Quantum key distribution (QKD) is a concept of secret key exchange supported by fundamentals of quantum physics. Its perfect realization offers unconditional key security, however, known practical schemes are potentially vulnerable if the quantum channel loss exceeds a certain realization-specific bound. This discrepancy is caused by the fact that any practical photon source has a non-zero probability of emitting two or more photons at a time, while theory needs exactly one. We report an essentially different QKD scheme based on both quantum physics and theory of relativity. It works flawlessly with practical photon sources at arbitrary large channel loss. Our scheme is naturally tailored for free-space optical channels, and may be used in ground-to-satellite communications, where losses are prohibitively large and unpredictable for conventional QKD.

Quantum key distribution (QKD) is a concept of secret key exchange supported by fundamentals of quantum physics. Its perfect realization offers unconditional key security, however, known practical schemes are potentially vulnerable if the quantum channel loss exceeds a certain realization-specific bound. This discrepancy is caused by the fact that any practical photon source has a non-zero probability of emitting two or more photons at a time, while theory needs exactly one. We report an essentially different QKD scheme based on both quantum physics and theory of relativity. It works flawlessly with practical photon sources at arbitrary large channel loss. Our scheme is naturally tailored for free-space optical channels, and may be used in ground-to-satellite communications, where losses are prohibitively large and unpredictable for conventional QKD.

PACS numbers: 03.67.Dd, 42.50.Ex

Quantum cryptography [1–6] gained its popularity from a promise of its absolute security against eavesdropping. In this sense, “absolute” means that it is guaranteed by fundamental laws of physics, rather than by our technological abilities. Nowadays, QKD is arguably the only practical technology explicitly operating with properties of the quantum world. At the same time, practical QKD is a serious challenge for scientists, because all implementations are somewhat different from underlying theoretical models. Two major problems are the lack of true single-photon sources [7, 8] and the presence of loss in quantum channel; neither of them can be perfectly eliminated. In result, known protocols guarantee key security only if losses do not exceed a certain realization-specific level. In this paper we address this issue and demonstrate a relativistic protocol taking into account relativistic properties of our world, which guarantee key security regardless of the particular channel loss.

Conventional, non-relativistic, quantum cryptography is based on fundamental principles of quantum mechanics [9, 10], however, it is not directly tied to elementary particles or other physical objects that carry transmitted quantum states. In the proposed relativistic quantum cryptography it must be a massless particle traveling at the speed of light, i.e., a photon, that carries information. This makes a difference if the space-time structure of the communication in Minkowsky space is taken into account, calling to nonexistence of faster-than-light information transmission. This explicit connection with the space-time is completely ignored in conventional QKD protocols.

Our protocol is based on time-spread coherent quantum states, which, due to their distributed nature inevitably cause delays, if successful intercept and resend attack is performed. Thus, detection of adversary actions can be performed by controlling both detection errors and signal delays. This eventually makes the protocol completely immune to arbitrarily large loss in the quantum channel and creates a potential for its use in ground-to-satellite free space quantum links enabling global QKD service [6].

As signal delays play a critical role in our relativistic approach, the protocol is only viable for line-of-sight free space communication links, where no alternative shortcut paths are possible and the signal propagates at the speed of light. Importantly, the protocol is tolerant to the presence of air in the light path, which slightly delays the signal vs. the vacuum speed of light; it only requires enough time-spreading of the transmitted quantum states. In typical conditions it requires about 1 ns of spreading per kilometer of the transmission distance in air, topping to less than 20 ns for ground-to-satellite links.

Although keeping track of precise timing requires, in general, external clock synchronization, the proposed protocol takes care of clock synchronization between the communicating parties Alice and Bob by itself; no other external synchronization scheme is needed. At the same time the protocol requires an a-priori knowledge of a distance between the parties, which is essential, e.g. if the adversary Eve chooses to delay any light transmissions between Alice and Bob.

The understanding that special relativity may offer new features to quantum cryptography, was around as
early as in 1990s, when the first relativistic quantum protocol on orthogonal states was proposed \[11\]. Another use of relativistic causality in QKD was demonstrated in \[17\], where a two-fold increase of key generation rate for BB84 protocol \[17\] was shown.

