Quantum secure direct communication network with superdense coding and decoy photons

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Received 17 April 2007
Accepted for publication 3 May 2007
Published 1 June 2007
Online at stacks.iop.org/PhysScr/76/25

Abstract

A quantum secure direct communication network scheme is proposed with quantum superdense coding and decoy photons. The servers on a passive optical network prepare and measure the quantum signal, i.e. a sequence of the $d$-dimensional Bell states. After confirming the security of the photons received from the receiver, the sender codes his secret message on them directly. For preventing a dishonest server from eavesdropping, some decoy photons prepared by measuring one photon in the Bell states are used to replace some original photons. One of the users on the network can communicate to any other one. This scheme has the advantage of high capacity, and it is more convenient than others as only a sequence of photons is transmitted in quantum line.

PACS number: 03.67.Hk

1. Introduction

Recently, a novel branch of quantum communication, quantum secure direct communication (QSDC) was proposed and actively pursued by some groups [1–15]. Different from QKD, the goal of QSDC is that the two parties of communication, say Bob and Charlie, can exchange the secret message directly without generating a private key first and then encrypting the message. The scheme proposed by Beige \textit{et al} [1] can be used to transmitted the secret message after the transmission of an additional classical bit for each qubit. Yan and Zhang [2] proposed a QSDC protocol with quantum teleportation. Gao \textit{et al} [3] introduced a QSDC protocol with quantum entanglement swapping. Man \textit{et al} [4] also presented a QSDC protocol with entanglement swapping. Zhu \textit{et al} [5] proposed a QSDC protocol with Einstein–Podolsky–Rosen (EPR) pairs based on the encryption on the order of the transmission of the particles, similar to that in the QKD protocol [16]. Wang \textit{et al} [6] revised this QSDC protocol with single photons, and Li \textit{et al} [7] improved its security against Trojan horse attack. The secret message in all these QSDC protocols can be read out by the receiver only after at least one bit of classical information is exchanged for each qubit. More accurately, they are deterministic secure quantum communication protocols pointed out by Li \textit{et al} [17], and are very useful for deterministic communication when the noise in a quantum line is not very low. Boström and Felbinger [8] proposed an interesting ping-pong QSDC following some ideas in quantum dense coding [18] with an EPR pair even though Wójcik [19] proved that the ping-pong protocol is insecure for direct communication if there are losses in a practical quantum channel and we [20] showed that it can be eavesdropped with a multi-photon fake signal fully if there is noise in the quantum channel. Cai and Li [9] improved the capacity of ping-pong protocol. We put forward a two-step QSDC protocol [10] with EPR pairs transmitted in block and another one based on a sequence of polarized single photons [11]. Wang \textit{et al} introduced a QSDC protocol with high-dimensional quantum superdense coding [12] and another one with Greenberger–Horne–Zeilinger (GHZ)
Many users

Carol1
Carol2
Bob1
Bob2
Alice1
Server1

Many branches and users

CarolM
Alice3
Bob1
Bob2
Server2

(a) Many users

Davidm
Davidd
Serverd

Many branches and users

Carolm
Alice2
Bob2
Serverd

(b) Many branches and users

Carol1
Carol2
Bob1
Bob2
Alice1
Server1

Many branches and users

CarolM
Alice3
Bob1
Bob2
Server2

Figure 1. The topological structure of the network, similar to those in [24–26]. (a) Star-configuration network; (b) loop-configuration network.

