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Deterministic Joint Remote Preparation of an Arbitrary Two-Qubit State Using the Cluster State*

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Abstract *Recently, deterministic joint remote state preparation (JRSP) schemes have been proposed to achieve 100% success probability. In this paper, we propose a new version of deterministic JRSP scheme of an arbitrary two-qubit state by using the six-qubit cluster state as shared quantum resource. Compared with previous schemes, our scheme has high efficiency since less quantum resource is required, some additional unitary operations and measurements are unnecessary. We point out that the existing two types of deterministic JRSP schemes based on GHZ states and EPR pairs are equivalent.*

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Key words: joint remote state preparation, cluster state, unit success probability

1 Introduction

Quantum entanglement is a crucial resource in quantum information and quantum computation. An amazing application of quantum entanglement is quantum teleportation,[1−5] which can securely transmit a quantum state from a preparer to a remote receiver by virtue of pre-shared quantum entanglement between two participants. If the preparer has already known full information about the state, the transmission task can be achieved by RSP[6−9] with simpler measurement and less classical communication costs (CCC). For example, using an EPR pair, a Bell basis measurement and two cbits are needed to teleport a single-qubit state, while only a single-qubit measurement and one cbit are required to remotely prepare a known single-qubit state. In a general RSP scheme that involves only a preparer and a receiver, the preparer knows all the information of the prepared state. But for highly sensitive and important information, it might not be a reliable way to let one preparer hold everything. To solve this potential problem, a specific type of RSP, namely joint RSP (JRSP) has been proposed.[10] A JRSP scheme involves at lest two preparers. Each preparer holds partial information of the secret state and only if certain preparers work together can the state be remotely prepared, which is similar to the idea of secret sharing.

Since the first appearance of JRSP, various JRSP schemes[11−17] using different types of quantum entanglements have been presented. However, a serious problem for most of the existing JRSP schemes is that they are probabilistic, i.e. the success probability of these schemes are less than 1. Recently, a new direction of JRSP, namely deterministic JRSP has been put forward. In [18], Xiao *et al.* introduced the three-step strategy to increase the success probability of JRSP by using GHZ states as shared quantum resource. In their scheme,[18] two preparers need to measure their particles orderly rather than independently. Initially, the first preparer performs a projective measurement in the basis which is fully decided by his/her secret share, then he/she sends the measurement outcome to both the receiver and the second preparer. In the second step, the second preparer chooses a proper measurement basis according to both the first preparer's measurement outcome and his/her own secret share. Based on the received measurement outcomes, the receiver can recovery the prepared state in the third step. By adding some classical communications and local operations, the success probability of preparation can be increased to 1. Nguyen *et al.*[19] presented two deterministic JRSP schemes of general single- and two-qubit states by using EPR pairs as shared quantum resource. Cao *et al.*[20] showed a similar deterministic JRSP scheme of a single-qubit state using two EPR pairs and they also considered the situation of more than two preparers. Chen *et al.*[21] extended this idea to realize the deterministic JRSP of an arbitrary three-qubit state by using six EPR pairs. Besides, Jiang and Dong[22] proposed a deterministic RSP scheme for a class of quantum states with real parameters in a recursive way,

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which is helpful for applications using non-maximally entangled quantum resource.

Cluster states[23–24] are specific entanglements and an N-qubit cluster state can be written as[23]

$$|C_N\rangle = \frac{1}{2^{N/2}} \bigotimes_{a=1}^{N} (|0\rangle_a \sigma_z^{(a+1)} + |1\rangle_a)\,, \qquad (1)$$

with the convention $\sigma_z^{(N+1)} = 1$. Cluster states are maximally connected states with better persistency than GHZ states[23,25] and robust against decoherence.[26] They have been used for various applications, such as one-way quantum computation,[24] quantum teleportation[27] and quantum secret sharing,[28] etc. Some RSP schemes using cluster states as shared quantum resource have been studied in [29–31]. The remote preparation of a four-particle cluster-type state has also been shown in [32].

Following some ideas of Refs. [18–21], we present a deterministic JRSP scheme of an arbitrary two-qubit state by using the six-qubit cluster state as shared quantum resource. By adopting the three-step strategy, the success probability of our proposal can reach 100%, which highly increases the success probability of the scheme in Ref. [31] where the success probability for a general state can only reach 25%. The rest of this paper is organized as follows. In Sec. 2, we show the deterministic JRSP scheme of an arbitrary two-qubit state based on the six-qubit cluster state. We discuss the scheme in Sec. 3 and conclude the paper in Sec. 4.

