Optical designs for realization of a set of schemes for quantum cryptography

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Abstract

Several quantum cryptographic schemes have been proposed and realized experimentally in the past. However, even with an advancement in quantum technology and escalated interest in the designing of direct secure quantum communication schemes there are not many experimental implementations of these cryptographic schemes. In this paper, we have provided a set of optical circuits for such quantum cryptographic schemes, which have not yet been realized experimentally by modifying some of our theoretically proposed secure communication schemes. Specifically, we have proposed optical designs for the implementation of two single photon and one entangled state based controlled quantum dialogue schemes and subsequently reduced our optical designs to yield simpler designs for realizing other secure quantum communication tasks, i.e., controlled deterministic secure quantum communication, quantum dialogue, quantum secure direct communication, quantum key agreement, and quantum key distribution. We have further proposed an optical design for an entanglement swapping based deterministic secure quantum communication and its controlled counterpart.

1 Introduction

The first protocol for quantum key distribution (QKD) was proposed by Bennett and Brassard [1], which provided security not conditioned on computationally complex tasks. Since then it has been strongly established that the quantum cryptography can provide unconditional security [2,3], which is a clear advantage over its classical counterparts. Inspired by this advantage, various schemes of QKD and other cryptographic tasks have been proposed ( [4–6] and references therein). Some of them have also been realized experimentally ( [7,8] and references therein). Interestingly, the quantum resources and the experimental techniques used in these successful experiments are not the same. To stress on this particular point, we may note that the QKD entered into the experimental era with the pioneering experimental work of Bennett et al. [7]. In this work, randomly prepared polarization states of single photons were used; but as there does not exist any on-demand single photon source, they used faint light beams generated from light emitting diode as approximate single photon source. If such a source is used, to circumvent photon number splitting (PNS) attack [9], one has to use decoy qubits to obtain security [10]. Obviously, in 1992 work of Bennett et al., no decoy qubit was used. However, in later experiments, decoy states have been frequently used. For example, in 2006, Zhao et al., had realized a decoy state based QKD protocol [11] using the acousto-optic modulators (AOMs) to achieve polarization insensitive modulation. In the absence of on-demand single photon sources, various strategies have been used to realize single photon based QKD schemes, like BB84 [1] and B92 [12]. Some of the experimentalists have used weak coherent pulse (WCP) as an approximate single photon source [8,13,20], while the others have used heralded single photon source [21,22]. Qubits are also realized in the polarization [7], phase [11], time-bin [23], and frequency [24] encodings of the photons (see [4] for review). In the last 28 years, a continuous progress has been observed in the experimental QKD. It started from the experimental realization of a single photon based QKD scheme using WCP, but as time passes many other facets of QKD have been experimentally realized. For example, in one hand MDI-QKD has been realized using untrusted source [25,26] and heralded single photon source [27,28]. On the other hand, soon it was realized that continuous variable QKD can be used to circumvent the need of single photon sources and thus to avoid several attacks ( [29] and references therein). Naturally, some of the continuous variable QKD schemes have been realized in the recent past [30,32]. Alternative schemes based on distributed phase reference QKD are also proposed and realized, for example, we may mention differential phase shift [33] and coherent one-way [34] protocols. It is also worth mentioning about the schemes for counterfactual quantum cryptography [35], QKD with orthogonal states [36] and higher dimensional quantum systems [37].
Quantum communication with a classical party \[58\]. Beyond this, to address the concerns of the end users, over the time the devices used by them have become portable (say, a silicon photonic transmitter is designed for polarization-encoded QKD \[39, 40\] and chip-based QKD systems have been realized \[41\]); QKD has been realized using erroneous source \[19\]. Key generation rate over noisy channel has been increased (e.g., in \[42\], a key generation rate of 1.3 Gbit/s was achieved over a 10-dB-loss channel); distance over which a key can be securely distributed has been increased, for example, in \[43\], QKD is performed over 421 km in optical fiber, underwater QKD is reported over 23 km optical fiber \[44\], and in the last 2-3 years, a couple of QKD experiments have been performed using satellites \[45, 46\] - the one which needs special mention is the quantum communication between the ground stations located at China and Austria at a distance of about 7600 km \[46\]. Furthermore, various commercial products, like Clavis 2 and Clavis 3 of ID Quantique \[47\] and MagiQ QPN of MagiQ \[48\], have also been marketed. Clavis 2 was hacked later that is why it is not available now. Experimental implementations of secure communication schemes have not only revealed several interesting features relevant for quantum foundations, but have also led to new technologies having clear advantages over the traditional technologies. For instance, plug and play QKD systems to circumvent phase and polarization compensation required in optical fibers. Similarly, an eavesdropper may design specific attacks depending upon the configuration—Trojan-horse attack \[49\] which can be circumvented by clever use of technology. Additionally, eavesdropping attempts exploiting side-channels or device imperfection also depend on the implementation (see \[5\] for review). Aim of the cryptographers is to implement universally composable secure quantum communication schemes \[50\].

From the discussion above it seems that the experimental QKD is now a matured area. However, the same is not true for other aspects of quantum cryptography, i.e., for the schemes beyond QKD (e.g., schemes for two- and three-party secure direct quantum communication). The secure direct quantum communication schemes exploit feasibility of transmitting message in a secure manner without any requirement of key generation/distribution, such as two-party one-way (quantum secure direct communication (QSDC), deterministic secure quantum communication (DSQC)), two-party two-way (quantum dialogue (QD)), three-party one-way (controlled deterministic secure quantum communication (CDSQC)), three-party two-way (controlled quantum dialogue (CQD)). Only a handful of experiments have yet been performed. Specifically, QSDC has been realized with single photons \[41\] and entangled photons \[52, 53\]. On top of that, quantum secret sharing has also been demonstrated \[54, 55\] and extended to multiparty scenario as well \[56\]. However, our discussion is focused on secure direct quantum communication schemes and quantum secret sharing is beyond the scope of the present work.

The above status of the experimental works have motivated us to investigate possibilities of experimental realization of quantum cryptographic schemes, such as QD \[6, 57\], CQD \[58\], Kak’s three-stage scheme inspired direct communication scheme \[59, 60\], CDSQC with entanglement swapping \[61\], which have not been experimentally realized so far. In the process, to design optical schemes for the realization of these schemes, we have perceived that the implementation requires some modifications of the original schemes. Keeping this point in mind, in the following sections of this work, we have modified the original schemes which remain operationally equivalent to the original scheme/without compromising with the security and have designed optical circuits for the above mentioned quantum cryptographic schemes, which are based on single photon, two-qubit, and multi-qubit entangled states (such as GHZ-like state, W state) using available optical elements, like laser, beamsplitter (BS), polarizing beamsplitter (PBS), half-waveplate (HWP).

The rest of the paper is organized as follows. In Section 2, we have presented the designs of optical circuits for various quantum cryptographic tasks. Each circuit and the original protocol it implements are also described in the corresponding section. Finally, the paper is concluded in Section 3.

