Twin-field quantum key distribution over a 511 km optical fibre linking two distant metropolitan areas

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The basic principle of quantum mechanics guarantees the unconditional security of quantum key distribution (QKD) at the cost of forbidding the amplification of a quantum state. As a result, and despite remarkable progress worldwide, QKD networks18 over the past decades, a long-haul fibre QKD network without a trusted relay has not yet been achieved. Here, through the sending-or-not-sending protocol19, we achieve twin-field QKD and distribute secure keys without any trusted repeater over a 511 km long-haul fibre trunk that links two distant metropolitan areas. The fibre trunk contains 12 fibres in the cable, the quantum state of which is used for the quantum channel, synchronization and frequency locking, respectively. The remaining nine are used for classical fibre communication. Our secure key rate is around three orders of magnitude greater than that expected if the previous QKD field-test system was applied over the same length. Efficient quantum-state transmission and stable single-photon interference over such a long-haul deployed fibre pave the way to large-scale fibre quantum networks.

Quantum non-cloning theorem forbids perfect cloning of unknown quantum states or non-orthogonal states simultaneously. Based on the theorem, the first QKD protocol, known as BB84 (ref. 2), was proposed in which non-orthogonal states are exploited to encode a random key for distribution between two authorized users. Any probe from an unauthorized party intending to steal the key can be seen as a kind of clone, which will inevitably bring additional bit error according to the non-cloning theorem. This bit error can be found during postprocessing of the authorized users and thus the theoretical security of the information is achieved1-5.

Since then, QKD has been studied extensively and has grown to a matured technology in real-world applications. Quite a few metropolitan fibre networks have been built all over the world. Similar to optical-fibre communication (OFC), the quantum state will be attenuated exponentially with the transmission distance. For OFC, an optical amplifier is used to relay the optical signal every 80 km (ref. 12) to build a long-haul fibre network. The amplifier for a single unknown quantum state, however, does not exist because the amplification of a quantum signal can also be seen as a type of cloning, and any cloning of unknown quantum states will bring fatal errors. Therefore, a simple optical amplifier cannot be used for long-haul fibre QKD. So far, the longest reported field test of QKD is around 90 km (ref. 13).

A trusted relay is utilized to build up the long-haul trunk QKD, but the many relay stations must be well isolated and trusted. In the meantime, the quantum repeater technology has been invented to replace the optical amplifier. However, the current technology can only reach 50 km (refs. 12-14). Recently, it has been shown that there exists an upper bound for both repeater-less QKD and OFC. Therefore, the current main challenge towards large-scale fibre quantum communication networks is to beat the repeater-less bound and demonstrate QKD over real long-haul trunk line.

Among all the protocols, twin-field quantum key distribution (TF-QKD) promises high key rates over long distances to beat the repeater-less bound, which enhances the key rate to a square-root scaling to the channel transmittance (\(\sqrt{\eta}\)). Notably, experimental demonstrations of TF-QKD have achieved a record long-distance distribution of more than 500 km (refs. 23-25). However, all these experiments were implemented in a laboratory, leaving the question of whether or not this fancy protocol is feasible in a practical scenario.

In general, compared with laboratory experiments, field tests in an OFC network often introduce more noise due to complex environmental fluctuation and cross-talk from adjacent classical fibre communication. The condition becomes even more challenging for TF-QKD, which requires optical-phase stability for single-photon-level interference. For example, in the laboratory, a vibration due to a human voice or walking will influence the optical phase and decrease the interference visibility. However, the human voice or other activity cannot be forbidden in the field as it can be in the laboratory. Considering these challenges, putting the experiment to a field test is not only necessary to prove its feasibility, but also an important step for exploring the possibilities of future global QKD networks.

Here, we precisely control the wavelength of two 500-km-distant independent laser sources and rapidly compensate any small phase fluctuation in the channel. Then, we present a field test of a TF-QKD experiment through a total channel length of 511 km of ultra-low-loss fibre (including 430 km of long-haul fibre and...
an 81 km fibre spool) with a total loss of 89.1 dB connecting Qingdao and Jinan in Shandong Province, China. The secure key rate (3.37 × 10^−3 per pulse) at 511 km is higher than the absolute Pirandola–Laurenza–Ottaviani–Banchi (PLOB) bound, after collecting 4.7 h of data for finite-size and fluctuation analysis.