2 Deterministic JRSP of an Arbitrary Two-Qubit State

Let us suppose that two preparers Alice1 and Alice2, who located at two spatially separated sites, want to joint remotely prepare a two-qubit state for the receiver Bob. Generally, an arbitrary two-qubit state has the form

$$a_0\,\mathrm{e}^{\mathrm{i}\varphi_0}|00\rangle + a_1\,\mathrm{e}^{\mathrm{i}\varphi_1}|01\rangle + a_2\,\mathrm{e}^{\mathrm{i}\varphi_2}|10\rangle + a_3\,\mathrm{e}^{\mathrm{i}\varphi_3}|11\rangle\,, \quad (2)$$

where $a_j \in \mathcal{R}$, $\varphi_j \in [0, 2\pi]$ and $\sum_{j=0}^{3} a_j^2 = 1$ with $j \in \{0, 1, 2, 3\}$. As we know, the global phase factor of a quantum state can be ignored since it is irrelative to the observed system. For simplicity, the parameter $\mathrm{e}^{\mathrm{i}\varphi_0}$ can be viewed as a global phase factor. Without loss of generality, we let $\varphi_0 = 0$, which means the arbitrary two-qubit state to be prepared can be written as

$$|\Phi\rangle = a_0|00\rangle + a_1\,\mathrm{e}^{\mathrm{i}\varphi_1}|01\rangle + a_2\,\mathrm{e}^{\mathrm{i}\varphi_2}|10\rangle + a_3\,\mathrm{e}^{\mathrm{i}\varphi_3}|11\rangle. \quad (3)$$

The information of the prepared state is split in the following way: Alice1 knows $S_1 = \{a_j\}$ and Alice2 knows $S_2 = \{\varphi_j\}$.

The six-qubit cluster state is shared among Alice1, Alice2 and Bob as the shared quantum resource which can be written as

$$|C_6\rangle = \frac{1}{2}(|000000\rangle + |000111\rangle + |111000\rangle - |111111\rangle)_{A_1A_2B_1A_1'A_2'B_1'}\,, \qquad (4)$$

where the subscripts denote the particles of the cluster state. Here, Alice1 holds particles (A_1, A_1'), Alice2 holds particles (A_2, A_2') and Bob holds particles (B_1, B_1').

To complete the JRSP, Alice1 firstly performs a projective measurement on her particles (A_1, A_1') in the basis defined by S_1 as $\{|P_l\rangle = U_l|P_0\rangle; l \in \{0, 1, 2, 3\}\}$ with

$$|P_0\rangle = a_0|00\rangle + a_1|01\rangle + a_2|10\rangle - a_3|11\rangle\,,$$

where the unitary operation U_l is shown in Table 1.

Table 1 The unitary operation U_l with different l.

l	U_l
0	$I \otimes I$
1	$I \otimes \sigma_z\sigma_x$
2	$\sigma_z\sigma_x \otimes \sigma_z$
3	$\sigma_z\sigma_x \otimes \sigma_x$

As a consequence, the quantum resource shared among three participants can be rewritten as

$$|C_6\rangle_{A_1A_2B_1A_1'A_2'B_1'} = \frac{1}{2}\sum_{l=0}^{3} |P_l\rangle_{A_1A_1'}|Q_l\rangle_{A_2A_2'B_1B_1'}\,, \quad (5)$$

where

$$|Q_0\rangle_{A_2A_2'B_1B_1'} = a_0|0000\rangle + a_1|0101\rangle + a_2|1010\rangle + a_3|1111\rangle\,,$$
$$|Q_1\rangle_{A_2A_2'B_1B_1'} = a_1|0000\rangle - a_0|0101\rangle - a_3|1010\rangle + a_2|1111\rangle\,,$$
$$|Q_2\rangle_{A_2A_2'B_1B_1'} = a_2|0000\rangle + a_3|0101\rangle - a_0|1010\rangle - a_1|1111\rangle\,,$$
$$|Q_3\rangle_{A_2A_2'B_1B_1'} = -a_3|0000\rangle + a_2|0101\rangle - a_1|1010\rangle + a_0|1111\rangle\,.$$

For any possible $l = 0, 1, 2$ or 3, the qubits (A_2, A_2', B_1, B_1') will collapse into an entangled state $|Q_l\rangle$ with a probability $p_l = 1/4$. After Alice1 performed the measurement, she broadcasts her measurement outcome l via a public classical channel. It should be noted that the published measurement outcome does not contain any information about Alice1's secret information S_1.

