Quantum secret sharing (QSS), an important branch of classical secret sharing, is the generalization of classical secret sharing into quantum scenario and has attracted a lot of attention. It is used to distribute a private key among several parties or splitting a classical secret. For example, an original QSS scheme was proposed by Hillery, Bužek, and Berthiaume (HBB) in 1999 by using a three-particle QSS scheme [2]. The basic idea of this QSTS for an arbitrary two-particle state is described as

\[ \Phi_{xy} = a|00\rangle_{xy} + \beta|01\rangle_{xy} + \gamma|10\rangle_{xy} + \delta|11\rangle_{xy}, \] (1)

where \( x \) and \( y \) are the two particles in the state \( |\Phi\rangle_{xy} \), and

\[ |\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1. \] (2)

At first, Alice shares the four EPR pairs \( a_1b_1, c_1d_1, a_2b_2 \) and \( c_2d_2 \) with Bob and Charlie, respectively. Here \( a_1 \) and \( b_1 \) are the two particles in an EPR pair, and similar notations for the other EPR pairs. An EPR pair is in one of the four Bell states shown as follows [25]:

\[ |\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1 \pm |1\rangle_1 |0\rangle_2), \]

\[ |\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1 |0\rangle_2 \pm |1\rangle_1 |1\rangle_2), \] (3)

where \( |0\rangle \) and \( |1\rangle \) are the eigenvectors of the operator \( \sigma_z \). Without loss of generality, we assume that all the EPR pairs are originally in the entangled state \( |\phi^{+}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_1 |0\rangle_2 + |1\rangle_1 |1\rangle_2) \).

Before the measurement, the state of the composite quantum system composed of the ten particles is

\[ |\Psi\rangle_s = |\Phi\rangle_{xy}(\phi^+)_{a_1b_1}(\phi^+)_{c_1d_1}(\phi^+)_{a_2b_2}(\phi^+)_{c_2d_2}. \] (4)

Alice performs the three-particle GHZ state joint measurement \( M_1 \) on the particles \( x, a_1 \) and \( a_2 \) first, and then the \( M_2 \) on the particles \( y, c_1 \) and \( c_2 \). Bob takes the product measurement \( M_B = \sigma_x \otimes \sigma_x \) on the particles \( b_1d_1 \), and

A scheme for multipart quantum state sharing of an arbitrary two-particle state with Einstein-Podolsky-Rosen pairs. Any one of the \( N \) agents has the access to regenerate the original state with two local unitary operations if he collaborates with the other agents, say the controllers. Moreover, each of the controllers is required to take only a product measurement \( \sigma_x \otimes \sigma_x \) on his two particles, which makes this scheme more convenient for the agents in the applications on a network than others. As all the quantum source can be used to carry the useful information, the intrinsic efficiency of qubits approaches the maximal value. With a new notation for the multipartite entanglement, the sender need only publish two bits of classical information for each measurement, which reduces the information exchanged largely.

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and then Charlie can recover the original state $|\Phi_x\rangle$ with two local unitary operations $U_C = U_0 \otimes U_1$ according to the results obtained by Alice and Bob, see Fig. 1.

Let us use an example to demonstrate the principle of this QSTS protocol with one controller. First, we introduce a new notation for the three-particle GHZ states.

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

where $i, j \in \{0, 1\}, i = 1 - i$ and $j = 1 - j$.

Suppose Alice gets the results $R_{xa_1a_2} = R_{yc_1c_2} = |G_{00+}\rangle$, which will occur with the probability $\frac{1}{8} \times \frac{1}{8} = \frac{1}{64}$, then the state of the subsystem with the particles $b_1, d_1, b_2$ and $d_2$ becomes

$$|\Psi\rangle_{sub} = \alpha|00\rangle_{b_1d_1}|00\rangle_{b_2d_2} + \beta|01\rangle_{b_1d_1}|01\rangle_{b_2d_2} + \gamma|10\rangle_{b_1d_1}|10\rangle_{b_2d_2} + \delta|11\rangle_{b_1d_1}|11\rangle_{b_2d_2}. \quad (6)$$

