143 km free-space quantum teleportation

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ABSTRACT

In the field of quantum communication the teleportation[1] of single quanta plays a fundamental role in numerous quantum information-processing protocols. Quantum teleportation allows to faithfully transfer unknown quantum states over arbitrary distances and constitutes a method to circumvent the no-cloning theorem[2]. Even formally completely independent particles can become entangled via the process of entanglement swapping[3]. In a future quantum communication network[4] this will be of utmost importance, enabling quantum computers to become globally interconnected. In order to prove the feasibility of quantum teleportation under optical link attenuations that will arise in a future space-application scenario, we extended the communication distance to 143 km, employing an optical free-space link between the two Canary Islands of La Palma and Tenerife. This work proofs the feasibility of ground-based free-space quantum teleportation. With our setup we were able to achieve coincidence production rates and fidelities to cope with the optical link attenuation, resulting from various experimental and technical challenges, which will arise in a quantum transmission between a ground-based transmitter and a low-earth-orbiting satellite receiver[5]. In our experiment we gained an average state fidelity for the teleported quantum states of more than 6 standard deviations beyond the classical limit of 2/3 and a process fidelity of 0.710(42). We expect that many of the features implemented in this experiment will be key blocks for future investigations.

Keywords: quantum, teleportation, entanglement, communication, swapping, repeater

1. INTRODUCTION

The classical internet as we know it from everyday life is predicted to be augmented or even replaced by a future platform, the quantum internet[4]. It promises exponential speed-up in distributed computation and secure communication channels. For eventually realizing such a global quantum communication network, the distribution of single and entangled qubits (quantum bits) over large distances will be a key ingredient. In the past years, we have therefore pursued several experimental studies[6-8] in the field of long-distance quantum communication, utilizing a 144 km optical free-space link between the Canary Islands La Palma and Tenerife. These investigations involved either single photons or pairs of entangled photons being used in various schemes for quantum key distribution as well as for tests of the non-classical properties of quantum systems. Additionally, the distribution of qubits over large distances via quantum teleportation will also be essential in a future global quantum-communication platform. It allows unknown quantum states to be transferred over arbitrary distances to a party whose location is unknown.

The most efficient teleportation schemes require the generation and detection of multi-photon states with at least 3 photons (i.e. teleportation of a weak-coherent state). The ultimate teleportation protocol, the teleportation of a single photon Fock state, requires even 4 photons. Such an ultimate multi-photon, long-distance free-space quantum communication experiment has never been performed so far and therefore remained an experimental challenge.

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Here we present an experiment realizing quantum teleportation of a single-photon state over a 143 km free-space link between the Canary Islands La Palma and Tenerife. The most significant difference to our previous experiments with single photons and entangled photon pairs is the considerably low count rate in a multi-photon experiment associated with the simultaneous detection of 4 photons. Furthermore, sending one of the four photons through the 143km free-space channel drastically reduces the obtainable signal-to-noise ratio (SNR).

2. METHODS

Quantum teleportation utilizes a quantum channel and a classical channel between two parties generally called Alice and Bob[9] (see Figure 1).

