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## Possibility of creating a modular system for quantum key distribution in the atmosphere

© A.A. Boev<sup>1</sup>, S.S. Vorobey<sup>2</sup>, S.Y. Kazantsev<sup>3</sup>, M.Y. Kernosov<sup>1</sup>, O.V. Kolesnikov<sup>3</sup>,  
S.N. Kuznetsov<sup>1</sup>, Y.B. Mironov<sup>3</sup>, A.A. Parshin<sup>1</sup>, N.V. Rudavin<sup>2</sup>

<sup>1</sup> MOSTCOM, Ryazan, Russia

<sup>2</sup> QRate, Skolkovo, Russia

<sup>3</sup> Moscow Technical University of Communications and Informatics, Moscow, Russia

E-mail: s.i.kazantsev@mtuci.ru

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The possibility of quantum key distribution in the atmosphere has been experimentally demonstrated by coupling commercially available quantum key distribution units designed for fiber-optic communication lines with atmospheric optical communication terminals. For distances up to 3100 m, data on losses in a quantum channel on an optical path were obtained and the influence of systems for intelligent adjustment of atmospheric communication terminals on the synchronization system of quantum communication blocks was studied. It has been established that failures of synchronization systems in the case of quantum key distribution in the atmosphere at distances greater than 10 m are due to the peculiarities of the algorithm implemented in the quantum communication unit.

**Keywords:** quantum key distribution, atmospheric optical communication lines, FSO, decoy-state BB84 protocol, polarization coding.

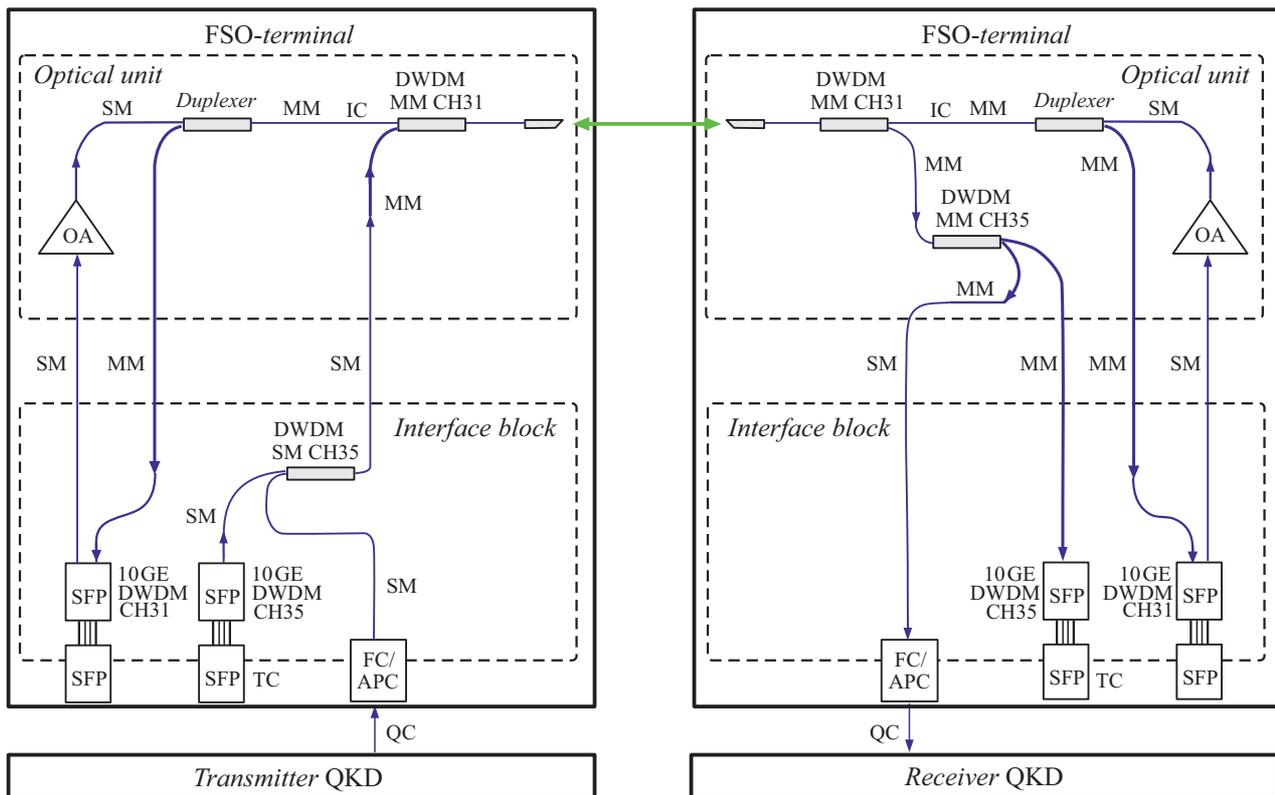
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Recently, systems of quantum key distribution (QKD) [1,2] were intensively created and studied. QKD technologies at the physical level guarantee the security of information transmission, and the possibility of data leakage can only be associated with the imperfection of a specific implementation of the technology [3,4]. Today, significant progress was made in the development of serial devices for QKD in fiber-optic communication lines (FOCL) [5], and QKD units in the atmosphere are still at the stage of demonstration prototypes [6]. At the same time, terminals for atmospheric optical communication lines (AOCL) have long proved their effectiveness for transmitting large amounts of data [7,8]. The purpose of this paper is to analyze the technical feasibility of building reliable QKD devices in the atmosphere by interfacing the QKD modules on the market for FOCL and AOCL terminals.

