Semi-quantum secret sharing using entangled states

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Abstract

Secret sharing is a procedure for sharing a secret among a number of participants such that only the qualified subsets of participants have the ability to reconstruct the secret. Even in the presence of eavesdropping, secret sharing can be achieved when all the members are quantum. So what happens if not all the members are quantum? In this paper we propose two semi-quantum secret sharing protocols using maximally entangled GHZ-type states in which quantum Alice shares a secret with two classical parties, Bob and Charlie, in a way that both parties are sufficient to obtain the secret, but one of them cannot. The presented protocols are also showed to be secure against eavesdropping.

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I. INTRODUCTION

Suppose a service provider Alice wants to distribute some secret information among clients, Bob and Charlie, such that Bob and Charlie can obtain the secret information through the cooperation, while one of them cannot. Classical secret sharing has been proposed as a solution [1, 2, 3]. A simple example is that Alice prepares a binary bit string related to her secret message and generates a random string of the same length, applies bitwise XOR operations on such two strings, and then sends the resulting string to Bob and a copy of the random string to Charlie. Obviously, Bob and Charlie acting together can access to Alice’s message, but one of them can obtain nothing about it.

Unfortunately, classical secret sharing cannot address the problem of eavesdropping if it is not used in conjunction with other techniques such as encryption. If an eavesdropper Eve (including one malicious participant of the Bob-Charlie pair) can control the communication channel and obtain both of Alice’s transmissions, then Alice’s message becomes transparent for her. Fortunately, quantum secret sharing can achieve secret sharing and eavesdropping detection simultaneously. Hillery et al. showed how to implement a secret sharing scheme using three-particle entangled Greenberger-Horne-Zeilinger (GHZ) states [4] in the presence of an eavesdropper [5]. Karlsson et al. presented a secret sharing scheme based on two-particle quantum entanglement such that only two members implementing together are able to obtain the information [6]. Gottesman showed that the size of each important share sometimes can be made half of the size of the secret if quantum states are used to share a classical secret [7]. The secret sharing protocol among n parties based on entanglement swapping of d-level cat states and Bell states was introduced by Karimipour et al. [8]. Guo et al. proposed a secret sharing scheme utilizing product states instead of entangled states and thus the efficiency is improved to approach 100% [9]. Xiao et al. generalized the scheme in Ref. [8] into any number of participants and gave two efficient quantum secret sharing schemes with the efficiency asymptotically 100% [10]. Zhang et al. considered a multiparty quantum secret sharing protocol of the classical secret based on entanglement swapping of Bell states [11]. There are also many quantum secret sharing protocols considering sharing quantum information [12, 13, 14, 15, 16, 17, 18, 19, 20]. Especially, Markham et al. developed a unified approach to secret sharing of both classical and quantum secrets employing graph states [20].

However, previous quantum secret sharing protocols requires all the parties to have quantum capabilities. So what happens if not all the parties are quantum? Actually, the situation that not all the participants can afford expensive quantum resources and quantum operations is more common in various applications. It is well known that semi-quantum key distribution in which one party Alice is quantum and the other party Bob just owns classical capabilities is possible [21, 22, 23], so it is interesting to ask whether semi-quantum secret sharing (the specific definition is given afterwards) is possible. The answer is affirmative.

In this paper, we consider the secret sharing protocol in which quantum Alice has to share a secret with classical Bob and classical Charlie such that the collaboration of Bob and Charlie can reconstruct the secret, while one of them cannot obtain anything about the secret. We say Alice is quantum when she is allowed to prepare arbitrary quantum states and perform any quantum operations. We follow the descriptions about “classical” in Refs. [21, 22, 23]. The computation basis \{ |0\rangle, |1\rangle \} is called “classical” and is replaced with the classical notations \{0, 1\}. Bob and Charlie is classical when they are restricted to performing four operations when they access a segment of the quantum channel: (1) measuring the qubits in the classical basis \{0, 1\}; (2) reordering the qubits (via proper delay measures); (3) preparing (fresh) qubits in the classical basis \{0, 1\}; (4) sending or returning the qubits without disturbance. The protocol of this kind is termed as “Semi-Quantum Secret Sharing (SQSS)”. SQSS protocols can have two
II. THREE-PARTICLE ENTANGLED STATES

In order to construct semi-quantum secret sharing protocols, we introduce a three-particle maximally entangled state in the following form

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle + |01\rangle + |10\rangle \right). \quad (1)$$

This state also can be rewritten as

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle + |11\rangle - |00\rangle \right) = \frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle \right). \quad (2)$$

Obviously, by implementing Hadamard operation on each particle of the state $|\psi\rangle$ respectively, $|\psi\rangle$ is transformed into the standard GHZ state, $\text{(GHZ)} = \frac{|000\rangle + |111\rangle}{\sqrt{2}}$. According to Ref. 24, if two three-particle entangled states can be mutually transformed by local unitary operations, they are equivalent. Hence, as an entangled state, $|\psi\rangle$ is equivalent to the standard GHZ state and belongs to the GHZ type.