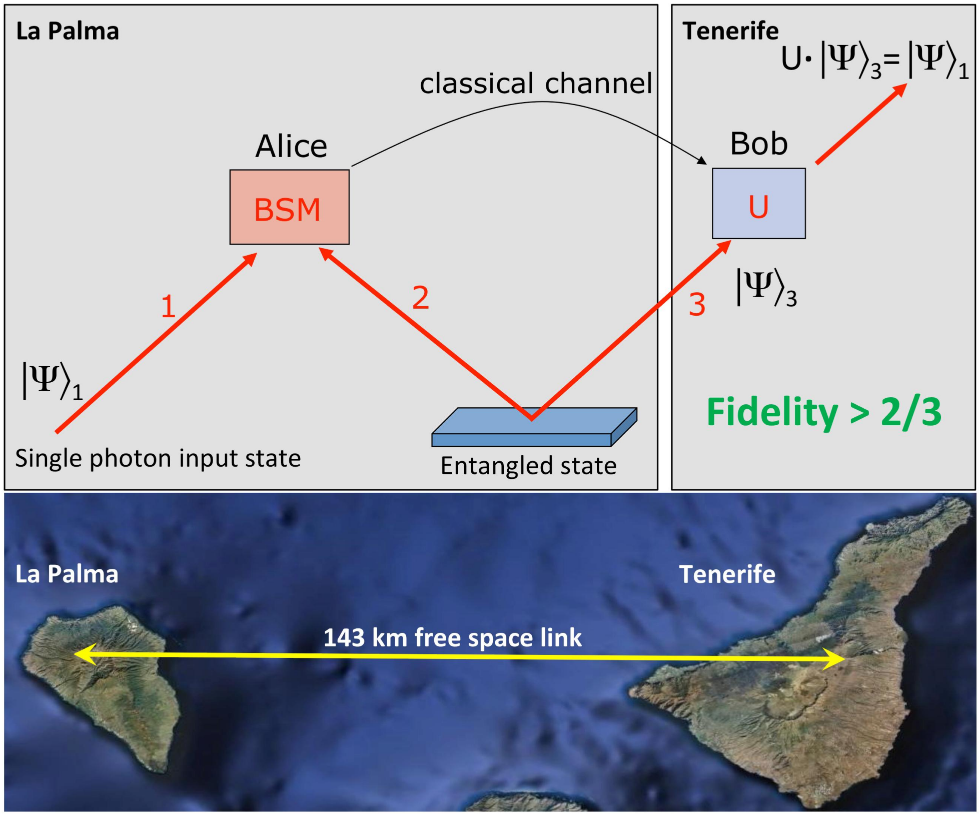

Figure 1. Schematics of the quantum-teleportation protocol[9] between the Canary Islands La Palma and Tenerife.

Via the quantum channel Alice and Bob share an entangled state

$$|\Psi^-\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|V\rangle_3 - |V\rangle_2|H\rangle_3), \tag{1}$$

where $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization states, respectively. A third party called Charlie provides photon 1 to be teleported in a general polarization state

$$|\Psi\rangle_1 = \alpha|H\rangle_1 + \beta|V\rangle_1 \text{ with } |\alpha|^2 + |\beta|^2 = 1, \tag{2}$$

which can be arbitrarily set using a linear polarizer and wave plates. Alice then performs a Bell-state measurement (BSM) on photons 1 and 2, projecting Bob's photon 3 onto the input state, up to a unitary transformation (U), which depends on the outcome of the BSM. At the BSM, photons 1 and 2 interfere at a beam splitter (BS) and are projected randomly onto one of the four maximally entangled Bell-states

$$
\begin{aligned}
|\Psi^{\pm}\rangle_{12} &= \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2) \\
|\Phi^{\pm}\rangle_{12} &= \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2),
\end{aligned} \tag{3}
$$

with probability 1/4. The full three-photon state can be reformulated in the basis of the Bell-states

$$
\begin{aligned}
|\Psi\rangle_{123} = |\Psi\rangle_1 \otimes |\Psi^-\rangle_{23} = \frac{1}{2}[&|\Psi^-\rangle_{12}(-\alpha|H\rangle_3 - \beta|V\rangle_3) \\
&+|\Psi^+\rangle_{12}(-\alpha|H\rangle_3 + \beta|V\rangle_3) \\
&+|\Phi^-\rangle_{12}(+\alpha|V\rangle_3 + \beta|H\rangle_3) \\
&+|\Phi^+\rangle_{12}(+\alpha|V\rangle_3 - \beta|H\rangle_3)],
\end{aligned} \tag{4}
$$

where one can see that photon 3 then contains full information on the original input polarization of photon 1. When Alice feeds the outcome of the BSM forward to Bob via the classical channel, he can implement the corresponding unitary operation in real time and thus obtain photon 3 in the initial state of photon 1. If Alice detects $|\Psi^-\rangle_{12}$ at the BSM, then U corresponds to the identity operation, which means that Bob needs to do nothing. If, on the other hand, $|\Psi^+\rangle_{12}$ is detected, Bob has to apply a π phase shift between the horizontal and the vertical component of his photon 3. With linear optics only, the remaining two Bell-states cannot be detected[10], as both photons end up in the same detector. The state of photon 3 will be analyzed by measuring its polarization using a polarizing beam-splitter (PBS) and wave plates at Bob. The result is then compared with the input state and will show the quality of the teleportation process. Please note that photon 1 is heralded by a trigger photon 0.