A practical quantum communication requires that any one on a passive optical network can communicate to another authorized user, similar to a classical communication network, such as the world wide web (i.e. www) and the classical telephone network. Usually, there are some servers (the number of the servers is much less than that of the users), say Alice7, who provide the service for preparing and measuring the quantum signal for the legitimate users on a passive optical network, which will reduce the requirements on the users’ devices for secure communication (not the servers) largely, the same as classical communication. By far, there are few any-to-any QSDC network schemes [23] although there are some point-to-point QSDC schemes [1–14] existing, which is different from QKD [24–26]. Moreover, the existing QSDC point-to-point schemes [1–9, 11–14] cannot be used directly to accomplish the task in a QSDC network except for the two-step QSDC protocol [10]. The reason is that a dishonest server can steal some information without being detected. In order to be practical and secure, the security of a QSDC network must be guaranteed against a dishonest server as the number of server is larger than one. For example, when the point-to-point QSDC schemes in [2–4, 8, 9, 11–13] are used for QSDC network directly, the server Alice can steal the information by using the intercepting-resending attack without disturbing the quantum signal as she prepares it and knows its original state. The QSDC network protocol in [23] is composed of three two-step point-to-point QSDC schemes. All the particles in the EPR pairs should be transmitted from the server to the sender and then to the receiver before they run back to the server. In 2005 Gao et al. [27] proposed a QSDC protocol for a central party and his agents. The quantum information can only be transmitted from the agents to the centre, not any one to any one on the network.

In this paper, we will introduce a QSDC network scheme following some ideas in quantum superdense coding [18, 28] with an ordered N EPR photon pairs. One authorized user can communicate to anyone on the network securely with the capability of measuring d-dimensional single-photon states. In this scheme, only one particle in each EPR pair is transmitted, which will make it more convenient than that in [23]. The decoy photons will ensure its security.

2. The QSDC network with superdense coding

In general, the structure of a QSDC network is the same as that for quantum key distribution (QKD) [24–26]. There are two kinds of topological structures for QSDC networks,

\[
|\Psi_{nm}\rangle_{AB} = \sum_{j=0}^{d-1} \frac{1}{\sqrt{d}} e^{2\pi i n j/d} |j\rangle_A \otimes |j + m \text{ mod } d\rangle_B \ ,
\]

where \(n, m = 0, 1, \ldots, d-1\), and \(A\) and \(B\) are the two photons in an EPR pair. The unitary operations

\[
U_{nm} = \sum_{j=0}^{d-1} e^{2\pi i n j/d} |j + m \text{ mod } d\rangle \langle j|.
\]

A symmetric \(d\)-dimensional EPR photon pair is in one of the Bell-basis states as follows [18, 28].

\[2\]

If the users on a passive optical network do not require that the servers provide the service for preparing the quantum signal, all the point-to-point QSDC protocols existing can be used to accomplish secure communication on the network. However, the communication, in this time, is just a point-to-point one, and each user should have the devices for preparing quantum signal and even taking joint multipartite measurements.

\[2\]
can transform the Bell-basis state

\[ |\psi_{00}\rangle_{AB} = \sum_j \frac{1}{\sqrt{d}} |j\rangle_A \otimes |j\rangle_B, \]

(3)

into the Bell-basis state \(|\psi_{nm}\rangle_{AB}\), i.e. \((I^A \otimes U^B_{nm})|\psi_{00}\rangle_{AB} = |\psi_{nm}\rangle_{AB}\). Here \(I^A\) is the identity matrix which means doing nothing on the photon \(A\), and \(U^B_{nm}\) are only operated on the photon \(B\). The two sets of unbiased measuring bases (MBs) can be chosen similar to those in a two-dimensional quantum system, labelled as \(Z_d\) and \(X_d\). Let us define the \(Z_d\)-MB which has \(d\) eigenvectors as the following:

\[ |0\rangle, \ |1\rangle, \ |2\rangle, \ldots, \ |d-1\rangle. \]

