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TELEPORTATION OF A TWO-QUBIT ARBITRARY UNKNOWN STATE USING A FOUR-QUBIT GENUINE ENTANGLED STATE WITH THE COMBINATION OF BELL-STATE MEASUREMENTS

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We propose a protocol transferring an arbitrary unknown two-qubit state using the quantum channel of a four-qubit genuine entangled state. Simplifying the four-qubit joint measurement to the combination of Bell-state measurements, it can be realized more feasible with currently available technologies.

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1. INTRODUCTION

Quantum mechanics with many amazing phenomena different from those in classical world is a charming and challenge subject in modern science. Among its appealing characteristics, quantum entanglement is in focus of the attention of researchers due to its potential and important applications to the tasks of quantum information processing.

Depending on an EPR pair, a quantum teleportation protocol is proposed [1] by which the state of one particle can be transferred to another remote place. Naturally, the researchers consider that multi-qubit entangled states as a quantum channel can be utilized to teleport quantum states of complicated systems. Moreover, a multi-qubit entangled state is the basement of quantum computing.

The simplest class of all entangled states, the two-qubit entangled state, is an EPR state. A little more complicated, three-qubit entangled states can be generally classified into GHZ states and W states under stochastic local operations and classical communication (SLOCC) [2]. However, some problems of the quantum entanglement of multi-qubit systems with regard to their characterization and classification are still open, and are being studied by numerous researchers [3–10].

We note that much attention has been paid to a class of four-qubit entangled states that is different from GHZ or W states under SLOCC and optimally violates a new Bell inequality [7]. It can be viewed as a genuine entangled state similar to an EPR state, by which a two-qubit arbitrary state can be teleported with only one state as a quantum channel. Additionally, it cannot be reduced to the product state of two EPR pairs.

In theory, a protocol to teleport a two-qubit arbitrary state using the entangled state was put forward in [6]. Based on the idea of dense coding [11], a secure protocol of two-party quantum communication was proposed in [12]. In addition, exploiting entanglement swapping [13], several quantum communication protocols were presented [14–18]. A deterministic secure quantum communication protocol with incomplete quantum teleportation was proposed in [19]. For realizing four-party communication, a protocol of quantum communication [20] employing the decoy-state method [21] was designed. Adopting the two-step protocol [22], a three-party quantum secret sharing protocol was conceived in [23].

So far, only the measurement basis of a four-qubit genuine entangled state was explored, while it is well

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known that the operation feasibility in practical applications is very important and critical and needs to be taken into account. Considering the feasibility in experiment, we present a quantum teleportation protocol of an arbitrary unknown two-qubit state, which can be realized with a combination of Bell-state measurements.

This paper is structured as follows. In Sec. 2, we describe a two-party secure distribution of a four-qubit genuine entangled state. As an application, a detailed quantum teleportation protocol of a two-qubit arbitrary unknown state is presented in Sec. 3. We discuss and summarize our work in Sec. 4.

2. THE SECURE TWO-PARTY DISTRIBUTION OF THE FOUR-QUBIT GENUINE ENTANGLED STATE

Above all, the quantum channel consisting of a four-qubit genuine entangled state should be shared successfully by two participants. The explicit process is as follows.

The sender, Alice, prepares a good number of qubits that are in the four-qubit genuine entangled states denoted as

$$\left|\chi^{00}\right\rangle = \frac{1}{2\sqrt{2}}(|0000\rangle - |0011\rangle - |0101\rangle + |1001\rangle + \\ + |0110\rangle + |1010\rangle + |1100\rangle + |1111\rangle). \quad (1)$$

She then sends the first two qubits of the four-qubit entangled states to the recipient, Bob, and keeps the remaining qubits to herself.

After he receives the transmitted qubits, Bob randomly selects a sufficiently large subset to check the security of the quantum channel. Many security check techniques such as the decoy-state method can be used [21], and we here follow the security check method proposed in [24] to analyze the security of the two-party distribution of four-qubit entangled states.

Bob performs randomly single-qubit measurements on qubits (3, 4) in the basis of

$$\{|0\rangle, |1\rangle\} \otimes \{|+\rangle, |-\rangle\}$$

or

$$\{|+\rangle, |-\rangle\} \otimes \{|0\rangle, |1\rangle\},$$

where

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \quad |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle),$$

and informs Alice of the positions of the qubits selected to check the security.