3. THE BELL-STATE MEASUREMENT (BSM)

The BSM is a joint measurement on two qubits, that determines in which of the four possible Bell-states the two qubits are in. If the qubits were not in a Bell-state before the measurement, they get projected randomly onto one of the four Bell states. Since the Bell-states are maximally entangled states, a BSM can also be seen as an entangling operation. Depending on coincidence detection events between two of the four detectors in the outputs of the PBSs, one of the Bell-states can be detected. As an example, the $|\Psi^-\rangle$ singlet Bell-state corresponds to a coincidence-detection event between the first and third detector (as illustrated in Figure 2, counting from the top) or the second and fourth detector, whereas the $|\Psi^+\rangle$ triplet Bell-state corresponds to simultaneous clicks of detectors one and two or three and four. Unfortunately, the remaining two Bell states ($|\phi^-\rangle$ and $|\phi^+\rangle$) cannot be distinguished with this linear-optics scheme. By post selection on the coincidence events for the $|\Psi^-\rangle$ and $|\Psi^+\rangle$ state we can simply ignore the other cases as undefined results. In order to have precise timing information for temporally overlapping two photons within their coherence length on the BS (as required for the BSM), the entangled photons and the teleportation input state have to be generated with a pulsed laser system.

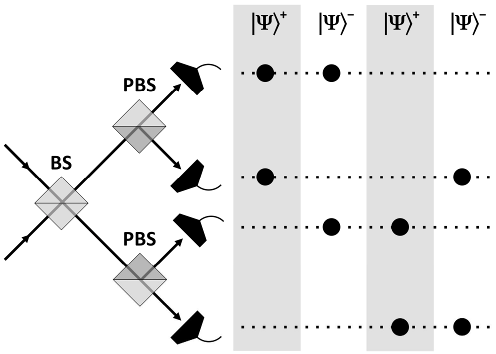

Figure 2. The Bell-state measurement (BSM) projects photon 1 and 2 onto the four Bell-states with equal probability of 1/4. Experimentally only two states can be resolved with linear optics only. Simultaneous clicks in the first and third detector (from the top) or the second and fourth detector indicate the projection on the $|\Psi^-\rangle_{12}$ Bell-state, whereas if detectors one and two or three and four click simultaneously a $|\Psi^+\rangle_{12}$ Bell-state is detected.

4. EXPERIMENT

The quantum-teleportation experiment was conducted between the Canary Islands La Palma and Tenerife, utilizing the infrastructure of the Jacobus Kapteyn Telescope (JKT) of the Isaac Newton Group of Telescopes (ING) on La Palma for Alice and the Optical Ground Station (OGS) of the European Space Agency (ESA) on Tenerife for Bob. Alice's transmitter was a 7 cm diameter f/4 lens and Bob's receiver a 1 m diameter reflector telescope. A 143 km high-loss quantum channel interconnected Alice and Bob. Link stabilization was implemented via a bidirectional tracking system utilizing beacon lasers at a wavelength of 532 nm and tracking cameras on both islands. The schematics of the experiment have been shown in Figure 1 and more detailed illustration of the setup can be seen in Figure 3.

The pump laser was a mode-locked Ti:Sapphire femto-second laser with a central wavelength of 808nm. We used a β-Barium Borate (BBO) crystal to up-convert the infrared pump pulses to blue pulses of 404 nm via second-harmonic generation and spectrally cleaned the blue pulses with several dichroic mirrors. Photons 2 and 3 were generated via spontaneous parametric down conversion (SPDC) in a BBO crystal with a type-II phase matching configuration. After walk-off compensation using half-wave plates (HWPs) and compensation BBO crystals, the photons are in a polarization-entangled state. Photons 0 (the trigger photon) and 1 (the input state) were generated in another BBO in a collinear type-II phase matching configuration and subsequently separated by a PBS. Charlie prepared the quantum state of photon 1, which is the original input state $|\Psi\rangle_1$. Photon 3 was sent to Bob to become the final teleported state. After generation and preparation, all the photons were coupled into single-mode (SM) fibers and photons 1 and 2 were guided to a fiber-based tunable BS to perform the BSM. To guarantee perfect temporal overlap on the BS, the relative temporal delay between photons 1 and 2 was adjusted with a motorized translation stage for the fiber coupler of photon 1. Fiber polarization controllers (FPC) were employed to compensate for polarization rotation in the SM fibers. Alice's photons were detected by avalanche photodiodes (APDs D1-D4).