Secondly, based on the received outcome l, Alice2 measures her particles (A_2, A_2') in a suitable basis $\{|O_m^{(l)}\rangle; l, m \in \{0, 1, 2, 3\}\}$ that determined by both S_2 and l. There are four possible bases Alice2 can choose, which have the form

$$\begin{pmatrix} |O_0^{(l)}\rangle \\ |O_1^{(l)}\rangle \\ |O_2^{(l)}\rangle \\ |O_3^{(l)}\rangle \end{pmatrix} = V^{(l)} \begin{pmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{pmatrix}\,, \qquad (6)$$

with

$$V^{(0)} = \frac{1}{2}\begin{pmatrix} 1 & \mathrm{e}^{-\mathrm{i}\varphi_1} & \mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_3} \\ 1 & -\mathrm{e}^{-\mathrm{i}\varphi_1} & \mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_3} \\ 1 & -\mathrm{e}^{-\mathrm{i}\varphi_1} & -\mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_3} \\ 1 & \mathrm{e}^{-\mathrm{i}\varphi_1} & -\mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_3} \end{pmatrix}\,, \qquad (7)$$

$$V^{(1)} = \frac{1}{2}\begin{pmatrix} \mathrm{e}^{-\mathrm{i}\varphi_1} & 1 & \mathrm{e}^{-\mathrm{i}\varphi_3} & \mathrm{e}^{-\mathrm{i}\varphi_2} \\ -\mathrm{e}^{-\mathrm{i}\varphi_1} & 1 & -\mathrm{e}^{-\mathrm{i}\varphi_3} & \mathrm{e}^{-\mathrm{i}\varphi_2} \\ -\mathrm{e}^{-\mathrm{i}\varphi_1} & 1 & \mathrm{e}^{-\mathrm{i}\varphi_3} & -\mathrm{e}^{-\mathrm{i}\varphi_2} \\ \mathrm{e}^{-\mathrm{i}\varphi_1} & 1 & -\mathrm{e}^{-\mathrm{i}\varphi_3} & -\mathrm{e}^{-\mathrm{i}\varphi_2} \end{pmatrix}, \tag{8}$$

$$V^{(2)} = \frac{1}{2}\begin{pmatrix} \mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_3} & 1 & \mathrm{e}^{-\mathrm{i}\varphi_1} \\ \mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_3} & 1 & -\mathrm{e}^{-\mathrm{i}\varphi_1} \\ -\mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_3} & 1 & -\mathrm{e}^{-\mathrm{i}\varphi_1} \\ -\mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_3} & 1 & \mathrm{e}^{-\mathrm{i}\varphi_1} \end{pmatrix}, \tag{9}$$

$$V^{(3)} = \frac{1}{2}\begin{pmatrix} \mathrm{e}^{-\mathrm{i}\varphi_3} & \mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_1} & 1 \\ -\mathrm{e}^{-\mathrm{i}\varphi_3} & \mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_1} & 1 \\ \mathrm{e}^{-\mathrm{i}\varphi_3} & -\mathrm{e}^{-\mathrm{i}\varphi_2} & -\mathrm{e}^{-\mathrm{i}\varphi_1} & 1 \\ -\mathrm{e}^{-\mathrm{i}\varphi_3} & -\mathrm{e}^{-\mathrm{i}\varphi_2} & \mathrm{e}^{-\mathrm{i}\varphi_1} & 1 \end{pmatrix}. \tag{10}$$

After Alice2 performed her measurement, $|Q_l\rangle$ can be rewritten as

$$|Q_l\rangle_{A_2A_2'B_1B_1'} = \frac{1}{2}\sum_{m=0}^{3}|O_m^{(l)}\rangle_{A_2A_2'}R_m^{(l)\dagger}|\Phi\rangle_{B_1B_1'}, \tag{11}$$

where $R_m^{(l)}$ denotes the recovery operator that Bob needs to perform to recover the prepared state, which can be found in Table 2. Clearly, Alice2 will get $|O_m^{(l)}\rangle_{A_2A_2'}$ with a probability $p_m = 1/4$.