Subsequently, Alice measures qubits $(1, 2)$ using the basis of

$$\{\left|\Phi_1^{\pm}\right\rangle, \left|\Psi_1^{\pm}\right\rangle\}$$

or

$$\{\left|\Phi_2^{\pm}\right\rangle, \left|\Psi_2^{\pm}\right\rangle\},$$

where

$$\left|\Phi_1^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(\left|\phi^{+}\right\rangle \pm \left|\psi^{-}\right\rangle), \quad \left|\Psi_1^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(\left|\psi^{+}\right\rangle \pm \left|\phi^{-}\right\rangle),$$

$$\left|\Phi_2^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(\left|\phi^{+}\right\rangle \pm \left|\psi^{+}\right\rangle), \quad \left|\Psi_2^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(\left|\psi^{-}\right\rangle \pm \left|\phi^{-}\right\rangle),$$

and

$$\left|\phi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle), \quad \left|\psi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

represent the four Bell states.

Finally, they analyze the security of the quantum channel by comparing their measurement results. If the distribution succeeds, their measurement results should be in accord with Eq. (2),

$$\left|\chi^{00}\right\rangle = \frac{1}{2}(\left|\Phi_1^{-}\right\rangle|0+\rangle + \left|\Phi_1^{+}\right\rangle|0-\rangle + \\ + \left|\Psi_1^{-}\right\rangle|1+\rangle + \left|\Psi_1^{+}\right\rangle|1-\rangle)_{1,2,3,4} = \\ = \frac{1}{2}(\left|\Phi_2^{+}\right\rangle|+0\rangle + \left|\Phi_2^{-}\right\rangle|-0\rangle - \\ - \left|\Psi_2^{+}\right\rangle|+1\rangle - \left|\Psi_2^{-}\right\rangle|-1\rangle)_{1,2,3,4}. \quad (2)$$

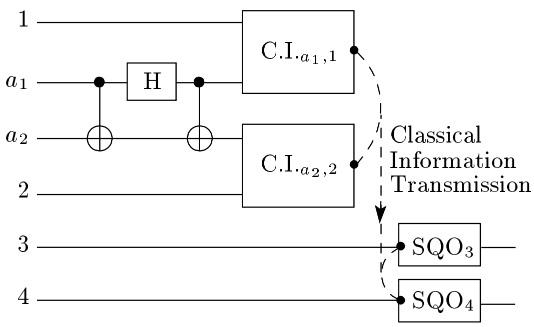
Once the quantum channel is shared successfully by two participants, a quantum teleportation protocol of a two-qubit arbitrary unknown state can be realized based on it.

3. A QUANTUM TELEPORTATION PROTOCOL OF AN ARBITRARY UNKNOWN TWO-QUBIT STATE

As is known, a two-qubit arbitrary unknown state cannot be teleported by only one EPR pair (either one GHZ state or one W state). With only one four-qubit genuine entangled state, the teleportation task can be fulfilled by using the four-qubit joint measurement [6]. In the present protocol, instead of the four-qubit joint measurement, the combination of Bell-state measurements is applied to fulfill the task of teleportation of an arbitrary unknown two-qubit state. We depict the protocol in the Figure, and explain it as follows.

A two-qubit arbitrary unknown quantum state can be denoted as

$$|\xi\rangle = (a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle)_{a_1,a_2}, \quad (3)$$



A scheme of the explicit teleportation procedure of a two-qubit arbitrary unknown state

where the unknown complex coefficients a, b, c, and d satisfy the normalization condition

$$|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1,$$

and which can also represent the product state of two single-qubit quantum states.

As the sender and the recipient, Alice and Bob securely share qubits (1,2) and $(3,4)$ in the state $|\chi^{00}\rangle_{1,2,3,4}$ in Eq. (1) by the methods mentioned in Sec. 2. Alice wants to teleport the arbitrary unknown two-qubit quantum state in Eq. (3) to Bob, and the state of the whole system can be described as

$$\begin{aligned}|\xi\rangle|\chi^{00}\rangle = \frac{1}{2\sqrt{2}}(a|00\rangle + b\,|01\rangle + c\,|10\rangle + \\ + d\,|11\rangle)_{a_1,a_2} \otimes (|0000\rangle - |0011\rangle - |0101\rangle + \\ +|1001\rangle+|0110\rangle+|1010\rangle+|1100\rangle+|1111\rangle)_{1,2,3,4}. \quad (4)\end{aligned}$$

In general, four-qubit joint measurements [6, 14–16, 18, 19] are performed to realize the quantum information processing. However, the four-qubit joint measurement is difficult to be operated in practical applications. To reduce the difficulty of experiment, we adopt the combination of Bell-state measurements to realize quantum teleportation of an arbitrary unknown two-qubit state in the present protocol.

