Elektrotechnik & Informationstechnik (2007) 124/5: 149–153. DOI 10.1007/s00502-007-0435-6

Applications of quantum communication protocols in real world scenarios toward space

R. Ursin, F. Tiefenbacher, T. Jennewein, A. Zeilinger

Quantum cryptography and quantum computation are based on the communication of single quantum states and quantum entanglement, respectively. Particularly in view of these high potential applications the question arises, whether quantum correlations can be sufficiently well communicated over global distances to be used in communication protocols as predicted by quantum mechanics. Various experiments and possible application of quantum communications on ground and in space are discussed in this article. Thereby, it confirms the feasibility of quantum communication in space on a global scale, involving the International Space Station (ISS) or satellites linking to optical ground stations.

Keywords: quantum entanglement; quantum cryptography

Anwendungen der Quantenkommunikation auf der Erde und im Weltraum.

Quantenkryptographie und Quantencomputer basieren auf dem Austausch und der Manipulation von einzelnen Quantenzuständen und auf deren Verschränkung. Im Hinblick auf das große Potential dieser Anwendungen muss man sich die Frage stellen, ob solche Quantenzustände auch mit für die Verwendung in den Quantenkommunikationsprotokollen ausreichend guter Qualität über globale Distanzen hinweg ausgetauscht werden können, wie das gemäß der Theorie der Quantenmechanik möglich sein sollte. Dieser Artikel diskutiert verschiedene Experimente und mögliche Anwendungen der Quantenkommunikation sowohl auf der Erde als auch im Weltraum. Dabei wird gezeigt, dass die technische Realisierung von globaler Quantenkommunikation im Weltall durch die optische Vernetzung der Internationalen Raumstation (ISS) oder von Satelliten mit optischen Bodenstationen machbar ist.

Schlüsselwörter: quantenmechanische Verschränkung; Quantenkryptographie

Eingegangen am 7. März 2007, angenommen nach Revision am 14. März 2007

1. Introduction

Quantum communication (*Zoller, 2005*) is an important ingredient in future information processing technologies and basically transfers a quantum state from one location to another. In quantum key distribution (QKD) (*Gisin et al., 2001*) such a quantum channel is used to share a quantum state or, more excitingly, to use quantum mechanical correlations (entanglement) (*Schrödinger, 1935*) to the partner's quantum state to generate a provable unconditional secure key at any distance. This offers for the first time an absolute secure way to distribute a confidential key between distant partners enabling secure communication among them by classical means only (see *A. Poppe et al.,* in the same issue). Furthermore, quantum entanglement enables us to teleport (*Bennett et al., 1993*) a quantum state to a location at distance without actually moving the correlation-carrying entity in the case of photons (*Bouwmeester et al., 1997; Ursin et al., 2004*) or Ions (*Riebe et al., 2004; Barrett et al., 2004*). In practical implementations of quantum communication, the link consists of a series of quantum state representing the quantum information, for instance encoded in their individual polarization state or in the correlation of quantum states between two or more qubits. The requirements for quantum communication therefore include a reliable optical link with low attenuation and the ability at the receiver to discriminate these single photons from the background.

Particularly, in view of these applications the question arises, whether quantum correlations can still be used in communication protocols as predicted by quantum mechanics even over global distances. Up to now, this has been verified over distances of up to 13 km (*Weihs et al., 1998; Aspelmeyer et al., 2003; Resch et al., 2005; Peng et al., 2005*) using polarization entangled photons via free-space links through the atmosphere. For time-bin entanglement a 10 km link was demonstrated in optical fibers (*Tittel et al., 1998*) and an experiment was done in coiled fiber (*Marcikic et al., 2004; Takesue et al., 2005*) over 105 km. In order to go well beyond and to significantly expand the distance between the observers measuring the entangled particles one has to go into space.

2. Real world scenarios

Various experimental demonstrations of quantum communication protocols have already been demonstrated in installed fiber systems which is an important proof-of-principle demonstration in the view of quantum communication protocols application in terrestrial real world scenarios.