We adopt the sending-or-not-sending (SNS) protocol^9 with actively odd-parity pairing (AOPP)\(^{30,31}\) method for data postprocessing in the field experiment of TF-QKD. In this protocol, Alice and Bob use three weak coherent state (WCS) sources in the X basis, with probabilities 1 − \(p_z\), and 0, which are used for decoy-state analysis. Moreover, in the Z basis, Alice and Bob randomly decide to send the WCS pulses \(\mu_x\) or not sending, where those pulses are used to extract the final keys. To improve the key rate, we take the odd-parity-error rejection method through AOPP in the data postprocessing, which can efficiently deduce the bit-error rate of the raw keys and thus largely improve the key rate. We use the zig-zag approach proposed in ref.\(^{32}\) to analyse the finite key effects of AOPP, which assures the high performance of the SNS-TF-QKD protocol with AOPP in the finite key size.

In this protocol, Alice and Bob randomly choose the X basis or the Z basis with probabilities 1 − \(p_z\) and \(p_z\). For the Z basis, with probabilities 1 − \(p_z\), \(p_z\), and \(p_z\), Alice and Bob randomly prepare and send out pulses with intensities \(\mu_x\) or not sending with probabilities \(\epsilon\) and 1 − \(\epsilon\). For the received pulse pair, if Charlie announces that there is only one detector click, we call this a one-detector heralded event. The corresponding bits of one-detector heralded events in the Z basis are used to estimate the yield of single-photon pairs before AOPP. Besides, if the phase of a pulse pair in the X basis satisfies the phase postselection criterion, its corresponding one-detector heralded event can be used to estimate the phase-flip error rate before AOPP. (The detailed calculation of AOPP is presented in Supplementary Information section 1.)

We realize TF-QKD in field-deployed fibre between two non-adjacent metropolitan areas, Qingdao (Alice, 36° 6’ 13” N, 120° 24’ 32” E) and Jinan (Bob, 36° 36’ 50” N, 117° 6’ 22” E). In addition to our experiment, classical communications are running in transmission (the QKD link), one for clock synchronization and the ‘start’ signal (synchronization), and one for wavelength calibration to lock the optical bundle of optical fibres in the field-deployed optical cable. Three of the bundle of 12 fibres are used in this experiment: one for single-photon-level signal and sent to the measurement station. AOM, acoustic-optic modulator; BS, beam splitter; PM, phase modulator; IM, intensity modulator; ATT, passive attenuator; HWP, half-wave plate; PBS, polarization beam splitter; QWP, quarter-wave plate; PD, photoelectric detector; PC, polarization controller.
24° 32′ E) and Jinan (Bob, 36° 36′ 50″ N, 117° 6′ 22″ E) in Shandong Province of China, which are connected by a 430 km long-haul fibre network, as shown in Fig. 1. The measurement station is placed in Mazhan (Charlie, 36° 0′ 19″ N, 118° 42′ 35″ E) in the middle of the fibre link. The long-haul network contains 12 fibres in the cable, which are mainly used for classical fibre communication testing. All 12 fibres are G.654.E ultra-low-loss fibre with a nominal loss of 0.158 dB km$^{-1}$.

Among the 12 fibres, we have rented three for our experiment and the other nine are still used for classical fibre communications by China Unicom. Our three fibres are used to transfer the quantum signal, the optical synchronizing signal and the laser-frequency-locking signal. The time–frequency dissemination signal is used to lock the frequency of the two independent lasers in Jinan and Qingdao. In addition, for the synchronization channel and the wavelength-locking channel, erbium-doped fibre amplifiers are used approximately every 70 km to amplify the signal. In the meantime, the quantum single does not have any relay node. Similar to our previous TF-QKD experiment in the laboratory, Alice and Bob use independent lasers: the commercial kilohertz continuous-wave fibre lasers are locked to an ultra-low-expansion glass cavity in both sides as the light source. The linewidth for both Alice's and Bob's lasers is less than 1 Hz. The central wavelength of Alice's laser is set to 1,550.12460 nm. We then split the light into two, where one part is to transfer the quantum signal and the other one is used for wavelength locking. Instead of locking two lasers in a same room, the field experiment needs to lock the two lasers 400 km away. Alice adopts the time–frequency dissemination...
technology\textsuperscript{35}, and sends the frequency-locking laser through the 84.1 dB (430 km) fibre channel with six erbium-doped fibre amplifiers in between. The light interferes with Bob’s laser at a photodiode. Based on the beating result, Bob sets his laser wavelength with an acoustic-optic modulator. The relative frequency drift of the two sources is measured to be approximately 0.1 Hz s\textsuperscript{-1}, giving an accumulated phase difference of about π/60 per hour. Therefore, instead of continuing to calibrate the wavelength, we only need to calibrate the wavelength difference every hour or two, which is good enough for the experiment. This can eliminate the cross-talk noise from the wavelength-locking channel.