The GHZ-type state $|\psi\rangle$ is not only theoretically existent but also practically feasible. It can be obtained from the standard GHZ state, and also can be generated in the following way. To gain $|\psi\rangle$, we may begin with preparing the state $|0\rangle$ and the Bell state $\frac{|00\rangle + |11\rangle}{\sqrt{2}}$, and then apply the Hadamard gate to the first qubit, and finally apply the controlled-NOT gate to the first two qubits. The specific steps are illustrated by the quantum circuit showed in Figure 1. Let us follow the states in the circuit to see clearly the process of generating $|\psi\rangle$. The input state of circuit is

$$|\psi_0\rangle = |0\rangle \otimes \frac{|00\rangle + |11\rangle}{\sqrt{2}}, \quad (3)$$

After sending the first qubit through the Hadamard gate, we have

$$|\psi_1\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \otimes \frac{|00\rangle + |11\rangle}{\sqrt{2}} = \frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle \right) + |10\rangle + |01\rangle.$$ \quad (4)

Then we send the first two qubits through the controlled-NOT gate to obtain

$$|\psi_2\rangle = \frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle \right) + |10\rangle + |01\rangle = |\psi\rangle.$$ \quad (5)

III. RANDOMIZATION-BASED SQSS PROTOCOL

In this section, we propose a randomization-based SQSS protocol in which quantum Alice and the other two classical parties, Bob and Charlie, share a secret string such that Bob and Charlie can recover the secret string only when they work together. Quantum Alice has the ability to prepare the maximally entangled GHZ-type state $|\psi\rangle$ and perform some quantum operations such as Bell measurements and three-particle measurements. Classical parties, Bob and Charlie, are restricted to implementing three operations: (1) measuring the qubits in the classical basis $\{0, 1\}$; (2) reordering the qubits (via proper delay measures); (3) sending or returning the qubits without disturbance. All the participants can access a quantum channel and an authenticated public channel that is susceptible to eavesdropping. The detailed steps are given in the following.

1. Alice creates a sufficiently long string of three-particle entangled states in the form of Eq. (1) (Suppose N triplet states are in the string and theses states are indexed from 1 to $N$). After that, Alice sends the second and the third particle of each entangled state to Bob and Charlie, and keeps the remaining for herself.

2. Upon receiving each qubit, Bob randomly determines, either to measure the qubit using the classical...
TABLE I: Participants’ actions on the qubits in each position

| Case | Bob      | Charlie  | Alice       |
|------|----------|----------|-------------|
| (1)  | SHARE    | SHARE    | ACTION 1   |
| (2)  | SHARE    | CHECK    | ACTION 2   |
| (3)  | CHECK    | SHARE    | ACTION 3   |
| (4)  | CHECK    | CHECK    | ACTION 4   |

*aMeasuring her qubit in the classical basis \(\{0,1\}\) (we refer to this action as “SHARE”), or to reflect it back to Alice (we refer to this action as “CHECK”).

*bCombining her qubit with Charlie’s reflected qubit and performing a Bell measurement.

*cCombining her qubit with Bob’s reflected qubit and performing a Bell measurement.

*dCombining her qubit with the two reflected qubits and performing an appropriate three-particle measurement.

basis \(\{0,1\}\) (we refer to this action as “SHARE”), or to reflect it back to Alice (we refer to this action as “CHECK”). Particularly, Bob reflects the qubits in a new order such that nobody else could distinguish which qubits are returned. Each measurement outcome is interpreted as a binary 0 or 1. Similarly, Charlie also randomly decides either to measure the qubits or to reflect the qubits in another order.

3. Alice temporarily restores the qubits reflected by Bob and Charlie in quantum registers according to their incoming sequences, and announces that she has received their reflected particles in a public channel.

4. Bob and Charlie declare which qubits were reflected by them and the order in which their qubits were returned, respectively.

