Free-Running Long-Distance Reference-Frame-Independent Quantum Key Distribution

Bang-Ying Tang,1 Huan Chen,2 Ji-Peng Wang,3 Hui-Cun Yu,4,5 Lei Shi,4 Shi-Hai Sun,6 Wei Peng,1 Bo Liu,5† and Wan-Rong Yu1,†

1 College of Computer Science and Technology, National University of Defense Technology, Changsha 410073, China
2 College of Liberal Arts and Sciences, National University of Defense Technology, Changsha 410073, China
3 School of Science and State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
4 Information and Navigation College, Air Force Engineering University, Xi’an 710077, China
5 College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China
6 School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519082, China

Rapidly and randomly drifted reference frames will shorten the link distance and decrease the secure key rate of realistic quantum key distribution (QKD) systems. However, an actively or inappropriately implemented calibration scheme will increase complexity of the systems and may open security loopholes. In this article, we present a free-running reference-frame-independent (RFI) QKD scheme, where measurement events are classified into multiple slices with the same misalignment variation of reference frames and each slice performs the post-processing procedure individually. We perform the free-running RFI QKD experiment with a fiber link of 100 km and the misalignment of the reference frame between Alice and Bob is varied more than 29 periods in a 50.7-hour experiment test. The average secure key rate is about 734 bps with a total loss of 31.5 dB, which achieves the state-of-art performance of the long-distance RFI QKD implementations. Our free-running RFI scheme can be efficiently adapted into the satellite-to-ground and drone based mobile communication scenarios, as it can be performed with rapidly varying reference frame and a loss more than 40 dB, where no secure key can be obtained by the original RFI scheme.

Quantum key distribution (QKD) has the potential to generate the information-theoretical-secure keys between distant users (Alice and Bob) [1–3]. Since the first BB84 protocol proposed [4], QKD has stepped into realistic applications from the laboratory [5–11]. The communication distance of QKD over different communication scenarios is significantly improved, such as 509 km with fiber link [12], 4600 km space-to-ground communication network [13], 1 km optical-relayed entanglement distribution over drones [14].

In general, the realistic QKD systems have a common need of establishing a shared reference frame between distant users by characterizing and calibrating the polarization or phase of photons. Nevertheless, an actively or inappropriately implemented calibration scheme may increase the complexity of the systems and may open an unpredictable security loophole [15] [16].

Reference-frame-independent (RFI) QKD protocol, proposed in 2010, is robust for the slowly varying reference frames and suitable to the satellite-to-ground and drone-based systems [17]. The secure key rate of RFI QKD systems varies a lot with given misalignment (θ0) of reference frames [18]. Furthermore, F. Wang et al. shows the valid condition of RFI-QKD is that the misalignment variation Δθ ≤ π [19]. With the assumption of Δθ ≈ 0, the fiber link distance of RFI QKD reaches to 160 km implemented with measurement-device-independent scheme [11] [20] and the free space RFI QKD experiment was demonstrated with total loss of 38.0 dB [9] [21]. However, the misalignment of reference frames in realistic RFI QKD scenarios varies randomly, and the communication distance will be reduced heavily. W. Liang et al. performed a proof-of-principle experiment of RFI QKD with random θ0 and slowly varying phase environment, nevertheless, the communication distance was limited to 65 km when considering the finite-length effects [22] [23].

In this article, we proposed a free-running RFI scheme that can be adapted to the long-distance QKD systems with randomly and rapidly varying misalignment of reference frames. We implemented a free-running RFI QKD experiment over 100 km fiber link with a total loss of 31.5 dB and the system repetition rate of 80 MHz. In the experiment, time-bin encoded photons in Z basis are used for generating secure keys and the phase-encoded photons in the X (Y) basis are used for quantifying the characteristics of the quantum link. The experiment ran for 50.7 hours and the misalignment of reference frame between Alice and Bob was more than 29 periods. The secure key rate of our implementation reaches 734 bps, which achieves the state-of-art performance of the long-distance RFI QKD systems.