Even more substantial changes relativistic privacy provided for bit commitment protocols \[15–24\], which are prohibited in a conventional quantum world by the Mayers-Lo-Chau no-go theorems \[23\]. The search for qualitatively new features in QKD was on since an early work \[26\] in 2001. Followed by a series of publications, these ideas distilled into a practical relativistic QKD protocol \[27–29\], experimentally demonstrated in the present work for the first time.

The main features of the realized relativistic protocol include: (i) spreading of quantum states does not have to be as large as the channel length; it only has to compensate for delays in the channel with respect to the ideal one with the vacuum speed of light; (ii) as relativistic principles allow for clock synchronization, no other external synchronization is required; (iii) the protocol provides unconditional key security even with conventional faint laser pulses at arbitrarily large channel loss; practical limitations on the channel loss are only determined by the dark count rate in the single photon detector used.

The realized system has a double-pass configuration, where optical pulses initially generated by Bob are first transmitted to Alice as classical signals. Alice in turn attenuates the received signals to quantum level, encodes them with randomly chosen bits and sends back to Bob. Bob detects them at exactly calculated moments in time, choosing his measurement basis at random. Such configuration allows reusing the same fiber delay interferometer, installed at Bob’s, and does not require its phase stabilization.

The protocol serves for the two goals: first, to provide relativistic QKD by itself and, second, to synchronize the clocks between Alice and Bob. The first goal is achieved by the following procedure shown in figure 1 as a space-time diagram. Alice receives from Bob pairs of short optical pulses spread in time by a fixed amount \(\Delta t\). As each pair is generated in the delay interferometer from a single laser pulse, the pair would interfere destructively in the detector port of the interferometer if returned to Bob without any phase shifts. Alice flips a coin to decide whether to change the phase of the second pulse by \(\varphi\) or not. After performing (or not performing) the modulation she attenuates the pulses to achieve a pre-defined average number of photons \(\mu\) in each of the pulses and sends them back to Bob. Bob also randomly chooses whether to apply an additional phase shift \(\varphi\) to the first pulse or not and detects the result of their interference exactly at the time \(T\) after initial pulse generation. This value \(T\) should be equal to the round-trip time with the accuracy better than \(\Delta t\). All time delays shorter than \(\Delta t\) are considered insignificant.

As one may notice, so far the protocol directly repeats the B92 protocol \[30\], so where does relativity come into play? An explanation is given by the following argument. There are two weak coherent states in the channel: \(|\alpha\rangle\) going first and \(|e^{i\varphi b A }\alpha\rangle\), where \(b_A\) is the bit sent by Alice and \(\alpha = \sqrt{\mu} e^{i\varphi_0}\). The first state carries no information and is considered to be known by Eve. However, Bob will use it to test the data state traveling later, thus, it is essential for the communication. If the first state gets blocked in the transmission line, Bob’s measurement result will not depend on his modulator setting, which will result in the 50% error rate. If, similarly, the second, data, state is missing, while the first is present, Bob apparently gets 50% errors again.

![Space-time diagram of the line-of-sight free-space quantum channel operation.](image)
FIG. 2: Space-time diagram of a series of transmissions, realizing clock synchronization between Alice and Bob. Initiating each transmission, Bob randomly chooses whether to transmit at the beginning of a time slot of size \( t_0 \) or to transmit delayed. This creates a unique Bob’s timing sequence. Alice compares her observed timing sequence with that of Bob and if they differ, Alice and Bob discard corresponding raw key sequence. As Bob’s timing information reaches Alice with the maximum possible speed — the speed of light — Eve’s attempts to pre-poll Alice’s random bit \( b_A \) (see figure 1), keeping the timing sequence the same, fail due to inability of faster than light delivery of timing sequence from Bob to Alice.

Eve may choose whether to block or do not block the first state in the line, but when she receives the second one, she faces uncertainty of the quantum world: as the data carrier states are not orthogonal to each other \( \langle e^{i\alpha}a|\alpha\rangle = \exp[-2|\alpha|^2\sin^2(\varphi/2)] > 0 \), it is not possible to guarantee reconstruction of the bit sent. If Eve succeeds in obtaining the bit, e.g. with an unambiguous measurement, she is okay only in the case if she has let the first state propagate in the line, because otherwise Bob would see an error. If she fails to get the bit, she is okay only if the first state has been blocked. Due to relativistic causality she cannot correct for her decision about the first pulse made earlier, as there is no faster-than-light communication. Thus, introduction of errors into the line by Eve now does not depend on the channel loss.