For implementing teleportation, Alice performs beforehand the following operations on the state to be teleported. First, she operates a Controlled-NOT gate on the two-qubit arbitrary unknown state, with the qubit a_1 as the control qubit and the qubit a_2 as the target qubit. After that, a Hadamard gate is performed on the qubit a_1 by Alice. Finally, another Controlled-NOT gate with the qubit a_1 as the control qubit and the qubit a_2 as the target qubit is performed. As a consequence, the state to be teleported can be changed to

$$\begin{aligned}|\xi'\rangle_{a_1,a_2} =&\mathrm{CNOT}_{a_1,a_2} H_{a_1} \mathrm{CNOT}_{a_1,a_2} |\xi\rangle_{a_1,a_2} = \\ =&(a\,|00\rangle + a\,|11\rangle + b\,|01\rangle + b\,|10\rangle + \\ &+ c\,|01\rangle - c\,|10\rangle + d\,|00\rangle - d\,|11\rangle)_{a_1,a_2}. \quad (5)\end{aligned}$$

After the above preparation, Alice performs Bell-state measurement on the qubits $(a_1,1)$ and $(a_2,2)$:

$$\begin{aligned}&|\xi'\rangle_{a_1,a_2}|\chi^{00}\rangle_{1,2,3,4} = \frac{1}{4}\times \\ &\times[|\Phi^+\rangle_{a_1,1}|\Phi^+\rangle_{a_2,2}(a|00\rangle+b|10\rangle-c|01\rangle-d|11\rangle)_{3,4}+ \\ &+|\Phi^+\rangle_{a_1,1}|\Phi^-\rangle_{a_2,2}(-a|11\rangle+b|01\rangle-c|10\rangle+d|00\rangle)_{3,4}+ \\ &+|\Phi^-\rangle_{a_1,1}|\Phi^+\rangle_{a_2,2}(-a|11\rangle-b|01\rangle+c|10\rangle+d|00\rangle)_{3,4}+ \\ &+|\Phi^-\rangle_{a_1,1}|\Phi^-\rangle_{a_2,2}(a|00\rangle-b|10\rangle+c|01\rangle-d|11\rangle)_{3,4}+ \\ &+|\Phi^+\rangle_{a_1,1}|\Psi^+\rangle_{a_2,2}(a|10\rangle+b|00\rangle-c|11\rangle-d|01\rangle)_{3,4}+ \\ &+|\Phi^+\rangle_{a_1,1}|\Psi^-\rangle_{a_2,2}(-a|01\rangle+b|11\rangle-c|00\rangle+d|10\rangle)_{3,4}+ \\ &+|\Phi^-\rangle_{a_1,1}|\Psi^+\rangle_{a_2,2}(-a|01\rangle-b|11\rangle+c|00\rangle+d|10\rangle)_{3,4}+ \\ &+|\Phi^-\rangle_{a_1,1}|\Psi^-\rangle_{a_2,2}(a|10\rangle-b|00\rangle+c|11\rangle-d|01\rangle)_{3,4}+ \\ &+|\Psi^+\rangle_{a_1,1}|\Phi^+\rangle_{a_2,2}(a|10\rangle+b|00\rangle+c|11\rangle+d|01\rangle)_{3,4}+ \\ &+|\Psi^+\rangle_{a_1,1}|\Phi^-\rangle_{a_2,2}(a|01\rangle-b|11\rangle-c|00\rangle+d|10\rangle)_{3,4}+ \\ &+|\Psi^-\rangle_{a_1,1}|\Phi^+\rangle_{a_2,2}(a|01\rangle+b|11\rangle+c|00\rangle+d|10\rangle)_{3,4}+ \\ &+|\Psi^-\rangle_{a_1,1}|\Phi^-\rangle_{a_2,2}(a|10\rangle-b|00\rangle-c|11\rangle+d|01\rangle)_{3,4}+ \\ &+|\Psi^+\rangle_{a_1,1}|\Psi^+\rangle_{a_2,2}(a|00\rangle+b|10\rangle+c|01\rangle+d|11\rangle)_{3,4}+ \\ &+|\Psi^+\rangle_{a_1,1}|\Psi^-\rangle_{a_2,2}(a|11\rangle-b|01\rangle-c|10\rangle+d|00\rangle)_{3,4}+ \\ &+|\Psi^-\rangle_{a_1,1}|\Psi^+\rangle_{a_2,2}(a|11\rangle+b|01\rangle+c|10\rangle+d|00\rangle)_{3,4}+ \\ &+|\Psi^-\rangle_{a_1,1}|\Psi^-\rangle_{a_2,2}(a|00\rangle-b|10\rangle-c|01\rangle+d|11\rangle)_{3,4}]. \quad (6)\end{aligned}$$

After the measurement, Alice obtains one of sixteen potential combinations of Bell states, and then she tells Bob the measurement results. On the basis of the measurement results from Alice, Bob performs single-qubit operations on qubit 3 and qubit 4. As a consequence, the two-qubit arbitrary unknown quantum state has been teleported successfully from Alice to Bob.

