical information about the outcomes of her measurement to Bob. Bob can apply a suitable unitary operation from the set of $\{I, \sigma_x, -\mathrm{i}\,\sigma_y, \sigma_z\}$ to recover the original state. This protocol consumes one ebit of entanglement and two bits of classical communication, like that with using the Bell state. Then the authors of Ref. [13] stated that the W-class state could not be used to teleport

an unknown state by making two-particle and one-particle measurements.

In our scenario we let Alice possess particles a and 3, Bob possess particles 1 and 2. After Alice's Bell-state measurement on the particles a and 3, the state of the subsystem 1 and 2 is

$$\alpha|\psi^+\rangle \pm \beta|00\rangle, \quad \alpha|00\rangle \pm \beta|\psi^+\rangle. \tag{8}$$

Introducing a unitary operation on particles 1 and 2,

$$U = |11\rangle\langle\psi^+| + |00\rangle\langle 00| + |01\rangle\langle\psi^-| + |10\rangle\langle 11|, \tag{9}$$

which can be decomposed into a set of universal and elementary gates[18]

$$U_{ab} = C^{ab}_{\rm NOT} R^a_y\left(\frac{\pi}{4}\right) C^{ba}_{\rm NOT} R^a_y\left(-\frac{\pi}{4}\right) C^{ba}_{\rm NOT},$$
$$R_Y(\theta) = \begin{pmatrix} \cos(\theta/2) & -\sin(\theta/2) \\ \sin(\theta/2) & \cos(\theta/2) \end{pmatrix}. \tag{10}$$

Then, the state of particles 1 and 2 evolves into

$$\alpha|11\rangle \pm \beta|00\rangle, \quad \alpha|00\rangle \pm \beta|11\rangle. \tag{11}$$

Bob makes a single particle measurement on particles 1 or 2 in the basis $\{|\pm\rangle\}$ where $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$. According to the outcomes of both measurements, Bob can reconstruct the initial information on the other particle by performing an appropriate local operation from $\{I, \sigma_x, \mathrm{i}\sigma_y, \sigma_z\}$.

As a remark, in the scenario we present here, the W-class state can be used for the quantum teleportation of a single-particle state by making two-particle and one-particle measurements.

3.2. Teleportation of a two-particle state

3.2.1. Teleportation of a two-particle entangled state

Suppose that Alice and Bob share the W-class state in Eq. (5), and Alice has a pair of entangled particles a and b in the state $|\psi\rangle_{ab} = \alpha|00\rangle + \beta|11\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. Particles 3, a and b belong to the sender Alice. The other two particles belong to the receiver Bob. The state of the whole system is given by

$$\begin{aligned} |\psi\rangle_{ab} \otimes |W\rangle_{123} &= (\alpha|00\rangle_{ab} + \beta|11\rangle_{ab}) \otimes \frac{|\psi^+\rangle_{12}|0\rangle_3 + |00\rangle_{12}|1\rangle_3}{\sqrt{2}} \\ &= \frac{1}{2}[|G^{\pm}_0\rangle_{ab3}(\alpha|\psi^+\rangle_{12} \pm \beta|00\rangle_{12}) + |G^{\pm}_1\rangle_{ab3}(\alpha|00\rangle_{12} \pm \beta|\psi^+\rangle_{12})], \end{aligned} \tag{12}$$

where

$$|G^{\pm}_0\rangle = (|000\rangle \pm |111\rangle)/\sqrt{2},$$
$$|G^{\pm}_1\rangle = (|001\rangle \pm |110\rangle)/\sqrt{2}.$$

In order to realize the teleportation, a GHZ-state measurement on particles 3, a and b is made by Alice.

Bob utilizes the unitary operation introduced in Eq. (9) on particles 1 and 2 to evolve the state into $\alpha|11\rangle_{12} \pm \beta|00\rangle_{12}, \alpha|00\rangle_{12} \pm \beta|11\rangle_{12}$ with the same probabilities. According to the outcome of Alice's measurement, Bob can choose one of local unitary transformations $\{I, \sigma_x, \mathrm{i}\sigma_y, \sigma_z\}$ on the particles 1 and 2 to recover the initial state.

