Device-Independent Quantum Secure Direct Communication with User Authentication

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Abstract

Quantum Secure Direct Communication (QSDC) is an important branch of quantum cryptography, which enable secure transmission of messages without prior key encryption. However, traditional quantum communication protocols rely on the security and trustworthiness of the devices employed to implement the protocols, which can be susceptible to attacks. Device-independent (DI) quantum protocols, on the other hand, aim to secure quantum communication independent of the devices used by leveraging fundamental principles of quantum mechanics. In this research paper, we introduce the first DI-QSDC protocol that includes user identity authentication to establish the authenticity of both sender and receiver before message exchange. We also extend this approach to a DI Quantum Dialogue (QD) protocol where both parties can send secret messages upon mutual authentication.

Keywords—Identity authentication Device-independent Quantum cryptography Quantum dialogue

1 Introduction

Quantum cryptography is a field of cryptography that utilizes the properties of quantum mechanics to achieve secure communication. Unlike traditional cryptography, the security of quantum cryptography does not rely on solving complex mathematical problems. Instead, the principles of quantum mechanics are used to ensure the unconditional security of the communication protocols.

The first protocol of quantum cryptography, known as quantum key distribution (QKD), was proposed by Bennett and Brassard in 1984 [1]. This protocol was based on Wiesner’s theory of quantum conjugate coding [2]. QKD has since been extensively studied both theoretically [3, 4, 5, 6] and experimentally [7, 8, 9, 10, 11].

In addition to QKD, Quantum secure direct communication (QSDC) is an important primitive of quantum cryptography [5, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31]. The key difference between QKD and QSDC is that QKD generates random keys between...
communication parties, whereas QSDC directly transmits secret information. QSDC enables secure transmission of a secret message over a quantum channel without the need for pre-shared secret keys for encryption and decryption. Quantum dialogue (QD) is a bidirectional extension of QSDC, allowing both parties to exchange secret messages simultaneously through a quantum channel. The first QD protocol was proposed in 2004 by Nguyen [32], which is a generalized version of the ping-pong protocol [33]. Since then, QD has undergone rapid development over the past two decades [34, 35, 36, 37, 38, 39, 40, 41]. Several QSDC protocols have been proposed for more than two parties, as discussed in [42, 43, 44, 45, 46, 47, 48, 49, 50]. These protocols extend the concept of QSDC to allow secure transmission of secret messages among multiple parties over a quantum channel.

Device-Independent Quantum Secure Direct Communication (DI-QSDC) is a type of QSDC protocol that does not rely on the trustworthiness of the quantum devices used in the communication. In other words, it is a quantum communication protocol that guarantees security even if the devices used by the communication parties are compromised or controlled by an eavesdropper. DI-QSDC protocols are designed to overcome the limitations of traditional QSDC protocols, which rely on the assumption that the quantum devices used by the communication parties are trustworthy. In a DI-QSDC protocol, the security of the communication is ensured by the violation of certain Bell inequalities, which is a consequence of the non-local correlations of entangled quantum states. The first DI-QSDC protocol was proposed by Zhou et al. in 2020 [22]. Since then, several other DI-QSDC protocols have been proposed and studied [51, 52]. DI-QSDC has the potential to be used in scenarios where the security of the communication is critical and where traditional QSDC protocols may not be sufficient to guarantee the security of the communication.

Identity authentication of each user is essential for any secure communication to prevent impersonation attacks. In 1995, Crépeau et al. proposed the first quantum user identification scheme [53]. Lee et al. later proposed the first QSDC protocol with user authentication in 2006 [54]. Since then, several new QSDC protocols with authentication have been developed [55, 56, 57, 58, 24, 26].

Here in this paper, we compose both the above concepts of DI-QSDC and user identity authentication and present the first protocol of DI-QSDC with user authentication. We extend our DI-QSDC protocol to an DI-QD protocol, which also provides user authentication.

The rest of this paper is organized as follows: in Section 2, we briefly describe our proposed DI-QSDC with user authentication protocol and its security analysis. Then in the next section, we generalize MDI-QSDC protocol into an MDI-QD with user authentication protocol. Finally, Section 4 concludes our results.

Notations

Throughout the paper, we use some notations and we describe those common notations here.