## 2 Quantum cryptographic protocols

In the previous section, we have already mentioned that there exist unconditionally secure protocols for various quantum communication tasks and a good number of experiments have been done. However, until the recent past, experimental works on secure quantum communication were restricted to the experimental realizations of different protocols of QKD. Only recently (in 2016), a protocol of QSDC was realized experimentally by Hu et al. \[51\]. Specifically, Hu et al., realized DL04 protocol \[62\] using single-photon frequency coding. This pioneering work was a kind of proof-of-principle table-top experiment. In this work, the requirement of quantum memory was circumvented by delaying the photonic qubits in the fiber coils. However, soon after Hu et al.’s pioneering work, Zhang et al., \[52\] reported another experimental realization of QSDC protocol through a table top experiment. Zhang et al.’s experiment was fundamentally different from Hu et al.’s experiment in two aspects—firstly Zhang et al., used entangled states and secondly they used quantum memories based on atomic ensembles. Almost immediately after the Zhang et al.’s experiment, in 2017, Zhu et al., reported experimental realization of a QSDC scheme over a relatively longer distance \[53\]. With these three experiments, experimental quantum cryptography arrived at a stage beyond QKD, where a set of schemes of two-party one-way secure direct communication was experimentally realized using the available technologies. However, there exist many multi-party schemes of secure direct quantum communication, some of which are also two-way schemes. For example, any scheme for QD would require two-way communication, whereas any
scheme of controlled quantum communication involves at least three parties (say, a scheme for CQD). No such protocol has yet been realized experimentally. In what follows, we will see that many of these protocols can be realized experimentally using the existing technology. However, to do so, some of the protocols would require some modifications, which are needed for experimental realizations. Here, we would concentrate on such suitably modified protocols, and the optical circuits which can be used to experimentally realize those schemes. The optical designs proposed here can also be used for experimental implementation of some other DSQC schemes, for instance, MDI-QSDC scheme [63] using two-qubit entanglement and single photon source as well as Bell measurement to accomplish required teleportation.

In the following subsection, we will briefly describe a protocol of CQD and how to implement that using the existing optical technology. To do so, we will be very precise and restrict ourselves from the detailed discussion of the protocols or their security proof as those are available elsewhere and those are not of the interest of the present work. Specifically, we will briefly describe a protocol in a few steps which are essential. We will also provide a clear schematic diagram of the optical setup that can be used to realize the protocol, and will provide a step-wise description of the working of the setup. The same strategy will be followed in describing the other protocols, too.

2.1 Controlled quantum dialogue

To begin with, we may note that CQD is a three-party scheme. In any CQD scheme, Alice and Bob want to exchange their secret messages simultaneously to each other with the help of a third party Charlie (controller). In what follows, we will first summarize a set of CQD schemes of our interest [58,64] and the bottleneck present in the implementation of the theoretical schemes. After that we will explicitly show that it is possible to design optical circuits to experimentally realize CQD with entangled photons and single photon (in more than one way).

2.1.1 Scheme T1: CQD with single photons

Working of a CQD scheme based on single-qubit is summarized in the following steps:

Cs.1: Charlie prepares a random string of single qubits prepared in one of four states \( |0\rangle, |1\rangle, |+\rangle \) and \( |--\rangle \).

Cs.2: Charlie sends the string to Alice.

Cs.3: After Alice confirms that she has received the string, she randomly measures one-half of the qubits either in \( \{|0\rangle, |1\rangle\} \) or \( \{|+\rangle, |--\rangle\} \) basis and announces her measurement basis and results with corresponding position for checking the eavesdropping. Then Charlie compares the Alice’s measurement result with that of state preparation by using classical communication (CC) in all the cases where they have chosen the same basis\(^a\).

Cs.4: Alice encodes her message on the one-half of the remaining qubits by using Pauli operations \( I \) or \( iY \) to encode 0 or 1, respectively.

Cs.5: Alice sends the message encoded and (remaining) decoy qubits to Bob.

Cs.6: Bob receives the encoded photons (along with the remaining one-half to be used as decoy qubits).

Cs.7: To ensure the absence of Eve, Alice discloses the positions of the decoy qubits and Charlie announces corresponding choice of basis.

Cs.8: Bob encodes his message on the same qubits as was used by Alice to encode her message. Charlie announces the basis information for the message encoded qubits when he wishes the task to be accomplished. After knowing the basis of the initial state from Charlie, Bob measures the corresponding qubits in that basis and announces the measurement outcomes. Using the measurement outcomes both Alice and Bob can decode each other’s messages.

The aforementioned CQD scheme has not yet been realized experimentally due to unavailability of quantum memory, difficulty in building on-demand single photon sources, permutation of particles, and limitation in performing the scheme over scalable distance due to the complexity of the task. However, there is a silver lining that the CQD protocol using single photons can be realized using the existing technology, such as using frequency encoding, and permutation of particles can be circumvented at the cost of reduced qubit efficiency. To stress on this point a schematic diagram of the optical setup that can be used to realize the above protocol using polarization qubits is illustrated in Fig. [1] and in what follows, the same is elaborated in a few steps.

\(^a\)Throughout this paper, transmission of qubits in all Schemes \( T_j \) is performed along the same line after concatenation of a randomly prepared string of decoy qubits followed by permutation of qubits in the enlarged string. Subsequently, the error estimation on the transmitted decoy qubits provides an upper bound of the errors introduced during transmission on the remaining message qubits, which can be solely attributed to the disturbance caused due to an eavesdropping attempt for the sake of simplicity and attaining utmost security. The choice of decoy qubits could be the single-qubit states used in BB84 protocol or entangled states (see [65] for a detailed discussion).
Figure 1: Schematic diagram for CQD scheme based on polarization qubit. Four lasers are used to prepare the polarization states of photons. In the proposed optical design, BS stands for symmetric (50:50) beam splitter, PBS is polarizing BS, M is mirror, AM is amplitude modulator, PhM is phase modulator, QRNG is quantum random number generator, PC is polarization controller, HWP is half wave plate, OD is optical delay, PM is polarization modulator, OS is optical switch, $D_i$ represents the detector; whereas $D_H$ and $D_V$ correspond to detectors used for measurements in horizontal and vertical basis and similarly $D_+$ and $D_-$ correspond to measurements in the diagonal basis; and CC is classical communication.

**Scheme E1: Optical design for CQD protocol using single photons (polarization qubits)**

The Scheme T1 can be implemented in the following steps.

**Cs-O.1:** Charlie uses four lasers to generate the polarization state of the photons and two PBSs, three mirrors, one symmetric (50:50) BS, two amplitude modulators (AMs), one phase modulator (PhM), to generate the random string of single photons in one of the four polarization states $|H\rangle$, $|V\rangle$, $|+\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$ and $|-\rangle = \frac{|H\rangle - |V\rangle}{\sqrt{2}}$. Whereas, the first AM is used to generate the decoy photons, the second AM is used to control the intensity of light, and PhM randomizes phase to generate mixture of photon number states [8]. This is not a unique method for the preparation of polarization qubit, which can also be generated by heralding one outputs of the spontaneous parametric down conversion (SPDC) outputs.