After locking the wavelength, the fibre fluctuation becomes the main source of phase noise. The ambient temperature change during the day–night cycle affects the effective length of the deployed fibre and thus the phase and the arrival time of the signal. We monitor the arrival time of the signal by measuring the arriving time of the reference pulse at the idler port of the polarization beam splitter (PBS) from Alice and Bob. As shown in Fig. 2a, without any feedback the arrival time is strongly related to the ambient temperature and changes by up to 20 ns in one day. The arrival-time drift may also deteriorate the interference of the signal by affecting the overlap between the two pulses.

We utilize a two-stage procedure to fix the time fluctuation problem. First, we synchronize the laser pulses of Alice and Bob with Charlie’s clock\textsuperscript{34,35}. Charlie sends two 250 MHz synchronized laser-pulse trains, one to Alice and one to Bob, through the synchronization fibre channel. The two laser trains are used to lock the local clock of the signal generators, which then generate signal pulses in both sides with a pulse duration of 280 ps. The measured arrival times at Charlie’s side are used as a feedback signal to adjust the relative delay between the synchronization laser trains of Alice and Bob. With such an arrangement, the fluctuation of the arrival time decreases to 10 ps, which is negligible compared with the signal-pulse duration of 280 ps.

After fixing the time drift, the phase fluctuation is the target for the second stage, which is also larger than fluctuations in the laboratory due to environmental vibration. We measured a phase rate of 0.03 rad μs\textsuperscript{-1} through field-deployed fibre, or equivalent to 17° in 10 μs, as shown in Fig. 2b. The phase-reference pulse and the corresponding phase-estimation method\textsuperscript{35,29} are used to compensate for this phase drift in postprocessing. We time-multiplex the quantum signal together with strong phase-reference pulses using an intensity modulator. The superconducting nanowire single-photon detectors (SNSPDs) used in our experiment had a 60 dB dynamic range, which can measure both the quantum signal and the strong phase-reference signal. According to the measurement result of the phase-reference signals, we can compensate the phase difference in postprocessing, and then the optical phase-sensitive interference is achieved. (See Supplementary Information section 2 for details of the experimental setup.)

In addition to the time drifting and phase fluctuation, the polarization drift in the deployed fibre also ruins the interference. To solve this problem, electric polarization controllers and polarization beam splitters (PBSs) are inserted before the beam splitter in Charlie. The signals from the idler port of the PBS are directed to an SNSPD to monitor the polarization, for Alice and Bob respectively. The target-counting rate is set to 175 kHz for feedback. Without the feedback, the intensity changes by 30% in four hours; this is compared with it being almost stable when the feedback is on. (See Supplementary Information section 6 for details.)

After fixing all these fluctuations, we also need to filter out the cross-talk noise from adjacent fibre bundles, which is also new compared with the laboratory experiment. The cross-talk noise count rate from synchronization pulses and classical communication in the fibre bundle is around 486 and 616 counts per second (c.p.s.) for Alice and Bob, respectively. We set our QKD wavelength outside of the noise spectrum and add 100 GHz (0.8 nm) dense wavelength division multiplexing to filter out the noise. After the filtering, these instances of cross-talk noise drop to less than 10 c.p.s. for both sides.

Besides cross-talk noise counts, there are also noise counts from re-Rayleigh scattering noise\textsuperscript{36}, which are caused by backscattering of the Rayleigh backscattered phase-reference light and detector dark counts. We estimate this re-Rayleigh scattering noise to be about 8 c.p.s. on each single-photon detector, based on the detected reference counts. The dark counts for the SNSPDs are 4 and 6 c.p.s., with detection efficiencies of 77 and 91%, respectively. In total, the noise count for each detector is about 24 c.p.s. We then further use 350 ps time filtering to reduce the noise probability per gate, achieving a noise count rate of 7 × 10\textsuperscript{-2}.

With all the above improvements, we realized the field test of SNS-TF-QKD with a total of 511 km of ultra-low-loss fibre deployed between Jinan and Qingdao. The experimental parameters and results are shown in Table 1, and are shown in detail in Supplementary Table 4. With an effective system frequency of 100 MHz, we sent 1.679 × 10\textsuperscript{12} pulses in approximately 4.7 h. A total of 4.987 × 10\textsuperscript{6} valid detections were recorded, where one and two counts. We estimate this re-Rayleigh scattering noise to be about 8 c.p.s. on each single-photon detector, based on the detected reference counts. The dark counts for the SNSPDs are 4 and 6 c.p.s., with detection efficiencies of 77 and 91%, respectively. In total, the noise count for each detector is about 24 c.p.s. We then further use 350 ps time filtering to reduce the noise probability per gate, achieving a noise count rate of 7 × 10\textsuperscript{-2}.

