Quantum Inf Process
DOI 10.1007/s11128-016-1500-z

Quantum broadcast scheme and multi-output quantum teleportation via four-qubit cluster state

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Received: 8 September 2016 / Accepted: 15 December 2016

Abstract In this paper, two theoretical schemes of the arbitrary single-qubit states via four-qubit cluster state are proposed. One is three-party quantum broadcast scheme, which realizes the broadcast among three participants. The other is multi-output quantum teleportation. Both allow two distant receivers to simultaneously and deterministically obtain the arbitrary single-qubit states, respectively. Compared with former schemes of an arbitrary single-qubit state, the proposed schemes realize quantum multi-cast communication efficiently, which enables Bob and Charlie to obtain the states simultaneously in the case of just knowing Alice's measurement results. The proposed schemes play an important role in quantum information, specially in secret sharing and quantum teleportation.

Keywords Three-party quantum broadcast scheme · Multi-output quantum teleportation · Four-qubit cluster state

1 Introduction

Quantum entanglement is an important valuable resource for the implementation of quantum computation and quantum communication protocols, like quantum teleportation, quantum key distribution, quantum secure direct communication, dense coding, quantum computation and so on [1–5]. In 1993, Bennett et al. [6] proposed the first quantum teleportation protocol, using a maximally entangled two-qubit state to teleport an arbitrary single-qubit. Four years later, this protocol was experimentally demonstrated [7]. The experimental techniques developed here allowed one to per-

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Published online: 28 December 2016

form the transfer of any arbitrary quantum state, which in the process of entanglement swapping enabled one to create non-classical correlations between particles that never interacted with each other [8,9]. This was confirmed experimentally [10]. Moreover, with these experimental techniques, generating entanglement between three out of four particles finally came within reach [11]. In 1998, Karlsson and Bourennane proposed a protocol for quantum teleportation of an arbitrary single-qubit state by using a three-particle entanglement state [3]. In recent years, several quantum teleportation schemes have been extended to multi-party or multi-particle quantum state [12–23]. In 2004, Yang et al. [24] presented a multi-party controlled teleportation protocol to teleport multi-qubit quantum information. In 2005, Deng et al. introduced a symmetric multi-party controlled teleportation scheme for an arbitrary two-particle entangled state [25]. In 2008, Dai et al. [16] investigated a remote state preparation scheme of an entangled two-qubit state with three parties from a sender to either of two receivers, where, however, the receivers cannot obtain the quantum state to be prepared simultaneously. Up to now, many teleportation and controlled teleportation schemes have been reported, but multi-output quantum teleportation has not been presented.

Broadcast encryption involves a sender and multiusers (receivers) [26]. The sender first encrypts his content and then transmits it to a dynamically changing set of users via insecure broadcasting channels. The broadcast encryption scheme ensures that only the privileged receivers can recover the content subscribed and the unauthorized users cannot learn anything. Therefore, broadcast encryption plays an important role in quantum information, specially, secret sharing and quantum teleportation.

In this paper, one of the proposed schemes is based on the quantum three-party broadcast using four-qubit cluster state, so that the broadcasting message to legitimate receivers is resolved among three participants. The result may be used in many fields such as secret sharing and teleportation. The other is the multi-output quantum teleportation, in which a four-qubit cluster state quantum channel was initially shared by Alice, Bob and Charlie, and through which Alice wants to transmit her own states of particle a and b to Bob and Charlie, respectively, and simultaneously.

This paper is arranged as follows. In Sect. 2, the three-party quantum broadcast scheme based on four-qubit cluster state is presented. The other proposed scheme of multi-output quantum teleportation is illustrated in Sect. 3. The conclusions are drawn in Sect. 4.