That is, the information of the state $|\Psi\rangle_{xy}$ is transferred to the state of the subsystem shared between Bob and Charlie. If they want to recover the quantum information $|\Psi\rangle_{xy}$, one of them performs $\sigma_x \otimes \sigma_x$ on his/her two particles and the other takes two local unitary operations on the two particles according to the information provided by the first one. For example, let us assume that Bob performs the $\sigma_x \otimes \sigma_x$ measurement on his two particles, and Charlie will reconstruct the original state when she collaborates with Bob. We can rewrite the state $|\Psi\rangle_{sub}$ as

$$|\Psi\rangle_{sub} = \frac{1}{2}(|+x\rangle_{b_1} + |x\rangle_{d_1})(\alpha|00\rangle_{b_2d_2} + \beta|01\rangle_{b_2d_2} + \gamma|10\rangle_{b_2d_2} + \delta|11\rangle_{b_2d_2}),$$

where $|+x\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|-x\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$ are the two eigenstates of the measuring basis $\sigma_x$. Provided that Bob agrees to cooperate with Charlie, Charlie can recover the unknown state by performing the unitary operations $U_0 \otimes U_0, U_0 \otimes U_1, U_1 \otimes U_0, \text{and } U_1 \otimes U_1$ on the particles $b_2$ and $d_2$ if the outcomes obtained by Bob are $|+x\rangle_{b_1} + |x\rangle_{b_2}, |+x\rangle_{b_1} - |x\rangle_{b_2}, |x\rangle_{b_1} + |x\rangle_{b_2}$ and $|x\rangle_{b_1} - |x\rangle_{b_2}$, respectively. Here $U_0 = I, U_1 = \sigma_x, U_2 = \sigma_y, \text{and } U_3 = \sigma_y$, and $I$ is the identity matrix and $\sigma_i (i = x, y, z)$ are the Pauli matrices.

For the other cases, the relation between the results of the measurements done by Alice and Bob and the local unitary operations with which Charlie reconstructs the unknown quantum information $|\Psi\rangle_{xy}$ is shown in Table I. Here $V_{xa_1a_2}$ and $V_{yc_1c_2}$ represents the bit value of the results of the GHZ state joint measurements on $xa_1a_2$ and $yc_1c_2$, respectively. Define

$$V_{(ij\pm)} \equiv j, \quad P_{(ij\pm)} \equiv \pm, \quad P_{(\pm x)} \equiv \pm \quad (8)$$

where $i, j \in \{0, 1\}$. In detail, $V_{xa_1a_2} = 1$ and $P_{xa_1a_2} = -1$ if the result of the three-particle joint measurement on particles $xa_1a_2$ is $R_{xa_1a_2} = |G_{01-}\rangle$ or $R_{xa_1a_2} = |G_{11-}\rangle$; $P_{b_1} = -1$ when $R_{b_1} = |+\rangle - |\rangle$. $U_i \otimes U_j$ means that Charlie performs $U_i$ and $U_j$ on the two particles $b_2$ and $d_2$, respectively, here $i, j = 0, 1, 2, 3$.

Table I shows that the unknown state $|\Psi\rangle_{xy}$ can be shared by Bob and Charlie completely, and they can reconstruct the state with two single-qubit measurements along the $x$-direction and two local unitary operations. They need not do Bell state measurement on the particles, which makes this QSTS protocol more convenient for the agents than in Ref. [20]. Moreover, Alice needs only to publish two bits of classical information for her agents to recover the state $|\Psi\rangle_{xy}$.

