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Original article

Hybrid quantum communication protocol for fiber and atmosphere channel

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ABSTRACT In this paper, we explore a hybrid quantum communication protocol that operates concurrently over fiber optic and atmospheric channels. This new protocol addresses challenges in urban settings where laying optical fiber may be impractical or costly. By integrating the subcarrier wave (SCW) quantum key distribution (QKD) with phase coding, our approach enhances the flexibility and reliability of quantum communication systems. We have developed and tested an atmospheric optical module equipped with an auto-tuning system to ensure precise optical axis alignment, crucial for minimizing signal loss in turbulent environments. Experimental results demonstrate stable sifted key rates and low quantum bit error rate (QBER) across various channel lengths, confirming the efficacy of our hybrid protocol in securing communication over diverse transmission environments.

KEYWORDS free-space optics, quantum communication, quantum key distribution, atmosphere channel.

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1. Introduction

Protocols for quantum key distribution (QKD) are being developed for both fiber optic networks [1,2] and atmospheric links [3–5]. However, integrating fiber optic and atmospheric links to overcome challenges requiring the flexibility and reliability of both transmission media remains a key need. Atmospheric links are actively being developed for both traditional communication tasks within Internet networking and quantum cryptography. Atmospheric laser communication lines are effectively used at short and medium distances (up to 1 km), where laying fiber lines or radio frequency channels is technically or economically impractical. Modern atmospheric quantum communication systems are usually designed for long distances (ranging from 50 to 150 km) using ground-to-satellite or ground-satellite-ground configurations.

This paper presents a quantum communication system utilizing a universal "hybrid" protocol that generates a quantum key simultaneously in both the fiber and atmospheric channels. This scheme's relevance stems from the specific requirements of constructing quantum telecommunication networks in urban environments, where areas often exist where laying fiber lines is impossible or economically unfeasible. This issue is known as the "last mile" problem [6,7]. A hybrid scheme is feasible when the sites are within the line of sight of each other. Subcarrier wave (SCW) quantum communication systems adopt a different approach to coding quantum states, avoiding issues prevalent in polarization coding systems.

2. Quantum key distribution in a hybrid communication channel

The scheme of the SCW QKD protocol with phase coding in free space is shown in Fig. 1 [8]. According to the scheme, the source of coherent radiation emits monochromatic light with frequency ω. After phase modulation with an electrical signal with low modulating frequency Ω and phase ϕ_A, the modulated signal passes through an attenuator and enters the quantum channel (atmosphere), where it undergoes attenuation.

After passing through the second electro-optic modulator with the same modulating frequency Ω and phase ϕ_B, the amplitudes of the sidebands increase (taking part of the energy from the carrier mode in the case $\phi_A = \phi_B$) or decrease (energy flows to the carrier mode). The narrowband spectral filter passes only the sidebands, and then the signal is detected by a single photon detector.

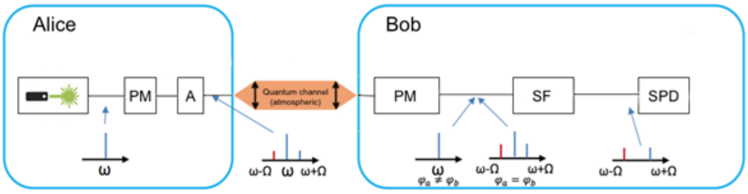

FIG. 1. Experimental setup of free-space subcarrier wave quantum communication system. PM is the phase modulator, A is the optical attenuator, SF is the spectral filter, and SPD is the single photon detector

TABLE 1. Statistics of optical line operation under typical turbulence conditions

Optical line	optical losses, average value, dB	optical loss, average deviation, dB	optical losses, minimum value, dB	optical losses, maximum value, dB	time
20 m	9,78	2,54	7,65	15,43	134 min

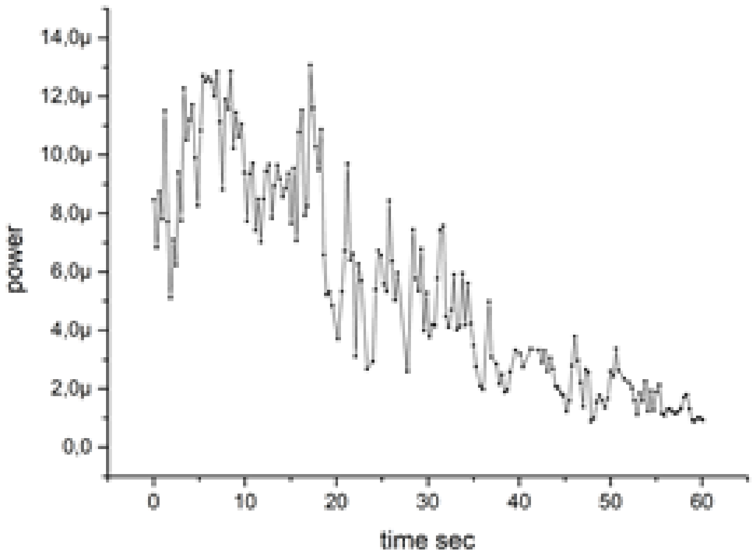

FIG. 2. The power of the laser radiation transmitted through the atmospheric line without auto-tuning system