AOCL terminals M1-40GE of JSC „Mostcom“ [9] and QKD blocks QKD312 of „KuRate“ LLC [10] were selected for research. The selected AOCL equipment allows creating a point-to-point wireless communication channel with minimal effort and provides parallel transmission of data streams through 10GBASE(SFP+) interfaces [9]. The transmission of information signals by the AOCL terminal is carried out at wavelengths of 1535–1560 nm, it also uses a laser at a wavelength of 785 nm to organize a service channel between the terminals [8].

It is known that for QKD it is necessary to have two communication channels, the first of which is open and is carried out by the standard connection of the AOCL terminals, described above, and the second is quantum [2]. A quantum

communication channel serves to receive and transmit information carried by single photons, usually in open space it is encoded by the single photon polarization [11]. The problem of creating true sources of single photons that meet the requirements of the telecommunications industry was not yet solved, so commercial QKD blocks use attenuated laser pulses [12]. To organize a quantum communication channel, QKD312 blocks were used, in which the transfer of cryptographic key is carried out using a modified protocol decoy-state BB84, and the information was encoded by photon polarization [10]. The QKD312 block was developed for FOCL without polarization preservation, since this QKD block uses special algorithms for intelligent tuning of the quantum communication channel synchronization system when the fiber polarization changes [5,10]. In our experiment, the optical blocks of the AOCL terminals were installed on the roofs of different buildings so that they were in the line of sight and were oriented to each other. The QKD blocks were connected by a single-mode optical fiber to the interface units of the AOCL terminals. The complete connection diagram in the experimental equipment is shown in Fig. 1, which shows the information channel (IC), quantum channel (QC), test channel (TC). The possibility of implementing the quantum communication channel through AOCL terminals M1-40GE is due to the fact that the architecture of this equipment allows organizing a „transparent“ communication channel for QKD tasks without changing the design, working on the principle of passive optics-active tracking, therefore, the transmission of an information signal through AOCL carried out with