**Cs-O.2:** Charlie sends the string of single photons to Alice through optical fiber, open-air, satellite, or under-water (in case of maritime cryptography). A polarization controller is used to compensate for the changes in polarization in case of transmission through an optical fiber.

**Cs-O.3:** Alice receives the string of photons and randomly selects one-half of the incoming photons using a BS to check any eavesdropping attempt. She randomly measures the reflected photons either in $\{|H\rangle, |V\rangle\}$ or in $\{|+, |-\rangle\}$ basis (again using a BS) and announces her measurement basis and results with corresponding position for checking the eavesdropping. Then Charlie compares Alice’s measurement result with that of state preparation. While the eavesdropping checking between Charlie and Alice, she uses an optical delay (serving as a quantum memory) for the rest of the photons.

Suppose Charlie prepares the photon from Laser1, i.e., in state $|V\rangle$ then detector $D_V$ is expected to click in the ideal case, but if the detector $D_H$ clicks, then it will be registered as bit error. However, if the detector $D_+$ or $D_-$ clicks then this case will be discarded.

**Cs-O.4:** Alice encodes her message on one-half of the transmitted photons by using a polarization modulator (PM) or a set of a half-waveplate sandwiched between two quarter-wave plates.

**Cs-O.5:** Alice sends encoded and decoy photons to Bob.

**Cs-O.6:** Bob receives the encoded photons along with the decoy photons and keeps the received photons in an optical delay. Subsequently, Alice discloses the positions of the decoy qubits, Charlie discloses corresponding basis, and Bob passes the string of photons through an optical switch which sends the encoded photons and decoy photons on different paths.
Cs-O.7: To ensure the absence of Eve, Bob chooses the basis of the decoy qubits by using a PM and measures them to compute the error rate. They proceed if the errors are below threshold.

Cs-O.8: Bob encodes his message using a PM on the same photons used by Alice to encode his message. Subsequently, Charlie reveals the basis information of corresponding state preparation. After knowing the basis choice of the initial state from Charlie, he measures the message encoded photons using two single photon detectors and a PM to choose the basis of the states to be measured and announces his result. In fact, Bob can perform the same task using only one PM if he delays his encoding till Charlie reveals the basis information. From the measurement outcomes both Alice and Bob will be able to decode each other’s messages.

2.1.2 Scheme T2: Kak’s three-stage scheme inspired five-stage scheme of CQD with single photons

A three-stage QKD scheme proposed in the past [59] was recently shown to be able to perform secure direct quantum communication [60]. Here, we propose a three-stage scheme inspired CQD protocol, which can be viewed as a five-stage protocol of CQD. The protocol is summarized in the following steps:

CK.1: Charlie prepares a string of single qubits in the computational basis. Subsequently, he applies random unitary operators on each qubit and keeps the corresponding information with himself.

CK.2: Same as Cs.2.

CK.3: After Alice confirms that she has received the qubits she measures one-half of the received qubits to check eavesdropping chosen by Charlie, who also disclose corresponding rotation operator and the initial state.

CK.4: Alice applies a random rotation operator on all the qubits.

CK.5: Same as Cs.5.

CK.6: Same as CK.3, here Bob measures one-half of the received qubits with the help of information of rotation operators by Charlie and Alice as well as the initial state revealed by Charlie.

CK.7: Same as CK.4, but Bob applies his rotation operator.

CK.8: Bob sends all the qubits to Charlie.

CK.9: After Charlie confirms that he has received the qubits he measures one-half of the received qubits to check eavesdropping with the help of Alice’s, Bob’s, and his own rotation operators.

CK.10: Charlie applies an inverse of his rotation operator applied in CK.1.

CK.11: Same as Cs.2.

CK.12: Same as CK.3, but here Alice requires information of the rotation operator from Bob.

CK.13: Alice applies inverse of the rotation operator applied in CK.4. Subsequently, she also encodes her message on one-half of the remaining qubits using Pauli operations $I$ or $X$ to send 0 or 1, respectively.

CK.14: Same as Cs.5.

CK.15: Same as CK.6, but Bob needs only his rotation operator, while positions of the decoy qubits are disclosed by Alice and initial state by Charlie.

CK.16: Bob applies inverse of his rotation operator and encodes his message on all the qubits. He subsequently measures the transformed qubits in the computational basis and announces the measurement outcomes. Finally, Charlie reveals the initial states when he wishes them to accomplish the task. With the help of the initial and final states both Alice and Bob can decode each other’s messages.

To complete two rounds, first for locking and second for unlocking, between three parties the qubits should travel five times through the lossy transmission channel which sets limitations on the experimental implementation of the present scheme. However, to remain consistent with the theme of the present work, where we aim to discuss the possibilities of reduction of complex quantum cryptographic tasks to obtain the solutions of simpler secure communication tasks, we now discuss the optically implementable scheme. In principle, the protocol described here can also be realized using available optical elements and a schematic diagram for that is shown in Figure [3] and the same is described below in a few steps.
Figure 2: Optical design of the CQD scheme with entangled photons and a complete Bell state measurement. In Charlie’s lab Cr1 and Cr2 are two nonlinear crystals which are used to generate the entangled photons. Attenuator (Att) is used to control the intensity of light so that a single Bell pair can be generated. This can also be controlled by changing the pump power. Sum frequency generation (SFG) type-I and type-II are nonlinear interactions, which are used to perform the Bell state measurement. DBS is dichroic BS and PP1 and PP2 are 45° projector. BSM is shown in the box.

Scheme E2: Optical design for five-stage scheme using single photons (polarization qubits)

Optical implementation of Scheme T2 works as follows.

CK-O_1: Charlie prepares a random string of horizontal and vertical polarized single photons and uses PM_C to rotate the polarization of these photons randomly.

CK-O_2: Same as Cs-O_2.

CK-O_3: Same as Cs-O_3, but here Charlie informs the decoy qubits by revealing the positions and corresponding random unitary operation using which Alice measures the photons in the computational basis with the help of optical switch, PM and single photon detectors. They proceed only if fewer than the threshold bit-flip errors are observed.

CK-O_4: Alice applies a random rotation on the rest of the qubits using PM_A.

CK-O_5: Same as Cs-O_5.

CK-O_6: Same as CK-O_3, here Alice and Bob perform eavesdropping checking with the help of Charlie.

CK-O_7: Same as CK-O_4, but Bob applies the random operation using PM_B.

CK-O_8: Bob sends all the qubits to Charlie.

CK-O_9: Same as CK-O_3, here Charlie needs assistance of both Alice and Bob to perform eavesdropping checking.

CK-O_10: Charlie applies the inverse of his rotation operator PM_C'.

CK-O_11-12: Same as CK-O_2-3.
Figure 3: A proposed optical implementation using polarization qubit of the five-step CQD scheme inspired from the three-stage scheme. Laser is used to prepare the polarization encoded qubits. In all the lab's, PM_{A,B,C} is polarization modulator used to implement a rotation operator, and PM'_{A,B,C} performs corresponding inverse rotation operator.

**CK-O.13:** Alice applies an inverse operation of her rotation operator using PM'_{A}. She also encodes her message on one-half of the qubits in this step (by using PM'_{A} only).