To create a stable atmospheric channel, we developed transmitting and receiving optical modules equipped with an auto-tuning system. For the optical line to operate reliably, it is crucial to keep the optical axes of the receiver and the transmitter aligned with the accuracy of just a few microradians. When the length of the optical line increases from 5 to 100 meters, the losses in the optical signal remain relatively stable and range from 6 to 10 dB. The main part of the losses is associated with the deformation of the energy profile of the beam in a turbulent atmosphere. The automatic tuning system is based on the use of reference radiation of an optical diode at a wavelength of 900 nm, which is coaxially aligned with the optical axis of the quantum channel. The coordinates of the reference radiation are determined by a CCD matrix that generates a signal for a mirror controlled by four electromagnets. Thus, the auto-tuning system always maintains the alignment of the transmitter and receiver.

In the absence of an auto-tuning system, misalignment of the optical axes can occur within one minute. Fig. 2 shows an example of the dependence of the power of laser radiation at a wavelength of 1550 nm transmitted through an atmospheric line without an auto-tuning system.

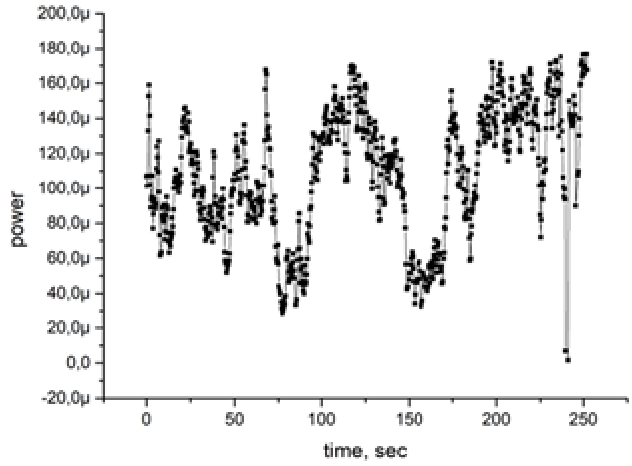

FIG. 3. The power of the laser radiation transmitted through the atmospheric line. Deviation from the maximum value is associated with the influence of turbulence

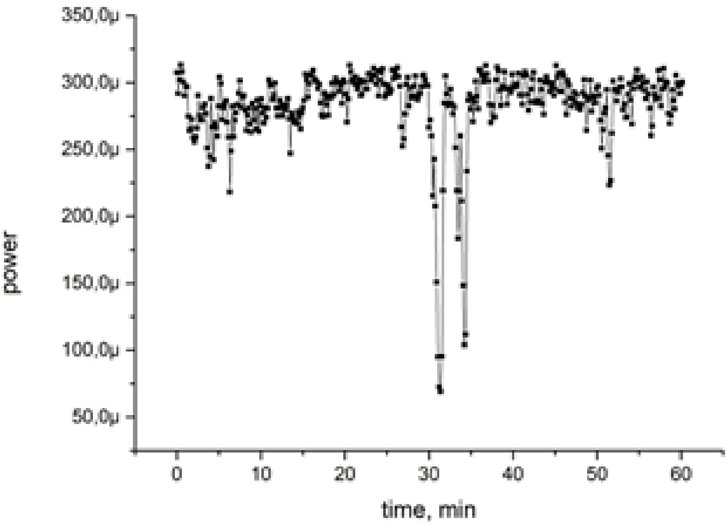

FIG. 4. The power dependence of the signal transmitted through the optical line on time. The operation of the auto-tracking system for a long time is demonstrated

Fig. 3 shows an example of the effect of turbulence on losses in the optical channel. The magnitude and nature of turbulence depend on the location of the optical line, the speed of movement of air masses, and the temperature gradient. Fig. 4 shows the effectiveness of the auto-tracking system over a long time. The accuracy of our track system was 7 microradian, which made it possible to keep the optical signal at the level of 1 dB.

After setting up the optical and QKD systems, we measured the performance of the systems over different channel lengths: 25 meters, 40 meters, and 50 meters. For all optical channels, the optical loss was 6.5 dB, and the sifted key generation rate was 1.45 KB/s, with a quantum bit error rate (QBER) of 6%. Losses at the output and input into the optical fiber determined losses in the optical line. An optical beam with an aperture of 80 mm has a low diffraction divergence, thus at a distance of 15, 25, and 40 meters, we get the same key generation rate.

3. Conclusion

Measurements of the key rate in a hybrid communication protocol including fiber optic and atmospheric sections have been carried out. The atmospheric link was implemented using the developed transceivers equipped with an auto-tuning system. The results show that the SCW QKD protocol functions effectively in the atmospheric link, and the key generation rate depends solely on the optical loss. In the future, it is planned to improve the persistence of the protocol by detailed theoretical analysis of the possibility of using turbulence to obtain information accessible by an intruder (Eve).

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