Semi-quantum communication: Protocols for key agreement, controlled secure direct communication and dialogue

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Abstract

Semi-quantum protocols that allow some of the users to remain classical are proposed for a large class of problems associated with secure communication and secure multiparty computation. Specifically, first time semi-quantum protocols are proposed for key agreement, controlled deterministic secure communication and dialogue, and it is shown that the semi-quantum protocols for controlled deterministic secure communication and dialogue can be reduced to semi-quantum protocols for e-commerce and private comparison (socialist millionaire problem), respectively. Complementing with the earlier proposed semi-quantum schemes for key distribution, secret sharing and deterministic secure communication, set of schemes proposed here and subsequent discussions have established that almost every secure communication and computation tasks that can be performed using fully quantum protocols can also be performed in semi-quantum manner. Further, it addresses a fundamental question in context of a large number problems- how much quantumness is (how many quantum parties are) required to perform a specific secure communication task? Some of the proposed schemes are completely orthogonal-state-based, and thus, fundamentally different from the existing semi-quantum schemes that are conjugate-coding-based. Security, efficiency and applicability of the proposed schemes have been discussed with appropriate importance.

Keywords: Semi-quantum protocol, quantum communication, key agreement, quantum dialogue, deterministic secure quantum communication, secure direct quantum communication.

1 Introduction

Since Bennett and Brassard’s pioneering proposal of unconditionally secure quantum key distribution (QKD) scheme based on conjugate coding \cite{1}, various facets of secure communication have been ex-

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explored using quantum resources. On the one hand, a large number of conjugate-coding-based (BB84-type) schemes [2–4] have been proposed for various tasks including QKD [2–4], quantum key agreement (QKA) [5], quantum secure direct communication (QSDC) [6, 7], deterministic secure quantum communication (DSQC) [8, 9], quantum e-commerce [10], quantum dialogue [11–30], etc., on the other hand, serious attempts have been made to answer two extremely important foundational questions– (1) Is conjugate coding necessary for secure quantum communication? (2) How much quantumness is needed for achieving unconditional security? Alternatively, whether all the users involved in a secure communication scheme are required to be quantum in the sense of their capacity to perform quantum measurement, prepare quantum states in more than one mutually unbiased basis (MUBs) and/or the ability to store quantum information? Efforts to answer the first question have led to a set of orthogonal-state-based schemes [5, 31–34], where security is obtained without using our inability to simultaneously measure a quantum state using two or more MUBs. These orthogonal-state-based schemes [5, 31–34] have strongly established that any cryptographic task that can be performed using a conjugate-coding-based scheme can also be performed using an orthogonal-state-based scheme. Similarly, efforts to answer the second question have led to a few semi-quantum schemes for secure communication which use lesser amount of quantum resources than that required by their fully quantum counterparts (protocols for same task with all the participants having power to use quantum resources). Protocols for a variety of quantum communication tasks have been proposed under the semi-quantum regime; for example, semi-quantum key distribution (SQKD) [35–49], semi-quantum information splitting (SQIS) [50], semi-quantum secret sharing (SQSS) [51–53], semi-quantum secure direct communication (SQSDC) [54, 55], semi-quantum private comparison [34, 56], authenticated semi-quantum direct communication [57] have been proposed. The majority of these semi-quantum schemes are two-party schemes, but a set of multi-party schemes involving more than one classical Bob have also been proposed [42]. In some of these multi-party semi-quantum schemes (especially, for multiparty SQKD) it has been assumed that there exist a completely untrusted server/center Charlie who, is a quantum user and either all [41] or some [39] of the other users are classical. Further, some serious attempts have been made for providing security proof for semi-quantum protocols [57–62]. However, to the best of our knowledge until now no semi-quantum protocol has been proposed for a set of cryptographic tasks, e.g., (i) semi-quantum key agreement (SQKA), (ii) controlled deterministic secure semi-quantum communication (CDSSQC), (iii) semi-quantum dialogue (SQD). These tasks are extremely important for their own merit as well as for the fact that a scheme of CDSSQC can be easily reduced to a scheme of semi-quantum e-commerce in analogy with Ref. [63], where it is shown that a controlled-DSQC scheme can be used for designing a scheme for quantum online shopping. Further, a scheme for online shopping will be of much more practical relevance if end users (especially buyers) do not require quantum resources and consequently can be considered as classical users. In brief, a semi-quantum scheme for e-commerce is expected to be of much use. It is also known that a Ba An type scheme for QD [11, 16] can be reduced to a scheme of QPC [16, 34] and then the same can be used to solve socialist millionaire problem [16]; a scheme of QKA can be generalized to multiparty case and used to provide semi-quantum schemes for sealed bid auction [54]; and in a similar manner, a CDSSQC scheme can be used to yield a scheme for semi-quantum binary quantum voting in analogy with [65, 66]. The fact that no semi-quantum scheme exists for SQD, SQKA and CDSSQC and their wide applicability to e-commerce, voting, private comparison and other cryptographic tasks have motivated us to design new protocols for SQD, SQKA and CDSSQC and to critically analyze their security and efficiency. To do so, we have designed 2 new protocols for CDSSQC and one protocol each for SQD and SQKA. These new protocols provide some kind of completeness to the set of available semi-quantum schemes and allows us to safely say that any secure communication task that can be performed using full quantum scheme can also be performed with a semi-quantum scheme. Such reduction of quantum resources is extremely important as quantum resources are costly and it is not expected that
all the end users would possess quantum devices.

Before we proceed further, it would be apt to note that in the existing semi-quantum schemes different powers have been attributed to the classical party (let's call him as Bob for the convenience of the discussion, but in practice we often name a classical user as Alice, too). Traditionally, it is assumed that a classical Bob does not have a quantum memory and he can only perform a restricted set of classical operations over a quantum channel. Specifically, Bob can prepare new qubits only in the classical basis (i.e., in $Z$ basis or $\{|0\rangle, |1\rangle\}$ basis). In other words, he is not allowed to prepare $|\pm\rangle$ or other quantum states that can be viewed as superposition of $|0\rangle$ and $|1\rangle$ states. On receipt of a qubit Bob can either resend (reflect) the qubit (independent of the basis used to prepare the initial state) without causing any disturbance or measure it only in the classical basis. He can also reorder the sequence of qubits received by him by sending the qubits through different delay lines. In fact, first ever semi-quantum scheme for key distribution was proposed by Boyer et al., in 2007 [35]. In this pioneering work, the user with restricted power was referred to as classical Bob and in that work and in most of the subsequent works ([37, 40, 41, 54] and references therein) it was assumed that Bob has access to a segment of the quantum channel starting from Alice's lab going back to her lab via Bob's lab; as before, the classical party Bob can either leave the qubit passing through the channel undisturbed or perform measurement in the computational basis, which can be followed by fresh preparation of qubit in the computational basis. This was followed by a semi-quantum scheme of key distribution [36], where the classical party can either choose not to disturb the qubit or to measure it in the computational basis, and instead of preparing the fresh qubits in the computational basis he may reorder the undisturbed qubits to ensure unconditional security. Later, these schemes were modified to a set of SQKD schemes with less than four quantum states, where Alice requires quantum registers in some of the protocols [37], but does not require it in all the protocols. In what follows, we attribute the same power to Bob in the schemes proposed in this paper. In the schemes proposed below, senders are always classical and they are referred to as classical Bob/Alice. This is in consistency with the nomenclature used in most of the recent works ([35–37, 40, 41, 54] and references therein). However, in the literature several other restrictions have been put on classical Bob. For example, in Ref. [43] a SQKD scheme was proposed where Bob was not allowed to perform any measurement and he was referred to as “limited classical Bob”. It was argued that a limited classical Bob can circumvent some attacks related to the measurement device [67–69]. However, the scheme proposed in [43] was not measurement device independent. Similarly, in [39] a server was delegated the task of performing measurement and application of one of the two Pauli operations, while the classical users role was restricted in randomly sending the received qubits to the server for random application of operator or measurement. Such a classical user was referred to as “nearly classical Bob”.

