

Long-Distance Quantum Communication With Entangled Photons Using Satellites

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Invited Paper

Abstract—The use of satellites to distribute entangled photon pairs (and single photons) provides a unique solution for long-distance quantum communication networks. This overcomes the principle limitations of Earth-bound technology, i.e., the range of the order of 100 km afforded by both optical fiber and by terrestrial free-space links.

Index Terms—Quantum communication, quantum entanglement, satellite applications, space technology.

I. INTRODUCTION

QUANTUM entanglement is at the heart of quantum physics [1] and, at the same time, the basis of most quantum communication protocols such as quantum cryptography [2]–[5], quantum dense coding [6], quantum teleportation [7], or methods to exploit the computational advantages of quantum communication complexity [8]–[10]. Each of those schemes allows efficient communication and computation beyond the capabilities of their classical counterparts, which results in a new emerging quantum information technology. This makes a global quantum communication network desirable, where the distribution and manipulation of quantum entanglement on a global scale is a central task. However, while the realization of such schemes is routine work in the laboratory, nontrivial problems emerge in long-distance applications. At present, the only suitable system for long-distance quantum communication are photons. Other systems such as atoms or ions are studied thoroughly, however their

applicability for quantum communication schemes is presently not feasible within the near future, leaving photons as the only choice for long-distance quantum communication. One of the problems of photon-based schemes is the loss of photons in the quantum channel. This limits the bridgeable distance for single photons to the order of 100 km in present silica fibers [11], [12]. Recent quantum cryptography experiments already achieve such distances [13], [14]. In principle, this drawback can eventually be overcome by subdividing the larger distance to be bridged into smaller sections over which entanglement can be teleported. The subsequent application of so-called “entanglement swapping” [15] may result in transporting of entanglement over long distances. Additionally, to diminish decoherence effects possibly induced by the quantum channel, quantum purification might be applied to eventually implement a full quantum repeater [16]. In fact, the experimental building blocks for a full-scale quantum repeater based on linear optics have been successfully demonstrated over the last years by the realization of teleportation and entanglement swapping [17]–[19] and, only recently, by the implementation of a quantum purification protocol [20]. Two related, recent results, both of relevance for long-distance applications, are the demonstration of quantum state teleportation over a distance of several tens of meters [21] and the first realization of freely propagating teleported quantum bits (qubits) [22], which eventually will allow the subsequent use of teleported states. From the present point of view it seems obvious that a full implementation of a quantum repeater is within reach.

Despite those achievements of quantum communication experiments, the distances over which entanglement can be distributed in a single section, i.e., without a quantum repeater inbetween, are by far not of a global scale. Experiments based on present fiber technology have demonstrated that entangled photon pairs can be separated by distances ranging from several hundreds of meters up to 10 km [23]–[25], but no improvements by orders of magnitude are to be expected. On the other hand, optical free-space links could provide a unique solution to this problem since they allow in principle for much larger propagation distances of photons due to the low absorption of the atmosphere in certain wavelength ranges. Also, the almost nonbirefringent character of the atmosphere [26] guarantees the preservation of polarization entanglement to a high degree. Free-space optical links have been studied and successfully

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implemented already for several years for their application in quantum cryptography based on faint classical laser pulses [26]–[28]. Recently, we succeeded in demonstrating a next crucial step, namely the distribution of quantum entanglement via a free-space link, which was verified by violating a Bell inequality between two distant receivers without a direct line of sight between them [29].

However, terrestrial free-space links suffer from obstruction of objects in the line of sight, from possible severe attenuation due to weather conditions and aerosols [30] and, eventually, from the Earth's curvature. They are thus limited to rather short distances. To fully exploit the advantages of free-space links, it will be necessary to use space and satellite technology. By transmitting and/or receiving either photons or entangled photon pairs to and/or from a satellite, entanglement can be distributed over truly large distances and thus would allow quantum communication applications on a global scale. Such a scenario looks unrealistic at first sight, but in this paper we will show that the demonstration of quantum communication protocols using satellites is already feasible today. To do so, we will describe possible space scenarios based on entanglement. We then analyze prerequisites to distribute entanglement via satellites, describe experimental scenarios for first proof-of-principle experiments and finally give an outlook on the perspectives of satellite-aided quantum communication.

