Experimental quantum cryptography scheme based on orthogonal states

Alessio Avella, Giorgio Brida, Ivo Pietro Degiovanni, Marco Genovese, Marco Gramenegna and Paolo Traina

INRIM, Strada delle cacce 91, Turin, Italy.

Since, in general, non-orthogonal states cannot be cloned, any eavesdropping attempt in a Quantum Communication scheme using non-orthogonal states as carriers of information introduces some errors in the transmission, leading to the possibility of detecting the spy. Usually, orthogonal states are not used in Quantum Cryptography schemes since they can be faithfully cloned without altering the transmitted data. Nevertheless, L. Goldberg and L. Vaidman [Phys. Rev. Lett. 75 (1995) 1239] proposed a protocol in which, even if the data exchange is realized using two orthogonal states, any attempt to eavesdrop is detectable by the legal users. In this scheme the orthogonal states are superpositions of two localized wave packets travelling along separate channels. Here we present an experiment realizing this scheme.

PACS numbers: 03.67.Hk, 03.67.Dd, 42.50.Ex, 42.50.St

Quantum Key Distribution (QKD) is a method for transmitting a secret key between two partners (usually named Alice and Bob) by exploiting quantum properties of light. The most important characteristic of this idea is that the secrecy of the generated key is guaranteed by the very laws of nature, i.e. by the properties of quantum states. In the last decade QKD has abandoned the laboratories becoming a mature technology for commercialization; communications over more than 100 km having been achieved both in fiber and open air.

Various protocols for realising QKD have been suggested, such as BB84, B92, Ekert. All of them are based on the use of non-orthogonal states, a condition that was considered necessary for guaranteeing security, up to a paper of Goldenberg and Vaidman (GV) in 1995. In that work was presented for the first time a scheme for realising a QKD protocol based on orthogonal states, whose security was based on two ingredients. First, the orthogonal states sent by Alice were superposition of two localized wave packets that were not sent simultaneously to Bob. Second, the transmission time of the photons was random.

This scheme, beyond its interest for application, has also a large conceptual interest for understanding the quantum resources/properties needed for QKD. Nevertheless, up to now, no experimental realization was still done. Purpose of this letter is to present its first experimental implementation.

In the theoretical proposal of Ref. [8], the orthogonal states sent by Alice are the superpositions of two localized wave-packets. Those are not sent simultaneously to Bob, but separated by a fixed delay. In this case there is a direct correspondence between the state prepared by Alice and the bit received by Bob, for instance,

\[
0 \rightarrow |\Psi_0\rangle = \frac{1}{\sqrt{2}}(|a\rangle + |b\rangle)
\]

\[
1 \rightarrow |\Psi_1\rangle = \frac{1}{\sqrt{2}}(|a\rangle - |b\rangle),
\]

where |a\rangle and |b\rangle are two localized wave-packets and the states |\Psi_0\rangle and |\Psi_1\rangle are orthogonal. The states |\Psi_0\rangle and |\Psi_1\rangle are emitted randomly in time, and the presence of an eventual eavesdropper can be detected by legitimate users exploiting the information on the detection times. The scheme works as follows: Alice sends Bob either |\Psi_0\rangle or |\Psi_1\rangle. The launch on the quantum channel of the wave-packet |b\rangle is delayed for some amount of time \(\tau\) with respect to the launch of wave-packet |a\rangle. \(\tau\) could be chosen larger than the traveling time \(T\) of photons between Alice’s and Bob’s locations. As |b\rangle will travel through the quantum channel only after the wave-packet |a\rangle has already reached Bob’s location, both packets are never simultaneously present in the quantum channels. Furthermore, as pointed out in Ref. [8], the requirement of \(\tau\) greater than the traveling time \(T\) is not strictly necessary. Indeed the security of the protocol is ensured even if \(\tau\) is only greater than the overall uncertainty in the measurement of the transmission/detection times \(t_s\) and \(t_r\).

In our proof-of-principle experiment this is obtained exploiting a balanced Mach-Zehnder Interferometer (MZI) with two equal optical delays \(OD_1\) and \(OD_2\). According to Fig. 1, sources of single photon \(S_0\) and \(S_1\) at the two input ports of the beam splitter on Alice side provide single photons propagating in the transmission channel in the state |\Psi_0\rangle or |\Psi_1\rangle respectively. The emission time of the single photon in one of the two state is random, but it is registered by Alice.

As the packet |b\rangle is stored in \(OD_1\), wave-packet |a\rangle travels from Alice’s to Bob’s site along the upper channel and enters in \(OD_2\), where it is delayed until also |b\rangle reaches Bob’s site. In this way the two packets interfere as they simultaneously arrive to the second beam-splitter, thus, the click of detector \(D_1\) deterministically implies that the single photon state was in the state |\Psi_i\rangle, i.e. it was sent by source \(S_i\). Two security tests are performed by Alice and Bob to highlight the possible presence of an eavesdropper. The first one is a public comparison between the sending times \(t_s\) and the receiving times \(t_r\).
for each photon. If we assume that the traveling time between the two parties is $T$, only the events detected at time $t_\epsilon + \tau + T$ are considered as part of the message, while all the others highlight the presence of Eve. The second one is the comparison of corresponding portions of the legitimate users’ bit strings to estimate the quantum bit error rate (QBER). We underline that in the ideal case discrepancies in the transmission/detection times or in the bit strings can only be induced by an eavesdropper.