Remaining part of the paper is organized as follows. In Sec. 2, a protocol for SQKA among a quantum and a classical user is proposed. Two CDSSQC schemes with a classical sender and a receiver and controller both possessing quantum powers are proposed in Sec. 3. In Sec. 4, a SQD scheme between a classical and a quantum parties are designed. The security of the proposed schemes against various possible attacks are discussed in the respective sections. The qubit efficiency of the proposed schemes has been calculated in Sec. 5 before concluding the work in Sec. 6.

2 Protocol for semi-quantum key agreement

In analogy of the weaker notion of quantum key agreement, i.e., both the parties take part in preparation of the final shared key, most of the SQKD protocols may be categorized as SQKA schemes. Here, we rather focus on the stronger notion of the key agreement, which corresponds to the schemes where each party contribute equally to the final shared key, and none of the parties can manipulate or know the final
key prior to the remaining parties (for detail see [5] and references therein). We will also show that the proposed SQKA scheme can be reduced to a scheme for SQKD, first of its own kind, in which a sender can send a quantum key to the receiver in an unconditionally secure and deterministic manner.

In this section, we propose a two-party semi-quantum key agreement protocol, where Alice has all quantum powers, but Bob is classical, i.e., he is restricted to perform the following operations (1) measure and prepare the qubits only in the computational basis \{\ket{0}, \ket{1}\} (also called classical basis), and (2) simply reflects the qubits without disturbance. The working of the proposed protocol is illustrated through a schematic diagram shown in Fig. [1].

The following are the main steps in the protocol.

**Protocol 1**

**Step 1.1:** Preparation of the quantum channel: Alice prepares \(n+m = N\) number of Bell states, i.e., \(\ket{\psi^+} \otimes N\), where \(\ket{\psi^+} = \frac{\ket{00} + \ket{11}}{\sqrt{2}}\). Out of the total \(N\) Bell states, \(n\) will be used for key generation while the remaining \(m\) will be used as decoy qubits for eavesdropping checking. Subsequently, she

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prepares two ordered sequences of all the first qubits and all the second qubits from the initial Bell states. She keeps the first sequence with herself as home qubits (H) and sends the second sequence to Bob as travel qubits (T) as shown by arrow in Step1.1 of Fig. [1] Using a quantum random number generator (QRNG), Alice also prepares her raw key of $n$ bits $K_A = \{K_1, K_2, \ldots, K_i, \ldots, K_n\}$, where $K_i$ is the $i^{th}$ bit of $K_A$, and $K_i \in \{0, 1\}$ as shown in Step1.1 of Fig. [1]

**Step1.2: Bob’s encoding:** Bob also prepares his raw key $K_B = \{K_B^1, K_B^2, \ldots, K_B^i, \ldots, K_B^n\}$ of $n$ bits by using a RNC[1] (which is independent of Alice’s QRNG), where $K_B^i$ is the $i^{th}$ bit of the $K_B$ with $K_B^i \in \{0, 1\}$. After receiving all the qubits from Alice, Bob randomly chooses one of the two operations, either to measure or reflect as shown in Step1.1 of Fig. [1] Specifically, he measures $n$ qubits (chosen randomly) in the computational basis, while reflects the remaining $m$ qubits to be used later for eavesdropping checking.

He forms a string of his measurement outcomes as $r_B = \{r_B^1, r_B^2, \ldots, r_B^i, \ldots, r_B^n\}$, where $r_B^i$ is the measurement outcome of $i^{th}$ qubit chosen to be measured by Bob in the computational basis, and therefore, $r_B^i \in \{0, 1\}$. Then to encode his raw key $K_B$, he performs a bit wise XOR operation, i.e., $r_B \oplus K_B$ and prepares corresponding qubits in the computational basis. Finally, he inserts the encoded $n$ qubits back into the string of reflected $m$ qubits and sends the resultant sequence $r_B$ back to Alice only after applying a permutation operator $\Pi_N$ as shown by the first arrow in Step1.2 of Fig. [1]. These qubits would further be used to make the final shared key $K_f$.

**Step1.3: Announcements and eavesdropping checking:** After receiving an authenticated acknowledgment of the receipt of all the qubits from Alice, Bob announces the permutation operator $\Pi_m$ corresponding to the qubits reflected by him. Though, this would reveal which qubits have been measured and which qubits have been reflected by Bob but Eve or Alice cannot gain any advantage due to lack of information regarding the permutation operator $\Pi_n$. Further, to detect eavesdropping, Alice firstly measures the reflected qubits in Bell basis by combining them with respective partner home qubits. If she finds the measurement result as $|\psi^+\rangle$ state then they confirm that no eavesdropping has happened, because the initial state was prepared in $|\psi^+\rangle$ state, and they move on to the next step, otherwise they discard the protocol and start from the beginning.

**Step1.4: Extraction of the final shared key $K_f$ by Bob:** After ensuring that there is no eavesdropping, Alice announces her secret key $K_A$ publicly as shown by the first arrow in Step1.4 of Fig. [1] and Bob uses that information to prepare his final shared key $K_f = K_A \oplus K_B$ as he knows $K_B$. Subsequently, he also reveals the the permutation operator $\Pi_n$.

Here, it is important to note that Alice announces her secret key $K_A$ only after the receipt of all the encoded qubits from Bob. So, now Bob can not make any further changes as per his wish.

**Step1.5: Extraction of the final shared key $K_f$ by Alice:** Once Alice has reordered Bob’s encoded qubits she measures both the home (H) and travel (T) qubits in the computational basis. She obtains a string of $n$ bits $r_A$ corresponding to measurement outcomes of home qubits, and she can

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1Bob being classical, we refer to his random number generator as a traditional pseudo random number generator, instead of a true random number generator which is required to be quantum. This aspect of random key generation in Bob’s side is not explicitly discussed in the existing works on semi-quantum protocols. However, it’s not a serious issue as on one hand, extremely good quality pseudo random numbers can be generated classically (thus, use of a classical RNG will be sufficient for the present purpose); on the other hand, QRNG are now commercially available and is not considered as a costly quantum resource, so if one just allows an otherwise classical user to have an QRNG, the modified scheme could still be considered as a semi-quantum scheme as Bob would still lack the power of performing quantum measurement and or storing quantum information. In fact, measurement in classical basis would be sufficient for generation of true random number if Bob can create a $|\pm\rangle$ state using a beam splitter.
use the measurement outcomes of the travel qubits to know Bob’s encoded raw key as the initial Bell states are publicly known. For the specific choice of initial Bell state here, i.e., $|\psi^+\rangle$, the relation $r_A = r_B$ holds. Therefore, the final shared key would be

$$K_f = K_A \oplus K_B = (r_A \oplus K_A) \oplus (r_B \oplus K_B).$$

Hence, the final shared key $K_f$ is shared between Alice and Bob.

| Alice’s measurement result $r_A$ on home (H) qubits | Bob’s measurement result $r_B$ | Bob’s secret key $K_B$ | Alice’s measurement result on travel (T) qubits |
|-----------------------------------------------------|-------------------------------|------------------------|-----------------------------------------------|
| $|0\rangle$                                           | $|0\rangle$                   | $|0\rangle$             | $|0\rangle$                                   |
| $|1\rangle$                                           | $|1\rangle$                   | $|0\rangle$             | $|1\rangle$                                   |

Table 1: All the possibilities during Alice’s extraction of Bob’s secret key.