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The secure key rate, considering data fluctuation and the finite data size effect, is calculated following the theory\textsuperscript{37}:

\[
R = \frac{N(t)}{N} \left( \frac{1}{2} \left( n_1 n_0 \left( 1 - H(E_Z) \right) \right) - \frac{1}{2} n_1 n_0 H(E_Z) \right)
- 2 \log_2 \frac{\epsilon_{\mathrm{fl}}}{\epsilon_{\mathrm{fl}} + \epsilon_{\mathrm{in}}}
- 2 \log_2 \frac{1}{\epsilon_{\mathrm{fl}} + \epsilon_{\mathrm{in}}}
\]

where \( R \) is the final key rate, \( H(x) = -x \log_2 (x) - (1-x) \log_2 (1-x) \) is the binary Shannon entropy function, \( n_1, n_0, \epsilon_{\mathrm{fl}}, \epsilon_{\mathrm{in}}, E_Z \) are the number of untagged bits, the phase-flip error rate, the number of survived bits and the bit-flip error rate of untagged bits after AOPP, respectively. The parameter \( f \) is the error-correction efficiency, here set to \( f = 1.16 \); \( N \) is the total number of signal pulses, \( \epsilon_{\mathrm{in}} = 1 \times 10^{-16} \) is the failure probability of the error-correction process, \( \epsilon_{\mathrm{fl}} = 1 \times 10^{-16} \).

Table 1 | Experimental parameters and results

| Parameter | Result |
|-----------|--------|
| \( \mu_1 \) | 0.100  |
| \( \mu_2 \) | 0.298  |
| \( \mu_3 \) | 0.422  |
| \( p_1 \) | 0.846  |
| \( p_2 \) | 0.076  |
| \( p_3 \) | 0.735  |
| \( \epsilon \) | 0.269  |
| \( n_1' \) | 576,130 |
| \( n_0' \) | 219,136 |
| \( \epsilon_{\mathrm{fl}} \) | 16.06% |
| \( E_Z \) | 0.43%  |
| \( N \) | 1.679 × 10\textsuperscript{12} |
| Valid detections | 4,987 × 10\textsuperscript{6} |
| Key rate | 3.37 × 10\textsuperscript{-5} |

The parameters \( \mu_1, \mu_2, \) and \( \mu_3 \) are the mean photon numbers for the sent pulses of the weak decoy state, strong decoy state and signal state, \( p_1, p_2, \) and \( p_3 \) are the probabilities of the weak decoy state and strong decoy in the X basis, \( \epsilon \) is the probability of the Z basis, \( v \) is the sending probability in the Z basis.
Fig. 3 | Secure key rates of the SNS-TF-QKD experiment. The red star indicates the experimental result over the 511 km field-deployed fibres, with the secure key rate of $R = 3.37 \times 10^{-6}$. The yellow circle and the green square indicate the experimental result of ref. 24 and ref. 27, respectively, with attenuators simulating the channel loss. The four triangles indicate the experimental results of ref. 25, ref. 26, ref. 28 and ref. 29, respectively, with in-laboratory fibre spools. The cyan curve is the simulation result with the experimental parameters. The blue dot-dashed line and the brown dashed line show the relative and absolute PLOB bound, respectively.

Finding immediate use in more general applications such as quantum repeaters and phase-based architecture for the quantum internet.

Online content
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Author contributions
Y.L., X.-B.W., Q.Z. and J.-W.P. conceived the research. W.-J.Z., H.Li., L.-X.Y. and Z.W. developed the SNSPD. J.-P.C., C.Z., Y.-H.L. and H.-F.J. implemented the stable laser system and the wavelength-locking system in the field. J.-P.C., C.Z., Z.-Y.H. and Q.Z. performed the field experiments. C.J., X.-L.H. and X.-B.W. developed the theory and calculated the secure key rate. J.-P.C., S.-Z.M., H.Liu., Z.-Y.H., F.Z. and T.-Y.C. arranged and tested the field fibre. All authors performed the data analysis and prepared the manuscript.

Competing interests
The authors declare no competing interests.

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