For articulate description, we consider an example where the measurement results on qubits $(a_1,1)$ and qubits $(a_2,2)$ are $|\Phi^+\rangle_{a_1,1}$ and $|\Phi^-\rangle_{a_2,2}$. The state of the whole system then collapses onto the state

$$\begin{aligned}\langle\Phi^+|_{a_1,1}\,\langle\Phi^-|_{a_2,2}\,|\xi'\rangle_{a_1,a_2}\,|\chi^{00}\rangle_{1,2,3,4} = \\ = \frac{1}{4}(-a\,|11\rangle + b\,|01\rangle - c\,|10\rangle + d\,|00\rangle)_{3,4}. \quad (7)\end{aligned}$$

To obtain the state that originally resided in Alice's place, Bob should perform (XZ, X) gate operations on qubits $(3,4)$. After that, Bob obtains the same state as the state to be teleported on his qubits $(4,3)$. As an

Table. Details of the process whereby Bob obtains the two-qubit arbitrary unknown quantum state teleported from Alice. Alice publicizes the classical information $C.I._{a_1,1}$ and $C.I._{a_2,2}$ of Bell-state measurements on qubits $(a_1, 1)$ and $(a_2, 2)$. After he receives Alice's information, Bob performs single qubit operations (SQO_3, SQO_4) on qubits (3, 4) according to the classical information ($C.I._{a_1,1}$ and $C.I._{a_2,2}$) from Alice, and thus he reconstructs the state that Alice wants to teleport. The difference between the reconstructed states and the original ones can be found in the column of remarks, where I stands for the identical one, and $\exp(i\pi)$ denotes the phase difference π

$C.I._{a_1,1}$	$C.I._{a_2,2}$	SQO_3	SQO_4	Remarks
$\|\Phi^+\rangle$	$\|\Phi^+\rangle$	I	Z	I
$\|\Phi^+\rangle$	$\|\Phi^-\rangle$	$XZ(ZX)$	X	$I(\exp(i\pi))$
$\|\Phi^-\rangle$	$\|\Phi^+\rangle$	X	$XZ(ZX)$	$I(\exp(i\pi))$
$\|\Phi^-\rangle$	$\|\Phi^-\rangle$	Z	I	I
$\|\Phi^+\rangle$	$\|\Psi^+\rangle$	X	Z	I
$\|\Phi^+\rangle$	$\|\Psi^-\rangle$	Z	X	$\exp(i\pi)$
$\|\Phi^-\rangle$	$\|\Psi^+\rangle$	I	$XZ(ZX)$	$I(\exp(i\pi))$
$\|\Phi^-\rangle$	$\|\Psi^-\rangle$	$ZX(XZ)$	I	$I(\exp(i\pi))$
$\|\Psi^+\rangle$	$\|\Phi^+\rangle$	X	I	I
$\|\Psi^+\rangle$	$\|\Phi^-\rangle$	Z	$ZX(XZ)$	$I(\exp(i\pi))$
$\|\Psi^-\rangle$	$\|\Phi^+\rangle$	I	X	I
$\|\Psi^-\rangle$	$\|\Phi^-\rangle$	$ZX(XZ)$	Z	$I(\exp(i\pi))$
$\|\Psi^+\rangle$	$\|\Psi^+\rangle$	I	I	I
$\|\Psi^+\rangle$	$\|\Psi^-\rangle$	$ZX(XZ)$	$ZX(XZ)$	$I(I)$
$\|\Psi^-\rangle$	$\|\Psi^+\rangle$	X	X	I
$\|\Psi^-\rangle$	$\|\Psi^-\rangle$	Z	Z	I

Note: the elements in the brackets in the columns (SQO_3 and SQO_4) denote another Bob's operation selection and the corresponding ones in the line Remarks are the states obtained by Bob.

alternative option, Bob can also obtain the teleported state by performing (ZX, X) gate operations on qubits $(3, 4)$. Only a minor difference occurs if Bob adopts the second option, — a phase difference π generated between the reconstructed state and the original one. However, it can produce no effect on the required state since it is only a global phase on qubits $(3, 4)$.