The \(d\) eigenvectors of the \(X_d\)-MB can be described as

\[ |0\rangle_x = \frac{1}{\sqrt{d}} (|0\rangle + |1\rangle + \cdots + |d-1\rangle), \]

\[ |1\rangle_x = \frac{1}{\sqrt{d}} (|0\rangle + e^{2\pi i/d} |1\rangle + \cdots + e^{(d-1)2\pi i/d} |d-1\rangle), \]

\[ |2\rangle_x = \frac{1}{\sqrt{d}} (|0\rangle + e^{4\pi i/d} |1\rangle + \cdots + e^{(d-1)4\pi i/d} |d-1\rangle), \]

\[ \ldots \]

\[ |d-1\rangle_x = \frac{1}{\sqrt{d}} (|0\rangle + e^{2(d-1)\pi i/d} |1\rangle + \cdots + e^{(d-1)^2\pi i/d} |d-1\rangle). \]

(5)

The two vectors \(|k\rangle\) and \(|l\rangle\) coming from two MBs satisfy the relation \(|k|l\rangle_\times^2 = \frac{1}{d^2}\), and the Hadamard (\(H_d\)) operation

\[ H_d = \frac{1}{\sqrt{d}} \begin{pmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{\pi i/d} & \cdots & e^{(d-1)\pi i/d} \\ 1 & e^{2\pi i/d} & \cdots & e^{(d-1)2\pi i/d} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{(d-1)\pi i/d} & \cdots & e^{(d-1)(d-1)\pi i/d} \end{pmatrix} \]

(6)

can realize the transformation between the states coming from the \(Z_d\)-MB and the \(X_d\)-MB, i.e. \(H_d|j\rangle_\times = |j\rangle_x\). Certainly, there are at most \(d+1\) sets of unbiased MBs for people to prepare and measure a \(d\)-dimensional quantum system [30]. Let us assume that the users use \(M\) MBs for preparing and measuring their quantum signals.

For the quantum communication, the server Alice prepares a sequence of EPR pairs, an ordered \(N\) \(d\)-dimensional photon pairs, in the same state \(|\psi_{00}\rangle_{AB}\). She takes one photon (A) from each entangled photon pair to make up an ordered partner photon sequence, say the sequence \(S_A\): \([P_1(A), P_2(A), \ldots, P_N(A)]\), the same as [10]. Here the subscript numbers are the orders of the \(N\) EPR pairs. The remaining partner photons in the photon pairs make up the other sequence, say \(S_B\): \([P_1(B), P_2(B), \ldots, P_N(B)]\). Here \(P_i(A)\) and \(P_i(B)\) are the two photons in the \(i\)th EPR pair. Different from the QKD network schemes [24–26], the server Alice first sends the sequence \(S_B\) to the receiver Charlie, and always keeps the sequence \(S_A\) by herself, depicted in figure 2. Charlie chooses one of the two modes, a small probability \(p\) with the checking mode and a large probability \(1 - p\) with the coding mode, for the photons received. If he chooses the checking mode, Charlie requires Alice to perform the measurements on the correlated photons in the sequence \(S_A\) with \(M\) MBs first, and then tell him the results. Charlie measures the samples with the same MBs as those of Alice’s and analyses the error rate of the samples. If the coding mode is chosen, Charlie operates each photon in the sequence \(S_B\) with one of the \(d\times d\) local unitary operations \(U_{nm}\), \((n, m = 0, 1, 2, \ldots, d-1)\) chosen randomly, say \(U_C\). For the eavesdropping check of the transmission between Charlie and Bob, Charlie picks up some samples distributing randomly in \(S_B\) and replaces them with the decoy photons [17, 26] which are prepared by Bob with one of the \(M\) MBs chosen randomly. He sends the sequence \(S_B\) to Bob. After confirmation of the security of the transmission, Bob codes his message on the photons received and announces the results. Before his coding, Bob chooses \(k\) photons in \(S_B\) and operates them choosing randomly one of the unitary operations \(U_{nm}\), and uses them for the eavesdropping check in the transmission from Bob to Alice.

After the security of the transmission of one batch of \(N\) order entangled photons is confirmed, the user codes the message on the photons and then sends them to the server Alice. The operation \(U_C\) done by the receiver Charlie is used to hide the message (i.e. the operation \(U_B\)) coded by the sender Bob, and the decoy technique is used to forbid the dishonest server to steal the information about the operation \(U_C\) freely. In this way, the QSDC network is performed until the communication session is ended.