The setup of our free-running RFI QKD experiment is shown in FIG. 1. At Alice’s side, photons are generated by a homemade laser with a repetition rate of 80 MHz and a pulse width of 1.0 ns. An intensity modulator (IM1) and an attenuator (ATT) are used to modulate quantum (signal and decoy) states of the corresponding intensity. An asymmetric Mach–Zehnder interferometer (AMZI) divides each pulse into two adjacent pulses (s and t) with a separation time of 4.6 ns. The intensity modulator IM2 prepares the bit 0 or 1 of Z basis by...
suppressing $s$ or $l$ randomly. When both $s$ and $l$ pulses pass through IM2, a phase of $\{0, \pi/2, \pi, 3\pi/2\}$ will be randomly added to $s$ pulse with two phase modulators (PM1 and PM2), where $0$ and $\pi$ indicate bit 0 and 1 in $X$ basis, $\pi/2$ and $3\pi/2$ indicate bit 0 and 1 in $Y$ basis. Then, pulses are sent to Bob through a 100 km optical fiber with a loss of 0.235 dB/km.

At Bob’s side, the detection basis ($X$ and $Y$) is randomly chosen by the phase modulator (PM3), where a phase of 0 ($\pi/2$) is added to $s$ pulse. Then another asymmetric Mach–Zehnder interferometer (AMZI2) which has the same path difference with the AMZI1 divides each pulse into two pulses, resulting four pulses, $\{s + s, s + l, l + s, l + l\}$. $s + l$ and $l + l$ pulses will merge into one pulse due to the same arriving time and interfere at AMZI2. The interference determines the exiting port of the $s + l$ ($l + s$) pulse at the AMZI2, indicating the bit 0 or 1 of $X$ ($Y$) basis, respectively. $s + s$ and $l + l$ pulses represent bit 0 and 1 of $Z$ basis. Then, photons are coupled to two channels of the superconducting nanowire single photon detector (SNSPD), and the arriving time is recorded with a time-to-digital converter (TDC). The optimal detection efficiency, about 80%, is ensured by the polarization controllers (PC2 and PC3). The dark count rate of the SNSPD is about 200 per second. The programmable modules (National Instruments 6556) are used to control the laser and modulators. The total loss of Bob’s receiving module is around 10 dB.

Furthermore, an active feedback mechanism is performed to stabilize the intensity of the quantum state, where a beam splitter (BS) and an avalanche photon detector (APD) are performed to monitor the intensity of quantum states. The optimal detection parameters are analyzed from the recorded events of Bob’s side and then feedback to the programmable polarization controller (PC1) and PM3.

In the RFI QKD system, the reference frame of $X$ ($Y$) is defined as

$$ X_B = X_A \cos \theta + Y_A \sin \theta, $$
$$ Y_B = Y_A \cos \theta - X_A \sin \theta, $$

where $\theta$ is the misalignment angle of reference frames between Alice and Bob and $\theta \in [0, 2\pi]$. The quality of the quantum channel $C$ can be estimated as $17$

$$ C = (X_A X_B)^2 + (Y_A Y_B)^2 + (X_A Y_B)^2 + (Y_A X_B)^2. $$

Given initial $\theta_0$, the RFI-QKD can be performed with the varying $\Delta \theta$ which satisfies

$$ \frac{3 \times 10^4}{\eta N_0} \omega \leq \Delta \theta \leq \pi, $$

where $\eta$ is the total efficiency of system, $\omega$ denotes the intense constant of noise and $N_0$ is the photon-generating rate $19$.

Assume $E_{k}^{\alpha,\beta}$ is the QBER, where $k \in \{\mu, \nu\}$ is the mean photon number of signal and decoy states, $\alpha, \beta \in \{X, Y, Z\}$ are the basis chosen by Alice and Bob, respectively. And the total pulses sent by Alice is $N_t$.