2 Three-party quantum broadcast scheme

The quantum channel initially shared by Alice, Bob and Charlie is a four-qubit cluster state, which is given by

$$|\phi\rangle_{1234} = \frac{1}{2}(|0000\rangle + |0101\rangle + |1010\rangle - |1111\rangle)_{1234}. \quad (1)$$

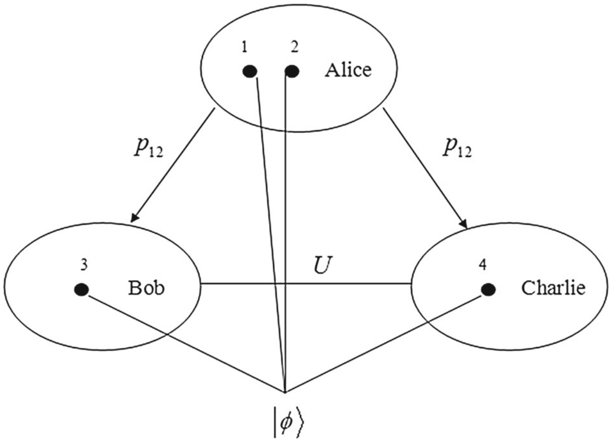

Fig. 1 A sketch of the scheme of an arbitrary two-qubit states with three-party. A four-qubit cluster state is used as the quantum channel. $P_{1,2}$ stands for a projective measurement on particles (1, 2), which is performed by Alice. U stands for Hadamard operation and a projective measurement on Particle 3 and 4, respectively, which are performed by Bob and Charlie. In this figure, a qubit is represented by a *dot*, entangled qubits are connected by *solid lines*, and a classical communication from one site to another is represented by a vector

Four basic unitary transformation matrixes are

$$\begin{aligned} U_1 &= I = |0\rangle\langle 0| + |1\rangle\langle 1| = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ U_2 &= \sigma_z = |0\rangle\langle 0| - |1\rangle\langle 1| = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \\ U_3 &= i\sigma_y = |0\rangle\langle 1| - |1\rangle\langle 0| = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \\ U_4 &= \sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0| = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \end{aligned} \tag{2}$$

Alice intends to transmit a quantum state $|\chi\rangle$ to receivers Bob and Charlie simultaneously and remotely,

$$|\chi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{3}$$

where α and β are real numbers known to Alice while unknown to Bob and Charlie, and satisfy the normalization condition

$$|\alpha|^2 + |\beta|^2 = 1. \tag{4}$$

Here particles (1,2) are in the possession of Alice, while particles (3) belong to the Bob and Charlie owns particles (4). Figure 1 shows the schematic diagram for teleporting an arbitrary single-qubit state with three parties.

Three-party quantum broadcast scheme based on the is four-qubit cluster state involve the following steps:

(1) To fulfill the preparation of the desired state, Alice measures her qubits in an appropriate basis. The measurement basis chosen by Alice is a set of mutually orthogonal basis vectors

$$\begin{aligned}|\varphi^1\rangle_{12} &= (\alpha^2|00\rangle + \alpha\beta|01\rangle + \alpha\beta|10\rangle - \beta^2|11\rangle)_{12}\\ |\varphi^2\rangle_{12} &= (\alpha\beta|00\rangle - \alpha^2|01\rangle + \beta^2|10\rangle + \alpha\beta|11\rangle)_{12}\\ |\varphi^3\rangle_{12} &= (\alpha\beta|00\rangle + \beta^2|01\rangle - \alpha^2|10\rangle + \alpha\beta|11\rangle)_{12}\\ |\varphi^4\rangle_{12} &= (\beta^2|00\rangle - \alpha\beta|01\rangle - \alpha\beta|10\rangle - \alpha^2|11\rangle)_{12}\end{aligned} \tag{5}$$

The above four non-maximally entangled basis states $\{|\varphi^1\rangle, |\varphi^2\rangle, |\varphi^3\rangle, |\varphi^4\rangle\}$ are related to the computation basis vectors $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$,i.e.,

$$\begin{aligned}|00\rangle_{12} &= (\alpha^2|\varphi^1\rangle + \alpha\beta|\varphi^2\rangle + \alpha\beta|\varphi^3\rangle + \beta^2|\varphi^4\rangle)_{12}\\ |01\rangle_{12} &= (\alpha\beta|\varphi^1\rangle - \alpha^2|\varphi^2\rangle + \beta^2|\varphi^3\rangle + \alpha\beta|\varphi^4\rangle)_{12}\\ |10\rangle_{12} &= (\alpha\beta|\varphi^1\rangle + \beta^2|\varphi^2\rangle - \alpha^2|\varphi^3\rangle - \alpha\beta|\varphi^4\rangle)_{12}\\ |11\rangle_{12} &= (-\beta^2|\varphi^1\rangle + \alpha\beta|\varphi^2\rangle + \alpha\beta|\varphi^3\rangle + \alpha^2|\varphi^4\rangle)_{12}\end{aligned} \tag{6}$$