**CK-O.14-15:** Same as CK-O.5-6, but positions of decoy qubits are disclosed by Alice.

**CK-O.16:** Bob applies his inverse rotation operator PM'_{B} and encodes his message. Then he measures the polarization of the transformed qubits and announces the result. When Charlie wishes them to complete the task, he reveals the initial choice of polarization of his qubit.

So far, we have discussed schemes of CQD using single photons. Extending the idea, in what follows, we will discuss the CQD scheme using entangled states and subsequently discuss the optical implementation of such scheme.

### 2.1.3 Scheme T3: CQD protocol with entangled photons

CQD scheme based on entangled qubits is summarized in the following steps:

**Ce.1:** Charlie prepares a string of three qubit GHZ-like states \(|\psi\rangle_{123} = |\psi^+0\rangle + |\phi^+1\rangle\) with \(|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle), |\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)\).

He uses first and second qubit as a travel qubit and third qubit as a home qubit.

**Ce.2:** Charlie keeps all the third qubits and sends the strings of first and second qubits to Alice and Bob, respectively after inserting some decoy qubits in each string.

**Ce.3:** Same as Cs.3, but here both Alice and Bob perform eavesdropping checking on the strings received from Charlie.

**Ce.4:** Same as Cs.4, but Alice can use dense coding and encode 2 bits of message using all four Pauli operations.
Ce.5: Same as Cs.5, but here Alice randomly inserts freshly prepared decoy qubits before sending message encoded qubits to Bob.

Ce.6: Same as Cs.6.

Ce.7: Same as Cs.7, but Charlie need not disclose anything.

Ce.8: Bob encodes his message on the same qubits which were used by Alice to encode her message. Subsequently, Bob performs the Bell measurement on the messages encoded string and the string received from Charlie. Then he announces the measurement results. Now, Alice and Bob decode the message with the help of Charlie’s measurement results of the third qubits.

The CQD protocol using entangled photons described above can be realized using optical elements. A schematic diagram for that is shown in Figure [3] which is described briefly below in a few steps.

Scheme E3: Optical design for CQD protocol using entangled photons (polarization qubits)

Scheme T3 can be implemented as

Ce-O.1: Charlie uses two lasers and two non-linear crystals (Cr1 and Cr2) to generate the two pairs of Bell states with the help of SPDC process.

\[ |\psi\rangle_1 = \left(\frac{|HH\rangle + |VV\rangle}{\sqrt{2}}\right)_{12} \otimes \left(\frac{|HH\rangle + |VV\rangle}{\sqrt{2}}\right)_{34}, \]

where \( H \) and \( V \) represent the horizontal and vertical polarizations, respectively.

Now, 2nd and 4th photons pass through the HWP (\( 2\theta = 45^0 \)) and the state becomes

\[ |\psi\rangle_2 = \left(\frac{|H+\rangle + |V-\rangle}{\sqrt{2}}\right)_{12} \otimes \left(\frac{|H+\rangle + |V-\rangle}{\sqrt{2}}\right)_{34} = \frac{1}{2} \left( |H + H+\rangle + |H + V-\rangle + |V - H+\rangle + |V - V-\rangle\right)_{1234}. \]  

Subsequently, the 2nd and 4th photons pass through the two input ports of a PBS (which transmits the horizontal photon and reflects the vertical photon). The postselected state after passing through PBS such that only one photon will be in each output path can be written after renormalization as

\[ |\psi\rangle_3 = \frac{1}{2} \left( |H H H+\rangle + |H V V-\rangle + |V H H+\rangle - |V V V-\rangle\right)_{1234}. \]

Then photon 2’ passes through a HWP (\( 2\theta = 45^0 \)) and state transforms as

\[ |\psi\rangle_4 = \frac{1}{2} \left( |+\rangle_{2'} \left( | + H+\rangle + | - V-\rangle\right)_{134'} + | -\rangle_{2'} \left( | + H+\rangle - | - V-\rangle\right)_{134'} \right) \]

\[ = \frac{1}{2} \left( |+\rangle_{2'} \left( |+\rangle_{2'} |\psi^+\rangle_{14} + |\phi^+\rangle_{14} \right)_{134'} + | -\rangle_{2'} \left( |+\rangle_{2'} |\phi^+\rangle_{14} + |\psi^+\rangle_{14} \right)_{134'} \right) \]

\[ = \frac{1}{2} \left( |+\rangle_{2'} \left( |\Phi_1\rangle_{14} + |\Phi_2\rangle_{14} \right) \right). \]  

From the obtained state one can clearly see that if Charlie measures qubit 2’ and announces the measurement outcome, depending upon which all the parties can decide which channel they are sharing. Otherwise, if Charlie measures |+\rangle_{2'}, then he will get |+\rangle_{3'} |\psi^+\rangle_{14} + |\phi^+\rangle_{14}, need not apply any gate, i.e., identity, if he measures |−\rangle_{2'}, then he will get |+\rangle_{3'} |\phi^+\rangle_{14} + |−\rangle_{14}, it applies NOT gate on 1 or 4, then the state will be |+\rangle_{3'} |\psi^+\rangle_{14} + |−\rangle_{14}, |\phi^+\rangle_{14}. Also note that |\Phi_i\rangle are the unitary equivalent of the state prepared in Ce.1. The experimental preparation of three-qubit states using this approach can be found in Ref. [60].

Ce-O.2: Charlie sends corresponding photons 1 and 4 to Alice and Bob, respectively.

Ce-O.3: Both Alice and Bob receive the photons and choose the same set of photons using an optical switch to check their correlations with Charlie to check the eavesdropping. Bob keeps her photons in an optical delay. Here, it is worth mentioning that Alice and Bob can also use BS (as in Cs-O.3) for this task, but that will reduce qubit efficiency as the cases where one of them has measured entangled state, but not other will be discarded.

Ce-O.4: Same as Cs-O.4, but Alice uses dense coding as well.

Ce-O.5-6: Same as Cs-O.5-6.
Ce-O.7: Same as Cs-O.7, but Charlie has to reveal the measurement outcome for the corresponding decoy qubits 3' in diagonal basis.

Ce-O.8: Same as Cs-O.8, but Bob encodes his 2 bits of message on each photon used by Alice to encode her message by using PM. After that, Bob performs Bell measurement \[67\] and announces the measurement outcomes. Similarly, Charlie measures his qubit in the diagonal basis and announces the measurement results when he wishes Alice and Bob to decode the messages. There are schemes for probabilistic Bell measurement, but is not desirable in the implementation of direct communication schemes as it is prone to loss in encoded message. The drawback of deterministic Bell state measurement is small efficiency due to involvement of nonlinear optics in its implementation.

In principle, Charlie can measure qubit 3’ in Ce-O.1 and keep measurement result until Ce-O.7-8.

2.2 Controlled direct secure quantum communication

There is three-party one-way another controlled communication scheme where QSDC/DSQC from Alice to Bob is supervised by a controller. Specifically, Alice can directly transmits the message in a secure manner to Bob with the help of controller. QSDC (DSQC) scheme require no (an) additional CC by receiver for decoding the message. However, their controlled counterparts fall in CDSQC because Charlie has to disclose his information in the end.