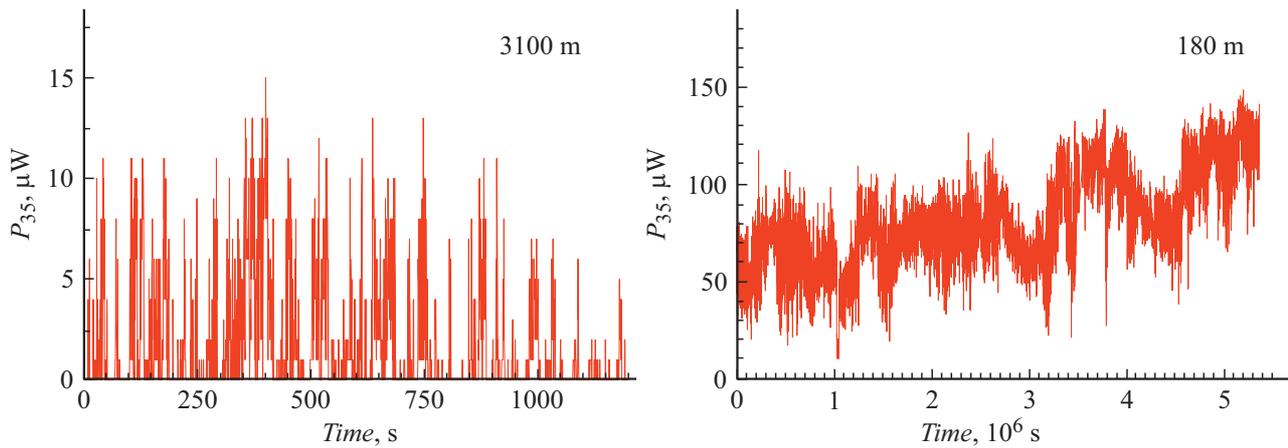


**Figure 1.** Diagram connecting AOCL equipment to QCD blocks. IC — information channel, QC — quantum channel, TC — test channel.

a minimum of transformations, only an active guidance system is used. Information signals from the equipment are sent to the AOCL interface unit, which transmits them to the optical unit of the terminal via an interface cable. To analyze the atmospheric transmission effect on the quantum channel (wavelength 1554.9 nm), a separate test communication channel was organized between the terminals at a wavelength of 1549.3 nm (channel 35 in the ITU DWDM grid with an interval of 100 GHz). From the QKD receiver side in the AOCL receiving module, this channel was connected to the receiver, which measured the received power level  $P_{35}$ . Since the quantum and test communication channels were multiplexed using DWDM technology and passed along the same path between the terminals,  $P_{35}$  was used to estimate the loss level in the quantum channel. One of the objectives of this paper was to study the influence of the active guidance system of the AOCL terminal on the synchronization of the QKD blocks. For this purpose, on a Teledyne LeCroy WaveRunner 620zi oscilloscope connected to the service outputs of the QKD receiver the synchronization pulses of the quantum communication channel were analyzed under various operating modes of the AOCL terminals. The accuracy of oscillographic measurements was minimum 8%.

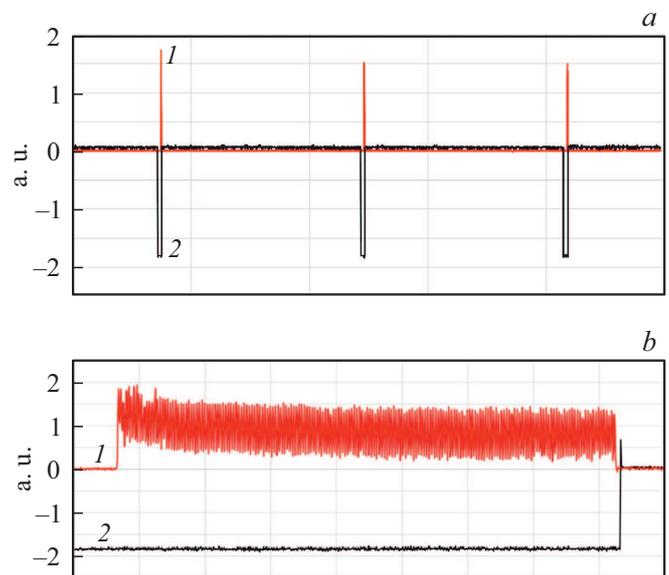
Fig. 2 shows the dependence of the signal power  $P_{35}$  at the receiving module of the AOCL terminal on time for paths of length 3100 and 180 m. For a distance of