Two polarization entangled particles at a wavelength of 810 nm were distributed through an 1.4 km long single-mode fiber between the headquarters of an Austrian bank and the Vienna City Hall (Fig. 1) (*Poppe et al., 2004*). At both measurement stations, each incoming photon was randomly analyzed at two distinct polarization basis states generating a symmetric key at each receiver station. The produced key was directly handed over to a computer application

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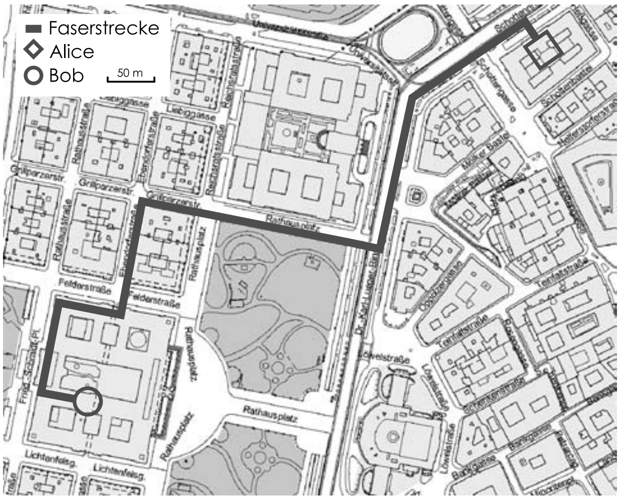

Fig. 1. A quantum cryptography system was installed between the headquarters of a large bank (Alice) and the Vienna City Hall (Bob). The beeline distance between the two buildings is about 650 m. The optical fibers were installed some weeks before the experiment in the Vienna sewage system and have a total length of 1.45 km

that was used to send a quantum secured online wire transfer from the City Hall to the headquarters of Bank-Austria Creditanstalt in Vienna.

3. Quantum teleportation

Efficient long-distance quantum teleportation (*Bennett et al., 1993*) is a crucial ingredient for future quantum computer application (*Deutsch, Ekert, 1998*), necessary since quantum computers (*Gottesmann, Chuang, 1999; Laflamme, Milburn, 2001*) internally compute quantum states and will have to communicate among each other. Quantum repeater (*Briegel et al., 1998*) will allow to distribute quantum entanglement over distances thus being vital for future global quantum communication networks. At present the only suitable system for efficient long-distance quantum communication is photons.

A quantum teleportation over long-distances was performed in fiber over 600 m (*Ursin et al., 2004*). Quantum teleportation is based on a quantum channel, here established through a pair of polarization-entangled photons shared between Alice and Bob (Fig. 2). This was implemented by using an 800-metre-long optical fiber installed in a public sewer system located in a tunnel underneath the River Danube, where it is exposed to temperature fluctuations and other environmental factors.

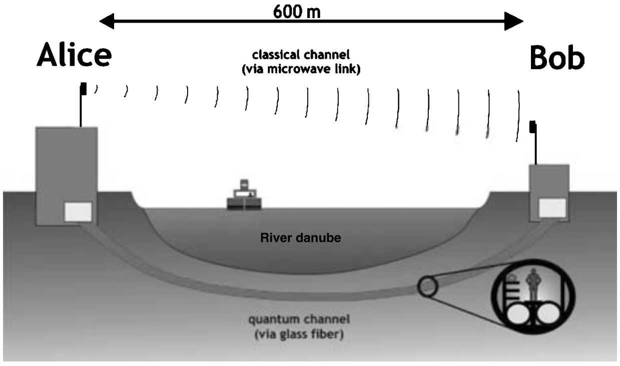

Fig. 2. Arrangement of the experiment on both sides of the river Danube. The slower quantum channel (fiber) passes through a large sewage pipe tunnel below the river and the faster classical channel (mirowave) passes above