5. For her own qubit in each position, Alice performs one of the four actions according to Bob’s and Charlie’s actions on the corresponding qubits, as illustrated in Table I.

It is supposed that there are four cases appearing in the same probability: (1) both Bob and Charlie choose to SHARE, then Alice can implement ACTION 1 to obtain a bit (we name this bit as SHARE bit) that can be retrieved if Bob and Charlie use the XOR operation on their measurement outcomes; (2) Bob chooses to SHARE and Charlie chooses to CHECK, then Alice can perform ACTION 2 to check whether Bob’s measurement outcome is right and the resulting two-particle state is the correct Bell state; (3) Bob chooses to CHECK and Charlie chooses to SHARE, then Alice can utilize ACTION 3 to check if Charlie’s measurement result is right and the resulting two-particle state is the correct Bell state; and (4) both Bob and Charlie choose to CHECK, then Alice can check whether the original three-particle entangled states in the form of Eq. (1) is changed by carrying out ACTION 4.

For instance, let Bob randomly measure the qubits in \(N/2\) positions (SHARE) and reflect the qubits in the other \(N/2\) positions in a new order \(l_B = l_1 l_2 \cdots l_{N/2}\) (CHECK), and Charlie performs the similar operations as Bob does and reflects the qubits in another order \(m_C = m_1 m_2 \cdots m_{N/2}\). Suppose \(N = 8\), \(l_B = 4731\) and \(m_C = 6427\). Then the lists of the qubits measured by Bob and Charlie are indexed by their complements \(\bar{l}_B = 2568\) and \(\bar{m}_C = 1358\), respectively. Hence Alice performs ACTION 1 in the positions 5 and 8 and interprets the measurement outcomes as classical bits 0 or 1, and performs ACTION 4 in the positions 4 and 7. Alice also implements ACTION 2 in the positions 2 and 6 and ACTION 3 in the positions 1 and 3.

6. Alice checks the error rate in cases (2), (3), and (4) given in Table I. If the error rate in any case is higher than some predefined threshold value, the protocol aborts.

7. Alice requires Bob and Charlie to reveal a random subset (assume the size of the subset is about \(N/8\)) of the bits which are used to generate Alice’s SHARE bits. Actually this process is used to check the error rate in case (1). If the values of Bob’s and Charlie’s bits are the same (or opposite), then Alice’s bit should be 0 (or 1) according to the Eq. (1). From step 5, we know that approximately \(N/4\) positions are selected by both Bob and Charlie to SHARE. If the error rate on SHARE bits is not significant, the remaining \(N/8\) SHARE bits of Alice forms the final secret string which can be recovered only when Bob and Charlie work together.

We show the above randomization-based SQSS protocol is secure against eavesdropping in two situations. The first is that one dishonest classical party Bob (or Charlie) attempts to find Alice’s secret without cooperating with the other party in the recovery stage. The second is that a fourth eavesdropper Eve who has quantum capabilities is involved and aims to find Alice’s secret without being detected.

We first suppose the dishonest classical party Bob can access both of Alice’s transmissions. In some of the positions, Bob may measure both qubits using the classical basis \(\{0,1\}\) and resend one of them in the state he found Charlie. In terms of the Eq. (1), if both of the measurement outcomes are the same (or opposite), he learns that Alice’s bit must be 0 (or 1). In the other positions, Bob may behave like a honest party and do nothing on Charlie’s qubits. However, this cheating strategy can hardly succeed since Bob does not know Charlie’s choices. If Bob measures Charlie’s qubit in the position where Charlie chooses to CHECK, he suffers a problem. According to the state \(|\psi\rangle\) in Eq. (1), if Bob just measures his own qubit, then the two-particle state resulting from combining Alice’s qubit and Charlie’s reflected qubit should be the Bell state, while if Bob measures both qubits of him and Charlie, then the two-particle state resulting from combining Alice’s qubit and Charlie’s reflected qubit will be the product state, and thus Alice will find this abnormality with probability \(1/2\) using a Bell measurement. But if Bob measures Charlie’s qubit in the position where Charlie chooses to SHARE, his cheating will not be found. In each position, Charlie has a probability of \(1/2\) of making either choice, so the probability that Bob escapes detection is \(1/2 \times 1/2 + 1/2 = 3/4\). Assume that Bob has to measure both qubits in \(l(l \leq N/4)\) positions to obtain the significant information of Alice’s
secret without the aid of Charlie, then the probability that Bob goes undetected is \((3/4)l\) which may be arbitrarily small by picking an appropriate \(l\) and \(N\).

