Quantum Teleportation Over a 143 km Free-Space Link

Thomas Herbst, Thomas Scheidl, Daqing Wang, William Naylor, Bernhard Wittmann, Rupert Ursin, Anton Zeilinger
Institute for Quantum Optics and Quantum Information
Austrian Academy of Sciences
Vienna, Austria

Thomas Herbst, Bernhard Wittmann, Anton Zeilinger
Vienna Center for Quantum Science and Technology
University of Vienna
Vienna, Austria

Xiao-Song Ma
Department of Electrical Engineering
Yale University
New Haven, USA

Johannes Kofler
Max-Planck-Institute of Quantum Optics
Max-Planck-Gesellschaft
Garching/Munich, Germany

Elena Anisimova, Vadim Makarov, Thomas Jennewein
Institute for Quantum Computing
University of Waterloo
Waterloo, Canada

***Abstract*—Quantum teleportation [1] is a quintessential prerequisite of many quantum information-processing protocols. By using quantum teleportation, one can circumvent the no-cloning theorem [2] and faithfully transfer unknown quantum states. It can also be used to create entanglement between formally completely independent particles via the process of entanglement swapping [3], which will be of utmost importance in a future quantum-communication network [4], since it enables the global interconnection of quantum computers. We employed a 143 km optical free-space link between the two Canary Islands La Palma and Tenerife and successfully showed quantum teleportation under real world conditions. In particular the average state fidelity for the teleported quantum states was more than 6 standard deviations beyond the classical limit of 2/3 and the process fidelity was 0.710(42). Our work proofs the feasibility of ground-based free-space quantum teleportation. This experiment represents a crucial step towards future quantum networks in space. The technology implemented in our experiment reached the required maturity both for satellite and for long-distance ground communication.**

Keywords*—Quantum teleportation, quantum communication, quantum information, quantum optics, free-space, long distance

I. INTRODUCTION

For eventually realizing a future 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 [5]-[7] 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.

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).

II. METHODS

Quantum teleportation utilizes a quantum channel and a classical channel between two parties generally called Alice and Bob [8] (see Fig. 1). Via the quantum channel Alice and Bob share an entangled state

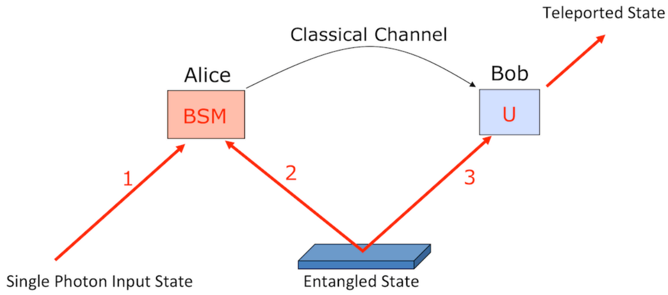

Fig. 1 Schematics of the quantum-teleportation protocol [8].

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

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

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

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

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

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

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

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 [9], 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.

A. *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 Fig. 2, counting from the left) 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 by a pulsed laser system.

III. 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

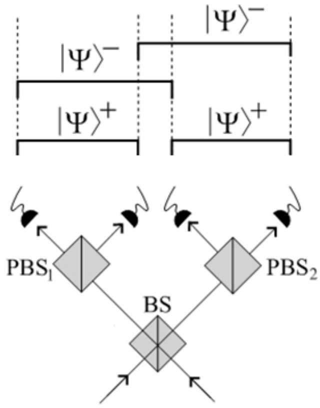

Fig. 2 The Bell-state measurement (BSM) projects photon 1 and 2 onto the four Bell-states with equal probability of 1/4. Experimentally only two states can be resolved with linear optics only. Simultaneous clicks in the first and third detector (from the left) or the second and fourth detector indicate 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.

implemented via a bidirectional tracking system utilizing beacon lasers at a wavelength of 532 nm and tracking cameras on both islands. The setup is schematically shown in Fig. 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).