In Eq. (1), Eve may know Alice’s secret key $K_A$ as this was announced through a classical channel. She is also aware of $r_A = r_B$ due to public knowledge of the initial choice of Bell state. However, it does not affect the secrecy of the final shared key $K_f$ which is prepared as $K_A \oplus K_B$, because Eve does not know anything about Bob’s secret key $K_B$ and the value of $r_A$ (or $r_B$).

Further, it should be noted here the computational basis measurement is not the only choice by Alice, rather she can extract Bob’s encoding by performing Bell measurement. Here, we will skip that discussion as the same has been discussed in the following section for semi-quantum dialogue protocol.

If we assume that Alice is not intended to send her raw key (i.e., she does not announce her raw key) in the proposed SQKA protocol, indeed following it faithfully, then it will reduce to a deterministic SQKD protocol. Specifically, in analogy of ping-pong protocol [6] to perform a quantum direct communication task, which was also shown to share a quantum key in a deterministic manner.

2.1 Possible attack strategies and security

1. Eve’s attack: As mentioned beforehand Eve’s ignorance regarding the final shared key solely depends on the fact whether Alice receives Bob’s raw key in a secure manner. In other words, although Eve is aware of the initial state and Alice’s raw key, she still requires Bob’s key to obtain the final shared key. In what follows, we will discuss some attacks, she may attempt to extract this information.

The easiest technique Eve may incorporate is a CNOT attack (as described and attempted in Refs. [35, 36, 70]). To be specific, she may prepare enough ancilla qubits (initially as $|0\rangle$) to perform a CNOT with each travel qubit at control and an ancilla as a target while Alice to Bob communication. This way the compound state of Alice’s, Bob’s and Eve’s qubits, prior to Bob’s measurement, becomes $|\psi_{ABE}\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$. As Bob returns some of the qubits performing single qubit measurement in the computational basis on his qubit (B). The reduced state of Alice’s and Eve’s qubits may be written as $|\rho_{AE}\rangle = \frac{1}{2}(|00\rangle\langle 00| + |11\rangle\langle 11|)$ corresponding to Bob’s measurement, while the three qubit state remains unchanged for reflected qubits. Suppose Bob prepares a fresh qubit $|\xi_B\rangle = |r_B \oplus K_B\rangle$ and returns the string of encoded qubits (in other words, measured qubits) and reflected qubits to Alice (without applying a permutation operator). Subsequently,
Eve again performs a CNOT operation while Bob to Alice communication with control on travel qubits and target on the ancilla qubits. It is straightforward to check that in case of reflected qubits the state reduces to $|\psi_{ABE}\rangle = \frac{1}{\sqrt{2}} (|00\rangle \otimes |0\rangle + |11\rangle \otimes |0\rangle)$. Whereas, for encoded qubits it may be written as $|\rho_{ABE}\rangle = \frac{1}{2} (|0\rangle \langle 0| \otimes |K_B\rangle \langle K_B| + |1\rangle \langle 1| \otimes |K_B\oplus 1\rangle \langle K_B\oplus 1|) \otimes |K_B\rangle \langle K_B|$. From which it may be observed that Eve will always obtain Bob’s secret key. However, this problem is circumvented using a permutation operator (in Step 1.2) by Bob on the string of encoded and reflected qubits.

As Eve’s CNOT attack strategy is foiled by the use of a permutation operator she may attempt other attack strategies. Suppose she performs an intercept and resend attack. Specifically, in this attack, she can prepare an equal number of Bell states as Alice and send all the second qubits to Bob, keeping the Alice’s original sequence with herself. Bob follows the protocol and encodes $n$ qubits randomly and sends them to Alice, which is again intercepted by Eve. Subsequently, Eve performs the Bell measurement on all the Bell pairs (which she had initially prepared), and she may come to know which $n$ qubits were measured by Bob. Quantitatively, she can get this knowledge 75% of the time as in the Bell measurement outcomes anything other than the original state would result in a measurement performed by Bob. Depending upon the Bell measurement outcomes Bob’s encoding can also be revealed as $|\psi^-\rangle$ and $|\phi^\pm\rangle$ will correspond to Bob’s 0 and 1 in the computational basis, respectively (see Section 4 and Table 2 for more detail). Subsequently, she performs a measurement in the computational basis on the qubits sent by Alice corresponding to each qubit Bob has measured. Finally, she sends the new string of qubits (comprising of freshly prepared and Alice’s original qubits) to Alice which will never fail in eavesdropping checking and Alice will announce her key and Eve can get at least 75% of the shared key.

It is important to note here that 25% of the key of Alice and Bob will also not match in this case. This may be attributed to the disturbance caused due to eavesdropping, which left that signature and is a characteristic nature of quantum communication. This fact can be explored to achieve the security from this kind of an attack. Specifically, Alice and Bob may choose to perform a verification strategy of a small part of the shared key to check this kind of an attempt.

As we have already incorporated a permutation of particles scheme (performed by Bob) for security against CNOT attack, it becomes relevant to see the feasibility of this attack in this case as well. Bob discloses the permutation operator for decoy qubits only after an authenticated acknowledgment by Alice. Therefore, Eve fails to obtain the encoded bit value prior to this disclosure of Bob as it is, although it’s encoded in the computational basis, but she does not know the partner Bell pair due to randomization. She will require this Bell pair to decode the information as the measurement outcome of the partner Bell particle acts as a key for decoding the Bob’s information. Further, Bob announces the correct order of particles only when less than a threshold of errors are found during eavesdropping checking.

Indeed, most of the attacks by an eavesdropper can be circumvented if the classical Bob is given power to permute the string of qubits with him, i.e., Bob can secure his raw key (information) in the proposed SQKA scheme by permuting the particles before sending to Alice.

There are some other attacks (see [71, 72] for details) which do not affect the security of the proposed protocol, like disturbance attack, denial of service attack, and impersonation attack (as it becomes void after incorporating an authentication protocol).

2. **Alice’s attack:** In the eavesdropping checking, at the end of the round trip of Bell pairs, Bob announces the positions of the reflected qubits in each of the Bell pairs and the remaining string (i.e., encoded string after measurement) is in the computational basis and Alice can know Bob’s encoding before she announces her own. In other words, she can control the final key completely as she can announce her raw key accordingly. However, this is not desired in a genuine key agreement.
scheme. This possible attack by Alice is circumvented by the use of permutation operator discussed in the last attack. As Bob reveals the permutation he had applied on the freshly prepared qubits (on which his raw key is encoded) only after Alice announces her raw key, she can not extract his raw key due to lack of knowledge of pair particles corresponding to each initially prepared Bell state. Hence, only after Alice’s announcement of her raw key she comes to know Bob’s raw key with his cooperation.