Let us mention for the sake of completeness that it was argued by Peres that this protocol introduced no novelty with respect to BB84. To this claim GV replied that while in other protocols like BB84 the security is guaranteed by nonorthogonality, in GV protocol it is based on causality, since they proved that a successful eavesdropping would require superluminal signaling. Furthermore, while all cryptographic schemes require two steps for sending information (sending the quantum object and then some classical information), in GV protocol only the first step is needed for communication, the second step is used only for assuring security against eavesdropping.

Fig. 1 shows the setup of the experiment representing the first realization of the GV protocol. The single photon states are obtained exploiting an heralded single photon source based on parametric down-conversion (PDC) obtained by pumping with a 406 nm CW laser beam a type I BBO crystal) are injected in the MZI, one at the time. Alice’s site is composed by the two single photon sources and the first optical delay ($OD_1$). Bob’s site is composed by the second optical delay ($OD_2$, identical to $OD_1$) and the two single photon detectors ($D_0$, $D_1$).

FIG. 1: Experimental set-up. Two single photon sources ($S_0$, $S_1$), realized exploiting an heralded single photon source based on parametric down-conversion (PDC) obtained by pumping with a 406 nm CW laser beam a type I BBO crystal) are injected in the MZI, one at the time. Alice’s site is composed by the two single photon sources and the first optical delay ($OD_1$). Bob’s site is composed by the second optical delay ($OD_2$, identical to $OD_1$) and the two single photon detectors ($D_0$, $D_1$).
FIG. 2: Number of detected events per second at detector $D_0$ and $D_1$ as a function of the path length difference $\Delta l$ between the two arms of the interferometer for source $S_0$ (top picture) and $S_1$ (bottom). As expected, the phase shifts between $D_0$ and $D_1$ sine fits of the coincidence counts are consistent with $\pi$.

TABLE I: Main results obtained in the implementation of the QKD protocol proposed in Ref. [8]. $V_{D0}$, $V_{D1}$ are the visibilities of the interference fringes observed at the two outputs of the interferometer by scanning the path length difference, $QBER$ is the estimated quantum bit error rate for the transmission.

|       | $V_{D0}$   | $V_{D1}$   | $QBER$       |
|-------|------------|------------|--------------|
| $S_0$ | (89 ± 1)\% | (82 ± 1)\% | (7.0 ± 1.6)\% |
| $S_1$ | (88 ± 1)\% | (85 ± 1)\% | (7.1 ± 1.4)\% |

Thank L. Vaidman for having pointed out to our attention his theoretical work.

[1] N. Gisin et al., Rev. Mod. Phys. 74, 145 (2002).

FIG. 3: Detection events at both detectors $D_1$ and $D_0$. Top: source $S_0$ is active, corresponding to the transmission of a string of bit 0. Bottom: source $S_1$ is active, corresponding to the transmission of a string of bit 1. The evaluated Quantum Bit Error Rate ($QBER$) in the two cases are $QBER_{S_1} = 0.071 ± 0.014$ and $QBER_{S_0} = 0.070 ± 0.016$ on a series of 60 measurements 5 seconds long, showing a remarkable phase stability of the interferometer.

[2] T. Langer and G. Lenhart New J. Phys. 11 (09) 055051.
[3] E. Diamanti et al., arXiv 0608110; P.A. Hiskett et al., NJP 8 (06) 193; I. Marcikic et al., arXiv0404124; T. Kimura et al., Jpn. J. Appl. Phys. 43 (04) L 217; A. Tanaka et al., Opt. Exp. 16 (08) 11354; A. Dixon et al., Opt. Exp. 16 (08) 19118; D. Stucki et al., arXiv 0906.9187; D. Rosenberg et al., NJP 11 (09) 050551 ;
[4] A. Semenov et al., PRA 80 (09) 021802; C. Erven et al., qph0807.2489; T. Manderbach et al, PRL 98 (07) 010504; R. Ursin et al., Nat. Phys. 3 (07) 481; C. Bonato et al., NJP 11 (09) 045017; N. Antonietti et al., Int. Journ Quant. Inf. 7 (2009) 213.
[5] C. H. Bennett and G. Brassard, Proc. of IEEE Int. Conf. on Computers, Systems and Signal Processing, Bangalore, India, IEEE New York, 175 (1984).
[6] C. H. Bennett et al., J. Cryptology 5, 3 (1992).
[7] A. K. Ekert, Phys. Rev. Lett. 67, 661 (1991).
[8] L. Goldenberg and L. Vaidman, Phys. Rev. Lett. 75 (1995) 1239; 77 (1996) 3265.
[9] A. Peres, Phys. Rev. Lett. 77 (1996) 3264.
[10] P. W. Shor, in Proceedings of 35th Annual Symposium on Foundations of Computer Science (IEEE, New York, 1994), p. 124.
[11] L. Mandel, E. Wolf, Optical Coherence and Quantum Optics, Cambridge University Press, Cambridge, 1985; M. Genovese, Phys. Rep. 413, 319 (2005) and refs therein.