2.2.1 CDSQC with single photons

The CQD schemes T1, T2 (E1, E2) discussed in the previous section can be reduced to CDSQC schemes if Bob does not encode his message in the last step. Additionally, he need not announce the measurement outcome as he is not sending message to Alice in this task.

2.2.2 CDSQC with entangled photons

The entangled states based CQD scheme T3 (E3) can also be reduced analogous to single photon based scheme to obtain a CDSQC scheme. Here, we have presented another entangled state based CDSQC \[3\] with entanglement swapping, where message encoded qubits are not accessible to Eve as those qubits do not travel through the channel.

2.2.3 Scheme T4: CDSQC with entanglement swapping

CDSQC with entanglement swapping is summarized in the following steps:

D.1: Charlie prepares a four qubit entangled state

\[
|\psi\rangle = \frac{1}{2} \left\{ (|\psi^+\rangle_{12}|0\rangle_3 + |\phi^+\rangle_{12}|1\rangle_3) |0\rangle_4 + (|\phi^+\rangle_{12}|0\rangle_3 + |\psi^+\rangle_{12}|1\rangle_3) |1\rangle_4 \right\},
\]

where qubit 4 corresponds to Charlie, qubits 1 and 2 for Alice and 3 for Bob.

D.2: Same as Ce.2 but Charlie keeps the fourth qubit, sends the first and second qubits to Alice and third qubit to Bob.

D.3: Same as Ce.3.

D.4: Alice prepares $|\psi^+\rangle_{A_1A_2}$ to encode her secret information. Specifically, she encodes 1 (0) by applying a $X (I)$ gate on one of the qubits of the Bell state. Thus, the combined state becomes

\[
|\psi'\rangle = \frac{1}{2}\sqrt{2} \left\{ (|\psi^+\rangle_{A_1A_2}(|\psi^+\rangle_{12}|0\rangle_3 + |\phi^+\rangle_{12}|1\rangle_3) |0\rangle_4 + (|\phi^+\rangle_{12}|0\rangle_3 + |\psi^+\rangle_{12}|1\rangle_3) |1\rangle_4 \right\}.
\]

D.5: Alice measures qubits $A_1$ and 1 as well as $A_2$ and 2 in the Bell basis, while Bob and Charlie can measure their qubits in the computational basis. Subsequently, Alice and Charlie announce their measurement outcomes, which should reveal Alice’s message to Bob.

To illustrate this point we can write the state before Alice’s and Bob’s measurements, while Charlie’s measurement result is $|0\rangle$ and Alice encodes 0, as

\[
|\psi'\rangle = \frac{1}{2}\sqrt{2} \left\{ (|\psi^+\rangle_{A_1}|\psi^+\rangle_{A_2}|\psi^+\rangle_{A_2} + |\phi^+\rangle_{A_1}|\phi^+\rangle_{A_2} + |\phi^-\rangle_{A_1}|\phi^-\rangle_{A_2} + |\psi^-\rangle_{A_1}|\psi^-\rangle_{A_2} + |\psi^-\rangle_{A_1}|\psi^-\rangle_{A_2}) |0\rangle_3 + (|\psi^+\rangle_{A_1}|\phi^+\rangle_{A_2} + |\psi^-\rangle_{A_1}|\phi^-\rangle_{A_2} + |\phi^+\rangle_{A_1}|\psi^+\rangle_{A_2} + |\phi^-\rangle_{A_1}|\psi^-\rangle_{A_2}) |1\rangle_3 \right\}.
\]
Notice that message encoded qubits \( D-O \) \( 4 \) will be clear from the optical design of corresponding scheme in Figure \( 4 \).

Similarly, if Charlie’s measurement result is \( |1\rangle \) and Alice encodes 1, the reduced state will be

\[
|\psi'\rangle = \frac{1}{\sqrt{2}} \left( \{|\psi^+\rangle A_1|\phi^+\rangle A_2 + |\phi^+\rangle A_1|\psi^+\rangle A_2 - |\phi^-\rangle A_1|\psi^-\rangle A_2 - |\psi^-\rangle A_1|\phi^-\rangle A_2\} |1\rangle_3 \\
+ \{|\psi^+\rangle A_1|\psi^+\rangle A_2 - |\psi^-\rangle A_1|\psi^-\rangle A_2 + |\phi^+\rangle A_1|\phi^+\rangle A_2 - |\phi^-\rangle A_1|\phi^-\rangle A_2\} |0\rangle_3 \right).
\]

(6)

If Charlie’s measurement result is \( |0\rangle \) and Alice encodes 1, the reduced state is

\[
|\psi''\rangle = \frac{1}{\sqrt{2}} \left( \{|\psi^+\rangle A_1|\phi^+\rangle A_2 - |\psi^-\rangle A_1|\psi^-\rangle A_2 + |\phi^+\rangle A_1|\phi^-\rangle A_2 - |\phi^-\rangle A_1|\phi^+\rangle A_2\} |1\rangle_3 \\
+ \{|\psi^+\rangle A_1|\phi^+\rangle A_2 + |\psi^-\rangle A_1|\phi^-\rangle A_2 + |\phi^+\rangle A_1|\psi^+\rangle A_2 + |\phi^-\rangle A_1|\psi^-\rangle A_2\} |0\rangle_3 \right);
\]

(7)

and if Charlie’s measurement result is \( |1\rangle \) and Alice encodes 0, the state is

\[
|\psi'\rangle = \frac{1}{\sqrt{2}} \left( \{|\psi^+\rangle A_1|\phi^+\rangle A_2 - |\psi^-\rangle A_1|\psi^-\rangle A_2 + |\phi^+\rangle A_1|\phi^-\rangle A_2 - |\phi^-\rangle A_1|\phi^+\rangle A_2\} |0\rangle_3 \\
+ \{|\psi^+\rangle A_1|\phi^+\rangle A_2 + |\psi^-\rangle A_1|\phi^-\rangle A_2 + |\phi^+\rangle A_1|\psi^+\rangle A_2 + |\phi^-\rangle A_1|\psi^-\rangle A_2\} |1\rangle_3 \right).
\]

(8)

Thus, if Charlie’s measurement outcome on qubit 4 and combined parity of Alice’s Bell measurements on \( (A_1, 1) \) and \( (A_2, 2) \) are same (opposite) then Bob knows her measurement outcome on qubit 3 is same (opposite) as Alice’s encoding.

Notice that message encoded qubits \( A_1 \) and \( A_2 \) are prepared and encoded locally by Alice and are not accessible to Eve. This will be clear from the optical design of corresponding scheme in Figure 4.

**Scheme E4: Optical design for CDSQC protocol with entanglement swapping using single photons (polarization qubits)**

The optical implementation of Scheme T4 works as follows.