Now let us consider the second case in which a fourth party Eve who has quantum capabilities is involved. Assume that Eve can obtain both of Alice’s transmissions and tries to obtain Alice’s secret. If Eve gets Bob’s and Charlie’s qubits of certain entangled states, she may measure the two qubits in the Bell basis and then resend the qubits in the states she found to Bob and Charlie, respectively. In terms of Eq. (1), if the measurement outcome is \(|\psi\rangle_k\), if the measurement outcome is \(|\psi\rangle_k\), Eve learns that Alice’s bit should be 0; otherwise she knows that Alice’s bit should be 1. However, Eve’s cheating is likely to be detected since she does not know Bob’s and Charlie’s choices. If she measures the qubits in the position where both Bob and Charlie choose to \textit{CHECK}, then the three-particle state resulting from combining Alice’s qubit and the other two reflected qubits will be the product of one single state and a Bell state but not the same as the original state \(|\psi\rangle_k\) in the form of Eq. (1), and thus Alice can discover this defraud with the probability \(1/2\) by measuring it in a three-particle orthogonal basis \(\{|\phi_0\rangle, |\phi_1\rangle, ..., |\phi_7\rangle\}\), where

\[
\begin{align*}
|\phi_0\rangle &= \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) + |01\rangle + |10\rangle, \\
|\phi_1\rangle &= \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) - |01\rangle + |10\rangle, \\
|\phi_2\rangle &= \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) + |01\rangle - |10\rangle, \\
|\phi_3\rangle &= \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) - |01\rangle - |10\rangle, \\
|\phi_4\rangle &= \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle) + |01\rangle + |10\rangle, \\
|\phi_5\rangle &= \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle) - |01\rangle + |10\rangle, \\
|\phi_6\rangle &= \frac{1}{\sqrt{2}}(|10\rangle - |01\rangle) + |01\rangle + |10\rangle, \\
|\phi_7\rangle &= \frac{1}{\sqrt{2}}(|10\rangle - |01\rangle) - |01\rangle - |10\rangle.
\end{align*}
\]  

Similarly, if Eve measures the qubits either in the position where Bob chooses to \textsc{share} and Charlie chooses to \textit{check}, or in the position where Bob selects to \textit{check} and Charlie selects to \textit{share}, she also can be detected with probability \(1/2\) by implementing a Bell measurement. But if Eve measures the qubits in the position where both Bob and Charlie choose to \textit{share}, she cannot be detected. In every position, as Bob and Charlie have a probability of \(1/2\) of choosing to \textit{share} or \textit{check}, the probability that Eve’s cheating is undetected is \(1/4 \times 1/2 \times 1/2 = 1/8\). Suppose there are \(m(m \leq N/4)\) positions where Bob should measure the qubits in a Bell basis to learn the considerable information of the secret, then Bob’s cheating goes undetected with probability \((5/8)^m\) which can be small enough by choosing a suitable \(m\) and \(N\). In addition, Eve also obtains nothing about Alice’s secret information even if she manages to entangle an ancilla with each qubit of Bob (or Charlie). Suppose that in a certain position, Eve has entangled an ancilla \(|0\rangle\) with Bob’s qubit, and both Bob and Charlie measure their qubits, then the Alice-Eve system collapses to \(|00\rangle\) or \(|10\rangle\), which leaks no information to Eve about Alice’s qubit.

Particularly, notice that it is indispensable for Alice to announce that she has received all the reflected particles in step 3. If Eve can learn which qubits were reflected by Bob and Charlie and in which order they were reflected before Alice receives the reflected qubits, he can obtain the secret string of Alice without inducing errors by using the similar way to attack the mock protocol in Refs. [21, 22, 23]. For each incoming qubit of Bob, she entangles an ancilla \(|0\rangle\) with it and implements a controlled-NOT operation on them (Bob’s qubit as the control qubit and the ancilla qubit as the target qubit). Then she holds all the qubits that Bob reflected until Bob publishes which qubits were reflected and in which order they were reflected. Next she rearranges the reflected qubits in the same order as Alice sent them to Bob and performs another controlled-NOT operation on each returned qubit and the corresponding ancilla. After that, she resends the resulting qubits in the order that Bob declared to Alice. Finally, in the position where Bob chose to \textit{share}, she measures her ancilla and learns Bob’s bit. For the qubits sent to Charlie, Eve does the similar operations and learns Charlie’s bits. In the position where both Bob and Charlie chose to \textit{share}, Eve can obtain the \textit{share} bit by implementing XOR operation on their bits according to Eq. (1). Moreover, Eve goes undetected since she introduces no errors.

