Deterministic Plug-and-Play for Quantum Communication

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We present a scheme for secure deterministic quantum communication without using entanglement, in a Plug-and-Play fashion. The protocol is completely deterministic, both in the encoding procedure and in the control one, thus doubling the communication rate with respect to other setups; moreover, deterministic nature of transmission, apart from rendering unnecessary bases revelation on the public channel, allows the realization of protocols like ‘direct communication’ and ‘quantum dialogue’. The encoding exploits the phase degree of freedom of a photon, thus paving the way to an optical fiber implementation, feasible with present day technology.

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I. INTRODUCTION

Quantum Key Distribution (QKD) has been the first practical realization of communication based on the laws of the quantum mechanics. As Bennett and Brassard showed with their pioneer protocol BB84\(^1\), nonorthogonal quantum states, together with an unjammable classical channel, can be used to prevent an eavesdropper (Eve) from gaining information on the key without being revealed. There are already different working realizations of BB84\(^2\). Some of them\(^3\) exploit entanglement in polarization to encode a random string of bits in two unbiased polarization bases of a single photon, thus following the original proposal. However, polarization is not the most suitable degree of freedom for fiber communication because birefringence usually fluctuates randomly in a fiber, making the encoded information impossible to decode. The most appealing setup for real telecom communications is based on the phase degree of freedom.

As an example we consider the setup shown in the upper part of Fig.1 that has been used for a QKD up to 30 km.\(^4\) In this arrangement a relative phase \(\Phi \equiv \{0, \pi/2, \pi, 3\pi/2\}\) between two time-bins of a photon state is realized by the sender (Alice) with an unbalanced interferometer and a phase modulator. The receiver (Bob) measures incoming bins by means of a second interferometer, matched to the sender’s one, set to \(\Phi \equiv \{0, \pi/2\}\). With a probability of 50\% the phase difference between Alice and Bob’s interferometers will be 0 or \(\pi\), and their measures will be correlated; in the other half of cases measures will be discarded by the two users.

Another realization of phase encoded QKD, namely the “Plug-and-Play” setup\(^5\), is reported in the lower part of Fig.1 and it has been used for QKD up to a distance of 67 km.\(^6\) Using an intense pulse, Bob populates two time-bins with relative phase \(\Phi_B = 0\), and sends them to Alice. Alice applies a relative phase \(\Phi_A \equiv \{0, \pi/2, \pi, 3\pi/2\}\), reflects the pulses on a Faraday mirror, let them pass through an attenuator, and sends them back to Bob. The two pulses retrace in their backward path all the fluctuations they suffered in the forward path, thus arriving at Bob’s interferometer ready for being interferometrically revealed. As in the previous scheme Bob sets at random \(\Phi_B \equiv \{0, \pi/2\}\), and measures the outcomes, completing the probabilistic QKD run pertaining to BB84. This mechanism of automatic compensation of noise earned this setup the name of “Plug-and-Play”.

Recently Boström and Felbinger\(^7\) presented a variant for QKD, and named it “Ping-Pong” cryptography (PP) for its peculiarity of a forward and backward use of the quantum channel. This peculiarity seems to suit perfectly with the forward and backward dynamics typical of Plug-and-Play setups, as the one described above, and this motivated the present work. The main advantage of PP is the deterministic nature of its encoding-decoding procedure; its main flow is that it has been proved to be not completely secure\(^8\). A number of variants, still based on the polarization degree of freedom of a photon, have been proposed to solve this problem, some making use of entanglement\(^9\), and others making no use of it\(^10\)\(^,\)\(^11\).

We envisage here a protocol with phase-encoded information to have a secure, completely deterministic, quantum communication. A few variants and applications of the protocol are also discussed.

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II. PROTOCOL

The receiving user, Bob, prepares a photon in a superposition of two time-bins with a relative phase $\Phi_B$ randomly chosen between the values $\{0, \pi/2, \pi, 3\pi/2\}$. He sends the photon to Alice, the transmitting user, who chooses one of two possible tasks, control mode (CM) or message mode (MM), with probability $c$ and $1 - c$ respectively; the former realizes a control on the security of the channel, the latter the deterministic communication between the users.

**MM:** Alice encodes a bit of information with an unitary operation on the two time-bins: she can either apply the identity operation, choosing $\Phi_A = 0$ and encoding a ‘0’, or introduce a ‘phase-flip’, by applying a phase $\Phi_A = \pi$ between the time-bins and encoding a ‘1’. The photon is sent back to Bob who measures it with his apparatus set with the same phase $\Phi_B$ he prepared initially. In this way Bob’s measurement is deterministic, because the initial phase of the state (that he does know) is changed by an amount of 0 or $\pi$; he can thus guess Alice’s operation without any needs of a classical channel.