The teleportation protocol goes as follows: For Alice to be able to transfer the unknown polarization state of an input photon, she has to perform a joint so-called Bell-state measurement on the input photon and her member of the shared entangled photon pair (Alice in Fig. 2). Our scheme allows her to identify two of the four Bell states which is the optimum achievable with linear optics only (*Lütkenhaus, Calsamiglia, Suominen, 1999*). As a result of this Bell-state measurement, Bob's 'receiver' photon will always be found in a state already containing full information or a simple bit-flip operation depending on the specific Bell state that Alice observed. Our teleportation scheme therefore also includes active feed-forward of Alice's measurement results, which is achieved by means of a classical microwave channel together with a fast electro-optical modulator (EOM). It enables Bob to perform the bit-flip on his photon to obtain an exact replica of Alice's input photon. For successful operation of this experimental scheme, Bob has to set the EOM correctly before photon arrives. Because of the reduced velocity of light within the fiber-based quantum channel (two-thirds of that in vacuum), the classical signal arrives well before the photon which has to be teleported.

4. Free-space experiments

On the basis of present fiber and detector technology, it has been determined that absorptive losses and dark counts in the detectors limit the distance for distributing entanglement to the order of 100 km (*Zeevi, Yamamoto, Waks, 2002*). One approach to overcome this limitation is the implementation of quantum repeaters which, however, still need significant development (*Briegel et al., 1998*). Another approach is using free-space links, using telescopes for the transmission of single or entangled photon state towards the receiver (*Aspelmeyer, 2003; Resch et al., 2005*).

An experiment implemented with weak coherent laser pulses, between the Canary islands La Palma and Tenerife was performed via a free-space link over 144 km. The transmitter telescope was placed on the Roque de los Muchachos (2400 m above sea level) on the island of La Palma. In the experiment the optics of the QKD transmitter (Alice) consisted of four laser weak laser diodes, whose orientation was rotated by 45 relative to the neighboring ones. At a clock rate of $R_0 = 10$ MHz one of them emitted a 2 ns optical pulse centered at 850 nm with a full width at half maximum (FWHM) of 1.5 nm, according to random bit values, that were generated beforehand by a physical random number generator and stored on Alice's hard disk (see (*Schmitt-Manderbach et al., 2007*) and the references therein). The output beams of all diodes were overlapped by conical mirrors and coupled into a single mode optical fiber running to the transmitter telescope (*Weier et al., 2006*). The transmitter consisted of a single lens with a 150 mm diameter and $f = 400$ mm focal length ($f/2.7$) guiding the single photons to Bob in the Optical Ground Station (OGS) of the European Space Agency (ESA) on Tenerife, 2400 m above sea level (*Comeron et al., 2002*) over the 144 km free-space link.

Due to various atmospheric influences such as changes of the atmospheric layering and temperature and humidity gradients, the apparent bearing of the receiver station varied on timescales of tens of seconds to minutes. Most classical optical communication channels prevent the beam from drifting off the receiver aperture by defocusing the beam. This is not an option in single photon experiments, where maintaining the maximum link efficiency is essential. Hence in our experiment the alignment both of the transmitter and the receiver telescope was controlled automatically by a closed-loop tracking system using a 532 nm beacon laser shining from the OGS to the single photon transmitter and vice versa.

The OGS (Bob), a 1 m Richey-Chrétien/Coudé telescope with an effective focal length of 39 m (*f*/39), was used to collect the single photons with a field-of-view of 8 arcmin. The atmospheric turbulence caused significant beam wander in the focal plane of the telescope of up to 3 mm in the worst case. We measured a link efficiency for single photons of -25 dB under best conditions and typically -30 dB.

We experimentally implemented a Bennett-Brassard 1984 (BB84) (*Bennett, Brassard, 1984*) protocol type quantum key distribution over the 144 km free-space link using weak coherent laser pulses, the security was ensured by employing decoy-state analysis (*Hwang, 2003; Lo, Ma, Chen, 2005; Wang, 2005*).