To avoid this attack, we may also decide that both Alice and Bob share the hash values of their raw keys during their communication due to which if she wishes to change her raw key later, then the protocol is aborted as the hash value for her modified raw key will not match with original raw key.

3. **Bob’s attack:** As mentioned in the Alice’s attack that Bob announces the permutation operator only after receiving her raw key. One should notice here that the permuted string Bob has sent and corresponding Alice’s string are in computational basis. Further, Bob knows each bit value in Alice’s string as those are nothing but Bob’s corresponding measurement outcomes in Step 1.2. Once Bob knows Alice’s raw key, he may control the final key entirely by disclosing a new permutation operator that suits his choice of shared key. Therefore, it becomes important to incorporate the hash function as if Bob has already shared the hash value of his key he cannot change his raw key during announcement of permutation operator.

## 3 Controlled direct secure semi-quantum communication

If we observe the SQKA protocol proposed here, it can be stated that Bob sends his raw key by a DSSQC scheme and Alice announces her raw key. The security of the final key depends on the security of the raw key of Bob. Hence, a semi-quantum counterpart of direct communication scheme can be designed. However, avoiding the designing of various schemes for the same task, we rather propose a controlled version of direct communication scheme and discuss the feasibility of realizing this scheme, which would directly imply the possibility of direct communication scheme. Here, we will propose two controlled direct secure semi-quantum communication protocols. Note that in the proposed CDSSQC schemes only Alice is considered as a classical party, while Bob and Charlie possess quantum powers.

### 3.1 Protocol 2: Controlled direct secure semi-quantum communication

The working of this scheme is as follows.

**Step2.1: Preparation of shared quantum channel:** Charlie prepares \( n + m = N \) copies of a three qubit entangled state

\[
|\psi\rangle_{\text{GHZ-like}} = \frac{|\psi_1\rangle|a\rangle + |\psi_2\rangle|b\rangle}{\sqrt{2}},
\]

(2)

where \(|\psi_i\rangle \in \{|\psi^+\rangle, |\psi^-\rangle, |\phi^+\rangle, |\phi^-\rangle\} : |\psi\rangle = |00\rangle \pm |11\rangle \sqrt{2}, |\phi\rangle = |01\rangle \pm |10\rangle \sqrt{2}\rangle\} and \langle a|b\rangle = \delta_{a,b}. The classical user Alice will encode her \( n \)-bit message on the \( n \) copies, while the remaining \( m \) copies will be used as decoy qubits to check an eavesdropping attempt. Subsequently, Charlie prepares three sequences of all the first, second and third qubits of the entangled states. Finally, he sends the first and second sequences to Alice and Bob, respectively.

They can check the correlations in a few of the shared quantum states to avoid an eavesdropping attempt using intercept and resend attack, i.e., Charlie measures his qubits in \(|a\rangle, |b\rangle\rangle basis, while
Alice and Bob in computational basis. However, such an eavesdropping test would fail to provide security against measurement and resend attack. Security against such an attack is discussed later. In addition, Charlie and Bob both being capable of performing quantum operations may perform BB84 subroutine (cf. [65, 72, 73] and references therein) to ensure a secure transmission of the qubits belonging to quantum channel. This would provide additional security against intercept-resend attacks on Charlie-Bob quantum channel.

**Step2.2: Alice’s encoding:** Alice has a $n$ bit message $M = \{M_A^1, M_A^2, \ldots, M_A^n\}$. To encode this message Alice measures $n$ qubits (chosen randomly) in computational basis to obtain measurement outcomes $r_A = \{r_A^1, r_A^2, \ldots, r_A^n\}$, and prepares a new string of qubits in $\{|0\rangle, |1\rangle\}$ basis corresponding to bit values $M_A^i \oplus r_A^i$. Finally, she reinserts all these qubits back into the original sequence and sends it to Bob only after permuting the string. It is important that she leaves enough qubits undisturbed so that those qubits may be employed as decoy qubits.

**Step2.3: Announcements and eavesdropping checking:** After receiving an authenticated acknowledgement of the receipt of all the qubits from Bob, Alice announces which qubits have been encoded and which qubits have been left as decoy qubits. She also discloses the permutation operator applied only on the decoy qubits. Further, to detect eavesdropping, Bob firstly measures the pair of decoy qubits from Alice’s and Bob’s sequences in the Bell basis and with the help of Charlie’s corresponding measurement outcome (which reveals the initial Bell state Alice and Bob were sharing) he can calculate the errors. If sufficiently low errors are found they proceed to the next step, otherwise start afresh.

**Step2.4: Decoding the message:** To decode the message, Bob can perform a measurement in the computational basis on all the remaining qubits from both the sequences received from Charlie and Alice. Subsequently, Alice also discloses her permutation on the message encoded (or freshly prepared) qubits in her string. However, Bob cannot decode Alice’s secret message yet, as he remains unaware of the Bell state he was sharing with Alice until Charlie announces his measurement outcome.

**Step2.5: Charlie’s announcement:** Finally, Charlie announces his measurement outcome in $\{|a\rangle, |b\rangle\}$ basis using which Bob can decode Alice’s message.

### 3.2 Protocol 3: Controlled direct secure semi-quantum communication based on cryptographic switch

This controlled communication scheme is based on quantum cryptographic switch scheme proposed in the past [74] and has been shown to be useful in almost all the controlled communication schemes [65, 75–77].

**Step3.1: Preparation of the shared quantum channel:** Charlie prepares $n + m = N$ copies of one of the Bell states, out of which $n$ Bell pairs will be used for sending messages and the rest as decoy qubits. Subsequently, Charlie prepares two sequences of all the first and second qubits of the entangled state. He also performs a permutation operator on the second sequence. Finally, he sends the first and second sequences to Alice and Bob, respectively. Both Alice and Bob may check the correlations in a few of the shared Bell states to avoid an eavesdropping attempt as was done in Step2.1. Similarly, Charlie and Bob both being capable of performing quantum operations may also perform BB84 subroutine (cf. [65, 72, 73] and references therein).
Step3.2: Same as Step2.2 of Protocol 2.

Step3.3: **Announcements and eavesdropping checking:** After receiving an authenticated acknowledgment of the receipt of all the qubits from Bob, Alice announces which qubits have been encoded and which qubits have been left as decoy qubits. She also discloses the permutation operator corresponding to the decoy qubits only. Then Charlie announces the correct positions of the partner pairs of decoy Bell states in the Bob’s sequence. To detect eavesdropping, Bob measures the pairs of decoy qubits from Alice’s and Bob’s sequences in the Bell basis to calculate the errors. If sufficiently low errors are found they proceed to the next step, otherwise start afresh.

Step3.4: **Decoding the message:** To decode the message Bob can perform a measurement in the computational basis on all the remaining qubits from both the sequences received from Charlie and Alice. Meanwhile, Alice discloses her permutation operator enabling Bob to decode her message. However, he cannot decode Alice’s secret message yet as he is unaware of the permutation operator Charlie has applied.