**D-O.1:** Same as Ce-O.1. The four qubit state can be written as

\[
|\psi\rangle = \frac{1}{2} \left( |+\rangle_1 |+\rangle_2' \langle +| + \langle +| \psi^+\rangle_4 |+\rangle_4 + |+\rangle_1 |+\rangle_2' \langle +| \psi^+\rangle_4 |+\rangle_4 + |+\rangle_1 |+\rangle_2' \langle +| \phi^+\rangle_4 |+\rangle_4 + |+\rangle_1 |+\rangle_2' \langle +| \phi^+\rangle_4 |+\rangle_4 \right).
\]

(9)

**D-O.2:** Charlie sends corresponding photons \( 3' \) after passing through HWP (at \( 2\theta = 45^\circ \)) to Bob and photons 1 and 4 to Alice without any operation.

**D-O.3:** Bob randomly selects the photons by using BS from the received photons to check the eavesdropping and measures the photons in computational or diagonal basis by using single photon detectors. Same will be happen from Alice’s side, but, Alice’s photons will pass through two optical switches OS1 and OS2 to choose the decoy qubits. After that, she chooses a set of qubits (corresponding to computational basis measurement by Bob) using optical switches OS3 and OS4 to measure the received photons in Bell basis, while she performs single-qubit measurements on the rest of the qubits (corresponding to diagonal basis measurement by Bob) to check eavesdropping.
D-O.4: Alice prepares entangled state \(|\psi^+\rangle_{A_1A_2}\) to encode her secret information. Specifically, she applies a NOT gate using PM on one of the qubits of the Bell state to encode “1” and does nothing to send “0”. Therefore, the combined state of Alice and Bob before her encoding is

\[
|\psi'\rangle = \frac{1}{\sqrt{2}} \left( |\psi^+\rangle_{1A_2} + |\psi^+\rangle_{1A_2} \right) + \frac{1}{\sqrt{2}} \left( |\psi^+\rangle_{A_1A_2} + |\psi^+\rangle_{A_1A_2} \right) + |\psi^+\rangle_{A_1A_2} + |\psi^+\rangle_{A_1A_2} \right)
\]

D-O.5: Alice measures qubits \(A_1\) and \(1\) as well as \(A_2\) and \(2\) in Bell basis, while Bob can measure his qubits in the computational basis by using single photon detector. Subsequently, she announces her measurement outcomes, which should reveal her message to Bob. Finally, Charlie measures his qubit in diagonal basis and announces that when he wishes the task accomplished.

### 2.3 Quantum Dialogue

QD is a two-party scheme, where Alice and Bob as two parties wish to communicate their secret messages simultaneously to each other. QD can be reduced from the CQD as shown in [64]. Therefore, we have presented the feasibility of QD with single photons and entangled photons. Here, we briefly discuss the changes to be made in the CQD scheme to obtain the corresponding QD scheme.

#### 2.3.1 Scheme T5: QD with single photons

QD protocol, which can be reduced from Scheme T1, is summarized in the following steps:

Q.1: Same as Cs.1, but here Alice prepares the string.

Q.2: Alice sends the string to Bob as in Cs.2.

Q.3: Same as Cs.3, but Alice and Bob perform eavesdropping checking.

Q.4-7: Same as Cs.4-7, but roles of Alice and Bob are reversed from Scheme T1.

Q.8: Same as Cs.8, while Alice prepares the initial string, so she knows the basis used for its preparation. Therefore, in the end, Alice announces both initially prepared state and final states on measurement. Without loss of generality the initial state can be assumed public knowledge.

The above summarized QD protocol using single photons can be realized by optical elements and the optical circuit for that is illustrated in Figure 5 and the same is explained below in steps.

---

**Figure 5:** The proposed optical diagram using linear optics of the QD scheme which is based on single photons (polarization qubits).
Scheme E5: Optical design for QD protocol using single photons (polarization qubits)

Scheme T4 can be implemented in the following steps:

Q-O.1: Same as Cs-O.1, but here Alice prepares the string.
Q-O.2: Alice sends it to Bob.
Q-O.3-7: Same as Cs-O.3-7.
Q-O.8: Same as Cs-O.8, while Alice prepares the initial string so she knows the basis of string.

Similarly, the rest of the QD schemes using single photon (from Scheme T2) and entangled states (from Scheme T3) can be reduced from corresponding CQD schemes. Here, we have avoided such repetition and mentioned only briefly for the sake of completeness.

2.4 Quantum secure direct communication/Direct secure quantum communication

In quantum secure direct communication scheme, messages are transmitted directly in a deterministic and secure manner from Alice to Bob. A QSDC scheme can be viewed as a quantum dialogue, but the difference is only here that one party is restricted to encode the identity only. Similarly, a DSQC scheme can be deduced from a QSDC or CDSQC scheme where the receiver does not encode his/her message and requires an additional 1 bit of classical communication from the sender to decode the message.

2.5 Quantum key agreement

The proposed optical designs can also be used to reduce QKA schemes. Specifically, in quantum key agreement, all parties take part in the key generation process and none can control the key solely. A QKA scheme has been proposed in the recent past using a modified version of QSDC/DSQC scheme [68] which can be realized experimentally using present optical designs. Precisely, using QSDC scheme, one party sends his/her raw key to another party in a secure manner, while the other party publicly announces his/her key and the final key is combined from both raw keys. Therefore, the optical designs can be used for secure transmission of the first party’s raw key.

2.6 Quantum key distribution

The optical designs can be used to describe prepare-and-measure QKD schemes, too. Specifically, decoy qubit based QKD [10, 69] can be visualized from Cs-O.1-3 if Charlie (Bob) is the sender (receiver) and they share a quantum key by the end of this scheme. Similarly, the entangled state based CQD can be used to describe BBM scheme [70].

3 Conclusions

We have provided optical circuits for various quantum cryptographic schemes not yet experimentally realized (CQD, CDSQC with entanglement swapping, QD, etc.) with single and entangled photons (GHZ-like) as well as modified version of three-stage protocol. Interestingly, most of the designed optical circuits can be realized using both optical fiber based and open air based architectures. Specifically, we have shown feasibility (by providing optically implementable modified schemes) of three-party two-way scheme, i.e., a CQD scheme using single photons, a CQD scheme using tripartite entanglement, and a five-stage CQD scheme using single photons. We further deduced optical designs for three-party one-way and two-party one- and two-way quantum cryptographic schemes from these three CQD scheme, namely CDSQC, QD, QSDC, QKA, QKD. We have also proposed an entanglement swapping based DSQC and CDSQC schemes where encoded photons are both prepared and measured locally in sender’s lab and are thus never accessible to the eavesdropper. Additionally, the present results establish feasibility of several other secure communication schemes, such as asymmetric QD [71] and multiparty counterpart [72] of these schemes. Further, quantum solutions for some socio-economic solutions (which can be viewed as secure multiparty computation tasks) based on secure direct quantum communication schemes, for instance, sealed-bid auction [73], voting [74], e-commerce [75], private comparison [76]. Similar studies can be extended to semiquantum [77] and continuous variable [78, 79] counterparts of direct secure quantum communication schemes.