- **Z basis** = \{\ket{0}, \ket{1}\} basis.
- **X basis** = \{\ket{+}, \ket{-}\} basis.
- **I** = \ket{0} \bra{0} + \ket{1} \bra{1}.
- **σ_x** = \ket{1} \bra{0} + \ket{0} \bra{1}.
- $i\sigma_y = |0\rangle \langle 1| - |1\rangle \langle 0|.$
- $\sigma_z = |0\rangle \langle 0| - |1\rangle \langle 1|.$
- $H = \frac{1}{\sqrt{2}}(\sigma_x + \sigma_z)$ is the Hadamard operator.
- $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) = \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle).$
- $|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle) = \frac{1}{\sqrt{2}}(|+-\rangle + |--\rangle).$
- $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) = \frac{1}{\sqrt{2}}(|++\rangle - |--\rangle).$
- $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) = \frac{1}{\sqrt{2}}(|+-\rangle - |--\rangle).$
- Bell basis = $\{|\Phi^+\rangle, |\Phi^-\rangle, |\Psi^+\rangle, |\Psi^-\rangle\}$ basis.
- $S_i = i$-th element of finite sequence $S$.
- $S_{A,i} = i$-th element of finite sequence $S_A$.
- $\Pr(A) =$ Probability of occurrence of an event $A$.
- $\Pr(A|B) =$ Probability of occurrence of an event $A$ given that the event $B$ has already occurred.

## 2 Proposed DI-QSDC protocol with user authentication

In this section, we propose our new DI-QSDC protocol with user identity authentication process. Suppose Alice has an $n$-bit secret message $m$, which she wants to send Bob through a quantum channel. Alice and Bob have their secret user identities $Id_A$ and $Id_B$ (each of $2k$ bits) respectively, which they have shared previously by using some secured QKD. The protocol is as follows:

1. Alice selects $c$ check bits and randomly inserts them into $m$ at different positions. The resulting bit string is denoted as $m'$, which has a length of $n + c$. It is assumed that the length of $m'$ is even, i.e., $n + c = 2N$ where $N$ is an integer.

2. Bob:
   
   (a) He randomly prepares $(N + k + 2d)$ EPR pairs (where $d$ is a security parameter) in the states $|\Phi^+\rangle, |\Phi^-\rangle, |\Psi^+\rangle, |\Psi^-\rangle$, and then separates the entangled qubit pairs into two sequences, $S_A$ and $S_B$, each with a length of $(N + k)$. $S_A$ is formed by taking one qubit from each pair, while the remaining partner qubits form $S_B$.

   (b) Bob prepares $k$ EPR pairs according to his identity $Id_B$. For each $1 \leq i \leq k$, Bob prepares the $i$-th qubit pair $I_i$ in one of the states $|\Phi^+\rangle, |\Phi^-\rangle, |\Psi^+\rangle$, and $|\Psi^-\rangle$, depending on the value of $Id_{B,(2i-1)}Id_{B,2i}$ being one of 00, 01, 10, and 11, respectively. Subsequently, Bob creates two sequences $I_A$ and $I_B$ of single photons such that for each $1 \leq i \leq k$, the $i$-th qubits of $I_A$ and $I_B$ are partners of each other in the $i$-th EPR pair $I_i$. 


6. Security check and authentication process: Alice first check the authenticity of the receiver, and then they check the security of the channel. After that, Bob check the authenticity of the sender.
(a) Once Bob receives the sequence $Q_A'$, Alice discloses the positions of the qubits in $I'_A$ to him. Bob then performs measurements on the qubit pairs $(I'_{A,i}, I'_{B,i})$, where $1 \leq i \leq k$, in the Bell basis and announces the results. As Alice has knowledge of $I_B$, she is aware of the exact state of each $I_i$, which is the joint state $I_{A,i}I_{B,i}$. Due to Alice’s random application of Pauli operators on $I_{A,i}$, the joint state changes to $I_{A,i}'I_{B,i}'$. Alice matches the measurement results with $I_{A,i}'I_{B,i}'$ to authenticate Bob's identity. In case of a significant error, Alice will abort the protocol.

(b) After Alice has verified Bob’s identity, she reveals the positions of the qubits of $D_A$ in $Q_A'$. Then Bob check the security of the second transmission of the qubits. He randomly measures the qubits of $D_A$ in $B_{A_0}$, $B_{A_1}$ and $B_{A_2}$ basis, and their partner qubits in $B_{B_1}$ and $B_{B_2}$ basis. He calculates the value of the CHSH polynomial $S$, and decides to abort or continue.