Now, let us describe the steps for the subsystem of our QSDC network scheme in detail as follows.

\[(S1)\] The server Alice prepares a sequence of EPR photon pairs in the same state \(|\psi_{00}\rangle_{AB}\), and she divides them into two partner photon sequences \(S_A\) and \(S_B\). That is, she takes the photon \(A\) in each photon pair \(|\psi_{00}\rangle_{AB}\) to form the sequence \(S_A\), and the other photons make up the sequence \(S_B\). Alice sends the sequence \(S_B\) to the receiver of the secret message, Charlie, and always keeps the sequence \(S_A\) at home.

\[(S2)\] After receiving \(S_A\), Charlie checks the security of the transmission by the following method. (a) Charlie chooses randomly some photons from the sequence \(S_A\) as the samples for eavesdropping check. (b) Charlie requires Alice to measure the correlated photons in \(S_A\) with the \(M\) MBs.
chosen randomly, and tell him the results and her MBs. (c) Charlie takes the suitable measurements on the corresponding photons in his samples with the same MBs as those of Alice’s. (d) Charlie analyses the error rate by comparing his results with Alice’s to determine whether Eve is monitoring the quantum line. This is called the first eavesdropping check. If the error rate is very lower than the threshold $\epsilon_e$, they continue the quantum communication to the next step, otherwise they will discard the results and repeat the quantum communication from the beginning.

(S3) Charlie encrypts each photon in $S_B$ by choosing randomly one of the local unitary operations $\{U_{nm}\}$, say $U_C$, and then sends the sequence $S_B$ to the sender of the secret message, Bob. For the second eavesdropping check, Charlie chooses randomly some of the photons in $S_B$ as the samples, and replaces them with the decoy photons [17, 26], say $s_{e1}$, prepared in advance choosing randomly one of the $M$ MBs before they are sent to the quantum line. He keeps the secret about the positions and states of these samples.

(S4) Bob and Charlie take the second eavesdropping check with some samples. They can accomplish this task with the following method. (a) Charlie tells Bob the positions of the decoy photons $s_{e1}$ and their states. (b) Bob takes the suitable measurements on the photons in $s_{e1}$ with the correlated MBs. (c) Bob compares his results with those of Charlie’s and determines whether the transmission of the sequence $S_B$ from Charlie to Bob is secure. If the transmission is secure, the quantum communication is continued to the next step, otherwise it will be aborted and repeated from the beginning.

(S5) Bob codes his secret message on the photons remaining in $S_B$ with the corresponding local unitary operation $U_{ij}$, say $U_B$, according to his secret message. He picks up some of the photons in $S_B$ as the samples $s_{e2}$ for checking the security of the whole quantum communication. That is, he randomly performs one of the operations $\{U_{nm}\}$ on each sample. Bob sends the sequence $S_B$ to the server Alice.

(S6) Alice performs the joint $d$-dimensional Bell-basis measurements on the EPR photon pairs and publishes the results, say $U_A$.

(S7) Charlie and Bob check the security of the whole quantum communication with the samples $s_{e2}$. If the error rate of the samples is reasonably low, Charlie can read out the secret message $U_B$ as $U_A = U_C U_B$. Also, they can use some special techniques to correct the errors in the secret message, similar to the two-step protocol [10].