Being a theoretical physics group, we could not realize these optical circuits in the laboratory, but others having laboratory facility are expected to find the work reported here as interesting enough to perform experiments to realize the optical circuits designed in this paper. Further, we believe that this rigorous study will enable others to design new schemes for quantum
communication which will be experimentally realizable and to experimentally realize such new schemes as well as the existing schemes (after suitable modification following the approach adopted here) of various quantum communication tasks.

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References

[1] Bennett, C. H., Brassard, G.: Quantum cryptography: public key distribution and coin tossing. in: International Conference on Computer System and Signal Processing, IEEE, 1984 pp. 175–179 (1984)

[2] Shor, P. W., Preskill, J.: Simple proof of security of the BB84 quantum key distribution protocol. Physical Review Letters 85, 441 (2000)

[3] Renner, R.: Security of quantum key distribution. International Journal of Quantum Information 6, 1–127 (2008)

[4] Gisin, N., Ribordy, G., Tittel, W., Zbinden, H.: Quantum cryptography. Reviews of Modern Physics 74, 145 (2002)

[5] Pirandola, S., Andersen, U., Banchi, L., et al.: Advances in quantum cryptography. arXiv preprint arXiv:1906.01645 (2019)

[6] Pathak, A.: Elements of quantum computation and quantum communication. CRC Press (2013)

[7] Bennett, C. H., Bessette, F., Brassard, G., Salvail, L., Smolin, J.: Experimental quantum cryptography. Journal of Cryptology 5, 3–28 (1992)

[8] Lo, H.-K., Curty, M., Tamaki, K.: Secure quantum key distribution. Nature Photonics 8, 595 (2014)

[9] Brassard, G., Lütkenhaus, N., Mor, T., Sanders, B. C.: Limitations on practical quantum cryptography. Physical Review Letters 85, 1330 (2000)

[10] Lo, H.-K., Ma, X., Chen, K.: Decoy state quantum key distribution. Physical Review Letters 94, 230504 (2005)

[11] Zhao, Y., Qi, B., Ma, X., Lo, H.-K., Qian, L.: Experimental quantum key distribution with decoy states. Physical Review Letters 96, 070502 (2006)

[12] Bennett, C. H.: Quantum cryptography using any two nonorthogonal states. Physical Review Letters 68, 3121 (1992)

[13] Diamanti, E., Lo, H.-K., Qi, B., Yuan, Z.: Practical challenges in quantum key distribution. npj Quantum Information 2, 16025 (2016)

[14] Duplinskiy, A., Ustinchik, V., Kanapin, A., Kurochkin, V., Kurochkin, Y.: Low loss QKD optical scheme for fast polarization encoding. Optics Express 25, 28886–28897 (2017)

[15] Kiktenko, E. O., Pozhar, N. O., Duplinskiy, A. V., et al.: Demonstration of a quantum key distribution network in urban fibre-optic communication lines. Quantum Electronics 47, 798 (2017)

[16] Koashi, M.: Efficient quantum key distribution with practical sources and detectors. arXiv preprint quant-ph/0609180 (2006)

[17] Korzh, B., Lim, C. C. W., Houlmann, R., et al.: Provably secure and practical quantum key distribution over 307 km of optical fibre. Nature Photonics 9, 163 (2015)

[18] Wang, J., Qin, X., Jiang, Y., et al.: Experimental demonstration of polarization encoding quantum key distribution system based on intrinsically stable polarization-modulated units. Optics Express 24, 8302–8309 (2016)

[19] Xu, F., Wei, K., Sajeed, S., et al.: Experimental quantum key distribution with source flaws. Physical Review A 92, 032305 (2015)
[20] Gleim, A., Egorov, V., Nazarov, Y. V., et al.: Secure polarization-independent subcarrier quantum key distribution in optical fiber channel using BB84 protocol with a strong reference. Optics Express 24, 2619–2633 (2016)

[21] Soujaeff, A., Nishioka, T., Hasegawa, T., et al.: Quantum key distribution at 1550 nm using a pulse heralded single photon source. Optics Express 15, 726–734 (2007)

[22] Wang, Q., Chen, W., Xavier, G., et al.: Experimental decoy-state quantum key distribution with a sub-poissionian heralded single-photon source. Physical Review Letters 100, 090501 (2008)

[23] Gisin, N., Brunner, N.: Quantum cryptography with and without entanglement. arXiv preprint quant-ph/0312011 (2003)

[24] Sun, P., Mazurenko, Y., Fainman, Y.: Long-distance frequency-division interferometer for communication and quantum cryptography. Optics Letters 20, 1062–1064 (1995)

[25] Lo, H.-K., Curty, M., Qi, B.: Measurement-device-independent quantum key distribution. Physical Review Letters 108, 130503 (2012)

[26] Liu, C.-Q., Zhu, C.-H., Wang, L.-H., Zhang, L.-X., Pei, C.-X.: Polarization-encoding-based measurement-device-independent quantum key distribution with a single untrusted source. Chinese Physics Letters 33, 100301 (2016)

[27] Zhang, C.-H., Zhang, C.-M., Guo, G.-C., Wang, Q.: Biased three-intensity decoy-state scheme on the measurement-device-independent quantum key distribution using heralded single-photon sources. Optics Express 26, 4219–4229 (2018)

[28] Zhou, Y.-y., Zhou, X.-j., Su, B.-b.: A measurement-device-independent quantum key distribution protocol with a heralded single photon source. Optoelectronics Letters 12, 148–151 (2016)

[29] Srikara, S., Thapliyal, K., Pathak, A.: Continuous variable B92 quantum key distribution protocol using single photon added and subtracted coherent states. arXiv preprint arXiv:1906.07768 (2019)

[30] Grosshans, F., Grangier, P.: Continuous variable quantum cryptography using coherent states. Physical Review Letters 88, 057902 (2002)

[31] Gottesman, D., Preskill, J.: Secure quantum key distribution using squeezed states. Phys. Rev. A 63, 022309 (2001) doi:10.1103/PhysRevA.63.022309

[32] Ralph, T. C.: Continuous variable quantum cryptography. Physical Review A 61, 010303 (1999)

[33] Takesue, H., Nam, S. W., Zhang, Q., et al.: Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors. Nature Photonics 1, 343 (2007)

[34] Stucki, D., Valenta, N., Vannel, F., et al.: High rate, long-distance quantum key distribution over 250 km of ultra low loss fibres. New Journal of Physics 11, 075003 (2009)

[35] Brida, G., Cavanna, A., Degiovanni, I. P., Genovese, M., Traina, P.: Experimental realization of counterfactual quantum cryptography. Laser Physics Letters 9, 247 (2012)

[36] Avella, A., Brida, G., Degiovanni, I. P., et al.: Experimental quantum-cryptography scheme based on orthogonal states. Physical Review A 82, 062309 (2010)

[37] Gröblacher, S., Jennewein, T., Vaziri, A., Weihs, G., Zeilinger, A.: Experimental quantum cryptography with qudits. New Journal of Physics 8, 75 (2006)

[38] Boyer, M., Katz, M., Liss, R., Mor, T.: Experimentally feasible protocol for semiquantum key distribution. Physical Review A 96, 062335 (2017)