The second inherent part of the protocol guarantees clock synchronization between Alice and Bob. If it was missing, Eve could use a fake pair of pulses to poll Alice’s bit before getting a real signal from Bob. In this case Eve would always know whether she was successful with the last measurement by the time she needs to make a decision about the first state, which results in successful cracking of the protocol. To avoid that Bob sends his pulses aperiodically: in each data clock cycle he randomly chooses between the two time positions to send the pulse as shown in figure 2. This additional bit of information cannot reach Alice earlier than it does under normal system operation. Any attempts of Eve to pre-poll Alice’s bits will result in a different time sequence observed by Alice, because to keep it, transmission of the timing data from Bob to Alice would have been done superluminally. According to the protocol, after series of transmissions Alice and Bob compare their recorded timing data, taken by their unsynchronized, but precise in relative measurement clocks, and if they observe errors in the timing sequence, they discard the whole series.

Having realized both clock synchronization and key distribution in a single setup, we arrive at a relativistic protocol, where unlike the conventional QKD, optical loss and errors caused by the eavesdropper are completely decoupled. Thus, even at an arbitrarily large channel loss and unlimited Eve’s resources, any extra information obtained by Eve results in an increase of detection errors observed by Bob and detection of the intrusion.

The realized experimental system (figure 3) is an opti-
FIG. 4: Experimentally measured bit error rate and the obtained key lengths. During the run over 55 m long free space channel Alice was checking her observed timing sequence and compared it with that used by Bob. No timing errors were observed. Average number of photons per modulated pulse was kept at $\mu = 0.1$ and a depth of phase modulation was equal $130^\circ$. Detection of arriving photons was performed by Bob in a 4-ns time window, which is 5.5 times less than $\Delta t = 22$ ns, satisfying the requirements of the relativistic protocol.

tical fiber-based setup working at the wavelength of 850 nm with a 55 m long free-space channel between Alice and Bob (see Appendix B: Experimental setup.) In this demonstration with the clock rate of 250 kHz and $\mu = 0.1$ photons per pulse we obtained the average of 16.1 raw bits per series of 32768 pulses with a 3.5% quantum bit error ratio as shown in figure 4. This corresponds to a raw key generation rate of 123 bits/s and the secret key rate of 47 bits/s.

To conclude, we have proposed and experimentally demonstrated a novel type of QKD protocols based on the principle of relativistic causality. Security of such a scheme with a conventional faint laser photon source does not depend on a loss in the quantum channel, so it can be readily used for unconditionally secure satellite-based QKD networking, with the only practical reach limit in the presence of dark photodetector counts.

Acknowledgments

This work was supported in part by the Russian Ministry of Education and Science (state contracts no. 11.519.11.4009, 14.132.21.1400, 16.740.11.0662) and by RFBR, grant no. 12-02-31792.

Appendix A: Secret key rate.

Here we present a brief asymptotic analysis of the protocol performance, while a comprehensive study including finite sequences can be found in [29]. The secret key rate is bounded by

$$R = \lim_{n \to \infty} \frac{l_{secr}}{n} \leq (1 - \eta)(1 - C(\varphi)) - \eta - h(p_e),$$

where $\eta$ is the fraction of errors in the received timing sequence (assumed to be zero throughout the paper), $h(x)$ — binary entropy function, $p_e$ — bit error probability, and $C(\varphi)$ — Holevo bound [31] on classical throughput of the quantum channel with states $|\alpha\rangle$ and $e^{i\varphi}|\alpha\rangle$; $C(\varphi) = h\left(\frac{1 - e^{-\varphi}}{2}\right)$, where $\varepsilon = |\langle\alpha|e^{i\varphi}\alpha\rangle| = \exp\left(-2\mu \sin^2(\varphi/2)\right)$.