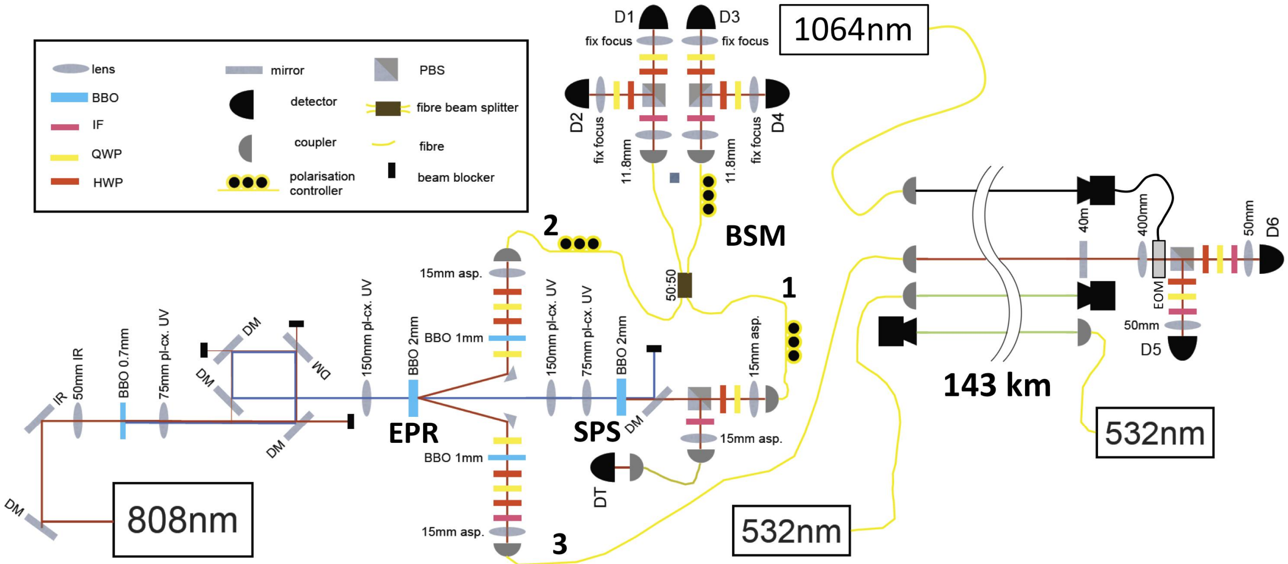

Figure 3. Setup of the 143 km free-space quantum-teleportation experiment between the Canary Islands La Palma and Tenerife. The input state (photon 1) is prepared from a single-photon source (SPS) to be teleported on photon 3. Alice then performs a Bell-state measurement (BSM) on photons 1 and 2, where photon 2 is from the entangled photon pair 2 and 3 of the Einstein-Podolsky-Rosen (EPR) pair source. Photon 3 gets delayed until the outcome of the BSM has been transmitted to Bob via a classical laser pulse of 1064 nm wavelength. Bob prepares the electro-optical modulator (EOM) to perform the corresponding unitary transformation on photon 3 and measures its polarization state by means of a quarter-wave plate (QWP), a half-wave plate (HWP) and a polarizing beam splitter (PBS). A bidirectional tracking system based on beacon lasers with 532 nm wavelengths and tracking CCD cameras on both sides is used to enhance the link stability.

When Alice's BSM outcome was the $|\Psi^{+}\rangle_{12}$ state, she encoded the information with a light-pulse signal and sent it over to Bob such that the required unitary operation could be implemented. The feed-forward (FFW) pulses were generated by a 1064 nm laser, modulated by an encoder and transmitted to Bob on Tenerife. Please note that photon 3 was delayed with a 50 m SM fiber to ensure that the classical information about the result of the BSM has arrived before photon 3 in order to give Bob enough time for the according local unitary transformation.

On Tenerife the quantum signal (808 nm), the classical FFW signal (1064 nm) and the tracking signal (532 nm) were guided through the telescope's Coudé path to Bob's measurement station. There all signals were separated using dichroic mirrors. The FFW signal was detected with a photo diode and the 532nm laser was guided onto a CCD camera. Bob then extracted the encoded results of the BSM with a decoder and implemented the according unitary transformation with a fast electro-optical modulator (EOM). Finally, the polarization of the teleported photon 3 was analyzed using wave-plates, a PBS and two free-space APDs (D5 and D6). All electronic signals (i.e. detection signals, classical signal about the result of the BSM) were fed into a time-tagging board and stored with a time-stamp for post-processing and analysis.

