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Twin-Field QKD: atmospheric and quantum-classical coexistence analysis

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Abstract— **This proposal examines the Twin-Field QKD over free-space optics, addressing atmospheric transmission and quantum–classical coexistence via wavelength-division multiplexing. We highlight the phase stability and weather-induced losses. In addition, we will investigate the phase modulation against these challenges scenarios. The theoretical results aim to guide future experimental implementations in metropolitan quantum networks in Rio de Janeiro, Brazil.**

***Keywords*— channel losses, quantum-classical coexistence, quantum communication, twin-field QKD.**

I. INTRODUCTION

The generation of secret random bits is the core of the RSA communication protocols (cryptosystem) [1]. The Quantum Key Distribution (QKD) arose as a reliable proposal to this problem. The primer protocol, BB84 (proposed by Bennet-Brassard in 1984), and its variations, such as SARG04 (named after Scarani-Acín-Ribordy-Gisin in 2004) [2], do not take into account the experimental component imperfections and intrinsic limitations. As an answer to this, we have the Measurement Device Independent QKD (MDI-QKD) [3], and inside this branch, a promising variation called Twin-Field QKD (TF-QKD) [4]. The basic idea behind a MDI-QKD protocol is that Alice (A) and Bob (Bob) need to send single photons to a mid-station, named Charlie (C). This mid-station is responsible for realizing a two-photon interference measurement and announcing the results in the classical channel.

A. Twin-Field QKD

The proposal of the TF-QKD is to deal with interference between coherent states, instead of two-photon interference. This can be interpreted as some kind of classical interference. It has an impact on the rate of bit generation, since the single-photon production is a more complex process than having coherent laser beams. This procedure increases the ability of the protocol to resist losses, since the phase difference between the two coherent states is kept the same in the channel. This requirement has some approaches, and we call attention to the recent work (Ref. [4]), which analyzes the passive polarization TF-QKD scheme proposed to keep the phase difference stable.

B. Atmospheric implications

The free-space brings some challenges to optical communication, in order to have robustness against losses in the channel [5]. However, Free-Space Optics (FSO) equipments alleviate the need of physical infrastructure, as it happens when using optical fibers for communication.

In this context, we have three main types of losses to be analyzed [6]: geometric attenuation, atmospheric attenuation, and losses caused by turbulence. This paper will focus on the first two losses.

II. CLASSICAL-QUANTUM COEXISTENCE

A clever and natural step toward feasible experimental realizations is to combine the already existing infrastructure (classical signals) with QKD, to produce a hybrid and robust ecosystem. On the classical side, we have a stronger signal with coherent lasers and a detector prepared for this kind of signal. On the other hand, on the quantum side, we have the single-photon generation and usually a discrete variable quantum key distribution (DV-QKD) using polarization to encode information. This hybridization can hit both security and high-level secret key rate (SKR) [7].

To deal with quantum and classical signals simultaneously, it is convenient to make use of wavelength-division multiplexing (WDM). In this way, the sender can launch a quantum signal in a specific wavelength and the classical one in a very close nearby wavelength channel. At the end, the receptor can make use of optical filters to separate them. The idea is to avoid the classical signal leaks to the quantum detector. In addition, geometric attenuation can be

There are some studies on exploring the fiber–wireless–fiber channel setup [8]. The fiber-dense medium evokes another class of challenges, since nonlinearities like Raman and Brillouin scattering can play a potentially compromising noise role for the quantum signal. In principle for the FSO hybrid transmissions, the Raman noise can be neglected. However, it deserves special attention considering the classical-quantum leakage problem. The quantum detectors must be very sensitive, in order to detect single-photons in DV-QKD. However, while it is a good point for detecting very small signals, it is also responsible for reducing the signal-to-noise ratio (SNR). So, we need to reach a balance.

The twin-field QKD introduces another key ingredient to the game: phase difference stability. The detector must not disturb the wavelength of the signal generated by a Wavelength Division Multiplexing (WDM). Accordingly, we propose to handle directly with the phase modulation to encode information.