Table 2 The recovery operator $R_m^{(l)}$ with different l and m.

l	0	0	0	0
m	0	1	2	3
$R_m^{(l)}$	$I\otimes I$	$I\otimes\sigma_z$	$\sigma_z\otimes\sigma_z$	$\sigma_z\otimes I$
l	1	1	1	1
m	0	1	2	3
$R_m^{(l)}$	$\sigma_z\otimes\sigma_z\sigma_x$	$\sigma_z\otimes\sigma_x$	$I\otimes\sigma_x$	$I\otimes\sigma_z\sigma_x$
l	2	2	2	2
m	0	1	2	3
$R_m^{(l)}$	$\sigma_z\sigma_x\otimes I$	$\sigma_z\sigma_x\otimes\sigma_z$	$\sigma_x\otimes\sigma_z$	$\sigma_x\otimes I$
l	3	3	3	3
m	0	1	2	3
$R_m^{(l)}$	$\sigma_x\otimes\sigma_z\sigma_x$	$\sigma_x\otimes\sigma_x$	$\sigma_z\sigma_x\otimes\sigma_x$	$\sigma_z\sigma_x\otimes\sigma_z\sigma_x$

In the third step, Alice2 announces her measurement result m publicly, then Bob can perform the recovery operator $R_m^{(l)}$ on his particles (B_1, B_1') to get the prepared state $|\Phi\rangle$. It is obvious that Bob always has a chance to obtain the original state. The total success probability p_T is

$$p_T = \sum_{l=0}^{3}\sum_{m=0}^{3} p_l p_m = 16\times\frac{1}{4}\times\frac{1}{4} = 1\,. \tag{12}$$

3 Discussions

Our scheme uses the same quantum resource as that in Ref. [31] for preparation of the same state. But we have obtained a probability of success 1 against the probability of success 25% in Ref. [31]. And the receiver Bob can always get the prepared state no matter what measurement outcomes the preparers get. The reason why our scheme works better than existing scheme lies in the fact that the measurement bases selected by two preparers are correlated in our scheme rather than independent in Ref. [31]. In our scheme, the first preparer Alice1 performs her measurement earlier than the second preparer Alice2. Alice1 defines her basis by her share S_1 and there is only one basis she can choose, while Alice2 defines her basis not only by her share S_2, but also by Alice1's measurement outcome l, and there are four bases Alice2 can choose. In contrast, there is no measurement order in Ref. [31] and two preparers define their measurement bases independently, i.e. there is only one basis for each preparer to choose.

The comparisons of our scheme to existing schemes[18−19,31] which complete similar tasks are summarized in Table 3. The CCC of our scheme is 4-cbits, 2 cbits published by Alice1 and 2 cbits published by Alice2. No extra CCC is added to achieve the unit success probability. It should be noted that a public classical channel is used in our scheme, similar to Refs. [19,21]. While if unicast classical channels are used like Ref. [18], the CCC required for our deterministic JRSP will be 6 cbits, i.e. 2 cbits from Alice1 to Alice2, 2 cbits from Alice1 to Bob and 2 cbits from Alice2 to Bob.

As is mentioned above, two schemes have been proposed to achieve the deterministic JRSP of an arbitrary two-qubit state by using two three-qubit GHZ states[18] and four EPR pairs[19] as shared quantum resource, respectively. We should notice that for the deterministic JRSP scheme based on EPR pairs, two extra single-qubit measurements have to be performed by the receiver in Ref. [19]. Besides, the receiver also needs to perform two CNOT operations to complete the task. However, these measurements and operations are unnecessary in our proposal. In Ref. [18], the second preparer needs to perform an additional operation after he/she has received the measurement outcomes from the first preparer, then he/she can perform the measurement on the only one basis. But we use four different bases for the second preparer to choose depending on the received measurement result from the first preparer. Indeed, these two methods can be regarded as equivalent.

The qubit efficiency η of a JRSP scheme can be defined as follows

$$\eta = \frac{n\times q_s}{q_t}\,, \tag{13}$$

where n represents the number of the participants, q_s denotes the number of the prepared qubits and q_t indicates the total number of the previously shared qubits. Our proposal requires only six qubits, which is also the least quantum resource needed so far. As is shown in Table 3, the qubit efficiency of the proposed scheme is 100%. In all aspect, our proposal is at least as efficient as Ref. [18].

