Quantum teleportation and entanglement distribution over 100-kilometre free-space channels

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Transferring an unknown quantum state over arbitrary distances is essential for large-scale quantum communication and distributed quantum networks. It can be achieved with the help of long-distance quantum teleportation1,2 and entanglement distribution. The latter is also important for fundamental tests of the laws of quantum mechanics3,4. Although quantum teleportation5,6 and entanglement distribution7,8 over moderate distances have been realized using optical fibre links, the huge photon loss and decoherence in fibres necessitate the use of quantum repeaters9,10 for larger distances. However, the practical realization of quantum repeaters remains experimentally challenging9. Free-space channels, first used for quantum key distribution11,12, offer a more promising approach because photon loss and decoherence are almost negligible in the atmosphere. Furthermore, by using satellites, ultra-long-distance quantum communication and tests of quantum foundations could be achieved on a global scale. Previous experiments have achieved free-space distribution of entangled photon pairs over distances of 600 metres (ref. 14) and 13 kilometres (ref. 15), and transfer of triggered single photons over a 144-kilometre one-link free-space channel16. Most recently, following a modified scheme17,18, free-space quantum teleportation over 16 kilometres was demonstrated19 with a single pair of entangled photons. Here we report quantum teleportation of independent qubits over a 97-kilometre one-link free-space channel with multi-photon entanglement. An average fidelity of 80.4 ± 0.9 per cent is achieved for six distinct states. Furthermore, we demonstrate entanglement distribution over a two-link channel, in which the entangled photons are separated by 101.8 kilometres. Violation of the Clauser–Horne–Shimony–Holt inequality4 is observed without the locality loophole. Besides being of fundamental interest, our results represent an important step towards a global quantum network. Moreover, the high-frequency and high-accuracy acquiring, pointing and tracking technique developed in our experiment can be directly used for future satellite-based quantum communication and long-scale tests of quantum foundations.

Following the original quantum teleportation scheme1,2, Alice and Bob share an entangled photon pair distributed by Charlie. An unknown state can be teleported from Alice to Bob by performing a joint Bell-state measurement on the two photons with Alice (see Supplementary Fig. 1a for details). Experimentally, we start with an ultra-bright entangled photon source20 based on type-II spontaneous parametric down-conversion21. On Charlie’s side (located at Gangcha, altitude 59.88°E; altitude 3,262 m; Fig. 1a), an entangled photon pair 2 and 3 in state |Φ+⟩23 = (|HH⟩23 + |VV⟩23)/√2 is created by Charlie and then distributed to Alice and Bob, where H (V) represents the horizontal (vertical) polarization of the photonic state (see Fig. 1b and Methods). An average twofold coincidence rate of 4.4 × 105 s⁻¹ for the entangled photon source was observed.

To prepare the unknown state to be teleported, Alice uses an ultra-violet laser to pump a collinear β-barium borate (BBO) crystal, which emits photon pairs in |HV⟩4 along the pumping direction (see Fig. 1c). After filtering out the pumping laser, a polarized beam splitter (PBS) splits the photon pair. A twofold coincidence rate of 6.5 × 10⁷ s⁻¹ was observed. A half-wave plate (HWP) and a quarter-wave plate (QWP) are applied to photon 1 to prepare the initial state |ψ⟩1 = α|H⟩ + β|V⟩, when triggered by photon 4. Alice then performs a joint Bell-state measurement on photons 1 and 2 by interfering them on a PBS and performing polarization analysis on the two outputs. The subsequent coincidence measurements can identify the (Φ±) Bell states in our experiment. In the joint Bell-state measurement, the observed visibility of interference on the PBS was 0.6. Finally, we observed a fourfold coincidence of 2 × 10⁵ s⁻¹ locally. Such a brightness supports successful quantum teleportation over a high channel loss, which can be greater than 50 dB (see Supplementary Fig. 1b and c).

Charlie sends photon 3 (by means of a compact transmitting system) through a 97-km free-space channel to Bob (Fig. 1b). A 127-mm f/7.5 (that is, aperture 127 mm, focal length 952.5 mm) extra-low dispersion apochromatic refractor telescope is used as an optical transmitting antenna. For near-diffraction-limited far-field divergence angles, we have designed our systems to reduce chromatic and spherical aberrations substantially. The divergence angle of our compact quantum transmitter is about 20 μrad.