Step3.5: **Charlie’s announcement:** Finally, Charlie sends the information regarding the permutation operator to Bob, using which Bob can decode Alice’s message.

It is important to note that two of the three parties involved in the CDSSQC protocols are considered quantum here. The possibilities of minimizing the number of parties required to have quantum resources will be investigated in the near future.

In the recent past, it has been established that the controlled counterparts of secure direct communication schemes [75–77] can provide solutions of a handful of real life problems. For instance, schemes of quantum voting [65,66] and e-commerce [63] are obtained by modifying the schemes for controlled DSQC. Here, we present the first semi-quantum e-commerce scheme, in which Alice (buyer) is classical, and Bob (merchant) and Charlie (online store) possess quantum resources. Both Alice and Bob are registered users of the online store Charlie. When Alice wishes to buy an item from Bob she sends a request to Charlie, who prepares a tripartite state (as in Eq. 2 of Protocol 2) to be shared with Alice and Bob. Alice encodes the information regarding her merchandise to Bob and encodes it as described in Step2.2. The merchant can decode Alice’s order in Step2.5 but will deliver the order only after receiving an acknowledgment from Charlie in Step2.5. Here, it is important to note that in some of the recent schemes, Charlie can obtain information about Alice’s order and/or change it, which is not desired in a genuine e-commerce scheme [10]. The semi-quantum e-commerce scheme modified from the proposed CDSSQC scheme is free from such an attack as Alice applies a permutation operator and discloses her permutation operator only after a successful transmission of all the travel particles. In a similar manner, another quantum e-commerce scheme may be obtained using CDSSQC scheme presented as Protocol 3, where the online store prepares only Bell states.

### 3.3 Possible attack strategies and security

Most of the attacks on the proposed CDSQC schemes may be circumvented in the same manner as is done in the SQKA scheme in Section 2.1. Here, we only mention additional attack strategies that may be adopted by Eve.

As discussed while security of SQKA scheme, the easiest technique for Eve would be a CNOT attack. Specifically, she may entangle her ancilla qubits with the travel qubits from Charlie to Alice and later disentangle them during Alice to Bob communication. She succeeds in leaving no traces using this attack.
and getting Alice’s all the information (see Section 2.1 for detail). However, Alice may circumvent this attack just by applying a permutation operator on all the qubits before sending them to Bob.

Eve may choose to perform an intercept and resend attack. Specifically, she can prepare an equal number of single qubits in the computational basis as Charlie has sent to Alice and send all these qubits to Alice, keeping the Charlie’s original sequence with herself. When Alice, Bob, and Charlie check the correlations in Step 1, they will detect uncorrelated string with Alice corresponding to this attack.

Eve can measure the intercepted qubits in the computational basis and prepares corresponding single qubits to resend to Alice. In this case, Eve will not be detected during correlation checking. However, Alice transmits the encoded qubits after permutation to Bob due to which Eve fails to decode her message, and consequently, Eve will be detected at Bob’s port during eavesdropping checking.

As mentioned beforehand both these attacks and the set of remaining attacks may be circumvented due to permutation operator applied by Alice.

4 Semi-quantum dialogue

In this section, we propose a two-party protocol for SQD, where Alice has all quantum powers and Bob is classical. The following are the main steps of the protocol.

Step 4.1: Alice’s preparation of quantum channel and encoding on it: Alice prepares \( n + m = N \) number of initial Bell states, i.e., \( |\psi^+\rangle^\otimes N \), where \( |\psi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \). She prepares two ordered sequences of all the first qubits as home (H) qubits and all the second qubits as travel (T) qubits from the initial Bell states. She keeps the home (H) qubits with herself and sends the string of travel qubits to classical Bob. The initial Bell states and encoding schemes are publicly known and let’s say that \( U_A \) and \( U_B \) are the measurement operations of Alice and Bob, respectively.

Step 4.2: Bob’s eavesdropping checking: Bob informs Alice about the reception of the travel sequence by a classical channel. Here, we can perform an eavesdropping checking strategy as discussed above in Step 1.1 of CDSSQC schemes in Section 3 that the joint measurement in the computational basis by Alice and Bob on the Bell pairs should be correlated. If they find error rate more than a threshold value, then they abort the protocol and starts from the beginning.

Step 4.3: Bob’s encoding: Bob measures \( n \) qubits (chosen randomly) in the computational basis and records all the measurement outcomes in a string of bits \( r_B \). Then he prepares a string of his message in binary as \( M_B \). Finally, he prepares fresh qubits in the computational basis for each bit value \( r_B \oplus M_B \) and reinserts them in the original sequence. Then he sends the encoded and decoy qubits back to Alice after performing a permutation on them. Here, it is important to note that the encoding operation used by Bob can be thought equivalent to Pauli operations \( \{I, X\} \) but they are performed classically by Bob, i.e., remaining within his classical domain.

Step 4.4: Alice’s eavesdropping checking: After receiving the authenticated acknowledgement of the receipt of all the qubits from Alice, Bob announces the positions of decoy qubits along with the corresponding permutation operator. Alice then measures all the decoy qubits in the Bell basis and any measurement outcome other than that of the initially prepared Bell state would correspond to an eavesdropping attempt.

Step 4.5: Alice’s encoding and measurement: For sufficiently low errors in eavesdropping checking Bob also discloses the permutation operator applied on the freshly prepared message qubits and Alice proceeds to encoding her secret on the qubits received from Bob by applying Pauli operations
| Bob’s message | Alice’s message | Final Bell state measurement outcome |
|---------------|----------------|--------------------------------------|
| $|0\rangle$    | $|0\rangle$    | $|\psi^\pm\rangle$                   |
| $|0\rangle$    | $|1\rangle$    | $|\phi^\pm\rangle$                   |
| $|1\rangle$    | $|0\rangle$    | $|\phi^\pm\rangle$                   |
| $|1\rangle$    | $|1\rangle$    | $|\psi^\pm\rangle$                   |

Table 2: All possible encoding of Alice and Bob with corresponding Bell measurement outcomes. Here, $|\psi^+\rangle$ is assumed to be the initial state.

$\{I, X\}$. Finally, she measures the partner pairs in Bell basis and announces her measurement outcomes. From the measurement outcomes, both Alice and Bob can extract Bob’s and Alice’s message, respectively.

Here, it should be noted that the Bell measurement performed in Step4.5 is not necessary, a two qubit measurement performed in the computational basis will also work in the above mentioned case.

In the recent past, it has been established that a scheme for quantum dialogue can be modified to provide a solution for the quantum private comparison, which can be viewed as a special form of socialist millionaire problem [16]. In the semi-quantum private comparison (SQPC) task [34], two classical users wish to compare their secrets of $n$-bits with the help of an untrusted third party possessing quantum resources. Before performing the SQPC scheme, the untrusted third party (Alice here) prepares a large number of copies of the Bell states using which both $Bob_1$ and $Bob_2$ prepare two shared unconditionally secure symmetric strings in analogy with the schemes described in [41]. They use one symmetric string as a semi-quantum key, while the other to decide the positions of the qubits they will choose to reflect or to measure. Specifically, both the classical users decide to measure the $i$th qubit received during the SQPC scheme if $i$th bit in the shared string is 1, otherwise they reflect the qubit. Using this approach both classical users prepare fresh qubit using the encoding operation defined in Step4.3, with the only difference that this time the transmitted information is encrypted by the shared key. Once Alice receives all the qubits and measures all of them in the Bell basis. Both the classical users disclose the string they had originally shared, using which Alice announces the measurement outcomes corresponding to the reflected qubits. $Bob_i$s can subsequently compute the error rate from the measurement outcomes and if the error rate is below the threshold, Alice publicly announces 1-bit secret whether both the users had the same amount of assets or not (see [34] for detail). Thus, we establish that a slight modification of Protocol 4 may lead to a new scheme for SQPC. This is interesting as to the best of our knowledge until now there exist only two proposals for SQPC [34,56].