For the sifting process, each photoevent had to be assigned an absolute pulse number in order to allow Alice and Bob to discuss their respective choice of basis. This was accomplished without any reference channel but solely by means of the dim pulses. Each photon-event was then accepted if it was detected within a time window Δt around the expected arrival time or rejected as background, otherwise. Finally, pseudorandom bit sequences in the photon stream (1.2% of the attenuated pulses) enabled Bob to find the absolute offset of the pulse number.

For raw key generation, we accepted photon events at the receiver within a time window $\Delta t = 5.9$ ns, leading to a QBER $= 6.48\%$ for the entire measurement run. We attribute 3% to spurious events within $\delta t \sim 3\%$ to alignment errors of the Alice module including compensation in the single mode fiber, and finally, another 0.5% to imperfections in the polarization analyzer at Bob. This enabled us to distribute a secure key at a rate of 12.8 bit/s.

The distance between Alice and Bob exceeds that of previous experiments by an order of magnitude, this exploits the limit for ground-based free-space quantum communication; significantly longer distances can only be reached using air- or space-based platforms.

5. Quantum communication in space

To extend the distances in quantum communication to a global scale, will require dedicated terminal with quantum communication hardware onboard a satellite or a space-station (ISS). This will enable us to establish a world wide quantum communication network (*Nordholt et al., 2002*) on the one hand, but on the other hand to expand fundamental experiments on quantum physics to a scale not possible on Earth. However, the quantum-communication between a partner onboard of an orbiting station and another on Earth requires an effective quantum-channel in a noisy ambient and of very-long path length. In particular, for the exchange of single photons, the strong rejection of background light must be enforced, together with the accurate pointing of the optical terminals and the precise synchronization of the receiver to the sender, including their continuously varying mutual separation. The technical feasibility with today's technology was investigated in great detail in (*Pfennigbauer, 2005*).

From a fundamental point of view, the important question is whether there are limits on the distance between two entangled quantum systems (so called Bell-type experiments). Primarily, such experiments would allow to expand the scale for testing the validity of quantum physics theory by several orders of magnitude in distance i.e. beyond the capabilities of purely Earth-based laboratories. On the long run, experiments on quantum entanglement in space might even provide the basis for fundamental tests of the interplay between gravitation and quantum physics (*Kaltenbaek, 2003*).

Space provides a unique ''lab''-environment for entanglement: In the case of massive particles, microgravity enables the expansion of investigating fundamental quantum properties to much more massive particles than it is possible today on Earth. In the case of photons, the space environment allows much larger propagation distances compared to purely Earth-bound free space experiments.

The experimental prerequisites to perform such Bell-type experiments are a source of entangled photons (located in a transmitter terminal) and two analyzing receiver-terminals at a distance, which individually allow to vary their measurement basis randomly and store the arrival time of single photon in the detector with respect to a local time standard (*Aspelmeyer et al., 2003*). For experiments over distances on the order of 1600 km it would be sufficient to place a source of entangled photons in an low-Earth orbit, which would transmit the two entangled photons to two separated ground based receivers, see Fig. 3. To guarantee the independence of the

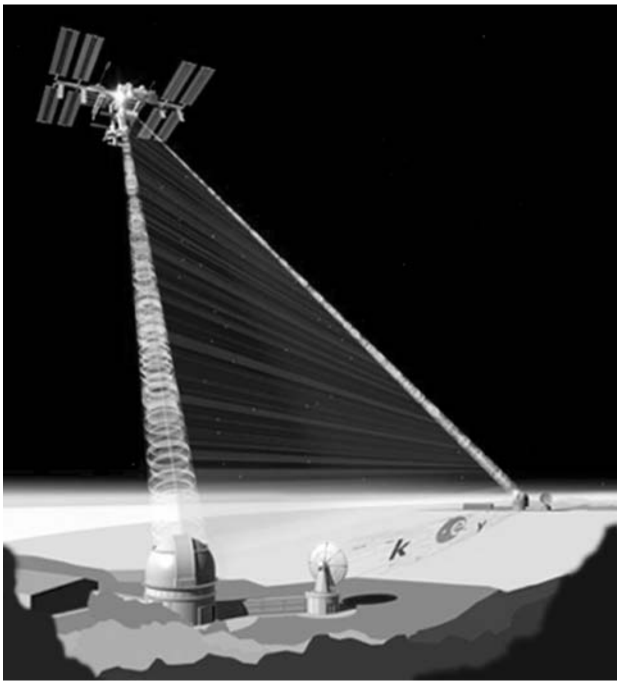

Fig. 3. Proposed long-distance Bell-type experiment in space, to perform a Bell-type experiment. The entangled photons are sent from a LEO-based entangled photon source, attached to the outside payload facility of the European Columbus module on the International Space Station (ISS), to two separated ground stations, about 1600 km apart

