Free-space subcarrier wave quantum communication

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Abstract. We experimentally demonstrate quantum communication in 10 dB loss outdoor atmospheric channel with 5 kbit/s bitrate using subcarrier wave coding method. Free-space link was organized by telescoping system with symmetric fiber-optic collimators.

1. Introduction
Quantum communication (QC) is a new technique of secure key exchanging between parties in communication network. Nowadays different groups demonstrating quantum communication in optical fibers up to 404 km [1] and up to 144 km in free space [2]. Free space experiments demonstrating the feasibility of QC for satellite-to-satellite and ground-to-ground application. For example in ground-to-ground applications free space QC can solve last-mile problem in quantum networks. To date, mostly method based on polarization-coding has been implemented in free space [3-5]. In this work we show that subcarrier wave coding technique [6-8] can be adapted to free space quantum communication.

2. Experimental setup
Experimental setup is shown in figure 1. Free-space subcarrier wave QC system consists of Alice and Bob modules connected by free-space atmospheric quantum channel.

Figure 1. Experimental setup of free-space subcarrier wave quantum communication system. PM – phase modulator, A – attenuator, SF – spectral filter, SPD – single photon detector.
Semiconductor laser at the Alice module emits a signal at optical frequency $\omega$ which is directly modulated in LiNbO$_3$ phase modulator by an electrical signal with frequency $\Omega$ and modulation depth $m<<1$. The optical spectra are composed of central peak and two subcarriers at frequencies $\omega + \Omega$ and $\omega - \Omega$ with phase shift $\varphi_A$ randomly chosen from four-state protocol. After modulation signal is attenuated and passed through beam expander and to receiver side by atmospheric quantum channel. The total optical power at the output of Alice module was equal to mean photon number 1 per pulse at subcarriers.

Free space atmospheric quantum channel was organized by telescoping system with symmetric fiber-optic collimators (Fig. 2.) An ideal atmospheric channel can be described by Gaussian beam solution of paraxial wave equation. Maximal length between Alice and Bob modules is limited by beam diffraction and depended on the collimator lens diameter.

$$L = \frac{2\pi \omega^2 \omega_0}{\lambda} \sqrt{1 - \left(\frac{\omega_0}{\omega}\right)^2},$$

where $\omega$ is the beam waist, and $\omega_0$ – radius of the beam at the lens. The length is maximized when $\omega_0/\omega = \frac{1}{\sqrt{2}}$.

At the receiver side signal is collected by symmetric beam collimator and coupled in an optical fiber and passed to Bob module. Here signal passed through phase modulator where random phase shift $\varphi_B$ is introduced according to four-state protocol. Then signal transmitted to an optical spectral filter that separates the carrier from subcarriers. After spectral filter two subcarriers at frequencies $\omega + \Omega$ and $\omega - \Omega$ passed to single photon detector. When Alice and Bob introduced equal phase shifts ($\varphi_A - \varphi_B = 0$), constructive interference was observed in the side frequency optical signal. When the difference in phase shifts was a multiple of $\pi$, destructive interference was observed. Key generation and sifting was performed experimentally using the BB84 protocol.

![Figure 2.](image)

**Figure 2.** Free-space channels with beam collimators in outdoor (a) and indoor (b) experiments.

The experiment was performed two times: indoor in lab with 1 m on-table-link (Fig. 2a.) and outdoor on a cloudy day (Fig. 2b.) with atmospheric channel between two beam collimators ~20 m. QC system parameters are shown in Table 1.
Table 1. QC system parameters.

| Parameter                                | Value  |
|------------------------------------------|--------|
| Central wavelength                       | 1550 nm|
| Modulation clock frequency               | 100 MHz|
| Modulation frequency                     | 4.8 GHz|
| Mean photon number                       | 1      |
| Measured losses in quantum channel       | 20 dB  |
| Losses in Bob module                     | 7 dB   |
| Quantum efficiency of detector           | 20%    |
| Spectral filter coefficient              | 99.99% |
| Spectral filter band                     | 7.5 GHz|

For measured losses in outdoor 20 m free-space link of 10 dB the sifted key rate was about 5kbit/s and QBER value was 6%.

For measured losses in indoor 1 m free-space link of 8 dB the sifted key rate was about 15 kbit/s and average QBER value was 3.28%. At the receiver side beam collimator was rotated 45 degrees 8 times. Figure 3 shows that QBER approximately the same for different positions of the telescope system.

![Figure 3. Dependence of QBER on collimator rotation angle](image)

3. Conclusion

In this work we have implemented subcarrier wave technique for free-space quantum communication using standard fiber-optical components in Alice and Bob modules. In free-space
regime this technique offers invariance to rotation of the telescope system and good capabilities in multiplexing.

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Erratum: Free-space subcarrier wave quantum communication

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Our paper «Free-space subcarrier wave quantum communication» in Journal of Physics: Conf. Series 917 (2017) 052003 contains the following misprints we would like to correct:

1. The expression for L on page 2, line 12 must be in the following form:

   \[ L = \frac{2\pi\theta^2}{\lambda} \frac{\theta_0}{\theta} \sqrt{1 - \left(\frac{\theta_0}{\theta}\right)^2} , \]

2. On page 2, line 13 should be as follows: «where \( \theta \) is the beam waist, and \( \theta_0 \) is the radius of the beam at the lens. The length is maximized when \( \theta_0/\theta = 1/\sqrt{2} \).»

3. The Acknowledgments section must be read as follows: This work was financially supported by the Ministry of Education and Science of Russian Federation (project № 14.578.21.0112, RFMEFI57815X0112).