Typically in the experiments (when there is no active eavesdropping) there are no errors in the received timing sequences, therefore we have chosen a simple strategy of discarding all packets with timing errors. In this case $\eta = 0$ and the above expression becomes $R \leq 1 - C(\varphi) - h(p_e)$, which has a simple intuitive interpretation: if we assume that all classical information that could be derived from the sent quantum sequence is known to Eve, from each raw bit we should subtract Eve’s information $C(\varphi)$ and the entropy associated with bit errors in the raw sequence $h(p_e)$.

One can also notice that there is an ambiguity of choosing $\mu$ and $\varphi$ for a particular value of $C(\varphi)$. However, from a practical point of view it is convenient to keep $\varphi$ close to $\pi$ to minimize the effect of experimental errors. In the particular experimental realization $C(\varphi) = 0.387$ bits, and the secret key rate depends on the observed $p_e$. Importantly, if the rate $R$ becomes zero or even negative, as in the case of a large $\mu$ and a non-zero $p_e$, there is no private shared information between Alice and Bob, i.e. all the raw key bits obtained have to be discarded.

Appendix B: Experimental setup.

To generate optical pulses we use a directly modulated Fabri-Perot laser diode (QPhotonics QFLD-850-755), which emits 4 ns long pulses at the wavelength of 850 nm. The delay interferometer is fusion spliced from a single-mode fiber HP780 and comprises a polarization controller (General Photonics PCD-M02-4X-NC-4) in one of the arms. We use lithium-niobate phase modulators (Photline NIR-MPX800-LN-05) and mechanical variable optical attenuators (OZ Optics DD-100-11-850-5/125-S-50) for further light processing. The transmission line is constructed from a pair of free-space couplers (Micro Laser Systems, Inc. FC20-NIR-T) with an output aperture of 23 mm placed on tripods; the channel loss is estimated as 3 dB. The setup on the other side of the free-space channel (Alice) is made of the same components and works in a slave mode. A signal from the PIN1 photodetector activates the setup, which selectively modulates the second optical pulse after its reflection from the mirror (OZ Optics FORF-11P-850-5/125-P). All random number generators in the whole system (two of them control corresponding phase modulators and one creates a timing sequence) are emulated by a pair of linear feedback shift register-based pseudo random generators with
Appendix C: Single-mode free-space channel requirements.

An ideal single-mode free-space channel is described by a paraxial wave equation with a solution in the form of a Gaussian beam. Beam diffraction limits the maximal length of the line, which becomes dependent on the lens diameter. In a general symmetric configuration the channel length

\[ L = \frac{2\pi w^2 w_0}{\lambda} \sqrt{1 - \left( \frac{w_0}{w} \right)^2}, \]

where \( w_0 \) is the beam waist, and \( w \) – radius of the beam at the lens. The length is maximized at \( w_0/w = 1/\sqrt{2} \), as shown in Fig. 5a. In this configuration

\[ L = \frac{\pi w^2}{\lambda} = 2 \frac{\pi w_0^2}{\lambda} = 2z_R, \]

where \( z_R \) is the Rayleigh length.

In our current implementation with 23 mm diameter free-space couplers, the radius \( w \) equals 5.8 mm, resulting in the working transmission distance up to \( L \approx 125 \) m. The demonstrated distance of 55 m, thus, should be considered as a proof-of-principle demonstration limited by the length of the hallway, rather than the actual range of the system. Larger, kilometer range, distances may be covered with larger free-space couplers or telescopes. As optical loss in such free-space lines strongly depends on atmospheric turbulence and fluctuates with time, the key generation rate may vary drastically, but without compromising system security due to the unique properties of the relativistic quantum key distribution.

Appendix D: Hardware implementation.

Overall, the system consists of two boxes housing Alice and Bob, and a pair of tripods with the free-space couplers mounted on them, see Fig. 5b,c. The boxes contain no free-space optical components so all light processing is realized in single-mode fiber-optic elements. Each box is connected to a free-space coupler via a single-mode fiber and may be connected to a computer with a USB interface.

All electronics controlling generation, processing and detection of optical signals is packaged in the same boxes side by side with optical components as shown in Fig. 6. High-speed electronic functions are directly performed by a field-programmable gate array (FPGA), which forms the core of each box. Auxiliary functions such as computer connectivity, display control, etc. are performed in a microcontroller.
Appendix E: Comparison with previous relativistic approaches.