For the case where the state $\alpha|01\rangle + \beta|10\rangle$ is to be teleported, the process is alike except for making a GHZ-state measurement in another basis $\{G^{\pm}_2, G^{\pm}_3\}$ and the corresponding local unitary operation in the retrieving stage, where $|G^{\pm}_2\rangle = (|010\rangle \pm |101\rangle)/\sqrt{2}$, $|G^{\pm}_3\rangle = (|011\rangle \pm |100\rangle)/\sqrt{2}$.

As a result, with the W-class state, the deterministic teleportation of two-particle entangled state can be realized with unit fidelity.

3.2.2. Teleportation of an arbitrary two-particle state

Assume that Alice has an arbitrary two-particle state,

$$|\psi\rangle_{ab} = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle, \tag{13}$$

which she has to teleport to Bob. Here $\alpha, \beta, \gamma, \delta$ are any set of complex numbers satisfying $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$. The quantum channel is composed of two W-class states, and it can be written as follows:

$$|W\rangle_{123} = \frac{|\psi^+\rangle_{12}|0\rangle_3 + |00\rangle_{12}|1\rangle_3}{\sqrt{2}},$$
$$|W\rangle_{456} = \frac{|\psi^+\rangle_{45}|0\rangle_6 + |00\rangle_{45}|1\rangle_6}{\sqrt{2}}. \tag{14}$$

Alice possesses particles 12 and 45 while Bob possesses particles 36. After Alice's two von Neumann measurements in the basis $\{|\eta^{\pm}\rangle, |\varepsilon^{\pm}\rangle\}$ on particles $(a12)$ and $(b45)$, we can obtain the whole state

$$
\begin{aligned}
&|\psi\rangle_{ab}\otimes|W\rangle_{123}\otimes|W\rangle_{456}\\
&=(\alpha|00\rangle+\beta|01\rangle+\gamma|10\rangle+\delta|11\rangle)_{ab}\otimes\frac{|\psi^{+}\rangle_{12}|0\rangle_{3}+|00\rangle_{12}|1\rangle_{3}}{\sqrt{2}}\otimes\frac{|\psi^{+}\rangle_{45}|0\rangle_{6}+|00\rangle_{45}|1\rangle_{6}}{\sqrt{2}}\\
&=\frac{1}{4}[|\eta^{+}\rangle_{a12}|\eta^{+}\rangle_{b45}(\alpha|00\rangle+\beta|01\rangle+\gamma|10\rangle+\delta|11\rangle)_{36}+|\eta^{+}\rangle_{a12}|\eta^{-}\rangle_{b45}(\alpha|00\rangle-\beta|01\rangle+\gamma|10\rangle-\delta|11\rangle)_{36}\\
&\quad+|\eta^{+}\rangle_{a12}|\varepsilon^{+}\rangle_{b45}(\alpha|01\rangle+\beta|00\rangle+\gamma|11\rangle+\delta|10\rangle)_{36}+|\eta^{+}\rangle_{a12}|\varepsilon^{-}\rangle_{b45}(-\alpha|01\rangle+\beta|00\rangle-\gamma|11\rangle+\delta|10\rangle)_{36}\\
&\quad+|\eta^{-}\rangle_{a12}|\eta^{+}\rangle_{b45}(\alpha|00\rangle+\beta|01\rangle-\gamma|10\rangle-\delta|11\rangle)_{36}+|\eta^{-}\rangle_{a12}|\eta^{-}\rangle_{b45}(\alpha|00\rangle-\beta|01\rangle-\gamma|10\rangle+\delta|11\rangle)_{36}\\
&\quad+|\eta^{-}\rangle_{a12}|\varepsilon^{+}\rangle_{b45}(\alpha|01\rangle+\beta|00\rangle-\gamma|11\rangle-\delta|10\rangle)_{36}+|\eta^{-}\rangle_{a12}|\varepsilon^{-}\rangle_{b45}(-\alpha|01\rangle+\beta|00\rangle+\gamma|11\rangle-\delta|10\rangle)_{36}\\
&\quad+|\varepsilon^{+}\rangle_{a12}|\eta^{+}\rangle_{b45}(\alpha|10\rangle+\beta|11\rangle+\gamma|00\rangle+\delta|01\rangle)_{36}+|\varepsilon^{+}\rangle_{a12}|\eta^{-}\rangle_{b45}(\alpha|10\rangle-\beta|11\rangle+\gamma|00\rangle-\delta|01\rangle)_{36}\\
&\quad+|\varepsilon^{+}\rangle_{a12}|\varepsilon^{+}\rangle_{b45}(\alpha|11\rangle+\beta|10\rangle+\gamma|01\rangle+\delta|00\rangle)_{36}+|\varepsilon^{+}\rangle_{a12}|\varepsilon^{-}\rangle_{b45}(-\alpha|11\rangle+\beta|10\rangle-\gamma|01\rangle+\delta|00\rangle)_{36}\\
&\quad+|\varepsilon^{-}\rangle_{a12}|\eta^{+}\rangle_{b45}(-\alpha|10\rangle-\beta|11\rangle+\gamma|00\rangle+\delta|01\rangle)_{36}+|\varepsilon^{-}\rangle_{a12}|\eta^{-}\rangle_{b45}(-\alpha|10\rangle+\beta|11\rangle+\gamma|00\rangle-\delta|01\rangle)_{36}\\
&\quad+|\varepsilon^{-}\rangle_{a12}|\varepsilon^{+}\rangle_{b45}(-\alpha|11\rangle-\beta|10\rangle+\gamma|01\rangle+\delta|00\rangle)_{36}+|\varepsilon^{-}\rangle_{a12}|\varepsilon^{-}\rangle_{b45}(\alpha|11\rangle-\beta|10\rangle-\gamma|01\rangle+\delta|00\rangle)_{36}],
\end{aligned}
\tag{15}
$$