3. Discussion and summary

It is obvious that the present protocol is secure if the process of the quantum communication between Charlie and Bob is secure. The principle of the security in a quantum communication protocol depends on the fact that an eavesdropper’s action can be detected by analysing the error rate of the samples chosen randomly with statistical theory. In essence, the procedure for analysing the error rate of the samples in this paper is the same as that in the BB84 QKD protocol [31] and its modified version, the favoured-MBs QKD protocol which has been proposed by Lo et al [32] and proven to be unconditionally secure. That is, the authorized users choose randomly $M$ MBs to prepare and measure the samples. So the security of this protocol is similar to those in the BB84 protocol and its modified version with quantum privacy amplification [33]. Moreover, it appears that high-dimensional quantum communication protocols provide better security than that obtainable with two-dimensional quantum systems, as has been discussed in detail in [34] because the two authorized users can use more than two sets of unbiased MBs to check eavesdropping. Suppose that the two authorized users use $M$ sets of unbiased MBs to check eavesdropping, the error rate introduced by Eve’s eavesdropping is in principle $\epsilon_e = \frac{Md+1-M-d}{Md}$. If $d = 3$ and $M = 4$, $\epsilon_e = 50\%$ which is twice of that in BB84 QKD. That is, Eve’s action will introduce more errors in the results obtained by the two authorized users with measurements on the decoy photons and then be detected easily. Bechmann–Pasquinucci and Peres gave out the four unbiased MBs for the three-dimensional quantum system in [34]. In this time, the MB $Z_3$ can be chosen as

$$|0\rangle, \quad |1\rangle, \quad |2\rangle, \quad |3\rangle,$$

and the MB $X_3$ as

$$|x_0\rangle = \frac{1}{\sqrt{3}}(0 + |1\rangle + |2\rangle),$$

$$|x_1\rangle = \frac{1}{\sqrt{3}}(0 + e^{2\pi i/3}|1\rangle + e^{-2\pi i/3}|2\rangle),$$

$$|x_2\rangle = \frac{1}{\sqrt{3}}(0 + e^{-2\pi i/3}|1\rangle + e^{2\pi i/3}|2\rangle).$$

The two other bases can be taken as

$$\frac{1}{\sqrt{3}}(e^{2\pi i/3}|0\rangle + |1\rangle + |2\rangle) \text{ and cyclic permutation,}$$

and

$$\frac{1}{\sqrt{3}}(e^{-2\pi i/3}|0\rangle + |1\rangle + |2\rangle) \text{ and cyclic permutation.}$$

In a low noise quantum channel, the entanglement purification technique [35] for a high-dimensional quantum system can be used to reduce the information leaked about the operation $U_C$.

It is worth pointing out the advantage that the sequence $S_B$ is sent first to the receiver Charlie, not the sender Bob. The server Alice cannot steal the secret message yet if she is dishonest. That is, Charlie first encrypts the quantum states which will be used to carry the secret message, by choosing randomly one of the local unitary operations $\{U_{nm}\}$, and then sends them to the sender Bob. The operations done by Charlie $U_C$ are equivalent to the quantum key in the quantum one-time-pad crypto-system [11, 29] if Alice or an eavesdropper does not eavesdrop the quantum line between Charlie and Bob. On the other hand, it is necessary for Charlie and Bob to exploit the decoy-photon technique [17, 26] to forbid the server Alice to eavesdrop on the quantum line between Charlie and Bob freely and fully. If there are no decoy photons in $S_B$, Alice can read out the operation $U_C$ fully by intercepting the sequence $S_B$ when it is transmitted from Charlie to Bob and take the Bell-basis measurements on the $N$ order EPR photon pairs. Fortunately, the decoy photons inserted by Charlie can prevent Alice from stealing the information about the quantum key $U_C$ as Alice’s eavesdropping will leave
a trace in the results of the samples $s_{\pm 1}$, the same as that in the high-dimensional BB84 QKD protocol \[34\]. That is, the powerful eavesdropper, Alice, will leave a trace in the outcomes of the decoy photons as they are prepared with some random unbiased MBs and Alice has no information about them, including their positions and their states. Moreover, the eavesdropping done by Alice in the quantum line between Charlie and Bob can only obtain some information about the key $U_C$, not the secret message $U_B$ at the risk of being detected. Charlie and Bob can reduce the information leaked with quantum privacy amplification.

