QTS: Quantum Teleportation for Space Systems

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	Name/Title	Signature	Date
Prepared by	Thomas Scheidl IQOQI – Vienna		07.11.2012
Reviewed and approved by:	Rupert Ursin IQOQI Group Leader		07.11.2012
Technical management	Eric Wille TEC-MMO		
IQOQI – Institute for Quantum Optics and Quantum Information Boltzmanngasse 3 1090 Vienna, Austria			

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1. Abbreviations

APD	Avalanche Photo Diode
BBO	Beta Barium Borate
Bit	Binary Digit
BS	Beam Splitter
BSM	Bell State Measurement
EOM	Electro-Optical modulator
EPR	Einstein, Podolsky, and Rosen
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FBS	Fiber Beam Splitter
FWHM	Full Width at Half Maximum
GPS	Global Positioning System
HSP	Heralded Single Photon
HWP	Half Wave Plate
IQOQI	Institut für Quantenoptik und Quanteninformation
IR	Infrared
ISS	International Space Station
JKT	Jacobus Kapteyn Telescope
kHz	Kilo Hertz
LD	Laser Diode
MHz	Mega Hertz
n.a.	not available / applicable
OEAW	Österreichische Akademie der Wissenschaften / Austrian Academy of Sciences
OGS	Optical Ground Station
PAT	Pointing Acquisition and Tracking
PBS	Polarizing Beam Splitter
PC	Personal Computer, Polarization Control
POCD	Proof of Concept Demonstrator
QBER	Quantum Bit error Ratio
Qbit	Quantum Binary Digit
QKD	Quantum Key Distribution
QWP	Quarter Wave Plate
QT	Quantum teleportation
SiAPD	Silicium Avalanche Photo Diode
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio

Space QUEST	Space - Quantum Entanglement in Space ExperimenTs
SPDC	Spontaneous Parametric Down Conversion
Sync.	Synchronization
TTL	Transistor-Transistor-Logik
UV	Ultra Violet
WCP	Weak coherent pulses

2. Abstract

For eventually realizing a future global quantum communication network, the distribution of single and entangled qubits over large distances will be a key ingredient. In the past years, we have therefore pursued several experimental studies in the field of long-distance quantum communication utilizing a 144km 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 because 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 up to now and therefore still remains an experimental challenge. In this program, we present an experiment realizing quantum teleportation of a single photon Fock state over a 143 km free-space link between two 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 associated with the simultaneous detection of 4 photons. Furthermore, sending one of the four photons through the 144km free-space channel drastically reduces the obtainable signal-to-noise ratio (SNR).

3. Executive Summary

The teleportation protocol involves a polarization entangled and a non-entangled photon pair generated in a non-linear crystal via the process of spontaneous parametric down conversion (SPDC). At the Bell-state measurement, two of these photons (one of each pair) interfere at a beam splitter and are projected randomly onto one of the four Bell-states. The second photon of the non-entangled pair is used as a trigger while the second photon of the entangled pair is, after the Bell state measurement (BSM), projected onto a polarization state that already contains full information of the original polarization of the input photon. That means that the information about the input state has been teleported onto the output photon. The input and the output states are then compared, thereby evaluating the quality of the teleportation process.

In order to have precise timing information for temporally overlapping two photons within their coherence length on a beam splitter (as required for the BSM), the entangled photons and the teleportation input state have to be generated with some pulsed laser system. Therefore, the general key components for the final free-space teleportation experiment can be summarized as follows:

- Alice (La Palma):
  - Two pulsed SPDC sources each for entangled and non-entangled photon pairs (Experiment 2)
  - A pulsed source for the weak coherent input state (Experiment 1)
  - Bell-state measurement setup
- Bob (Tenerife):
  - Detection module to analyze the teleported state
- Quantum Channel:
  - High-loss quantum free-space link from La Palma to Tenerife to transmit the photon to be teleported

In order to being able to specify the requirements of the individual components in the final experiment, we developed a numerical model at the beginning of the project for investigating the experimental situation based on the performance of a state-of-the-art pulsed SPDC source and based on the knowledge about the atmospheric conditions that was gained during our previous experiments on the Canary Islands. From the results we learned that the crucial parameter, the signal to noise ratio (SNR), can be optimized by:

- Reducing the link attenuation η.
- Reducing the dark-count rate n of the single-photon detectors in Tenerife.
- Enhancing the timing accuracy of the photon detection and thus reducing the coincidence time window τ.