where $|\eta^{\pm}\rangle = (|0\rangle_i|\psi^{+}\rangle_j \pm |1\rangle_i|00\rangle_j)/\sqrt{2}$, $|\varepsilon^{\pm}\rangle = (|1\rangle_i|\psi^{+}\rangle_j \pm |0\rangle_i|00\rangle_j)/\sqrt{2}$, $i = a(b)$, $j = 12(45)$. Bob retrieves the original state by applying approximate unitary operations as shown in Table 1.

Table 1. The outcome of Alice's measurement and set of Bob's necessary operations.

Alice's measurement	Bob's unitary operation
$\|\eta^{+}\rangle_{a12}\|\eta^{+}\rangle_{b45}$	$I_2^3\otimes I_2^6$
$\|\eta^{+}\rangle_{a12}\|\eta^{-}\rangle_{b45}$	$I_2^3\otimes\sigma_z^6$
$\|\eta^{+}\rangle_{a12}\|\varepsilon^{+}\rangle_{b45}$	$I_2^3\otimes\sigma_x^6$
$\|\eta^{+}\rangle_{a12}\|\varepsilon^{-}\rangle_{b45}$	$I_2^3\otimes(-\mathrm{i}\,\sigma_y^6)$
$\|\eta^{-}\rangle_{a12}\|\eta^{+}\rangle_{b45}$	$\sigma_z^3\otimes I_2^6$
$\|\eta^{-}\rangle_{a12}\|\eta^{-}\rangle_{b45}$	$\sigma_z^3\otimes\sigma_z^6$
$\|\eta^{-}\rangle_{a12}\|\varepsilon^{+}\rangle_{b45}$	$\sigma_z^3\otimes\sigma_x^6$
$\|\eta^{-}\rangle_{a12}\|\varepsilon^{-}\rangle_{b45}$	$\sigma_z^3\otimes(-\mathrm{i}\,\sigma_y^6)$
$\|\varepsilon^{+}\rangle_{a12}\|\eta^{+}\rangle_{b45}$	$\sigma_x^3\otimes I_2^6$
$\|\varepsilon^{+}\rangle_{a12}\|\eta^{-}\rangle_{b45}$	$\sigma_x^3\otimes\sigma_z^6$
$\|\varepsilon^{+}\rangle_{a12}\|\varepsilon^{+}\rangle_{b45}$	$\sigma_x^3\otimes\sigma_x^6$
$\|\varepsilon^{+}\rangle_{a12}\|\varepsilon^{-}\rangle_{b45}$	$\sigma_x^3\otimes(-\mathrm{i}\,\sigma_y^6)$
$\|\varepsilon^{-}\rangle_{a12}\|\eta^{+}\rangle_{b45}$	$(-\mathrm{i}\,\sigma_y^3)\otimes I_2^6$
$\|\varepsilon^{-}\rangle_{a12}\|\eta^{-}\rangle_{b45}$	$(-\mathrm{i}\,\sigma_y^3)\otimes\sigma_z^6$
$\|\varepsilon^{-}\rangle_{a12}\|\varepsilon^{+}\rangle_{b45}$	$(-\mathrm{i}\,\sigma_y^3)\otimes\sigma_x^6$
$\|\varepsilon^{-}\rangle_{a12}\|\varepsilon^{-}\rangle_{b45}$	$(\mathrm{i}\,\sigma_y^3)\otimes(\mathrm{i}\,\sigma_y^6)$