3100 m strong fluctuations in the signal power  $P_{35}$  are visible, since there was thick smog from boiler houses on the path route during the communication session, as a result of this, the maximum duration of stable communication, when the value of  $P_{35}$  exceeded  $1 \mu\text{W}$ , amounted to only 21 s during the measurement session. The maximum value of  $P_{35}$  reached  $15 \mu\text{W}$ , which, with a transmitter output power of  $1300 \mu\text{W}$ , makes it possible to estimate the minimum achievable loss in the synchronization channel as 19 dB. Taking into account the geometric losses on this path, they are 15 dB, this is in good agreement with direct measurements of losses in the synchronization channel that occur when the QKD unit is coupled to the FOLS terminal (4.6 dB). Taking into account the multimode fiber–single-mode fiber (MM–SM) transition, the quantum channel loss exceeds 34 dB. With a loss level in the quantum channel of more than 26 dB, the QKD312 manufacturer did not provide for the transmission of the cryptographic key, so most of the measurements were performed at a distance of 180 m. These studies were also carried out under adverse weather conditions, under the influence of snowfall and wind. As can be seen from Fig. 2, the level  $P_{35}$  for a distance of 180 m did not drop to zero during the entire time of measurements. The trend of the average value is determined by the change in the snowfall weakening during the measurements. The analysis of the signal power dynamics recorded by the AOCL receiver



**Figure 2.** Power dynamics on the terminal receiver  $P_{35}$  at distances 3100 and 180 m.

on 180 m path showed that the minimum achievable loss in the synchronization channel (excluding the MM–SM transition) is 11 dB. This value, taking into account the losses of 15 dB in the interface section MM–SM, already allows the QKD blocks to work. Fig. 3 shows typical oscillograms of signal pulses of the synchronization channel, obtained on the QKD block. The signals were recorded via two channels: 1 — receiver detector signal generated by the QKD receiving unit by the signal from the output junction of the quantum channel of AOCL receiving terminal; 2 — trigger-signal repeating the time cycle of QKD unit operation (the cycle beginning of this signal is determined by the end of the detected burst of syncropulses). The duration of a burst of syncropulses generated by the detector of QKD receiver was  $16\ \mu\text{s}$ , and the repetition period of the bursts was  $\sim 3.4\ \text{ms}$ . The indicated durations fully correspond to the parameters of the emitter of the synchronization channel of the QKD transmitting block [10]. In the course of the study, the operation of the AOCL was checked in the normal mode, then in the manual control mode the automatic guidance systems of the AOCL terminals were turned off, and the radiation power in the service and information channels of the terminals was regulated. Disabling of the automatic adjustment system for the period of measurement does not adversely affect the synchronization of the quantum communication channel. Changing the laser power of the service channel (at a wavelength of 785 nm) in the operating range did not affect the synchronization in the quantum channel. The only factor affecting the synchronization system on the AOCL side was the output power of the information channel of the terminal on side of QKD transmitting unit. At output power of 80 mW, a stable absence of syncropulses was observed at the QKD receiving unit. During the tests, a synchronization loss, clearly expressed readings of the quantum channel detector were observed for several minutes in the absence of the time cycle signal of the QKD receiving unit. This is due to the fact that the synchronization system of the QKD block



**Figure 3.** Oscillograms of synchronization signal received on QKD block. 1 — receiver detector signal, 2 — trigger-signal repeating the time cycle of the QKD unit operation. *a* — sweep 2 ms/div, *b* — 1  $\mu\text{s}$ /div.

was designed to compensate for the temperature effects acting on the FOCL, as a result of which the polarization of the radiation propagating in the FOCL changes. The atmosphere does not introduce noticeable distortions into the polarization of photons, and changes in the signal level are due to losses fluctuations in the atmospheric channel, so the QKD synchronization algorithm needs to be improved.

Thus, the paper demonstrates for the first time the possibility of constructing QKD system in the atmosphere based on a modular principle, when serially produced AOCL terminals and QKD blocks developed for FOCL are interfaced. In the actual conditions of the urban atmosphere, the main factors affecting the operation of synchronization systems of the quantum communication channel are inves-

tigated. The main reasons for the synchronization loss of the quantum communication channel are identified, which are a high level of losses in the section of interfacing the MM–SM terminals of the AOCL with the QKD block, and the features of the automatic tuning algorithms used in the QKD block. Elimination of the detected interface sections that introduce additional losses into the quantum channel and adaptation of the QKD block algorithms to the conditions of the atmospheric path will make it possible to develop effective atmospheric QKD systems that can be used in various applications [8].

### Conflict of interest

The authors declare that they have no conflict of interest.

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