For all possible measurement results of Alice, the corresponding operations that should be performed by Bob to reconstruct the original state are listed in the Table.

4. DISCUSSION AND SUMMARY

Using the quantum coherence of qubits, many functions that cannot be realized by the classical method can be perfectly implemented, and therefore the study of the quantum information processing of multi-qubit entanglement is important.

In the previous quantum teleportation scheme using four-qubit entanglement, the four-qubit joint measurement is adopted in general, which is not easy to be executed. To overcome the inconvenience, we propose the present protocol where the combination of Bell-state measurements is exploited rather than four-qubit joint measurements. Before Bell-state measurements, Alice needs to perform the gate operations including two Controlled-NOT gates and one Hadamard gate to change the state to be teleported. And then, she performs the combination of Bell-state measurements and publicizes the measurement outcomes. According to Alice's publicized information, Bob performs single-qubit transformations on qubits on his side. Finally, the teleported state can be reconstructed on Bob's qubits.

For transmitting each two-qubit arbitrary unknown state, Alice needs to send Bob four classical bits of information about Bell-state measurements, which is equivalent to the teleportation scheme using the four-qubit joint measurement. In the present protocol, only some single-qubit operations, two-qubit gate operations in the preliminary preparation, and the combination of Bell-state measurements are necessary, which is simpler in practical implementation than the four-qubit joint measurement. The present protocol can therefore decrease the difficulty in experiment.

We next consider the feasibility of implementing the present protocol.

Owing to the important applications, the generation schemes of four-qubit genuine entangled states are considered in quite a few physical systems. Wang and Yang [25] presented the theoretical generation protocol of the four-qubit genuine entangled state in an ion-trap system. Assisted by conventional photon detectors and linear optical elements, Wang and Zhang [26] showed that it can be effectively realized. The success probability of generation of four-qubit genuine entangled state reaches $3.0 \cdot 10^{-9}$ even when the quantum efficiency of the detector is $\eta = 0.75$. The large detuning interaction of atoms with a single-mode cavity field was considered in [27]. It was noted that the entangled state can be created, additionally driven by a strong classical field. A scheme for entangling four atoms in separated optical cavities into the entangled state was presented [28], where the inefficiency of photon detectors does not affect the quality of the generated entangled states but decreases the success generation probability of the state to be η^2 when the quantum efficiency of each photon detector is η. In addition, a generating scheme of the state among four atoms with cavity quantum electrodynamics exploiting atom–field interaction with large detuning was also constructed in [29]. The required atom–thermal-cavity–field interaction time is of the order of $t \approx 3 \cdot 10^{-4}$ s, and the total time to perform the scheme is $t \approx 9 \cdot 10^{-4}$ s, and hence the time required to complete the whole procedure is much shorter than the radiative time $t_r = 3 \cdot 10^{-2}$ s. Recently, the generation schemes of four-qubit genuine entangled states with charge-qubits and flux-qubits were conceived [30, 31], in which the interactions between qubits and a superconducting transmission line resonator or an LC circuit are mediated by adjusting the control parameters of charge qubit or exchanging virtual photons rather than real photons because of the large detuning between them.

Bell-state measurement and Controlled-NOT gates are necessary in the present protocol, and many efforts are devoted to these topics. A quantum teleportation experiment in which nonlinear interactions are used for Bell-state measurement was reported [32]. All four Bell states can be distinguished in principle in their experiment, and they showed that the practical achieved teleportation fidelity is 0.83. Another near-deterministic Bell-state analyzer setup with linear optics was presented in [33], whose efficiency is over 90 % for an ideal source of photons on demand. Moreover, many optically Controlled-NOT gates [24, 34, 35] were also designed. Up to the present, some communication protocols based on teleportation [19, 36, 37] and physical implementation of teleportation with cavity [36] or cross-Kerr nonlinearities [38] were studied in theory and experiment. Recently, experimental teleportation [39] and the generation of eight-photon entanglement [40] were reported. We therefore expect that the present protocol can be realized in the corresponding quantum information processing experiments.

In summary, we present a protocol for transferring a two-qubit arbitrary unknown state with a four-qubit genuine entangled state, replacing the four-qubit joint measurement with a combination of Bell-state measurements, which decreases the implementation difficulty and is more feasible with currently available technologies. The present method can be extended to the quantum information processing using multi-qubit entanglement, by which the difficulty of operations can be largely reduced.

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