As shown in Fig. 1d, on the other side of Qinghai Lake (Guanjing; 36°32’43.31” N, 100°28’9.81”E; altitude 3,682 m), Bob receives photon 3 in a 400-mm-diameter off-axis reflecting telescope. An integrated measurement system, consisting of an HWP, a QWP and a PBS, is assembled at the telescope’s exit for state analysis. Passing through two band-pass filters (full-width at half-maximum bandwidth ΔFWHM = 80 nm) and one narrow-band interference filter (ΔFWHM = 10 nm) used to reduce background noise (IF, shown in Fig. 1d), the photons are coupled in multi-mode fibres and then detected by the single-photon counting modules (SPCMs) with ultra-low dark counts (<20 s⁻¹). The noise that we observed, including the dark counts and ambient counts, was in total about 160 s⁻¹ to 300 s⁻¹, depending on the position of the Moon. On average, we obtained about 200 s⁻¹.

In addition, we assembled an acquiring, pointing and tracking (APT) system to account for effects due to ground settlement, mechanical deformation, atmospheric turbulence and so on. As shown in Fig. 1b, when the optical link is established for the first time, Charlie acquires the signal by global positioning system coordinates and a light guide. At the same time, he switches on the beacon laser (532 nm) pointing to the receiver, Bob. Bob then achieves acquisition and fires another beacon laser (671 nm) pointing back to Charlie.

The tracking system is composed of cascaded closed-loop control systems (the blue and green arrows in Fig. 1b and d). On Charlie’s side,
the beacon laser from the receiver, Bob, is detected by a wide-angle camera. Using a feedback loop, coarse alignment of the entire optical system is achieved by a platform rotatable in both azimuth and elevation (blue arrows in Fig. 1b). Similarly, the fine tracking indicated by the green arrows is achieved by a fast steering mirror (FSM) driven by piezo ceramics with the feedback from the four-quadrant detector (QD). Furthermore, the fine tracking system shares the same optical path as the quantum channel and is later separated by a dichroic mirror (DM). A high tracking accuracy can be obtained. The closed-loop bandwidth of the fine tracking is more than 150 Hz (see Supplementary Figs 2 and 3 for a detailed description for the APT system), which is sufficient to overcome most of the atmospheric turbulence. Finally, with this system design the tracking accuracy is better than 3.5 μrad over the 97-km free-space link.

There is also coarse and fine tracking on Bob’s side, by means of closed-loop control of the telescope’s own motor and FSM (Fig. 1d). Because the main purpose of the tracking at the receiver is to reduce the low-frequency shaking due to ground settlement and passing vehicles, the tracking bandwidth is about 10 Hz. The APT system is designed for tracking an arbitrarily moving object, and can be directly used for a satellite-based quantum communication experiment. In experiments between fixed locations, the first two steps, acquiring and pointing, do not need to be done every day.

After debugging the entire system, the channel loss of the 97-km horizontal atmospheric transmission at near ground level was measured to be between 35 and 53 dB, of which 8 dB was due to the imperfect optics and finite collection efficiency, and 8–12 dB was due to atmospheric loss. The geometric attenuation caused by the beam spreading wider than the aperture of the receiver telescope was between 19 and 33 dB, corresponding to a far-field spot size of between 3.5 and 17.9 m, depending on weather conditions. With a tracking accuracy of 3.5 μrad (a pointing error of 0.34 m at the receiver), we had stable count rates for single photons. The average channel attenuation was about 44 dB, and the time synchronization accuracy was better than 1 ns (see Supplementary Fig. 5 for details). Finally, we obtained 1,171 coincidences during an effective time of 14,400 s. Six distinct polarization states, namely, \(|H\rangle, |V\rangle, |\pm\rangle = (|H\rangle \pm |V\rangle)/\sqrt{2}, |R\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}\) and \(|L\rangle = (|H\rangle - i|V\rangle)/\sqrt{2}\) were teleported. The experimental fidelities for the six teleported states range from 76% to 80% (Table 1).