(2) With this basis, the quantum channel can be rewritten into Eq. (7)

$$\begin{aligned}|\phi\rangle_{1234} = \frac{1}{2}(&|\varphi^1\rangle_{12}(\alpha|0\rangle + \beta|1\rangle)_3(\alpha|0\rangle + \beta|1\rangle)_4\\ &+ |\varphi^2\rangle_{12}(\alpha|0\rangle + \beta|1\rangle)_3(\beta|0\rangle - \alpha|1\rangle)_4\\ &+ |\varphi^3\rangle_{12}(\beta|0\rangle - \alpha|1\rangle)_3(\alpha|0\rangle + \beta|1\rangle)_4\\ &+ |\varphi^4\rangle_{12}(\beta|0\rangle - \alpha|1\rangle)_3(\beta|0\rangle + \alpha|1\rangle)_4).\end{aligned} \tag{7}$$

(3) Alice carries out a two-particle two-dimensional projective measurement on Particles 1 and 2 in a set of mutually orthogonal basis vectors $\{|\varphi^1\rangle, |\varphi^2\rangle, |\varphi^3\rangle, |\varphi^4\rangle\}$.
(4) Alice sends Particles 3 and Particles 4 to Bob and Charlie via quantum channel, respectively, and reserves Particles 1 and 2.
(5) Alice performs a projective measurement $P_{1,2}$ on particles (1,2) under the general basis $\{|\varphi^1\rangle, |\varphi^2\rangle, |\varphi^3\rangle, |\varphi^4\rangle\}$ and broadcasts her measurement outcome via classical communication to Bob and Charlie simultaneously. The correlation between Alice's results and classical bits from Alice to Bob and Charlie is shown in Table 1.
(6) According to the classical bits from Alice, Bob reconstructs the state by performing corresponding unitary operations on Particles 3. Like Bob, Charlie reconstructs the state by performing corresponding unitary operation on Particle 4 according to the classical bits from Alice.

Next, the example for three-party quantum broadcast scheme is given.

Table 1 Measurement results and unitary operations of each party in the three-party quantum broadcast preparation of an arbitrary single-particle quantum states

Alice's results	Classical information	State of Particle 3	Bob's operation	State of Particle 4	Charlie's operation
$\|\varphi^1\rangle_{12}$	00	$\alpha\|0\rangle+\beta\|1\rangle$	U_1	$\alpha\|0\rangle+\beta\|1\rangle$	U_1
$\|\varphi^2\rangle_{12}$	01	$\alpha\|0\rangle+\beta\|1\rangle$	U_1	$\beta\|0\rangle-\alpha\|1\rangle$	$-U_3$
$\|\varphi^3\rangle_{12}$	10	$\beta\|0\rangle-\alpha\|1\rangle$	$-U_3$	$\alpha\|0\rangle+\beta\|1\rangle$	U_1
$\|\varphi^4\rangle_{12}$	11	$\beta\|0\rangle-\alpha\|1\rangle$	$-U_3$	$\beta\|0\rangle+\alpha\|1\rangle$	U_4

For Bob and Charlie, suppose that the classical bits from Alice are 11, according to Table 1, Bob can deduce that the measurement results of Particles 1 and 2 is $|\varphi^4\rangle$, and Particle 3 is in the state $(\beta|0\rangle-\alpha|1\rangle)_3$. Then, Bob can reconstruct the state $|\chi\rangle$ by performing unitary operation $-U_3$ on Particle 3. In the meanwhile, under the measurement results $|\varphi^4\rangle$, the Particle 4 is in the state $(\beta|0\rangle+\alpha|1\rangle)_4$, and then Charlie can reconstruct the state $|\chi\rangle$ by performing unitary operation U_4 on Particle 4. Other cases are also shown in Table 1.

3 Multi-output quantum teleportation

The basic process of this scheme can be described as follows. We assume that the quantum channel shared by sender Alice and receivers Bob and Charlie is a one-dimensional four-qubit cluster state as follows

$$|\phi\rangle=\frac{1}{2}(|0000\rangle+|0101\rangle+|1010\rangle-|1111\rangle), \tag{8}$$

where the particles(1,2) are in the possession of Alice, and the Particles 3 and 4 belong to Bob and Charlie, respectively. Figure 2 shows the schematic diagram of multi-output quantum teleportation with three participants.