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

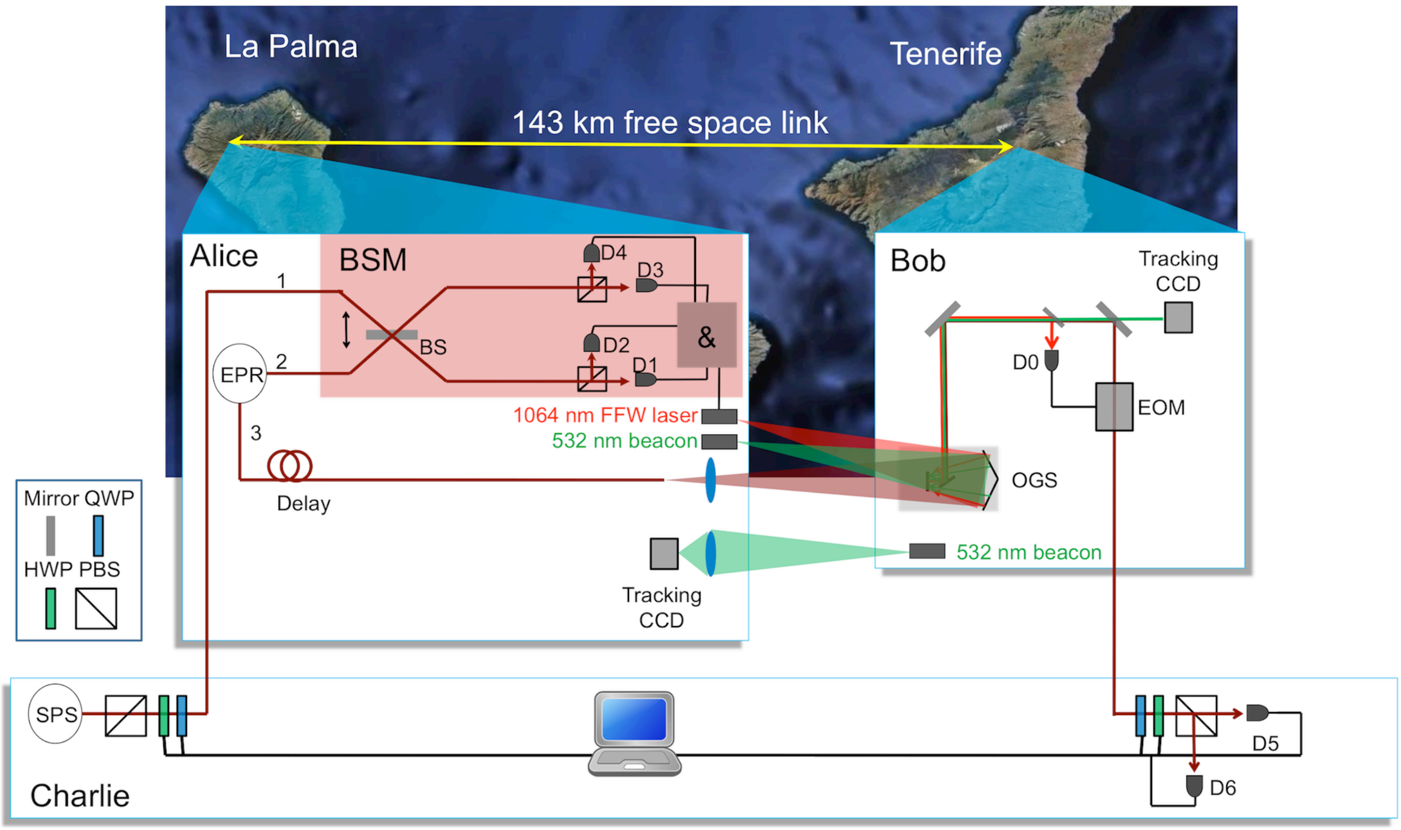

Fig. 3 Scheme of the 143 km free-space quantum-teleportation experiment between the Canary Islands La Palma and Tenerife. Charlie prepares the input state (photon 1) from a single-photon source (SPS) to be teleported on photon 3. Alice then performs a Bell-state measurement (BSM) on photons 1 and 2, 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.

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.

IV. 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 36dB. 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_{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 Fig. 4).

V. 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. Our setup was able to

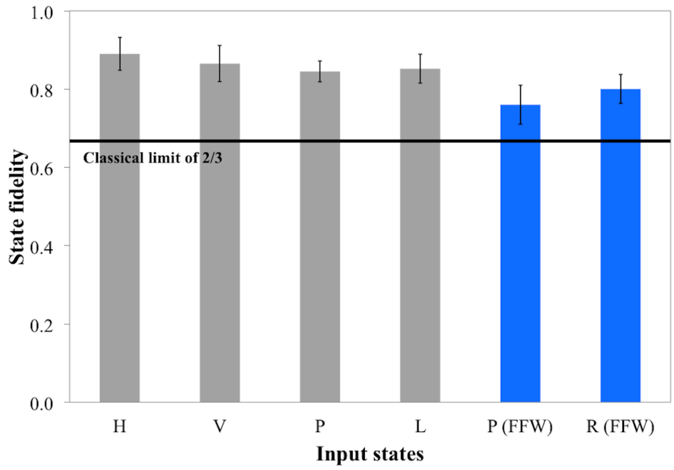

Fig. 4 Experimental results of the teleported state fidelities for first part (grey) without feed-forward (FFW) and second part (blue) with FFW. All observed fidelities are clearly above the classical limit of 2/3. Error bars are plus/minus 1 sigma, assuming Poissonian statistics.