In accordance to these conclusions, we identified the following strategies for optimizing the design and development of the teleportation setup:

- We need to handle long integration times of several hours and therefore, the setup must be designed to be very **compact and stable**
- To possibly reduce the integration time and hence reduce the project risk, the following investigations are inevitable:
  - Improving the **source performance** (i.e. the photon count rate and/or entanglement visibility) compared to what is state-of-the-art (i.e. on which the simulations were based on)
  - Improving the free-space link transmission by actively **tracking** or **using some adaptive optics system**
- In order to increase the tolerable link attenuation, the **detector dark counts** must be reduced in Tenerife

Our SPDC sources in the final experiment have been set up as follows. The pump laser is a mode-locked Ti:Sapphire femto-second laser with a central wavelength of 808nm. We use a β-Barium Borate crystal (BBO-0) for up-conversion to a wavelength of 404nm. Entangled photons are then generated from BBO-1 with a type-II phase matching configuration and using a spectral compensation scheme based on an interferometric Bell-state synthesizer. Non-entangled photon pairs are generated from BBO-2 in a collinear type-II phase matching configuration and are separated with a polarizing beam splitter (PBS). After generation and preparation, all the photons are coupled into single-mode fibers. The BSM was accomplished with a fiber-based tunable beam splitter, polarizing beam splitters and wave-plates. With this source we were able to measure 180 four-fold coincidences locally, which is a factor of 2.5 more than a state-of-the-art source at the beginning of the project.

As single photon detectors we decided to use actively quenched PerkinElmer silicon avalanche photo diodes (APDs) with quantum efficiency between 40% and 60%. In La Palma, these were fiber coupled devices while in Tenerife, the diodes were free-space coupled and exhibited an active area of 500µm. This was required to focus the received beam efficiently onto it. In order to reduce the dark count rate of these large detectors, we supplemented them with a self-built electronics and cooling assembly cooling them down to -80°C such that intrinsic dark count rates of typically <20Hz could be achieved.

In order to identify the photons that were generated from the same pump pulse between both stations (in La Palma and in Tenerife) among all detection event including dark counts and stray light we had to establish a common time reference, which we implemented with a highly stable 10 MHz signal from a GPS disciplined oscillator. Additionally, every detection event on both sides was fed into a time-tagging unit, relying on the established common time reference. After a measurement run, the time-tagging data files of both observers are used to calculate the cross-correlation function for fine synchronization purposes and for the evaluation of coincident detection events. In total we yielded a timing precision of 1-2ns with the employed detection system.

Before the final experiment at the Canary Islands, we investigated the feasibility of quantum teleportation over a high-loss channel using the proof-of-concept demonstrator (POCD) and employing a free-space link in Vienna. Introducing variable attenuation using neutral density filters, we could proof that we are able to perform teleportation of a weak coherent state (WCP teleportation) up to an attenuation of around 32dB, which is already in the regime as expected on the free-space link between La Palma and Tenerife. Most importantly, we could also show that we are able to perform teleportation of a single photon Fock state at an attenuation of up to 36dB well above the classical fidelity limit of 2/3. Note that at the beginning of the project, the teleportation of a weak coherent input state (WCP teleportation, Experiment 1) was planned as a first step, since in this case only three photons are involved in the teleportation protocol, enhancing the overall count rate. However, based on the test with the proof-of-concept demonstrator in Vienna it was decided to skip this experiment in the final measurement campaign and directly perform the teleportation of single photon Fock states (Experiment 2).