It is straightforwardly to generalize this QSTS scheme to the case with $N$ agents, say Bob, $i = 1, 2, \ldots, N - 1$ and Charlie. As the symmetry, we still assume that Charlie is the agent who will recover the unknown state with the help of the $N - 1$ controllers, Bob. For the end, Alice should share $2N$ EPR pairs $|\psi\rangle_{a_1b_1}$ and $|\psi\rangle_{c_1d_1}$, $i = 1, 2, \ldots, N$ with the $N$ agents. In this time, the state of the composite quantum system is

$$|\Phi\rangle_S \equiv |\Psi\rangle_{xy} \prod_{i=1}^{N} |\phi^+\rangle_{a_i b_i} \otimes |\phi^+\rangle_{c_i d_i}. \quad (9)$$

Define a set of orthogonal vectors as

$$|G_{ij\ldots k+}\rangle = \frac{1}{\sqrt{2}}(|0ij\ldots k\rangle + |1ij\ldots k\rangle),$$

$$|G_{ij\ldots k-}\rangle = \frac{1}{\sqrt{2}}(|0ij\ldots k\rangle - |1ij\ldots k\rangle), \quad (10)$$

where $i, j, k \in \{0, 1\}, \tilde{i}, \tilde{j}, \tilde{k}$ are the counterparts of the binary numbers $i, j, \text{and } k$, respectively.

In the quantum communication, Alice performs first the joint measurement on the $N + 1$ particles $x, a_1, \ldots, \text{and } d_N, \text{then on the } N + 1 \text{ particles } y, c_1, \ldots, \text{and } c_N$. When the agents want to reconstruct the unknown state
where $\Psi$ are the results of the joint measurements done by Alice. In more detail, the state of the quantum system (without being normalized) can be rewritten as

$$|\Psi\rangle_S = \sum_{i,j,k} \{ |G_{ij...k}\rangle |G_{mn...l}\rangle (\alpha|ij...k\rangle|mn...l\rangle + \beta|ij...k\rangle|\tilde{m}n...\tilde{l}\rangle + \gamma|\tilde{i}j...\tilde{k}\rangle|mn...l\rangle + \delta|\tilde{i}j...\tilde{k}\rangle|\tilde{m}n...\tilde{l}\rangle) |G_{ij...k,ij...k}\rangle |G_{mn...l,}ij...k\rangle \rangle (\alpha|ij...k\rangle|mn...l\rangle - \beta|ij...k\rangle|\tilde{m}n...\tilde{l}\rangle + \gamma|\tilde{i}j...\tilde{k}\rangle|mn...l\rangle - \delta|\tilde{i}j...\tilde{k}\rangle|\tilde{m}n...\tilde{l}\rangle) |G_{ij...k,ij...k}\rangle |G_{mn...l,}ij...k\rangle \rangle (\alpha|ij...k\rangle|mn...l\rangle - \beta|ij...k\rangle|\tilde{m}n...\tilde{l}\rangle - \gamma|\tilde{i}j...\tilde{k}\rangle|mn...l\rangle + \delta|\tilde{i}j...\tilde{k}\rangle|\tilde{m}n...\tilde{l}\rangle) |G_{ij...k,ij...k}\rangle |G_{mn...l,}ij...k\rangle \rangle (\alpha|ij...k\rangle|mn...l\rangle - \beta|ij...k\rangle|\tilde{m}n...\tilde{l}\rangle - \gamma|\tilde{i}j...\tilde{k}\rangle|mn...l\rangle + \delta|\tilde{i}j...\tilde{k}\rangle|\tilde{m}n...\tilde{l}\rangle),$$

where $|i\rangle = \frac{1}{\sqrt{2}}(|x\rangle + (-1)^t|\tilde{x}\rangle)$, $\{i, j, k, m, n, \ldots, l\}$ are $2N$ binary numbers, and $\tilde{m}$ is the counterpart of $m$, i.e., $\tilde{m} = 1 - m$. As the symmetry, the measurements done by the controllers can be expressed by the operation $M$,

$$M = [(|x\rangle)^{N-1-t}(-x\rangle)^t]_1 \otimes [(|x\rangle)^{N-1-q}(-x\rangle)^q]_2,$$