Table 3 Comparisons of our scheme to existing schemes. In this table, the superscript 1 denotes the measurements performed by the receiver, the superscript 2 denotes the additional operations performed by the receiver and the superscript 3 denotes the additional operations performed by the second preparer.

	Ref. [18]	Ref. [19]	Ref. [31]	Our scheme
Entanglements	GHZ states	EPR pairs	Cluster state	Cluster state
Probability	1	1	0.25	1
Qubit efficiency	100%	75%	100%	100%
Additional measurements^1	No	Yes (Single-qubit measurements)	No	No
Additional operations^2	No	Yes (CNOT)	No	No
Additional operations^3	Yes	Alternative	No	No
CCC(bit)	6	4	4	4

Actually, the existing two types of deterministic JRSP schemes that based on GHZ states[18] and EPR pairs[19−21] are equivalent to each other. Still, let us take the two deterministic JRSP schemes of a two-qubit state in [19] and in [18] as an example. In [19], four EPR pairs (A_1, B_1), (A'_1, B'_1), (A_2, B_2), and (A'_2, B'_2) are shared among Alice1, Alice2 and Bob where qubits A_1 and A'_1 belong to Alice1, qubits A_2 and A'_2 belong to Alice2, while qubits B_1, B'_1, B_2 and B'_2 belong to Bob. In the first step, two local unitary operations $\mathrm{CNOT}_{B_1B_2}$ and $\mathrm{CNOT}_{B'_1B'_2}$ are performed on particles (B_1, B_2) and (B'_1, B'_2) by Bob. Then after measuring particles (B_2, B'_2) in the computational basis, the particles (A_1, B_1, A_2) and (A'_1, B'_1, A'_2) shared among three participants will collapse into two three-qubit GHZ states. In this sense, the scheme is equivalent to the JRSP scheme of a two-qubit state using two three-qubit GHZ states in [18]. This procedure can be represented as follows

$$\begin{aligned}
&\mathrm{CNOT}_{B_1B_2}\otimes\mathrm{CNOT}_{B'_1B'_2}\Big(\frac{1}{\sqrt{2}}(|00\rangle+|00\rangle)_{A_1B_1(A'_1B'_1,A_2B_2,A'_2B'_2)}\Big)^{\otimes 4}\\
&=\frac{1}{4}[|00\rangle_{B_2B'_2}(|000\rangle+|111\rangle)_{A_1B_1A_2}(|000\rangle+|111\rangle)_{A'_1B'_1A'_2}\\
&\quad+|01\rangle_{B_2B'_2}(|000\rangle+|111\rangle)_{A_1B_1A_2}(|001\rangle+|110\rangle)_{A'_1B'_1A'_2}\\
&\quad+|10\rangle_{B_2B'_2}(|001\rangle+|110\rangle)_{A_1B_1A_2}(|000\rangle+|111\rangle)_{A'_1B'_1A'_2}\\
&\quad+|11\rangle_{B_2B'_2}(|001\rangle+|110\rangle)_{A_1B_1A_2}(|001\rangle+|110\rangle)_{A'_1B'_1A'_2}]\,,
\end{aligned}\tag{14}$$

where the subscripts indicate the particles of the states.

4 Conclusion

In summary, we have proposed a deterministic JRSP scheme of an arbitrary two-qubit state using the six-qubit cluster state as shared quantum resource. Our JRSP scheme has the following features. (i) The success probability can rise to 100% by adopting the three-step strategy. (ii) Our scheme has high efficiency. On the one hand, additional operations and measurements performed by the receiver are unnecessary in our scheme, and the receiver is only involved in the last step. On the other hand, the proposed scheme requires the least quantum resource. (iii) The CCC of our scheme is 4 cbits, i.e. no extra classical communication is needed. We also showed that the existing two types of deterministic JRSP schemes that based on GHZ states and EPR pairs are equivalent to each other. Cluster states are good choices for quantum information processing since they are robust against decoherence and have better persistency than GHZ states. In addition, the six-photon cluster state has been experimentally implemented in Ref. [33], which means our scheme can be realized within current technology.

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