In the present teleportation experiment, Alice and Charlie are close to each other. A more common situation would be that Alice is also far away from Charlie. In this case, distribution of entanglement between Alice’s side. Under a trigger of photon 4, photon 1 is prepared in the initial state \(|\psi\rangle\). A coincidence between detectors T1 and T2 (R2) or R1 and R2 (T2) indicates the incident state of \(|\Phi^+\rangle (|\Phi^-\rangle\) for system tracking and a pulsed infrared laser (1,064 nm, 10 kHz, 50 mW, 200 μrad) for synchronization (Supplementary Information). Lasers are shown as black boxes labelled with emission wavelength. x and y denote the azimuth and elevation axis of the rotatable platform for the transmitting telescope. c, Initial state preparation and BSM on

### Table 1 | Fidelity of quantum teleportation over 97 km

| State | Fidelity |
|-------|----------|
| \(H\) | 0.814 ± 0.031 |
| \(V\) | 0.886 ± 0.024 |
| \(\pm\) | 0.773 ± 0.031 |
| \(\mp\) | 0.781 ± 0.031 |
| \(R\) | 0.808 ± 0.026 |
| \(L\) | 0.760 ± 0.027 |

The data were accumulated for 14,400 s. Errors shown are statistical errors, ± 1 s.d.
Alice and Bob is a prerequisite for quantum teleportation. A feasible solution is to distribute the entanglement by Charlie via a two-link channel. To demonstrate the two-link entanglement distribution, we move the entanglement source close to the middle of the free-space channel, an island in the middle of Qinghai Lake (Haixin, 36° 51’ 38.75” N, 100° 8’ 15.22” E, Fig. 2a). In order to show a two-link entanglement distribution between two sites, which cannot see each other directly, Bob moves his receiving platform to a different position, provided by a local Tibetan family (Gonghe; 36° 2’ 20.66” N, 100° 33’ 45.38” E), that is next to Guanjing (Fig. 2a). Charlie first prepares the entangled photon pairs in the state \(|\Phi^+\rangle\), which are then sent to Alice and Bob via two telescopes each mounted on a two-dimensional rotatable platform (Fig. 2b–d). The distances between Charlie and the two receivers are 51.2 km (Alice) and 52.2 km (Bob), and the distance between Alice and Bob is 101.8 km.

Whereas the same APT system as in the teleportation experiment is used between Bob and Charlie, the APT system used between Alice and Charlie is slightly modified (see Supplementary Fig. 4 for details). Entangled photons are then collected by telescopes on both sides. In contrast to the 400-mm off-axis reflecting telescope used on Bob’s side, Alice uses a 600-mm Cassegrain telescope to collect the photons. To confirm the successful entanglement distribution between the two receivers, we measure the \(S\) parameter in the Clauser–Horne–Shimony–Holt (CHSH)-type Bell’s inequality defined as

\[
S = |E(\phi_1, \phi_2) - E(\phi_1, \phi_3) - E(\phi_4, \phi_2) + E(\phi_4, \phi_3)|,
\]

where \(E(\phi_1, \phi_2)\) is the correlation function, and \(\phi_1\) and \(\phi_4\) \((\phi_2\) and \(\phi_3\)) the measurement settings of the photon in Alice’s (Bob’s) site. The settings are randomly selected among \((0, \pi/8), (0, 3\pi/8), (\pi/4, \pi/8)\) and \((\pi/4, 3\pi/8)\) by two fast electro-optical modulators (EOMs) and their logical circuits controlled by two quantum random number generators (not shown). The optical axes of the EOMs are set at 22.5° such that the EOMs act as 22.5° HWPs when half-wave voltages are applied and act as absent wave plates when zero-wave voltages are imposed. Quantum random number generators are used to produce the random digital series between zero-wave and half-wave voltages. Together with the HWPs (0° at Alice’s side and 11.25° at Bob’s side) and the quantum random number generator, the EOM randomly switches between the two desired measurement bases: 0 and \(\pi/4\) for Alice and \(\pi/8\) and 3\(\pi/8\) for Bob.