where $[(|x\rangle)^{N-1-t}(-x\rangle)^t]_1$ is the measurement operation related to the state of the quantum subsystem $b_i$ (i.e., $\prod_{i=1}^N |\Psi_b\rangle$), and $[(|x\rangle)^{N-1-q}(-x\rangle)^q]_2$ is related to $d_i$, $t$ and $q$ are the numbers that the controllers obtain the result $-x$ when they measure the particle $b_i$ and $d_i$, respectively. After the measurements done by Alice and the $N-1$ controllers, the relation between the state of the particles $b_N$ and the results of the measurements can be expressed as:

$$M |\Psi\rangle_S = \sum_{i,j,k,...,l} \{ |G_{ij...k}\rangle |G_{mn...l}\rangle \otimes e^{-\theta_i} (\alpha|kl\rangle + (-1)^{i+q} \beta|\tilde{k}\rangle + (-1)^t \gamma|\tilde{l}\rangle + (-1)^{t+q+1} \delta|\tilde{k}\rangle) |G_{ij...k,ij...k}\rangle |G_{mn...l,}ij...k\rangle \rangle (\alpha|kl\rangle + (-1)^{i+q} \beta|\tilde{k}\rangle + (-1)^t \gamma|\tilde{l}\rangle + (-1)^{t+q+1} \delta|\tilde{k}\rangle) |G_{ij...k,ij...k}\rangle |G_{mn...l,}ij...k\rangle \rangle (\alpha|kl\rangle + (-1)^{i+q} \beta|\tilde{k}\rangle + (-1)^{t+q+1} \gamma|\tilde{l}\rangle + (-1)^{t+q+1} \delta|\tilde{k}\rangle),$$

where $e^{-\theta_i} (i = 1, 2, 3, 4)$ is an integer phase related to the state of quantum system $b_N d_N$, $\Psi_{b_N d_N}$, and it does not affect the result of the final state $\Psi_{b_N d_N}$ after all the measurements are completed.

Similar to the notations discussed above, we define

$$V_{|G_{ij...k}\rangle} = k, \quad P_{|G_{ij...k}\rangle} = \pm.$$ (15)

The relation between the results of the measurements and the local unitary operations with which Charlie reconstructs the unknown quantum information is as same as that in Table I with just a little modification. That is, $V_{|x_i a_1 \rangle}, V_{|y_i c_2 \rangle}, P_{|x_i a_2 \rangle} \otimes P_{b_1}$ and $P_{|y_i c_2 \rangle} \otimes P_{d_1}$ are replaced with $V_{|x_i a_3 ... a_N \rangle}, V_{|y_i c_3 ... c_N \rangle}, P_{|x_i a_3 ... a_N \rangle} \otimes (-1)^t$ and $P_{|y_i c_3 ... c_N \rangle} \otimes (-1)^q$, respectively.

The QSTS scheme can be made to be secure.

Quantum state sharing is the extension of quantum secret sharing, and is used to split an unknown quantum state. For sharing a classical information, single photons can be used as the quantum source for setting up the quantum channel [6, 7, 8]. For splitting an unknown state, the quantum source has to be an entangled quantum system. Although big process has been made for producing entanglement, the efficiency is still low, in particular for multipartite entanglement [24]. With the present techniques, the EPR pairs may be one of the optimal entangled quantum sources for quantum state sharing and quantum teleportation [25]. On the other hand, the disadvantage of this scheme is that the joint measurement done by the sender, Alice becomes more difficult with the increase of the agents. With the development of technology, it is likely easy for measuring a multipartite entanglement.

In summary, we have presented a way for quantum state sharing of an arbitrary two-particle state with $2N$ EPR pairs. Any one in the $N$ agents can recover the original state with two local unitary operations if he collaborates with the other agents, the $N-1$ controllers who are required only to perform two single-particle measurements along the $x$ direction, $\sigma_z$, without Bell state joint measurements, which makes it more convenient for the agents in its applications than others. Certainly, Alice has to perform two multipartite joint measurements on her particles. Another advantage is that all the par-
particles can be used to carry the useful information and the intrinsic efficiency for qubits approaches the maximal value. With the new notations for GHZ state, Alice need only publish four bits of classical information for recovering the original state, which reduces the information exchanged largely.