The first relativistic QKD protocol was proposed in 1995 [14], where due to relativistic causality it was possible to use orthogonal quantum states. As discussed in [12] [13], the actual states in the channel are not orthogonal because each state as a whole is never present in the channel. This approach can be classified as a whole class of relativistic protocols with quantum states spread for more than the channel length. Interestingly, the same idea of only partial quantum state presence in the channel, later found another application in counterfactual QKD [32, 33]. Following the first pioneer work, in [14] it was shown that transmission at unknown random moments of time is not required if globally non-orthogonal quantum states are used instead. Even with this modification, the protocol remained quite impractical as it requires on-site phase-stable delays equal to the time-of-flight between Alice and Bob and also precise clock synchronization between the parties. Nevertheless, it has been recently realized as a table-top experiment [15] and even as a 1 km long fiber realization [16]. Further theoretical developments [34] allowed to use shorter time delays and to obtain more than one secret key bit per photon transmitted, however, the requirement of a true single photon source and a lossless channel remained.

The next major breakthrough in relativistic quantum cryptography happened with the invention of relativistic bit commitment protocols [15] [19]. Without relativity principles, as has been shown earlier by Mayers, Lo, and Chau, quantum bit commitment is impossible [23, 24]. This is probably the first example of substantially new quantum cryptography protocol enabled by adding the theory of relativity. Later a few other relativistic bit commitment protocols have been proposed [20, 21] and even demonstrated experimentally [22].

The present paper shows a particular realization of a fundamentally new relativistic QKD approach, which uses relativistic principles to strengthen conventional QKD protocols. In result, the new relativistic protocols demonstrate unconditional security of generated keys, regardless of the quantum channel loss and with classical photon sources. It has to be mentioned that the proposed principle can be used as a general framework for future relativistic QKD protocols, whose application range is much superior than for conventional, non-relativistic QKD.

[1] C. H. Bennett and G. Brassard, “Quantum cryptography: Public key distribution and coin tossing,” in Proceedings of the IEEE International Conference on Computers, Systems, and Signal Processing, Bangalore, 1984, pp. 175–179.
[2] A. K. Ekert, “Quantum cryptography based on Bell’s theorem,” Phys. Rev. Lett., vol. 67, no. 6, pp. 661–663, 1991.
[3] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, “Quantum cryptography,” Rev. Mod. Phys., vol. 74, no. 1, pp. 145–195, 2002.
[4] V. Scarani, H. Bechmann-Pasquinucci, N. J. Cerf, M. Dušek, N. Lütkenhaus, and M. Peev, “The security of practical quantum key distribution,” Rev. Mod. Phys., vol. 81, no. 3, pp. 1301–1350, 2009.
[5] R. Hughes and J. Nordholt, “Refining quantum cryptography,” Science, vol. 333, no. 6049, pp. 1584–1586, 2011.
[6] P. K. Lam and T. C. Ralph, “Quantum cryptography: Continuous improvement,” Nature Photon., vol. 7, no. 5, pp. 350–352, 2013.
[7] B. Lounis and W. E. Moerner, “Single photons on demand from a single molecule at room temperature,” Nature, vol. 407, no. 6803, pp. 491–493, 2000.
[8] S. Benjamin, “Quantum cryptography - single photons on demand,” Science, vol. 290, no. 5500, p. 2273, 2000.
[9] D. Dieks, “Communication by EPR devices,” Phys. Lett. A, vol. 92, no. 6, pp. 271–272, 1982.
[10] W. K. Wootters and W. H. Zurek, “A single quantum cannot be cloned,” Nature, vol. 299, no. 5886, pp. 802–803, 1982.
[11] L. Goldenberg and L. Vaidman, “Quantum cryptography based on orthogonal states,” Phys. Rev. Lett., vol. 75, no. 7, pp. 1239–1243, 1995.
[12] A. Peres, “Quantum cryptography with orthogonal states?” Phys. Rev. Lett., vol. 77, no. 15, p. 3264, 1996.
[13] L. Goldenberg and L. Vaidman, “Goldenberg and vaidman reply,” Phys. Rev. Lett., vol. 77, no. 15, p. 3265, 1996.
[14] M. Koashi and N. Imoto, “Quantum cryptography based on split transmission of one-bit information in two steps,” Phys. Rev. Lett., vol. 79, no. 12, pp. 2383–2386, 1997.
[15] A. Avella, G. Brida, I. P. Degiovanni, M. Genovese, M. Gramigna, and P. Traina, “Experimental quantum cryptography scheme based on orthogonal states,” Phys. Rev. A, vol. 82, p. 062309, 2010.
[16] G. B. Xavier, G. P. Temporao, and J. P. von der Weid, “Employing long fibre-optical Mach-Zehnder interferometers for quantum cryptography with orthogonal states,” Electron. Lett., vol. 48, no. 13, pp. 775–777, 2012.
[17] E. Jeffrey, J. Altepeter, and P. G. Kwiat, “Relativistic quantum cryptography,” in OSA Frontiers in Optics, Rochester, New York, Oct. 2006.
[18] A. Kent, “Unconditionally secure bit commitment,” Phys. Rev. Lett., vol. 83, no. 7, pp. 1447–1450, 1999.
[19] S. N. Molotkov and S. S. Nazin, “Relativistic quantum bit commitment in real-time,” JETP, vol. 90, no. 4, pp. 714–723, 2000.
[20] G. P. He, “Quantum key distribution based on orthogonal states allows secure quantum bit commitment.” J. Phys. A: Math. Theor., vol. 44, p. 445305, 2011.
[21] A. Kent, “Unconditionally secure bit commitment by transmitting measurement outcomes,” Phys. Rev. Lett., vol. 109, p. 130501, 2012.
[22] T. Lunghi, J. Kaniewski, F. Bussières, R. Houlmann,
M. Tomamichel, A. Kent, N. Gisin, S. Wehner, and H. Zbinden, “Experimental bit commitment based on quantum communication and special relativity,” *Phys. Rev. Lett.*, vol. 111, no. 18, p. 180504, 2013.