Thus the quantum channel can be expressed as Eq. (9),

$$|\phi_4\rangle_{A_1A_2BC}=\frac{1}{2}(|0000\rangle+|0101\rangle+|1010\rangle-|1111\rangle)_{A_1A_2BC}. \tag{9}$$

Suppose that the unknown entangled states $|\chi\rangle_a$ and $|\chi\rangle_b$ to be teleported have the following form, and Alice wants to transmit the state of particle a to Bob and particle b to Charlie, respectively,

$$|\chi\rangle_a=(a_0(|0\rangle+a_1|1\rangle)_a,\ |\chi\rangle_b=(b_0(|0\rangle+b_1|1\rangle)_b, \tag{10}$$

where $a_i, b_i(i=0,1)$ satisfy the normalization condition

$$|a_0|^2+|a_1|^2=1,\ |b_0|^2+|b_1|^2=1. \tag{11}$$

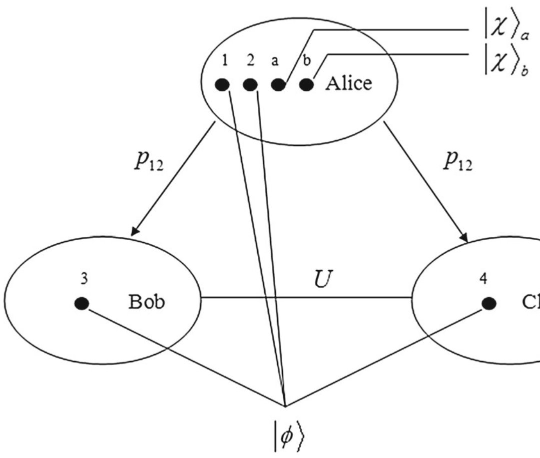

Fig. 2 A sketch of the scheme of multi-output quantum teleportation. A four-qubit cluster state is used as the quantum channel. $P_{1,2}$ stands for a projective measurement on particles (1, 2), which is performed by Alice. U stands for Hadamard operation and a projective measurement on Particle 3 and 4, respectively, which are performed by Bob and Charlie. In this figure, a qubit is represented by a dot, entangled qubits are connected by *solid lines*, and a classical communication from one site to another is represented by a vector

Thus the total state of the system can be expressed as

$$\begin{aligned}|\psi\rangle_S &= |\chi\rangle_a \otimes |\chi\rangle_b \otimes |\psi_4\rangle_{A_1A_2BC} \\ &= (a_0(|0\rangle + a_1|1\rangle)_a(b_0(|0\rangle + b_1|1\rangle)_b \\ &\quad \otimes \frac{1}{2}(|00000\rangle + |0101\rangle + |1010\rangle - |1111\rangle)_{A_1A_2BC}. \end{aligned} \tag{12}$$

In order to realize teleportation, Alice performs a measure on her particles in an appropriate basis. The measurement basis chosen by Alice is the set of mutually orthogonal basis vectors $\{|\varphi_1\rangle_{abA_1A_2}, |\varphi_2\rangle_{abA_1A_2}, \cdots, |\varphi_{16}\rangle_{abA_1A_2}\}$ which is given by

$$|\varphi_1\rangle_{abA_1A_2} = \frac{1}{2}(|0000\rangle - |0101\rangle - |1010\rangle - |1111\rangle)_{abA_1A_2}$$

$$|\varphi_2\rangle_{abA_1A_2} = \frac{1}{2}(|0000\rangle - |0101\rangle + |1010\rangle + |1111\rangle)_{abA_1A_2}$$

$$|\varphi_3\rangle_{abA_1A_2} = \frac{1}{2}(|0000\rangle + |0101\rangle - |1010\rangle + |1111\rangle)_{abA_1A_2}$$

$$|\varphi_4\rangle_{abA_1A_2} = \frac{1}{2}(|0000\rangle + |0101\rangle + |1010\rangle - |1111\rangle)_{abA_1A_2}$$

$$|\varphi_5\rangle_{abA_1A_2} = \frac{1}{2}(|0001\rangle - |0100\rangle + |1011\rangle + |1110\rangle)_{abA_1A_2}$$