In essence, the coding done by the users is performed only after they confirm the security of the transmission in this QSDC network scheme, the same as the two-step QSDC protocol \[10\] which is secure as an eavesdropper cannot steal the information about the secret message, similar to the Bennett–Brassard–Mermin 1992 QKD protocol \[36–38\]. The eavesdropping on the quantum line between Alice to Charlie or Bob to Alice will be found out when Bob and Charlie analyse the error rate of the outcomes of the Bell-basis measurement on the EPR photon pairs on which Bob chooses randomly one of the local unitary operations $U_{\text{in}}$. And the eavesdropping can only obtain the combination of the two operations $U_A = U_CU_B$ which will be announced in public. In this way, the three processes, Alice to Charlie, Charlie to Bob, and Bob to Alice, for the transmission of the photons $S_B$ are similar to that between the sender and the receiver in the two-step QSDC protocol \[10\]. If all the error rates are reasonably low, the present QSDC network scheme can be made to be secure with some other quantum techniques, such as quantum privacy amplification, entanglement purification, quantum error correction, and so on.

As for the decoy photons \[17, 26\], Charlie can also prepare them without another single-photon source. He can produce them with measurements. That is, Charlie requires Alice to choose $n_1 + n_2$ photons in $S_A$ as the samples in the process for the first eavesdropping check. Alice measures all these $n_1 + n_2$ photons by choosing randomly the MB $Z_d$ or $X_d$, and publishes their states. But Charlie only measures $n_1$ photons in his corresponding sampling photons in $S_R$, and keeps the other $n_2$ photons as the decoy photons. As Charlie completes the error rate analysis for the first eavesdropping checking by himself, it is unnecessary for him to publish the outcomes and positions of the sampling photons measured by Charlie. He need only publish the result that the error rate is reasonable low or not. In this way, none knows which photons are the decoy ones and their states. Also, Charlie can choose some unitary operations to change the basis of a decoy photon. This good nature will reduce the requirements on the users’ devices as they need not have an ideal single-photon source in their quantum communication.

As the quantum data in QSDC schemes \[2–5, 10–12\] should be transmitted with a block, the present QSDC network scheme with quantum storage technique will have a high source capacity as each photon can carry $2\log_2 d$ bits of information. Even though the technique is not fully developed, it is believed that this technique will be available in the future as it is a vital ingredient for quantum computation and quantum communication and there has been great interest \[39\] in developing it. As only a sequence of photons $S_B$ is transmitted in the present QSDC network scheme, it is more convenient than others \[23\]. The users need only exchange a little of the classical information for checking eavesdropping and the server publishes a bit of classical information for each qubit, the present scheme is an optimal one from the view of information capacity exchanged.

For implementing this QSDC network, high-dimensional quantum systems are required. At present, people can choose polarized photons as the two-dimensional quantum systems for this QSDC network without difficulty. Another feasible candidate of quantum information carriers may be the phases of photons. Recently, people employed orbital angular momentum states of photons to carry more information for communication \[40, 41\]. With the improvement of high-dimensional quantum systems become convenient and their application to optical communications is feasible.

In summary, a scheme for QSDC network is proposed with superdense coding and decoy photons. After confirming the security of the transmission, the user on the network codes his secret message on the quantum states which has been encrypted by the receiver with one of the local unitary operations $\{U_{\text{in}}\}$ chosen randomly. For preventing the dishonest server from eavesdropping, the receiver picks up some samples from the sequence received and replaces them with the decoy photons which can be produced with measurements and unitary operations before he sends the sequence to the sender. An authorized user on the network can communicate to another one securely. This scheme has the advantage of high capacity as each photon can carry $2\log_2 d$ bits of information and it is more convenient than others \[23\] as only a sequence of photons is transmitted in quantum line.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under grant nos 10604008 and 10435020, and the Beijing Education Committee under grant no XK100270454.

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