The setup used for the final experiment, which was conducted between the Canary Island La Palma and Tenerife, is depicted in *Figure 1*. We teleported a total of 4 states (e.g. *H*, *V*, *P* and *L*), which is 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. We obtained an average teleportation fidelity of f=0.863(38), clearly surpassing the classical fidelity limit of 2/3. Moreover, the measured process fidelity of $f_{process}$=0.710(42) clearly confirmed the quantum nature of our teleportation experiment as it is 5 standard deviations above the maximum process fidelity of 0.5, which is the limit one can reach with a classical strategy.

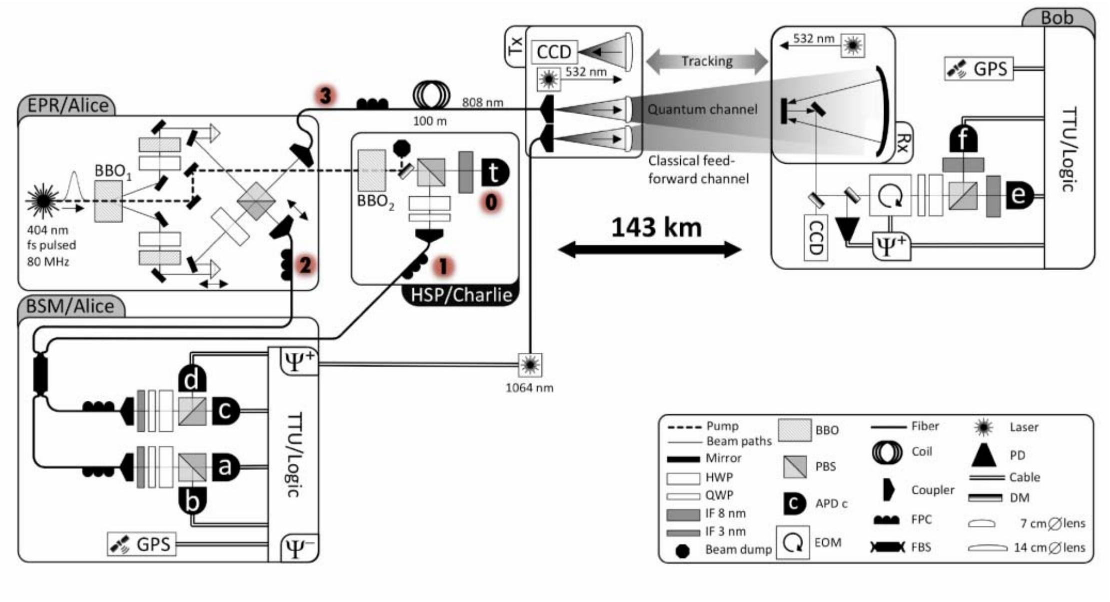

Figure 1 – Final Teleportation Setup: In La Palma, a frequency-uncorrelated polarization-entangled photon pair source generated photons 2 and 3 in BBO$_1$ (EPR/Alice) and a collinear photon pair source generated photons 0 and 1 in BBO$_2$ (HSP/Charlie). All single photons were coupled into single-mode fibers. For implementing the BSM, photons 1 and 2 interfered in a fiber beam splitter (FBS) followed by polarization-resolving single-photon detection (BSM/Alice). Photon 3 was guided to the transmitter telescope via a 100 m single-mode fiber and sent to Bob in Tenerife where the polarization of photon 3 was measured.

Our experiment represents a crucial step toward future quantum networks in space, which require space to ground quantum communication. The technology implemented in our experiment thus certainly reached the required maturity both for satellite and for long-distance ground communication. We expect that many of the features implemented here will be key blocks for a new area of fascinating experiments.