Finally, we obtained 208 coincidences during an effective time of 32,000 s. By comparison with the counts of our entanglement source, we found that the channel attenuation varied from 66 dB to 85 dB with an average value of 79.5 dB. For 20-cm-aperture satellite optics at an orbit height of 600 km and 1-m-aperture receiving optics, the total loss for a two-downlink channel between a satellite and two ground stations is typically about 75 dB. The measured correlation functions (shown in Fig 3) resulted in \(S = -2.51 \pm 0.21\), which violates Bell’s inequality by 2.4 standard deviations. This shows the feasibility of quantum teleportation with the modified scheme. Multi-photon, multi-link quantum teleportation, however, remains experimentally
challenging. The main difficulty is the spatial mode mismatching at the Bell-state measurement caused by atmospheric turbulence, which requires increasing the tracking bandwidth to more than one kilohertz: this requires the use of new technologies—such as an adaptive optics system, and photon collection with single-mode fibres. In addition, our experiment closed the locality loophole. The entangled photon pairs were distributed along two opposite directions to Alice and Bob: these parties are separated by 101.8 km, a distance that takes 340 μs for light to travel, and the path difference of the two links is 1 km, which results in a 3-μs delay between the two measurement events. Thus, the two measurement events on Alice’s and Bob’s sites are space-like separated. Furthermore, the two receivers used fast EOMs to switch between the two possible polarization bases. The two EOMs were controlled by two independent quantum random number generators, each of which generates a random number every 20 μs (less than 340 μs). Thus the measurement-setting choices are also space-like separated. Hence, the locality loophole is closed.

In this work, we experimentally realized free-space quantum teleportation for independent qubits over a 35–53-dB-loss one-link channel. In comparison with previous multi-photon experiments, we have enhanced the transmission distance by two orders of magnitude to 97 km. Furthermore, we demonstrated the distribution of entangled photon pairs over a two-link free-space channel to two receivers separated by more than 100 km. In contrast to previous long-distance free-space experiments with entangled photon pairs using only one-link channels, our two-link experiment requires tracking and synchronization between three different locations. Our two-link experiment—most comparable with satellite-to-ground quantum entanglement distribution—has achieved a distance between two receivers that is an order of magnitude larger than in previous experiments. Our results show that even with a high-loss ground-to-satellite uplink channel, or satellite-to-ground two-downlink channel, quantum teleportation and entanglement distribution can be realized. Furthermore, our APT system can be used to track an arbitrarily moving object with high frequency and high accuracy, which is essential for future satellite-based ultra-long-distance quantum communication. We believe our experiment will help fundamental tests of the laws of quantum mechanics on a global scale to be achieved.

METHODS SUMMARY

Entangled photon source. As shown in Fig. 1b, a femtosecond ultraviolet laser (394 nm, 1.3 W) is created by frequency doubling a pulsed laser (central wavelength of 788 nm with a pulse duration of 130 fs, a repetition rate of 76 MHz and an average power of about 3 W) with a LiB₃O₃ (LBO) crystal. After optimizing the beam profile with two cylindrical lenses (CL), the ultraviolet laser then pumps a type-II β-barium (BBO) crystal, creating a pair of polarization entangled photons in the state $|ψ⟩ = (|H, V⟩ + |V, H⟩)/\sqrt{2}$ with temporal and polarization information both entangled, where ordinary (o) and extraordinary (e) ray indicate the polarizations with respect to the pump. With an interferometric Bell-state synthesizer, we disentangle the temporal from the polarization information by guiding photons of different bandwidths through separate paths, resulting in the desired entangled state $|ψ⟩_{23} = (|HH⟩_{23} + |VV⟩_{23})/\sqrt{2}$. With a 3-mm filter in the e-ray path of photon 2 and an 8-mm filter in the o-ray path of photon 3, we observed an average twofold coincidence rate of $4.4 \times 10^5$/s with a visibility of about 91% in the $|H⟩/|V⟩$ basis and 90% in the $|+⟩/|−⟩$ basis. The generation rate of the entangled photons was about 0.1 pairs per pulse, and the overall detection efficiency was 23.6% locally.

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