In the free-running RFI scheme, we split the misalignment angle $\theta$ into $m$ slices as

$$ \Theta_i = \begin{cases} \{\theta | 2 - \frac{1}{m} \pi \leq \theta < 2\pi \text{ or } 0 \leq \theta < \frac{\pi}{m}\}, & i = 0 \\ \{\theta | 2i - \frac{1}{m} \pi \leq \theta < 2i + \frac{1}{m} \pi\}, & i > 0 \end{cases}, $$

where $i = 0, 1, \ldots, m - 1$.

According to Equ (5), the interval sampling time $T$ for quantifying the quantum channel should be less than $\pi/\omega$.

Given $T$, $\theta$ of each interval can be calculated as

$$ \theta = \begin{cases} \arccos \left(1 - 2E_{\mu}^{XX}\right) - \frac{1}{2} \pi & E_{\mu}^{XY} < 0.5 \\ 2\pi - \arccos \left(1 - 2E_{\mu}^{XX}\right) - \frac{1}{2} \pi & E_{\mu}^{XY} \geq 0.5 \end{cases}. $$

Thus, the measurement events can be split into $m$ slices according to the measured QBER in $XY$-basis and then generate the secure keys for each slice respectively.

In the experiment, the $Z$ basis is sent with the probability of 50%, $X$ and $Y$ basis are sent with the probability of 25%. The signal, decoy, and vacuum states are sent with the probability of 50%, 40%, and 10%, respectively. The mean photon number of signal and decoy states are 0.722 and 0.104. The experiment is free-running for about 50.7 hours. The sampling interval $T$ is set to 5 seconds. The slice number $m$ is set as 16 and the error correction efficiency is 1.16 $24$.

FIG. 2 shows the QBER of signal and decoy states for each bases and the count rate of $Z$ basis. The QBER
FIG. 2. The measured QBER in each bases, and the count rate in Z-basis. Each point is measured within 5s. (a) [(b)] shows the QBER of signal [decoy] state on X, Y basis for the total 50.7 hours, (c) shows the QBER of signal state and decoy state on Z basis: $E_{\mu Z}^{ZZ}$ and $E_{\mu Z}^{ZZ}$, and (d) shows the count rate of signal and decoy state on Z basis: $N_{\mu Z}^{ZZ}$ and $N_{\nu Z}^{ZZ}$.

FIG. 3. The QBER of the merged sets with the experimental measured data. (a) shows the QBER of signal state on X, Y basis, (b) shows the QBER of decoy state on X, Y basis, (c) shows the QBER on Z basis, and each point represents the merged result of each set.

FIG. 4. The $C$ value, secure key rate of merged sub-block and the simulated result with $N_i = 10^{12}$ and $\Delta \theta = \pi/8$. The $C$ value and secure key rate varies with $\theta$ because the misalignment of reference frame affects the leaked information [18].

of the X, Y bases varied periodically with the time due to the environmental noise which affects the phase of the two interferometers, while the QBER of the Z basis maintained stable with small fluctuations. The average QBER of the signal state on the Z basis is about 0.6%. The average count rate of the signal and decoy states of Z basis is about 2.6 kbps and 0.4 kbps. During the whole experiment, the reference frame varied for more than 29 periods and the noise $\omega$ reaches an upper bound of $6.9 \times 10^{-3}$ rad/s.

Without loss of generality, we use $\{0, 2\pi/m, \ldots, 2(m-1)\pi/m\}$ to represent the misalignment angle of the slices. FIG. 3 shows the average QBER of each slice. The QBERs of X, Y basis vary against the rotation $\theta$ while
and the number \(m\) scheme is conducted after the basis shifting procedure, running RFI scheme. Meanwhile, the free-running RFI scheme can be performed into the satellite-to-ground frames.

The experimental result and the noise \(\omega = 6.9 \times 10^{-3}\) rad/s and \(m = 16\).