(c) Alice discloses the positions of the qubits in $C_A$ that correspond to her identity, $I_{d_A}$. Bob measures those qubits with their partner qubits in $S_B$ (denoted as $C_B$), using the Bell basis. He then matches the measurement results with $I_{d_A}$ to validate Alice’s legitimacy. If there is a significant error, Bob will terminate the protocol.

7. Bob discards all the measured qubits and measures the remaining qubit pairs from $(S'_{A}, S_{B})$ in Bell basis. From the knowledge of $(S_A, S_B)$ and $(S'_{A}, S_B)$, Bob decodes the classical bit string $m'$ using Table (1).

8. Alice and Bob publicly verify the random check bits to ensure the integrity of the messages. If the error rate is deemed acceptable, Bob receives the secret message $m$ and the communication process is completed.

We present the proposed DI-QSDC with user authentication protocol in the form of an algorithm in figure [1], where we use the following notations.

- $P(Q)$: Positions of the qubits of $Q$.
- $C(Q)$: Cover operations on the qubits of $Q$.
- $BM(Q_1, Q_2)$: Measures the qubit pairs of $(Q_1, Q_2)$ in Bell bases.
- $A$: Announces the results.
- Sec.chk $(A, B)$: Checks the security of the channel from A to B.
- Cov. op.: Cover operation.
- Ins.: Inserts.

3 Proposed DI-QD protocol with user authentication

In this section, we present a generalized version of the previously discussed DI-QSDC protocol, which is a DI-QD protocol with user authentication. Both Alice and Bob simultaneously exchange their $n$-bit secret message after verifying each other’s authenticity. They use an EPR pair to exchange one-bit messages. Bob prepares $(n + c)$ EPR pairs randomly, using $|\Phi^+\rangle$ or $|\Psi^+\rangle$ ($|\Phi^-\rangle$ or $|\Psi^-\rangle$) corresponding to his secret message bit 0 (1), where $c$ represents the number of check
1. Ins. $c$ check bits into the secret message $m$ and $m \rightarrow m'$.

2(a)-(c). Prepares $Q_A = S_A \cup I_A$ and $Q_B = S_B \cup I_B$, where qubits pair of $(S_A, S_B)$, $(I_A, I_B)$ are entangled.

3(a). Separates $S_A, I_A$ from $Q_A$.

3(b)-(c). Sec.chk (Bob, Alice) $\xrightarrow{}$ 4.

4. Discards the measured qubits from $S_A$.

5(a). Encodes $m'$, $Id_A$ on $S_A$, $S_A \rightarrow S_A'$.

$C_A$: qubits corresponding to $Id_A$.

$D_A$: remaining qubits of $S_A$.

5(b). Cov. op. on $I_A$, $I_A \rightarrow I_A'$.

Ins. $I_A'$ into $S_A'$ and $Q_A' = S_A' \cup I_A'$.

5(b'). $Q_A' \xrightarrow{}$ 6(a).

6(a). $P(I_A')$ $\xrightarrow{}$ 6(a)', $BM(I_A', I_B) \& A$

6(b). $P(I_A)$ $\xrightarrow{}$ 6(b)', Sec.chk (Alice, Bob)

6(c). $P(C_A)$ $\xrightarrow{}$ 6(c)', $BM(C_A, C_B)$

Verifies Alice’s identity

7. $BM(S_A', S_B)$. Decodes $m'$.

8. Compare the check bits $\xrightarrow{}$ 8'. Extract $m$ from $m'$.

--- denotes quantum channel,

$\rightarrow$ denotes classical channel.

Step (i)' happens just after Step (i).
Table 1: Encoding and decoding rules of our proposed DI-QSDC.