\section{MEASURE-RESEND SQSS PROTOCOL}

In the following, a measure-resend SQSS protocol is introduced. Quantum Alice can prepare the three-particle GHZ-type state \(|\psi\rangle\) and perform some quantum operations and classical parties. Bob and Charlie, are restricted to performing three operations: (1) measuring the qubits in the classical basis \(\{0, 1\}\); (2) preparing (fresh) qubits in the classical basis \(\{0, 1\}\); (3) sending or returning the qubits without disturbance. This protocols is quite sim-
imilar to the randomization-based SQSS protocol except that step 2 and step 4 are adapted to the different restrictions of classical participants, so the modified steps are given as follows:

2. When Bob (or Charlie) receives each qubit he randomly determines, either to measure it in the classical basis \( \{0, 1\} \) and return it in the same state he found (SHARE), or to reflect it directly (CHECK).

4. Bob and Charlie declare the positions in which the qubits were measured (or reflected).

The proposed measure-resend SQSS protocol is secure against eavesdropping in a way similar to that in the randomization-based SQSS protocol. A dishonest party Bob (or Charlie) should not find Alice’s secret without collaborating with the other party and a fourth eavesdropper Eve who has quantum capabilities also should not obtain Alice’s secret without disturbance. Suppose Bob is dishonest and he has controlled both of Alice’s transmissions. In some of the positions, Bob measures both particles and resends one of them to Charlie. However, if Charlie does not measure the qubits in such positions, the Alice-Charlie systems should collapse to the Bell states but not product states, which might be discovered by Alice through implementing Bell measurements. Likewise, assume that a fourth party Eve who owns quantum capabilities has managed to obtain both Bob’s and Charlie’s particles. In certain positions, Eve measures the two qubits in the Bell basis and then resends the qubits to Bob and Charlie, respectively. However, if either Bob or Charlie does not measure their qubits in such positions, Eve’s cheating will be detected by Alice through performing appropriate measurements. Besides, even if Eve manages to entangle an ancilla with each qubit of Bob (or Charlie), she also obtains nothing about Alice’s secret since the ancilla is always left unchanged.

Note that it is also significant to demand Alice to publish that she has received all the reflected qubits in step 3 of this protocol. If this requirement is loss, Eve can cheat successfully. For instance, Eve holds the reflected qubits from Bob and Charlie until they announce the positions in which the qubits were measured and resent (SHARE), or reflected directly (CHECK). Then Eve measures the qubits that they measured and then resends them in the states she found, and reflects the qubits that they reflected without disturbance. In the position where both Bob and Charlie measured their qubits, if Eve’s measurements are the same, then she learns Alice’s bit must be 0; otherwise she learns Alice’s bit must be 1. Furthermore, Eve can escape detection since she does not introduce disturbance anywhere.

V. CONCLUSION AND DISCUSSION

We have introduce a maximally entangled GHZ-type state and shown that it is not only theoretically existent but also practically feasible. Furthermore, we have used such GHZ-type states to propose two semi-quantum secret sharing protocols in which Alice has quantum capabilities, while the other two parties, Bob and Charlie, are limited to classical operations: measure qubits in the classical basis \( \{0, 1\} \); send or reflect qubits without disturbance; reorder some qubits or prepare fresh qubits after measurements and resend them. The proposed protocols also have been showed to be secure against eavesdropping. Since the proposed SQSS protocols do not require all the participants owning quantum capabilities, the secret sharing can be achieved at a lower cost. Therefore, the applicability of secret sharing could be widen to the situation in which not all the participants can afford expensive quantum resources and quantum operations.

Nevertheless, we just consider the case that quantum Alice shares a secret with two classical parties, Bob and Charlie. An interesting question is: can a general SQSS protocol in which quantum Alice shares a secret with several parties who may be quantum or classical be achieved? Besides, note that no noise were assumed and so that three participants, namely, Alice, Bob, and Charlie, can share perfect entangled states if eavesdroppers introduce no errors. So another interesting question is: can entangled states can be shared of almost perfect fidelity if not all the parties are quantum when noisy quantum channels are used?

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