As is evident, the outputs of the measurement are each obtained with an equal probability and we can obtain the deterministic teleportation with unit fidelity just as the cases where the Bell state and GHZ state are used as entanglement resources. If there is another party Charlie who possesses the particles $(b45)$ and makes a von Neumann measurement on them, we can also achieve the controlled teleportation[19] or quantum state sharing[15] of the arbitrary two-particle state. So our peculiar W-class state can be viewed as a hybrid of the Bell state, GHZ state and W state. We can obtain some unexpected results in quantum information processing with it.

4. Information splitting via W-class state

Due to the fact that the entanglement shared between particles 3 and 1 is quantitatively equal to the one between the particles 3 and 2 in the peculiar W-class state in Eq. (3), the state can be used to split the information into two parts in a way of teleportation.[6]

The basic idea is that Alice has an unknown particle, and she wishes to transmit it to either Bob or Charlie. The no-cloning[20] theorem requires that only one of them can reconstruct the initial unknown state $|\psi\rangle_a = \alpha|0\rangle + \beta|1\rangle$. Thus, after receiving the outcome of joint Bell-state measurement, Bob and Charlie must cooperate to extract the quantum formation.

Suppose that Alice possesses a particle a, which is prepared in the unknown state, and that Alice, Bob, and Charlie share the peculiar W-class state in Eq. (6), while particles 3, 1 and 2 are distributed to Alice, Bob, and Charlie, respectively. After Alice's Bell-state measurement, the whole state of particles 1 and 2 is expressed as Eq. (8). The quantum information is encoded in the coefficients of the two components $(|01\rangle_{12} + |10\rangle_{12})/\sqrt{2}$ and $|00\rangle_{12}$. In order to recover the original state, Bob and Charlie must cooperate to

make the unitary operation introduced in Eq. (9) on the composite system. If the output of Bell-state measurement is $|\psi^+\rangle$, then the state of particles 1 and 2 becomes $\alpha|00\rangle + \beta|11\rangle$. Any one of Bob and Charlie can make a single particle measurement in the basis $\{|\pm\rangle\}$ where $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$, and convey the measurement to the other one. According to the results of both measurements, the other one can recover the information by applying an appropriate local operation from $\{I, \sigma_x, \mathrm{i}\,\sigma_y, \sigma_z\}$.

5. Conclusion

In this paper we have shown that there exists a peculiar three-particle W-class state. It has some particular entanglement properties with respect to bipartite entanglement which combines the particular entanglement properties of the Bell state, GHZ state and W state. We investigated its usefulness for the deterministic teleportation of the single-particle state by making two-particle and one-particle measurements, and extended the protocol to the process of teleporting the two-particle state and splitting information. In which, the teleportation of single and two-particle states can also be used to complete the scheme for quantum state sharing. Inspired by the peculiar three-particle W-class state, in the future, we will study the entanglement molecules about the multiparticle W state. It may have some potential applications in the aspects of quantum communication and computation. In addition, we expect it to be helpful for understanding the multiparticle entanglement.

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