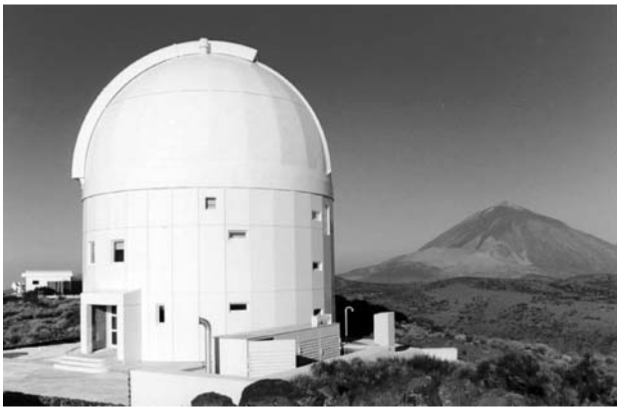

Fig. 4. The optical ground station (OGS) of the European Space Agency (ESA), on Tenerife. The 1 m telescope was used in our quantum communication experiments over 144 km, and is already suitable as a quantum communication receiver from a source on a satellite

measurements in each of the receiver terminals, the measurements have to be space-like separated, this means that the measurement result on one receiver cannot influence the result at the second receiver assuming the speed of light as the maximum speed of communication. This is more readily accomplished over large distances between the receiver terminals.

6. Proof of concept experiments for space

In a first experimental demonstration of a quantum-communication channel between a low-Earth orbit (LEO) satellite and a receiver station on Earth (the ASI-Matera-Laser-Ranging-Observatory, Italy), we effectively simulated a single-photon quantum communication channel by reflecting faint laser pulses off the optical retroreflecting satellite Ajisai, whose orbit has a perigee height of 1485 km, realizing a satellite-to-Earth quantum-channel. The identification of the exchanged photons was ascertained by observing a significant amount of detector counts at the expected arrival instant with respect to the background value (*Villoresi et al., 2004*).

An important component in space based quantum communication is a source for the entangled photons, which is suitable for space. We are presently working on a source based on new, and very highly effective down conversion crystals, which deliver the necessary numbers of photon pairs but with low power consumption (*Fedrizzi et al., 2007*).

7. Conclusion

We have presented several of our achievements towards long distance quantum communication, both in optical fibers and free space, and even towards satellite based quantum communication. These are the two most promising technologies for the communication of quantum information, where quantum cryptography allows secure links, and quantum teleportation the transport of quantum states. In addition, once quantum computers are developed, they will require quantum communication for their networking. Quantum computers deliver a fundamental boost in performance compared to existing classical computers, and will have applications such as factoring numbers, searching a database and simulating complicated quantum mechanical situations, e.g. molecular chemistry.

Here, we presented the demonstration of the world's first securing of a bank-transfer with quantum keys in an intercity link in Vienna, and the exchange of secure bits via quantum cryptography over a record-breaking link distance of 144 km across the Canary Islands. In a separate experiment we demonstrated quantum teleportation across the Danube, covering a distance of 600 m, which is a first step towards long distance linking of future quantum information processors.

These activities also have an important impact on fundamental science, as the limits of testing quantum mechanics are always stretched further. Our long-term plan is to place quantum hardware onto satellites in space, which allows us to investigate the fundamental limits of entanglement correlation between two photons over distances of thousands of kilometers.

We are convinced that quantum technologies will play a very important role in the future, and already to date, several companies are commercializing quantum communication systems.