Furthermore, we simulate the average secure key rate of the free-running RFI QKD versus the total loss with \(N_t = 10^{12}, 10^{13}\) and the noise \(\omega = 6.9 \times 10^{-3}\) rad/s. The results are shown in FIG. 5 The total loss tolerance of the original RFI QKD protocol is limited to 32.6 dB, which can be increased to around 43.3 dB with our free-running RFI scheme. Meanwhile, the free-running RFI scheme is conducted after the basis shifting procedure, and the number \(m\) of slices can be optimized to further improve the performance. Especially, our free-running RFI scheme can be performed into the satellite-to-ground and drone-based QKD scenarios, which avoids the complicated alignment of unpredictable varying reference frames.

This work was supported by National Natural Science Foundation of China under Grant No. 61972410 and No. 61971436, the Research Plan of National University of Defense Technology under Grant No. ZK19-13 and No. 19-QNCXJ-107 and the Postgraduate Scientific Research Innovation Project of Hunan Province under Grant No.CX20200003.

![FIG. 5. The simulated secure key rate of our free-running RFI scheme with \(N_t = 10^{12}, 10^{13}\). Our experimental result and the simulated optimal secure key rate of the original RFI scheme are also shown here. In the simulation, \(\omega = 6.9 \times 10^{-3}\) rad/s and \(m = 16\).](image-url)
N. Zhang, M. Hu, J. Guo, X. Cao, X. Hu, G. Zhao, Y.-Q. Lu, Y.-X. Gong, Z. Xie, and S.-N. Zhu, Optical-relayed entanglement distribution using drones as mobile nodes, Physical Review Letters 126, 020503 (2021).

[15] N. Jain, C. Wittmann, L. Lydersen, C. Wiechers, D. Elser, C. Marquardt, V. Makarov, and G. Leuchs, Device calibration impacts security of quantum key distribution, Physical Review Letters 107, 110501 (2011).

[16] Z.-Y. Dong, N.-N. Yu, Z.-J. Wei, J.-D. Wang, and Z.-M. Zhang, An attack aimed at active phase compensation in one-way phase-encoded qkd systems, The European Physical Journal D 68, 230 (2014).

[17] A. Laing, V. Scarani, J. G. Rarity, and J. L. O’Brien, Reference-frame-independent quantum key distribution, Physical Review A 82, 012304 (2010).

[18] C.-M. Zhang, J.-R. Zhu, and Q. Wang, Practical reference-frame-independent quantum key distribution systems against the worst relative rotation of reference frames, Journal of Physics Communications 2, 055029 (2018).

[19] F. Wang, P. Zhang, X. Wang, and F. Li, Valid conditions of the reference-frame-independent quantum key distribution, Phys.rev.a 94, 062330 (2016).

[20] C.-M. Zhang, J.-R. Zhu, and Q. Wang, Practical decoy-state reference-frame-independent measurement-device-independent quantum key distribution, Physical Review A 95, 032309 (2017).

[21] Y.-P. Li, W. Chen, F.-X. Wang, Z.-Q. Yin, L. Zhang, H. Liu, S. Wang, D.-Y. He, Z. Zhou, G.-C. Guo, and Z.-F. Han, Experimental realization of a reference-frame-independent decoy bb84 quantum key distribution based on sagnac interferometer, Optics Letters 44, 4523 (2019).

[22] W.-Y. Liang, S. Wang, H.-W. Li, Z.-Q. Yin, W. Chen, Y. Yao, J.-Z. Huang, G.-C. Guo, and Z.-F. Han, Proof-of-principle experiment of reference-frame-independent quantum key distribution with phase coding, Scientific Reports 4, 3617 (2014).

[23] L. Sheridan, T. P. Le, and V. Scarani, Finite-key security against coherent attacks in quantum key distribution, New Journal of Physics 12, 123019 (2010).

[24] B.-Y. Tang, B. Liu, W.-R. Yu, and C.-Q. Wu, Shannon-limit approached information reconciliation for quantum key distribution, Quantum Information Processing 20, 113 (2021).

[25] C. C. W. Lim, M. Curty, N. Walenta, F. Xu, and H. Zbinden, Concise security bounds for practical decoy-state quantum key distribution, Physical Review A 89, 022307 (2014).