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 to a low-earth-orbiting (LEO) satellite receiver [10]. We expect that many of the features implemented here will be key blocks for a new area of fascinating experiments.

ACKNOWLEDGMENT

We want to thank F. Sanchez-Martinez, A. Alonso, C. Warden, M. Serra and J. Carlos of the IAC and M. Balcells, C. Benn, J. Rey, O. Vaduvescu, A. Chopping, D. González, S. Rodríguez, M. Abreu, L. González of the ING. Also we thank the staff of ESA: J. Kuusela, E. Wille, Z. Sodnik and J. Perdigues. X.-S.M., T.J., R.U. and A.Z. thank S. Ramelow and P. Kolenderski for discussions, S. Zotter for help during the early stages of the experiment, as well as R. Steinacker for meteorological advice. J.K. was supported by the EU project MALICIA. E.A. and V.M. thank C. Kurtsiefer and Y.-S. Kim for detector electronics design, J. Skaar for support, and the Research Council of Norway (grant No. 180439/ V30) and Industry Canada for support. This work was supported by grants from the European Space Agency (contract 4000104180/11/NL/AF), the Austrian Science Foundation (FWF) under projects SFB F4008 and CoQuS, and the FFG for the QTS project (no. 828316) within the ASAP 7 program. We also acknowledge support by the European Commission, grant Q-ESSENCE (no. 248095) and the John Templeton Foundation.

REFERENCES

[1] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosenchannels," *Physical Review Letters*, vol. 70, no. 13, pp. 1895–1895, 1993.

[2] W. K. Wootters and W. H. Zurek, "A single quantum cannot be cloned," *Nature*, vol. 299, pp. 802–803, Oct. 1982.

[3] M. Zukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, "'Event-Ready-Detectors' Bell experiment via entanglement swapping," *Physical Review Letters*, vol. 71, no. 26, pp. 4287–4290, 1993.

[4] H. J. Kimble, "The quantum internet," *Nature*, vol. 453, no. 7198, pp. 1023–1030, Jun. 2008.

[5] A. Fedrizzi, R. Ursin, T. Herbst, M. Nespoli, R. Prevedel, T. Scheidl, F. Tiefenbacher, T. Jennewein, and A. Zeilinger, "High-fidelity transmission of entanglement over a high-loss free-space channel," *Nature Physics*, vol. 5, pp. 389–392, May 2009.

[6] T. Scheidl, R. Ursin, A. Fedrizzi, S. Ramelow, X.-S. Ma, T. Herbst, R. Prevedel, L. Ratschbacher, J. Kofler, T. Jennewein, and A. Zeilinger, "Feasibility of 300 km quantum key distribution with entangled states," *New Journal of Physics*, vol. 11, no. 8, p. 085002, Aug. 2009.

[7] T. Scheidl, R. Ursin, J. Kofler, S. Ramelow, X. S. Ma, T. Herbst, L. Ratschbacher, A. Fedrizzi, N. K. Langford, T. Jennewein, and A. Zeilinger, "Violation of local realism with freedom of choice," *Proceedings of the National Academy of Sciences*, vol. 107, no. 46, pp. 19708–19713, Nov. 2010.

[8] D. Bouwmeester, A. Ekert, and A. Zeilinger, *The Physics of Quantum Information*. Springer Verlag, 2000.

[9] J. Calsamiglia and N. Lütkenhaus, "Maximum Efficiency of a Linear-Optical Bell-State Analyzer," *Applied Physics B*, vol. 72, no. 1, pp. 67–71, 2001.

[10] P. Villoresi, T. Jennewein, F. Tamburini, M. Aspelmeyer, C. Bonato, R. Ursin, C. Pernechele, V. Luceri, G. Bianco, A. Zeilinger, and C. Barbieri, "Experimental verification of the feasibility of a quantum channel between space and Earth," *New Journal of Physics*, vol. 10, no. 3, pp. 033038–033038 (12pp), 2008.