### 4.1 Possible attack strategies and security

Most of the attacks on the proposed SQKA and CDSSQC schemes will also be valid on the SQD scheme. Further, as mentioned beforehand most of these attacks will be circumvented due to permutation operator Bob has applied. Here, it is worth mentioning that permutation operator is not a unique way to circumvent these attacks, a prior shared key will also ensure the security of the protocol. A similar strategy of using a prior shared key has been observed in a few protocols in the past [27]. We would like to emphasize here that employing a key for security is beyond the domain of direct communication. Therefore, we have preferred permutation of particles over a key in all the proposed schemes.

Further, it is shown in the past by some of the present authors [71,72] that if the information regarding the initial state is not a public knowledge and sent using a QSDC/DSQC protocol, then an inherent possible attack in QD schemes, i.e., information leakage attack, can be circumvented.
Performance of a quantum communication protocol can be characterized using qubit efficiency \( \eta = \frac{c}{q+b} \), which is the ratio of \( c \)-bits of message transmitted using \( q \) number of qubits and \( b \)-bits of classical communication. Note that the qubits involved in eavesdropping checking as decoy qubits are counted while calculating qubit efficiency, but the classical communication associated with it is not considered.

Before computing the qubit efficiency of the four protocols proposed here, we would like to note that in all the protocols the classical senders are sending \( n \) bits of secret, while in Protocol 4 (protocol for SQD, where both classical and quantum users transmit information), the quantum user Alice was also able to send the same amount of information to classical Bob. In all these cases, the classical sender encodes \( n \) bits secret information using \( n \)-qubits. However, to ensure the secure transmission of those \( n \)-qubits, another \( 3n \)-qubits are utilized (i.e., \( m = 3n \)). This is so because to ensure a secure communication of \( n \) qubits, an equal number of decoy qubits are required to be inserted randomly \([79]\). The error rate calculated on the decoy qubits decides, whether to proceed with the protocol or discard. In a semi-quantum scheme, a classical users cannot produce decoy qubits, so to securely transmit \( n \)-bit of classical information, he/she must receive \( 2n \) qubits from the quantum user, who would require to send these \( 2n \)-qubits to be used by user along with another \( 2n \) qubits, which are decoy qubits for the quantum user-classical user transmission. Thus, quantum user need to prepare and send \( 4n \) qubits to a classical user for sending \( n \) bits of classical communication.

The details of the number of qubits used for both sending the message (\( q_c \)) and checking an eavesdropping attempt (\( d \)) in all the protocols proposed here are explicitly mentioned in Table 3. In the last column of the table the computed qubit efficiencies are listed. From Table 3, one can easily observe that the qubit efficiency of three party schemes (Protocol 2 and 3) is less than that of two party schemes (Protocol 1 and 4). This can be attributed to the nature of three party schemes, where one party is supervising the one-way semi-quantum communication among two remaining parties, which increases the resource requirements to ensure the control power. In the controlled semi-quantum schemes, the qubit efficiency computed for Protocol 3 is comparatively more than Protocol 2 as the controller had chosen to prepare a bipartite entangled state instead of tripartite entangled state used in Protocol 2. This fact is consistent with some of our recent observations \([65]\). Among the two party protocols, Protocol 4 has a higher qubit efficiency than that of Protocol 1 as the quantum communication involved in this case is two-way.

Further, one may compare the calculated qubit efficiency with that of the set of protocols designed for the same task with all the parties possessing quantum resources. Such a comparison reveals that the requirement of unconditional security leads to decrease in the qubit efficiency for the schemes that are

| Protocol | Task  | \( c \) (bits) | \( q_c \) (qubits) | \( d \) (qubits) | \( q = q_c + d \) (qubits) | \( b \) (bits) | Qubit efficiency \( \eta = \frac{c}{q+b} \) |
|----------|-------|---------------|-------------------|----------------|-------------------------|-------------|----------------|-----------------|
| Protocol 1 | SQKA  | \( n \)       | 2\( n \)          | 3\( n \)       | 5\( n \)                | 5\( n \)    | \( \eta = 10\% \) |
| Protocol 2 | CDSSQC| \( n \)       | 4\( n \)          | 13\( n \)      | 17\( n \)               | 8\( n \)    | \( \eta = 4\% \) |
| Protocol 3 | CDSSQC| \( n \)       | 3\( n \)          | 10\( n \)      | 13\( n \)               | 8\( n \)    | \( \eta = 4.72\% \) |
| Protocol 4 | SQD   | 2\( n \)      | 2\( n \)          | 3\( n \)       | 5\( n \)                | 5\( n \)    | \( \eta = 20\% \) |

Table 3: The qubit efficiency of proposed semi-quantum protocols.
performed with one or more classical user(s) (for example, the qubit efficiency of a QKA scheme was 14.29% which is greater than 10% qubit efficiency obtained here for the SQKA protocol).

6 Conclusion

A set of schemes are proposed for various quantum communication tasks involving one or more user(s) possessing restricted quantum resources. To be specific, a protocol for key agreement between a classical and a quantum party is proposed in which both parties equally contribute in determining the final key and no one can control that key. To the best of our knowledge this is the first attempt to design a key agreement between classical and quantum parties. We have also proposed two novel schemes for controlled communication from a classical sender and a quantum receiver. It is important to note here that the proposed schemes are not only the first schemes of their kind, i.e., semi-quantum in nature, are also shown to be useful in designing a semi-quantum e-commerce schemes that can provide unconditional security to a classical buyer. The presented semi-quantum e-commerce schemes are relevant as the buyer is supposed to possess minimum quantum resources, while the online store (the controller) and the merchant may be equipped with quantum resources. This kind of a semi-quantum scheme can be used as a solution to a real life problem as in daily life, end users are expected to be classical. The present work is also the first attempt for designing semi-quantum schemes having direct real life application. Further, the first and an unconditionally secure scheme for dialogue among a classical and a quantum users is proposed here. Later it has also been shown that the proposed SQD scheme can be modified to obtain a solution for private comparison or socialist millionaire problem. The security of the proposed schemes against various possible attack strategies are also established.

The possibility of realizing semi-quantum schemes for these tasks establishes that the applicability of the idea of semi-quantum schemes is not restricted to key distribution and direct communication between a classical and quantum or two classical (only with the help of a third quantum party) parties. Our present work not only shows that almost all the secure communication tasks that can be performed by two quantum parties can also be performed in a semi-quantum manner at the cost of increased requirement of the quantum resources to be used by the quantum party. To establish this point, the qubit efficiencies of the proposed schemes are computed, which are evidently lower than the efficiency of the similar schemes with all the parties possessing quantum resources.