[39] Ma, C., Sacher, W. D., Tang, Z., et al.: Silicon photonic transmitter for polarization-encoded quantum key distribution. Optica 3, 1274–1278 (2016)

[40] Ding, Y., Bacco, D., Dalggaard, K., et al.: High-dimensional quantum key distribution based on multicore fiber using silicon photonic integrated circuits. npj Quantum Information 3, 1–7 (2017)

[41] Sibson, P., Erven, C., Godfrey, M., et al.: Chip-based quantum key distribution. Nature Communications 8, 1–6 (2017)
[42] Zhang, Z., Chen, C., Zhuang, Q., et al.: Experimental quantum key distribution at 1.3 Gbit/s secret-key rate over a 10-dB-loss channel. in: CLEO: QELS_Fundamental Science pp. FTu3G–5 Optical Society of America (2018)

[43] Boaron, A., Boso, G., Rusca, D., et al.: Secure quantum key distribution over 421 km of optical fiber. Physical Review Letters 121, 190502 (2018)

[44] Muller, A., Zbinden, H., Gisin, N.: Underwater quantum coding. Nature 378, 449–449 (1995)

[45] Khan, I., Heim, B., Neuzner, A., Marquardt, C.: Satellite-based QKD. Optics and Photonics News 29, 26–33 (2018)

[46] Liao, S.-K., Cai, W.-Q., Handsteiner, J., et al.: Satellite-relayed intercontinental quantum network. Physical Review Letters 120, 030501 (2018)

[47] Id quantique. https://www.idquantique.com/

[48] Magiq. https://www.magiqtech.com/

[49] Gisin, N., Fasel, S., Kraus, B., Zbinden, H., Ribordy, G.: Trojan-horse attacks on quantum-key-distribution systems. Physical Review A 73, 022320 (2006)

[50] Müller-Quade, J., Renner, R.: Composability in quantum cryptography. New Journal of Physics 11, 085006 (2009)

[51] Hu, J.-Y., Yu, B., Jing, M.-Y., et al.: Experimental quantum secure direct communication with single photons. Light: Science & Applications 5, e16144 (2016)

[52] Zhang, W., Ding, D.-S., Sheng, Y.-B., et al.: Quantum secure direct communication with quantum memory. Physical Review Letters 118, 220501 (2017)

[53] Zhu, F., Zhang, W., Sheng, Y., Huang, Y.: Experimental long-distance quantum secure direct communication. Science Bulletin 62, 1519–1524 (2017)

[54] Hai-Qiang, M., Ke-Jin, W., Jian-Hui, Y.: Experimental single qubit quantum secret sharing in a fiber network configuration. Optics Letters 38, 4494–4497 (2013)

[55] Schmid, C., Trojek, P., Bourennane, M., et al.: Experimental single qubit quantum secret sharing. Physical Review Letters 95, 230505 (2005)

[56] Smania, M., Elhassan, A. M., Tavakoli, A., Bourennane, M.: Experimental quantum multiparty communication protocols. npj Quantum Information 2, 16010 (2016)

[57] Nguyen, B. A.: Quantum dialogue. Physics Letters A 328, 6–10 (2004)

[58] 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 Information Processing 14, 2599–2616 (2015)

[59] Kak, S.: A three-stage quantum cryptography protocol. Foundations of Physics Letters 19, 293–296 (2006)

[60] Thapliyal, K., Pathak, A.: Kak’s three-stage protocol of secure quantum communication revisited: hitherto unknown strengths and weaknesses of the protocol. Quantum Information Processing 17, 229 (2018)

[61] Pathak, A.: Efficient protocols for unidirectional and bidirectional controlled deterministic secure quantum communication: different alternative approaches. Quantum Information Processing 14, 2195–2210 (2015)

[62] Deng, F.-G., Long, G. L.: Secure direct communication with a quantum one-time pad. Physical Review A 69, 052319 (2004)

[63] Niu, P.-H., Zhou, Z.-R., Lin, Z.-S., et al.: Measurement-device-independent quantum communication without encryption. Science Bulletin 63, 1345–1350 (2018)

[64] Thapliyal, K., Pathak, A., Banerjee, S.: Quantum cryptography over non-Markovian channels. Quantum Information Processing 16, 115 (2017)

[65] Sharma, R. D., Thapliyal, K., Pathak, A., Pan, A. K., De, A.: Which verification qubits perform best for secure communication in noisy channel? Quantum Information Processing 15, 1703–1718 (2016)
[66] Zhang, Q., Goebel, A., Wagenknecht, C., et al.: Experimental quantum teleportation of a two-qubit composite system. Nature Physics 2, 678 (2006)

[67] Kim, Y.-H., Kulik, S. P., Shih, Y.: Quantum teleportation of a polarization state with a complete Bell state measurement. Physical Review Letters 86, 1370 (2001)

[68] Shukla, C., Alam, N., Pathak, A.: Protocols of quantum key agreement solely using Bell states and Bell measurement. Quantum Information Processing 13, 2391–2405 (2014)

[69] Rosenberg, D., Harrington, J. W., Rice, P. R., et al.: Long-distance decoy-state quantum key distribution in optical fiber. Physical Review Letters 98, 010503 (2007)

[70] Bennett, C. H., Brassard, G., Mermin, N. D.: Quantum cryptography without Bell’s theorem. Physical Review Letters 68, 557 (1992)

[71] Banerjee, A., Shukla, C., Thapliyal, K., Pathak, A., Panigrahi, P. K.: Asymmetric quantum dialogue in noisy environment. Quantum Information Processing 16, 49 (2017)

[72] Banerjee, A., Thapliyal, K., Shukla, C., Pathak, A.: Quantum conference. Quantum Information Processing 17, 161 (2018)

[73] Sharma, R. D., Thapliyal, K., Pathak, A.: Quantum sealed-bid auction using a modified scheme for multiparty circular quantum key agreement. Quantum Information Processing 16, 169 (2017)

[74] Thapliyal, K., Sharma, R. D., Pathak, A.: Protocols for quantum binary voting. International Journal of Quantum Information 15, 1750007 (2017)

[75] Thapliyal, K., Pathak, A.: Quantum e-commerce: a comparative study of possible protocols for online shopping and other tasks related to e-commerce. Quantum Information Processing 18, 191 (2019)

[76] Thapliyal, K., Sharma, R. D., Pathak, A.: Orthogonal-state-based and semi-quantum protocols for quantum private comparison in noisy environment. International Journal of Quantum Information 16, 1850047 (2018)

[77] Shukla, C., Thapliyal, K., Pathak, A.: Semi-quantum communication: protocols for key agreement, controlled secure direct communication and dialogue. Quantum Information Processing 16, 295 (2017)

[78] Saxena, A., Thapliyal, K., Pathak, A.: Continuous variable controlled quantum dialogue and secure multiparty quantum computation. arXiv preprint arXiv:1902.00458 (2019)

[79] Srikara, S., Thapliyal, K., Pathak, A.: Continuous variable direct secure quantum communication using gaussian states. arXiv preprint arXiv:1909.09697 (2019)