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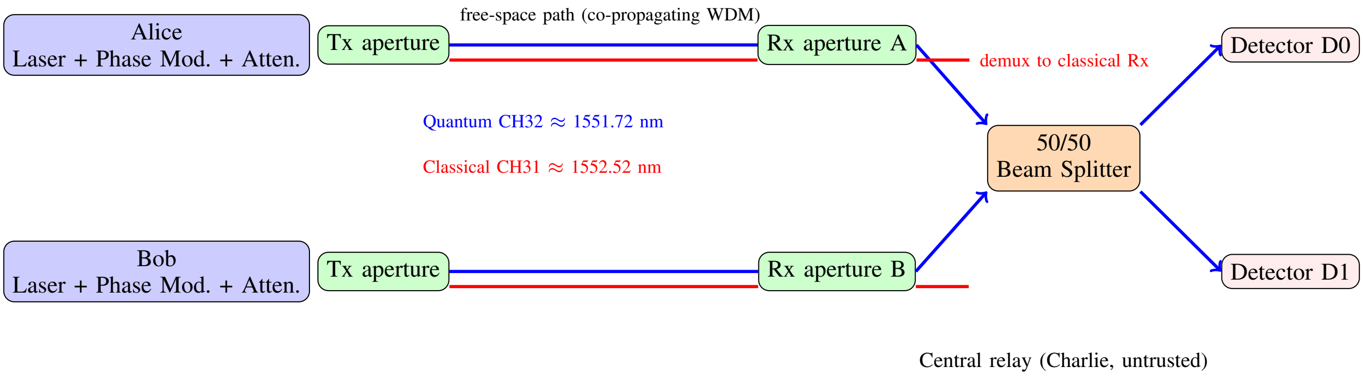

Fig. 1. A twin-field QKD protocol scheme: Alice and Bob prepare a coherent laser (classical signal) and an attenuated pulse (quantum signal). They send both signals using different channels 31 and 32. Charlie receives their signals and performs an interference using only the quantum signals coming from Alice and Bob. After interfering, Charlie can detect the interference pattern, D0 for a constructive D1 for a destructive interference. This is enough to Alice and Bob generate the secret key.

III. CHANNEL ANALYSIS

The present proposal aims to guide an FSO setup that will be used in two QKD networks being developed in Rio de Janeiro: the Rio Quantum Network and the Hermes Quantum Network, this last one with Defense purposes. Both can use FSO links to communicate with Charlie using a TF-QKD scheme [9].

Due to available equipment, a challenging issue that can occur is classical and quantum channel using neighboring DWDM channels (Dense-WDM), as 31 (1551.52 nm) and 32 (1551.72 nm), as depicted in Fig. 1. In this case, nonlinearities in the atmospheric channel must be carefully analyzed.

The geometric attenuation is given by the ratio between the area of the receptor lens and the area of the incident beam at the receiver plane. Although this attenuation is variable with the wavelength, it is a linear process, which shall not transfer power between different WDM channels. Atmospheric attenuation is the result of the interaction between the optical beam and molecules and aerosols along the propagation path. The main effects of these interactions are the absorption and scattering of the optical beam.

Concerning the quantum channel, these effects impact the overall detection performance, since many photons can be lost. Scattering is not a loss of energy, as in absorption, where the entire photon energy is absorbed, but rather the redirection of part of the beam's energy. Usually, the atmospheric attenuation is comprised of Rayleigh, Mie, and non-selective scattering, which are said to be elastic, because the scattered wave has the same frequency as the incident wave.

The study of these kinds of attenuation can impact the promising robustness offered by the Twin-Field QKD approach. In this sense, we propose a study to measure, for instance, the visibility parameter V, as estimated for the passive TF-QKD version, versus other standard expressions in the literature in the presence of phase modulation encoding. Another point of interest is the quantum-classical coexistence of TF-QKD systems, which is missing in the literature. We investigate whether this new kind of architecture is feasible when using an FSO channel.

IV. CONCLUDING REMARKS

The development of new quantum technologies based on quantum principles has paved a new route for secure and robust communication. Since BB84 protocol, another ways have been proposed, we highlight the twin-field QKD protocols using DV. However, the version exploring the CV is still lacking in the literature. In this order, the present work focuses on investigating the CV version and its limitations. A weather impact study is also put forward in this new scenario.

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