$$|\varphi_6\rangle_{abA_1A_2} = \frac{1}{2}(|0001\rangle - |0100\rangle - |1011\rangle - |1110\rangle)_{abA_1A_2}$$

$$|\varphi_7\rangle_{abA_1A_2} = \frac{1}{2}(|0001\rangle + |0100\rangle + |1011\rangle - |1110\rangle)_{abA_1A_2}$$

$$
\begin{aligned}
|\varphi_8\rangle_{abA_1A_2} &= \frac{1}{2}(|0001\rangle + |0100\rangle - |1011\rangle + |1110\rangle)_{abA_1A_2} \\
|\varphi_9\rangle_{abA_1A_2} &= \frac{1}{2}(|0010\rangle - |0111\rangle + |1000\rangle + |1101\rangle)_{abA_1A_2} \\
|\varphi_{10}\rangle_{abA_1A_2} &= \frac{1}{2}(|0010\rangle + |0111\rangle + |1000\rangle - |1101\rangle)_{abA_1A_2} \\
|\varphi_{11}\rangle_{abA_1A_2} &= \frac{1}{2}(|0010\rangle - |0111\rangle - |1000\rangle - |1101\rangle)_{abA_1A_2} \\
|\varphi_{12}\rangle_{abA_1A_2} &= \frac{1}{2}(|0010\rangle + |0111\rangle - |1000\rangle + |1101\rangle)_{abA_1A_2} \\
|\varphi_{13}\rangle_{abA_1A_2} &= \frac{1}{2}(|0011\rangle - |0110\rangle - |1001\rangle - |1100\rangle)_{abA_1A_2} \\
|\varphi_{14}\rangle_{abA_1A_2} &= \frac{1}{2}(|0011\rangle - |0110\rangle + |1001\rangle + |1100\rangle)_{abA_1A_2} \\
|\varphi_{15}\rangle_{abA_1A_2} &= \frac{1}{2}(|0011\rangle + |0110\rangle - |1001\rangle + |1100\rangle)_{abA_1A_2} \\
|\varphi_{16}\rangle_{abA_1A_2} &= \frac{1}{2}(|0011\rangle + |0110\rangle + |1001\rangle - |1100\rangle)_{abA_1A_2}.
\end{aligned} \tag{13}
$$

Having performed the measurements, Alice informs Bob and Charlie of her measurement results via a classical channel. Then Bob and Charlie can apply some appropriate operations to receive the state teleported. Without lose of generality, if Alice detects the particles in the state $|\varphi_1\rangle_{abA_1A_2}$, the state of BC will collapse into

$$
|\psi^1\rangle_{BC} =_{abA_1A_2} \langle\varphi_1|\psi\rangle_S = \frac{1}{4}(a_0|0\rangle - a_1|0\rangle)_B(b_0|0\rangle - b_1|0\rangle)_C. \tag{14}
$$

Depending on Alice's measurement outcomes, Bob and Charlie carry out the unitary transformation on their own particles, and then they obtain the states $|\chi\rangle_a$ and $|\chi\rangle_b$, respectively. If Alice's measurement result is $|\varphi_1\rangle$, Particle 3 is in the state $(a_0|0\rangle - a_1|1\rangle)_a$. Then, Bob can reconstruct the state $|\chi\rangle_a$ by performing unitary operation U_2 on Particle 3. In the meanwhile, the Particle 4 is in the state $(b_0|0\rangle - b_1|1\rangle)_b$, and Charlie can also reconstruct the state $|\chi\rangle_b$ by performing unitary operation U_2 on Particle 4. And other cases are given in Table 2.

4 Conclusion

In this paper, by exploiting the entanglement correlation in quantum mechanics, two schemes for three-party with four-qubit cluster state as the quantum channel are proposed. One is quantum three-party broadcast scheme, and the other is the multi-output quantum teleportation. In the proposed schemes, the arbitrary single-qubit states are sent by Alice, who constructs a set of mutually orthogonal basis vectors and performs measurement on her own particles. According to Alice's measurement results, Bob and Charlie measure their own particles in the corresponding quantum measurement bases and perform unitary operations on the corresponding particles to reconstruct the quantum state, respectively and simultaneously. The two schemes realize quantum

Table 2 Measurement results and unitary operations of each party in the multi-output quantum teleportation of two arbitrary single-particle quantum states