With the recent development of experimental facilities and a set of recent experimental realizations of some quantum cryptographic schemes, we hope that the present results will be experimentally realized in the near future and these schemes or their variants will be used in the devices to be designed for the daily life applications.

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References

[1] Bennett, C. H., Brassard, G.: Quantum cryptography: Public key distribution and coin tossing. In Proceedings of the IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore, India, 175-179 (1984)

[2] Pathak, A.: Elements of Quantum Computation and Quantum Communication. CRC Press, Boca Raton, USA (2013)

14
[3] Ekert, A. K.: Quantum cryptography based on Bell’s theorem. Phys. Rev. Lett. 67, 661 (1991)

[4] Bennett, C. H.: Quantum cryptography using any two nonorthogonal states. Phys. Rev. Lett. 68, 3121 (1992)

[5] Shukla, C., Alam, N., Pathak, A.: Protocols of quantum key agreement solely using Bell states and Bell measurement. Quantum Inf. Process. 13, 2391 (2014)

[6] Bostrom, K. Felbinger, T.: Deterministic secure direct communication using entanglement. Phys. Rev. Lett. 89, 187902 (2002)

[7] Banerjee, A., Pathak, A.: Maximally efficient protocols for direct secure quantum communication. Phys. Lett. A 376, 2944 (2012)

[8] Shukla, C., Banerjee, A., Pathak, A.: Improved protocols of secure quantum communication using W states. Int. J. Theor. Phys. 52, 1914 (2013)

[9] Long, G.-l., Deng, F.-g., Wang, C., Li, X.-h., Wen, K., Wang, W.-y.: Quantum secure direct communication and deterministic secure quantum communication. Front. Phys. China 2, 251 (2007)

[10] Huang, W., Yang, Y.-H., Jia, H.-Y.: Cryptanalysis and improvement of a quantum communication-based online shopping mechanism. Quantum Inf. Process. 14, 2211-2225, (2015)

[11] An, N. B.: Quantum dialogue. Phys. Lett. A 328, 6 (2004)

[12] An, N. B.: Secure dialogue without a prior key distribution. J. Kor. Phys. Soc. 47, 562 (2005)

[13] Man, Z. X., Zhang, Z. J., Li, Y.: Quantum dialogue revisited. Chin. Phys. Lett. 22, 22 (2005)

[14] Shi, G.-F.: Bidirectional quantum secure communication scheme based on Bell states and auxiliary particles. Opt. Commun. 283, 5275 (2010)

[15] Naseri, M.: An efficient protocol for quantum secure dialogue with authentication by using single photons. Int. J. Quantum Info. 9, 1677 (2011)

[16] Shukla, C., Kothari, V., Banerjee, A., Pathak, A.: On the group-theoretic structure of a class of quantum dialogue protocols. Phys. Lett. A 377, 518 (2013)

[17] Xia, Y., Fu, C.-B., Zhang, S., Hong, S.-K., Yeon, K.-H., Um, C.-I.: Quantum dialogue by using the GHZ state. J. Kor. Phys. Soc. 48, 24 (2006)

[18] Dong, L., Xiu, X.-M., Gao, Y.-J., Chi, F.: Quantum dialogue protocol using a class of three-photon W states. Commun. Theor. Phys. 52, 853 (2009)

[19] Gao, G.: Two quantum dialogue protocols without information leakage. Opt. Commun. 283, 2288 (2010)

[20] Zhou, N. R., Hua, T. X., Wu, G. T., He, C. S., Zhang, Y.: Single-photon secure quantum dialogue protocol without information leakage. Int. J. Theor. Phys. 53, 3829 (2014)

[21] Zhang, L.-L., Zhan, Y.-B.: Quantum dialogue by using the two-qutrit entangled states. Mod. Phys. Lett. B 23, 2993 (2009)
[22] Gao, G.: Information leakage in quantum dialogue by using the two-qutrit entangled states. Mod. Phys. Lett. B 28, 1450094 (2014)

[23] Yu, Z. B., Gong, L. H., Zhu, Q. B., Cheng, S., Zhou, N. R.: Efficient three-party quantum dialogue protocol based on the continuous variable GHZ states. Int. J. Theor. Phys. 55, 3147 (2016)

[24] Hwang, T., Luo, Y.-P.: Probabilistic authenticated quantum dialogue. Quantum Inf. Process. 14, 4631 (2015)

[25] Zheng, C., Long, G.F.: Quantum secure direct dialogue using Einstein-Podolsky-Rosen pairs. Sci. China Phys. Mech. Astron. 57, 1238 (2014)

[26] Ye, T.-Y.: Quantum secure direct dialogue over collective noise channels based on logical Bell states. Quantum Inf. Process. 14, 1487 (2015)

[27] Wang, H., Zhang, Y. Q., Liu, X. F., & Hu, Y. P.: Efficient quantum dialogue using entangled states and entanglement swapping without information leakage. Quantum Info. Process. 15, 2593-2603 (2016)

[28] Wen, X., Liu, Y., Zhou, N.: Secure quantum telephone. Opt. Commun. 275, 278 (2007)

[29] Sun, Y., Wen, Q.-Y., Gao, F., Zhu, F.-C.: Improving the security of secure quantum telephone against an attack with fake particles and local operations. Opt. Commun. 282, 2278 (2009)

[30] Jain, S., Muralidharan, S., Panigrahi, P. K.: Secure quantum conversation through non-destructive discrimination of highly entangled multipartite states. Eur. Phys. Lett. 87, 60008 (2009)

[31] Noh, T. G.: Counterfactual quantum cryptography. Phys. Rev. Lett. 103, 230501 (2009)

[32] Goldenberg, L., Vaidman, L.: Quantum cryptography based on orthogonal states. Phys. Rev. Lett. 75, 1239 (1995)

[33] Shukla, C.: Design and analysis of quantum communication protocols. Ph.D. thesis, Jaypee Institute of Information Technology, Sector-62, Noida, India, 1-166 (2015)

[34] Thapliyal, K., Sharma, R. D., Pathak, A.: Orthogonal-state-based and semi-quantum protocols for quantum private comparison in noisy environment. arXiv:1608.00101 (2016)

[35] Boyer, M., Kenigsberg, D., Mor, T.: Quantum key distribution with classical Bob. Phys. Rev. Lett. 99, 140501 (2007)

[36] Boyer, M., Gelles, R., Kenigsberg, D., Mor, T.: Semiquantum key distribution. Phys. Rev. A 79, 032341 (2009)

[37] Zou, X., Qiu., D., Li., L., Wu., L., Li, L.: Semiquantum-key distribution using less than four quantum states. Phys. Rev. A 79, 052312 (2009)

[38] Zou, X., Qiu, D., Zhang, S., Mateus, P.: Semiquantum key distribution without invoking the classical party’s measurement capability. Quantum Info. Process. 14, 2981-2996 (2015)

[39] Li, Q., Chan, W.-H., Zhang, S.: Semiquantum key distribution with secure delegated quantum computation. Sci. Rep. 6, 19898 (2016)
[40] Yu, K.-F., Yang, C.-W., Liao, C.-H., Hwang, T.: Authenticated semi-quantum key distribution protocol using Bell states. Quantum Inf. Process. 13, 1457-1465 (2014)