[23] D. Mayers, “The trouble with quantum bit commitment,” 1996, arXiv:quant-ph/9603015.

[24] ——, “Unconditionally secure quantum bit commitment is impossible,” *Phys. Rev. Lett.*, vol. 78, no. 17, p. 3414, 1997.

[25] H. K. Lo and H. F. Chau, “Is quantum bit commitment really possible?” *Phys. Rev. Lett.*, vol. 78, no. 17, p. 3410, 1997.

[26] S. N. Molotkov and S. S. Nazin, “The role of causality in ensuring the ultimate security of relativistic quantum cryptography,” *JETP Lett.*, vol. 73, no. 12, pp. 682–687, 2001.

[27] S. N. Molotkov, “Relativistic quantum cryptography for open space without clock synchronization on the receiver and transmitter sides,” *JETP Lett.*, vol. 94, no. 6, pp. 469–476, 2011.

[28] ——, “Relativistic quantum cryptography,” *JETP*, vol. 112, no. 3, pp. 370–379, 2011.

[29] ——, “On the resistance of relativistic quantum cryptography in open space at finite resources,” *JETP Lett.*, vol. 96, no. 5, pp. 342–348, 2012.

[30] C. H. Bennett, “Quantum cryptography using any two nonorthogonal states,” *Phys. Rev. Lett.*, vol. 68, no. 21, pp. 3121–3124, 1992.

[31] A. S. Holevo, “Quantum coding theorems,” *Russian Math. Surveys*, vol. 53, no. 6, pp. 1295–1331, 1998.

[32] T.-G. Noh, “Counterfactual quantum cryptography,” *Phys. Rev. Lett.*, vol. 103, no. 23, p. 230501, 2009.

[33] M. Ren, G. Wu, E. Wu, and H. Zeng, “Experimental demonstration of counterfactual quantum key distribution,” *Laser Physics*, vol. 21, no. 4, pp. 755–760, 2011.

[34] J. S. Cotler and P. W. Shor, “A new relativistic orthogonal states quantum key distribution protocol,” 2014, arXiv:quant-ph/1401.5493.