Alice's results	Classical information	State of Particle 3	Bob's operation	State of Particle 4	Charlie's operation
$\|\varphi_1\rangle_{abA_1A_2}$	0000	$a_0\|0\rangle - a_1\|1\rangle$	U_2	$b_0\|0\rangle - b_1\|1\rangle$	U_2
$\|\varphi_2\rangle_{abA_1A_2}$	0001	$a_0\|0\rangle + a_1\|1\rangle$	U_1	$b_0\|0\rangle - b_1\|1\rangle$	U_2
$\|\varphi_3\rangle_{abA_1A_2}$	0010	$a_0\|0\rangle - a_1\|1\rangle$	U_2	$b_0\|0\rangle + b_1\|1\rangle$	U_1
$\|\varphi_4\rangle_{abA_1A_2}$	0011	$a_0\|0\rangle + a_1\|1\rangle$	U_1	$b_0\|0\rangle + b_1\|1\rangle$	U_1
$\|\varphi_5\rangle_{abA_1A_2}$	0100	$a_0\|0\rangle - a_1\|1\rangle$	U_2	$b_0\|1\rangle - b_1\|0\rangle$	U_3
$\|\varphi_6\rangle_{abA_1A_2}$	0101	$a_0\|0\rangle + a_1\|1\rangle$	U_1	$b_0\|1\rangle - b_1\|0\rangle$	U_3
$\|\varphi_7\rangle_{abA_1A_2}$	0110	$a_0\|0\rangle - a_1\|1\rangle$	U_2	$b_0\|1\rangle + b_1\|0\rangle$	U_4
$\|\varphi_8\rangle_{abA_1A_2}$	0111	$a_0\|0\rangle + a_1\|1\rangle$	U_1	$b_0\|1\rangle + b_1\|0\rangle$	U_4
$\|\varphi_9\rangle_{abA_1A_2}$	1000	$a_0\|1\rangle + a_1\|0\rangle$	U_4	$b_0\|0\rangle + b_1\|1\rangle$	U_1
$\|\varphi_{10}\rangle_{abA_1A_2}$	1001	$a_0\|1\rangle + a_1\|0\rangle$	U_4	$b_0\|0\rangle - b_1\|1\rangle$	U_2
$\|\varphi_{11}\rangle_{abA_1A_2}$	1010	$a_0\|1\rangle - a_1\|0\rangle$	U_3	$b_0\|0\rangle + b_1\|1\rangle$	U_1
$\|\varphi_{12}\rangle_{abA_1A_2}$	1011	$a_0\|1\rangle - a_1\|0\rangle$	U_3	$b_0\|0\rangle - b_1\|1\rangle$	U_2
$\|\varphi_{13}\rangle_{abA_1A_2}$	1100	$-a_0\|1\rangle - a_1\|0\rangle$	$-U_4$	$b_0\|1\rangle + b_1\|0\rangle$	U_4
$\|\varphi_{14}\rangle_{abA_1A_2}$	1101	$-a_0\|1\rangle + a_1\|0\rangle$	$-U_3$	$b_0\|1\rangle + b_1\|0\rangle$	U_4
$\|\varphi_{15}\rangle_{abA_1A_2}$	1110	$-a_0\|1\rangle - a_1\|0\rangle$	$-U_4$	$b_0\|1\rangle - b_1\|0\rangle$	U_3
$\|\varphi_{16}\rangle_{abA_1A_2}$	1111	$-a_0\|1\rangle + a_1\|0\rangle$	$-U_3$	$b_0\|1\rangle - b_1\|0\rangle$	U_3

multi-cast communication successfully and can be applied to quantum multi-party synchronous communication.

Up to now, the progress of the single-qubit unitary operation in experiment in various quantum systems has been reported [7,27–29]. However, the four-qubit cluster state and measurements in our schemes have not been reported in experiment. Actually, the implementation of the existing schemes is very complicated and expensive. With the continuous development of quantum information theory and technology, the cost of the proposed schemes will be greatly reduced, and multi-cast quantum communication will be realized by experiment in the near future.

Acknowledgements This work was supported by the foundation of Shannxi provincial Educational Department under Contract No. 15JK1668 and the Natural Science Foundation of Shannxi provincial of China Grant Nos. 2015JM6263 and 2013JM1009.

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