[41] Krawec, W. O.: Mediated semiquantum key distribution. Phys. Rev. A 91, 032323 (2015)

[42] Zhang, X.-Z., Gong, W.-G., Tan, Y.-G., Ren, Z.-Z. & Guo, X.-T. Quantum key distribution series network protocol with m-classical Bobs. Chin. Phys. B 18, 2143-2148 (2009)

[43] Sun, Z.-W., Du, R.-G., Long, D.-Y.: Quantum key distribution with limited classical Bob. Int. J. Quant. Inf. 11, 1350005 (2013)

[44] Krawec, W. O.: Semi-Quantum key distribution: protocols, security analysis, and new models. PhD thesis submitted at Stevens Institute of Technology, New Jersey, USA (2015)

[45] Krawec, W. O.: Restricted attacks on semi-quantum key distribution protocols. Quantum Info. Process. 13, 2417-2436, (2014)

[46] Lu, H., Cai, Q.-Y.: Quantum key distribution with classical Alice. Int. J. Quantum Inf. 6, 1195-1202 (2008)

[47] Li, C. M., Yu, K. F., Kao, S. H. et al. Authenticated semi-quantum key distributions without classical channel. Quantum Inf Process. 15, 2881 (2016)

[48] Boyer, M., Mor. T.: Comment on “Semiquantum-key distribution using less than four quantum states”. Phys. Rev. A 83, 046301 (2011)

[49] Maitra, A., Goutam, P.: Eavesdropping in semiquantum key distribution protocol. Info. Processing Letters 113, 418-422 (2013)

[50] Nie, Y.-y., Li, Y.-h., Wang, Z.-s.: Semi-quantum information splitting using GHZ-type states. Quantum Info. process. 12, 437-448 (2013)

[51] Qin, L., Chan, W. H., Long, D.-Y.: Semiquantum secret sharing using entangled states. Phys. Rev. A 82, 022303 (2010)

[52] Li, L., Qui, D., and Mateus, P.: Quantum secret sharing with classical Bobs. Journal of Physics A Mathematical and Theoretical 46, 045304 (2013)

[53] Jason, L., Yang, C.-W., Tsai, C.-W., Hwang, T.: Intercept-resend attacks on semi-quantum secret sharing and the improvements. Int. J. of Theor. Phys. 52, 156-162 (2013)

[54] Luo, Y.-P., Hwang, T.: Authenticated semi-quantum direct communication protocols using Bell states. Quantum Inf. Process 15, 947-958 (2016)

[55] Zou, X.-F., Qiu, D.-W.: Three-step semiquantum secure direct communication protocol. Physics, Mechanics & Astronomy, 57 , 1696-1702 (2014)

[56] Chou, W.-H., Hwang, T., Gu, J.: Semi-quantum private comparison protocol under an almost-dishonest third party, arXiv:1607.07961v2 (2016)

[57] Krawec, W. O.: Security proof of a semi-quantum key distribution protocol. In Information Theory (ISIT), IEEE International Symposium, 686-690 (2015)
[58] Miyadera, T.: Relation between information and disturbance in quantum key distribution protocol with classical Alice. Int. J. of Quant. Inf. 9, 1427-1435 (2011)

[59] Krawec, W.O.: Security proof of a semi-quantum key distribution protocol. DOI: 10.1109/ISIT.2015.7282542, IEEE 2015.

[60] Krawec, W.O.: Security of a semi-quantum protocol where reflections contribute to the secret key. Quantum Inf. Process. 15 2067-2090 (2016)

[61] Zhang, W., Qiu, D., Zou, X. and Mateus, P.: A single-state semi-quantum key distribution protocol and its security proof. arXiv preprint arXiv:1612.03087 (2016)

[62] Zhang, W. and Qiu, D.: Security of a single-state semi-quantum key distribution protocol. arXiv preprint arXiv:1612.03170 (2016)

[63] Chou, Y.-H., Lin, F.-J., Zeng, G.-J.: An efficient novel online shopping mechanism based on quantum communication. Electron Commer. Res. 14, 349-367 (2014)

[64] Sharma, R. D., Thapliyal, K., Pathak, A.: Quantum sealed-bid auction using a modified scheme for multiparty circular quantum key agreement. arXiv preprint arXiv:1612.08844v1 (2016)

[65] Thapliyal, K., Sharma, R. D., Pathak, A.: Protocols for quantum binary voting. Int. J. of Quantum Info. 15, 1750007 (2017)

[66] Sharma, R. D., De, A.: Quantum voting using single qubits. Indian Journal of Science and Technology 9, 98637 (2016)

[67] Fung, C.-H. F., Qi, B., Tamaki, K., Lo, H.-K.: Phase-remapping attack in practical quantum-key-distribution systems. Phys. Rev. A 75, 032314 (2007)

[68] Zhao, Y., Fung, C.-H. F., Qi, B., Chen, C., Lo, H.-K.: Quantum hacking: Experimental demonstration of time-shift attack against practical quantum-key-distribution systems. Phys. Rev. A 78, 042333 (2008)

[69] Lydersen, L., Wiechers, C., Wittmann, C., Elser, D., Skaar, J., Makarov, V.: Hacking commercial quantum cryptography systems by tailored bright illumination. Nat. Photonics 4, 686 (2010)

[70] Boyer, M., Dan, K., Tal, M.: Quantum key distribution with classical Bob. In Quantum, Nano, and Micro Tech., ICQNM’07. First International Conference, IEEE, 10-10 (2007)

[71] Banerjee, A., Thapliyal, K., Shukla, C., Pathak, A.: Quantum conference. arXiv:1702.00389v1 (2017)

[72] Banerjee, A., Shukla, C., Thapliyal, K., Pathak, A., Panigrahi, P. K.: Asymmetric quantum dialogue in noisy environment. Quantum Inf. Process. doi:10.1007/s11128-016-1508-4 (2016)

[73] Sharma, R. D., Thapliyal, K., Pathak, A., Pan, A. K., De, A.: Which verification qubits perform best for secure communication in noisy channel? Quantum Inf. Process. 15, 1703-1718 (2016)

[74] Srinatha, N., Omkar, S., Srikanth, R., Banerjee, S., Pathak, A.: The quantum cryptographic switch. Quantum Inf. Process. 13, 59 (2014)
[75] Thapliyal, K., Pathak, A.: Applications of quantum cryptographic switch: Various tasks related to controlled quantum communication can be performed using Bell states and permutation of particles. Quantum Inf. Process. 14, 2599 (2015)

[76] Pathak, A.: Efficient protocols for unidirectional and bidirectional controlled deterministic secure quantum communication: Different alternative approaches. Quantum Inf. Process. 14, 2195 (2015)

[77] Yu, Z. B., Gong, L. H., Wen, R. H.: Novel multiparty controlled bidirectional quantum secure direct communication based on continuous-variable states. Int. J. Theor. Phys. 55, 1447 (2016)

[78] Cabello, A.: Quantum key distribution in the Holevo limit. Phys. Rev. Lett. 85, 5635 (2000)

[79] Nielsen, M. A., Chuang, I. L.: Quantum Computation and Quantum Information. Cambridge University Press, New Delhi (2008)