| Initial EPR pairs \((S_A, S_B)\) | Alice’s message bits | Alice’s unitary \(S_A \text{ to } S'_A\) | Final EPR pair \((S'_A, S_B)\) | Decoded message bits |
|----------------------------------|----------------------|----------------------------------------|-------------------------------|---------------------|
| \(|\Phi^+\rangle\)               | 00 \(I\)            | 00 \(|\Phi^+\rangle\)                 | 00                            | \(|\Phi^+\rangle\)   |
|                                  | 01 \(\sigma_x\)     | 01 \(|\Psi^-\rangle\)                | 01                            | \(|\Psi^-\rangle\)   |
|                                  | 10 \(i\sigma_y\)    | 10 \(|\Psi^+\rangle\)                | 10                            | \(|\Psi^+\rangle\)   |
|                                  | 11 \(\sigma_z\)     | 11 \(|\Phi^-\rangle\)                | 11                            | \(|\Phi^-\rangle\)   |
| \(|\Phi^-\rangle\)              | 00 \(I\)            | 00 \(|\Phi^-\rangle\)                | 00                            | \(|\Phi^-\rangle\)   |
|                                  | 01 \(\sigma_x\)     | 01 \(|\Psi^-\rangle\)                | 01                            | \(|\Psi^-\rangle\)   |
|                                  | 10 \(i\sigma_y\)    | 10 \(|\Psi^+\rangle\)                | 10                            | \(|\Psi^+\rangle\)   |
|                                  | 11 \(\sigma_z\)     | 11 \(|\Phi^-\rangle\)                | 11                            | \(|\Phi^-\rangle\)   |
| \(|\Psi^+\rangle\)              | 00 \(I\)            | 00 \(|\Psi^+\rangle\)                | 00                            | \(|\Psi^+\rangle\)   |
|                                  | 01 \(\sigma_x\)     | 01 \(|\Phi^-\rangle\)                | 01                            | \(|\Phi^-\rangle\)   |
|                                  | 10 \(i\sigma_y\)    | 10 \(|\Phi^-\rangle\)                | 10                            | \(|\Phi^-\rangle\)   |
|                                  | 11 \(\sigma_z\)     | 11 \(|\Phi^-\rangle\)                | 11                            | \(|\Phi^-\rangle\)   |
| \(|\Psi^-\rangle\)              | 00 \(I\)            | 00 \(|\Psi^-\rangle\)                | 00                            | \(|\Psi^-\rangle\)   |
|                                  | 01 \(\sigma_x\)     | 01 \(|\Phi^-\rangle\)                | 01                            | \(|\Phi^-\rangle\)   |
|                                  | 10 \(i\sigma_y\)    | 10 \(|\Phi^-\rangle\)                | 10                            | \(|\Phi^-\rangle\)   |
|                                  | 11 \(\sigma_z\)     | 11 \(|\Psi^+\rangle\)                | 11                            | \(|\Psi^+\rangle\)   |

bits. Bob also prepares \(k + 2d\) EPR pairs randomly from \(|\Phi^+\rangle, |\Phi^-\rangle, |\Psi^+\rangle, |\Psi^-\rangle\) for encoding the secret identity of Alice and security check purposes. He inserts these qubits into the previously prepared EPR sequence and announces their positions to Alice after she receives the first qubit sequence. Alice randomly applies Pauli operator \(I\) or \(\sigma_z\) (\(\sigma_x\) or \(i\sigma_y\)) to encode her message bit 0 (1) (refer to Table 2). The remaining steps of the protocol are the same as those described in Section 2 for the DI-QSDC protocol.

4 Conclusion

This paper presents the first-ever protocol for DI-QSDC that allows for mutual identity authentication of users. Both parties possess pre-shared secret identity keys, and the sender verifies the receiver’s authenticity before sending the secret message. Similarly, the receiver verifies the sender’s identity before receiving the message. We also introduce an extension to the DI-QD protocol, where both parties authenticate each other’s identity before exchanging their secret messages.

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Table 2: Encoding rules of our proposed DI-QD.

| Message bit | Bob prepares | Alice’s unitary | Final joint state |
|-------------|--------------|-----------------|-------------------|
| Alice       | Bob          | \((S_A, S_B)\)  | \(S_A \to S'_A\)  | \((S'_A, S_B)\) |
| 0           | 0            | \(|\Phi^+\rangle\) | \(I\)           | \(|\Phi^-\rangle\) |
|             |              | \(|\Psi^+\rangle\) | \(\sigma_z\)     | \(|\Psi^-\rangle\) |
| 0           | 1            | \(|\Phi^-\rangle\) | \(I\)           | \(|\Phi^+\rangle\) |
|             |              | \(|\Psi^-\rangle\) | \(\sigma_z\)     | \(|\Psi^+\rangle\) |
| 1           | 0            | \(|\Phi^+\rangle\) | \(\sigma_x\)     | \(|\Psi^-\rangle\) |
|             |              | \(|\Psi^+\rangle\) | \(i\sigma_y\)    | \(|\Phi^-\rangle\) |
| 1           | 1            | \(|\Phi^-\rangle\) | \(\sigma_x\)     | \(|\Psi^-\rangle\) |
|             |              | \(|\Psi^-\rangle\) | \(i\sigma_y\)    | \(|\Phi^+\rangle\) |

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