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TABLE I: The relation between the local unitary operations and the results $R_{xa_{1,2}}$, $R_{yc_{1,2}}$, $R_{b_{1}}$ and $R_{d_{1}}$. $\Phi_{b_{2}d_{2}}$ is the state of the two particles held in the hand of Charlie after all the measurements are done by Alice and Bob; $U_{C}$ are the local unitary operations with which Charlie can reconstruct the unknown state $|\Phi\rangle_{xy}$.

| $V_{xa_{1}a_{2}}$ | $V_{yc_{1}c_{2}}$ | $P_{xa_{1}a_{2}} \otimes P_{b_{1}}$ | $P_{yc_{1}c_{2}} \otimes P_{d_{1}}$ | $\Phi_{b_{2}d_{2}}$ | $U_{C}$ |
|------------------|------------------|-------------------------------|-------------------------------|-----------------|---------|
| 0                | 0                | +                             | +                             | $\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$ | $U_{0} \otimes U_{0}$ |
| 0                | 0                | +                             | $-$                           | $\alpha|00\rangle - \beta|01\rangle + \gamma|10\rangle - \delta|11\rangle$ | $U_{0} \otimes U_{1}$ |
| 0                | 0                | $-$                           | +                             | $\alpha|00\rangle + \beta|01\rangle - \gamma|10\rangle - \delta|11\rangle$ | $U_{1} \otimes U_{0}$ |
| 0                | 1                | +                             | $-$                           | $\alpha|01\rangle + \beta|00\rangle + \gamma|11\rangle + \delta|10\rangle$ | $U_{0} \otimes U_{2}$ |
| 0                | 1                | +                             | $-$                           | $\alpha|01\rangle - \beta|00\rangle + \gamma|11\rangle - \delta|10\rangle$ | $U_{0} \otimes U_{3}$ |
| 0                | 1                | $-$                           | +                             | $\alpha|01\rangle + \beta|00\rangle - \gamma|11\rangle - \delta|10\rangle$ | $U_{1} \otimes U_{2}$ |
| 0                | 1                | $-$                           | $-$                           | $\alpha|01\rangle - \beta|00\rangle - \gamma|11\rangle + \delta|10\rangle$ | $U_{1} \otimes U_{3}$ |
| 0                | 0                | +                             | +                             | $\alpha|10\rangle + \beta|11\rangle + \gamma|00\rangle + \delta|01\rangle$ | $U_{2} \otimes U_{0}$ |
| 1                | 0                | +                             | $-$                           | $\alpha|10\rangle - \beta|11\rangle + \gamma|00\rangle - \delta|01\rangle$ | $U_{2} \otimes U_{1}$ |
| 1                | 0                | $-$                           | +                             | $\alpha|10\rangle + \beta|11\rangle - \gamma|00\rangle - \delta|01\rangle$ | $U_{3} \otimes U_{0}$ |
| 1                | 0                | $-$                           | $-$                           | $\alpha|10\rangle - \beta|11\rangle - \gamma|00\rangle + \delta|01\rangle$ | $U_{3} \otimes U_{1}$ |
| 1                | 1                | +                             | $-$                           | $\alpha|11\rangle + \beta|10\rangle + \gamma|01\rangle + \delta|00\rangle$ | $U_{2} \otimes U_{2}$ |
| 1                | 1                | +                             | $-$                           | $\alpha|11\rangle - \beta|10\rangle + \gamma|01\rangle - \delta|00\rangle$ | $U_{2} \otimes U_{3}$ |
| 1                | 1                | $-$                           | +                             | $\alpha|11\rangle + \beta|10\rangle - \gamma|01\rangle - \delta|00\rangle$ | $U_{3} \otimes U_{2}$ |
| 1                | 1                | $-$                           | $-$                           | $\alpha|11\rangle - \beta|10\rangle - \gamma|01\rangle + \delta|00\rangle$ | $U_{3} \otimes U_{3}$ |