Acknowledgements

This work was supported by ESA under the General Studies Program (ESA contract number 18805/04/NL/HE), the Austrian Science Foundation (FWF project number SFB1520), the European projects SECOQC and QAP and by the ASAP program of the Austrian Space Agency (FFG).

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Die Autoren

Rupert Ursin

Quantenkommunikation in der realen Welt unter realen Umwelteinflüssen zu testen, ist die zentrale Maxime in der Forschungstätigkeit von Rupert Ursin. Nach seiner Diplomarbeit, die er am Antiwasserstoffspektroskopie-Experiment ATRAP am CERN absolvierte, widmete er sich der Quantenkommunikation. Die weltweit erste Quantenteleportation außerhalb des geschützten Labors gelang ihm und seinen Kollegen über eine Distanz von 600 m von einer Seite der Donau auf die andere. Auch die erste quantenkryptographisch verschlüsselte Banküberweisung wurde mit seiner Hilfe realisiert. Um Quantenkommunikation auch vom All aus testen zu können, wurde das Projekt Space-QUEST ins Leben gerufen, an dem er an theoretischen und experimentellen Untersuchungen beteiligt ist.

Felix Tiefenbacher

leitet das Quantencomputer-Team am Institut für Quantenoptik und Quanteninformation (IQOQI) der Österreichischen Akademie der Wissenschaften. Das Ziel dieses Forscherteams ist es, die fundamentalen Prozesse eines Quantencomputers zu studieren und mittels linearer Optik und Mikrooptik zu verwirklichen. Felix Tiefenbacher studierte Experimentalphysik an der Universität Basel, wo er sich mit chemisch-physikalischen Analysemethoden am Molekularstrahl beschäftigte. Seine Dissertation ,,Vom konstitutiven Verhalten fliessenden Schnees'' absolvierte er am Eidgenössischen Institut für Schnee- und Lawinenforschung, Davos, zum Thema Lawinendynamik. Seit 2004 arbeitet er für Prof. Anton Zeilinger in Wien zu den Themen Quantenkommunikation und Quantencomputer.

Thomas Jennewein

war nach seiner Dissertation bei Prof. Anton Zeilinger in der Industrie beschäftigt und ist nun seit 2004 am Institut für Quantenoptik und Quanteninformation der Österreichischen Akademie der Wissenschaften als Forscher tätig. Thomas Jennewein hat in seiner mehrjährigen Forschung auf dem Gebiet der Quantenoptik vielfältige Experimente mit verschränkten Photonenpaaren durchgeführt. Darunter fallen fundamentale Tests der Quantenverschränkung über lange Distanzen, die Realisierung der ersten Quantenkryptographie mit verschränkten Photonen sowie die erfolgreiche Teleportation von Verschränkung. Er betreibt aktiv das Vorhaben, die Verschränkung von Photonen über stets wachsende Distanzen zu übertragen und zu testen, langfristig sogar über tausende Kilometer mittels Weltraum-gestützter Systeme.

Anton Zeilinger

leistet international bedeutende Forschungsarbeit auf dem Gebiet der Quantenphysik. Zeilinger setzte so die Tradition Österreichs in der Quantenphysik, die mit Erwin Schrödinger ihren Anfang nahm, fort. Zeilinger wurde 1945 in Ried im Innkreis geboren. Er hatte Professuren am MIT, an der TU München, der TU Wien, der Universität Innsbruck, der Universität Melbourne und am Collége de France inne. Er hält zwei Ehrendoktorate und ist Mitglied des Ordens pour le mérite, der Leopoldina, der Academia Scientiarum et Artium Europaea sowie der Österreichischen, Berlin-Brandenburgischen, Slowakischen und Serbischen Wissenschaftsakademien. Zu seinen Auszeichnungen zählen u. a. der King Faisal-Preis, der Descartes-Preis, die Lorenz-Oken-Medaille und der Sartorius-Preis. Zeilinger ist derzeit Professor für Physik an der Universität Wien und der ÖAW.