5. RESULTS

In the first stage of the experiment we post selected on the BSM outcome $|\Psi^{-}\rangle_{12}$. Therefore we didn't have to feed-forward the classical signal, which reduced the complexity of the whole scheme. In this configuration we teleported a total of 4 states (the horizontal H, vertical V, plus P and left L polarization states), which was sufficient to conclusively demonstrate quantum teleportation while minimizing the required integration time. We teleported the four input states and performed tomographic measurements in three consecutive nights. In total, we accumulated data over 6.5 hours with 605 four-fold coincidence counts, which corresponds to an average free-space link attenuation of 36 dB. The fidelity of the teleported state is defined as the overlap of the ideal teleported state with the measured state. For our set of states, the teleported state fidelities f were measured to be

H with $f = 0.890(42)$,

V with $f = 0.865(46)$,

P with $f = 0.845(27)$ and

L with $f = 0.852(37)$.

This gives an average fidelity of $f = 0.863(38)$. The four input states (H, V, P, L) and their measured output states were used to compute the process fidelity $f_{\text{process}} = 0.710(42)$ which confirmed the quantum nature of our teleportation experiment, as it was 5 standard deviations beyond the maximum process fidelity of 0.5 for a classical strategy without entanglement.

The second stage of our experiment was realized including the FFW signal of the BSM outcome $|\Psi^{+}\rangle_{12}$. Sending the two input states (P and R polarization) we measured the state fidelities

P (FFW) with $f = 0.760(50)$ and

R (FFW) with $f = 0.800(37)$,

with a classical link efficiency of only 21.3%.

Despite the high loss in the quantum free-space channel, the classical average fidelity limit of 2/3 was clearly surpassed by all our observed fidelities (see Figure 4).

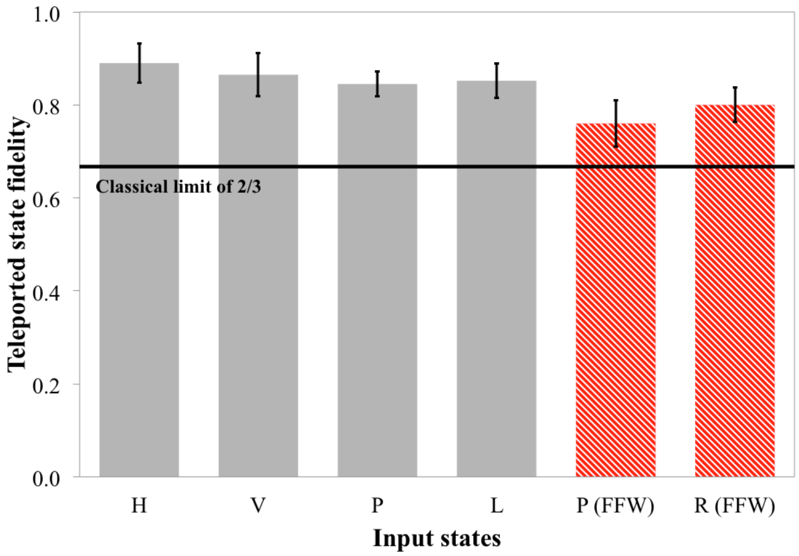

Figure 4. Experimental results of the teleported state fidelities for first part (grey, solid) without feed-forward (FFW) and second part (red, hatched) with FFW. All observed fidelities are clearly above the classical limit of 2/3. Error bars are plus/minus 1 sigma, assuming Poissonian statistics.

6. CONCLUSION

We successfully showed the quantum teleportation of single photon states over a horizontal 143 km inter-island free-space link under harsh atmospheric conditions. The implementation of a classical feed-forward link also proved the feasibility of future experiments with even more complex quantum-communication protocols comprising both classical and quantum channels. Cutting edge technology such as ultra-low-noise single-photon detectors, entanglement assisted clock synchronization and a frequency-uncorrelated polarization-entangled photon-pair source were used in order to faithfully teleport the input state from Alice to Bob. We tackled issues arising when dealing with high-loss turbulent free-space channels and employed space infrastructure by utilizing ESA's 1 m diameter receiver telescope. The technology implemented in our experiment reached the required maturity both for satellite and for long-distance ground communication. This experiment represents a crucial step towards future quantum networks in space.

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