**CM:** Alice detects the photon with her interferometer randomly set to $\Phi_A = 0$ or $\Phi_A = \pi/2$. After that Alice prepares a new photon state with a phase $\Phi'_A = \Phi_A + \pi/2$, and sends it back to Bob who, analogously to what he did in MM, measures it with the same phase $\Phi_B$ he prepared initially. We notice that if phase difference between Bob’s interferometer and Alice’s one is 0 or $\pi$ then the two users share correlated information, while in the other two cases they do not. It is straightforward to realize that Alice procedure in preparing the new photon let the two users’ interferometers to be necessarily correlated either in the forward path or in the backward one. This entails that the CM of our protocol results as deterministic as the MM is, thus achieving that doubling of the whole rate transmission we mentioned before. None of the qubits, neither destined to MM nor to CM, is discarded.

III. SECURITY AND IMPLEMENTATION

Given an unjammable public channel two users can exchange information in a secure manner by means of the above protocol. Eve can try to gain information by inquiring the phase of the photon both on the forward and in the backward path; alternatively, she can prevent Bob from gaining information (DoS attack) by randomly measuring the state of the traveling photon; finally, on a lossy channel, she can conceal her presence behind losses. Nevertheless no attack can remain undetected by the control procedure since it is akin to a BB84 check test,
performed either on the forward path or on the backward one. This guarantees the protocol is unconditionally secure, as BB84 is, even if the security threshold may be different. Our protocol gives a probability of 25% to detect DoS attack as well as a general attack providing Eve with full information.

The practical implementation requires to gather the two interferometers of Fig.1. The resulting scheme is shown in Fig.2: the upper interferometer is devoted to CM, the lower to MM, and they are connected by a 1x2 fiber-coupler. The signal prepared by Bob goes at random into CM or into MM with probability $c$ and $1-c$, respectively. Later on, when the photon is on the backward path, this device redirects it to Bob. The MM interferometer resembles the one used for testing BB84 up to 67 km [5]. It is a typical Plug-and-Play scheme, with the unique difference that the attenuator is inserted just after the laser-diode (LD), at Bob's side. A laser pulse with a mean photon number much lower than unity goes through Bob's interferometer and comes out into two time-bins with a relative phase $\Phi_B$ and opposite polarizations. In the Plug-and-Play setup an intense pulse is sent to Alice to provide a trigger signal for Alice's electronics. In our case, as the pulse is already attenuated at Bob's side, a further synchronization system, such as usually used in other practical QKD setup [2, 3, 4], is necessary. After reflection on the Faraday mirror, the photon travels back to Bob, retracing exactly those paths that let him compensate any undesired phase: this makes unnecessary the stabilization of the polarization. Eventually, Rayleigh backscattering is not a problem in this case because of the low value of the average photon number from the beginning of the protocol.

The CM-interferometer resembles the one used for BB84 QKD up to a distance of 30 km [4]. As a time-polarization division technique is implemented, this task is sensible to random phase changes, and needs adjustments during the protocol runs. A value of $\sim 0.6$ rad/min for slow thermal drift in the interferometer was estimated, thus requiring a compensation step every $\sim 5$ s [4]. Also in this case Alice must synchronize her electronics with detectors, phase-modulator, and laser-diode using a suitable synchronization system.

IV. CONCLUSIONS

We proposed a setup that fully exploits the potentialities of the two-way unbalanced interferometers of certain implementations of BB84 to merge the features of Plug-and-Play setup for BB84 and Ping-Pong cryptography. The scheme is completely deterministic, both in the encoding-decoding procedure and in the control one, thus achieving...
a doubling in the rate of information transmission. It seems to be quite practical to implement since it is based on existing working implementations.

Besides, due to its deterministic nature, several other advantages are available. Bases revelation on the public channel is avoided, and this feature, together with a slightly different Alice’s preparation procedure during the CM, leads to a QKD more secure than that achieved by means of BB84 \cite{11}. Furthermore a ‘quantum direct communication’ (QDC) between users is also possible \cite{6, 11}. Finally, we notice that once QDC is available also the novel protocol called ‘quantum dialogue’ \cite{12} can be achieved: if Alice delivered a message to Bob by means of a secure QDC, then Bob can use the message just received as the key of encryption of his answer, and simply communicate it to Alice on the public channel.

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