II. SCENARIOS OF SPACE EXPERIMENTS

When considering space scenarios that allow the distribution of entangled photon pairs, we can distinguish the cases in which a satellite is used to carry either: i) a transmitter of entangled photons, or ii) a receiver, or iii) a relay station to distribute photons to further locations. These scenarios will permit different applications.

A. Earth-Based Transmitter Terminal

The scenarios involving an Earth-based transmitter terminal allow to share quantum entanglement either between ground and satellite, or between two ground stations, or between two satellites and thus to communicate between such terminals employing quantum communication protocols. In the most simple case, a straight uplink to one satellite-based receiver [see Fig. 1(a)] can be used to perform secure quantum key distribution (QKD) between the transmitter station and the receiver. Here, one of the photons of the entangled pair is being detected right at the transmitter site and thus the entangled photon source is used as a triggered source for single photons. If the satellite acts as a relay station [see Fig. 1(b)], the same protocol can be established between two distant Earth-based communication parties. Shared entanglement between two parties can be achieved by pointing each of the photons of an entangled pair either toward an Earth-based station and a satellite or toward two separate satellites [see Fig. 1(c) and (d)]. Another set of satellite-based relays can be used to further distribute the entangled photons to two ground stations [see Fig. 1(e)]. Possible applications for shared entanglement between two parties are QKD or entanglement-enhanced communication protocols [31].

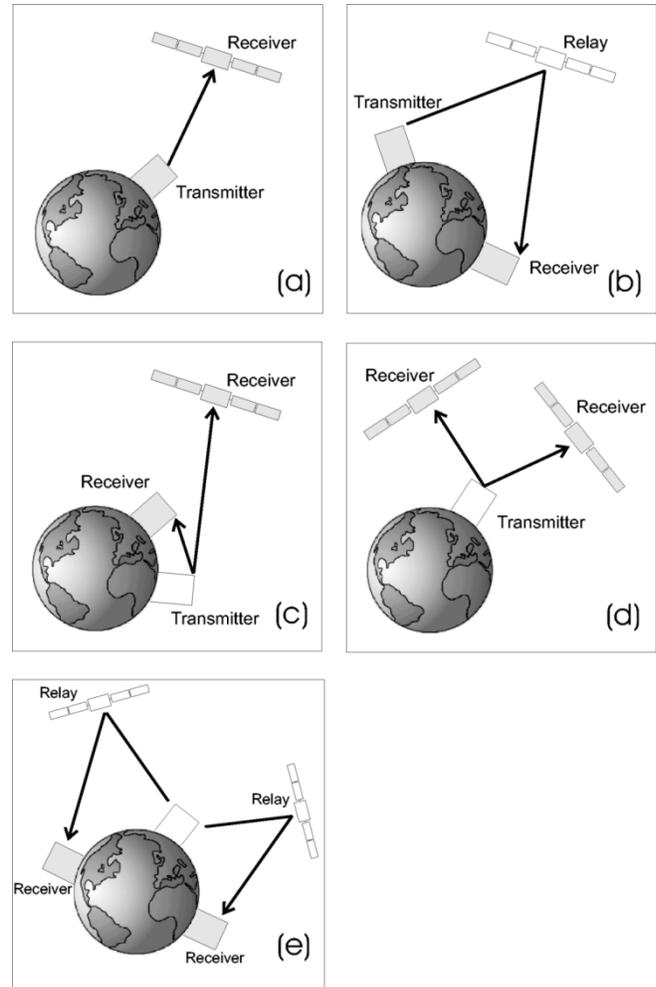


Fig. 1. Scenarios for satellite-aided quantum communication with an Earth-based transmitter terminal. The transmitter terminal distributes entangled photon pairs to the receivers which can perform an entanglement-based quantum communication protocol. As indicated, a relay module redirects and/or manipulates qubit states without actually detecting them.

B. Space-Based Transmitter Terminal

In a second scenario, a transmitter with an entangled photon source is placed on a space-based platform. This allows not only longer link distances because of reduced influence of atmospheric turbulence (see Appendix II). It will also be the preferred configuration for global quantum communication, since only one downlink per photon of the entangled pair is necessary to share entanglement between two Earth-based receivers. Again, already a simple downlink allows one to establish a single-photon link, e.g., for quantum cryptography [see Fig. 2(a)]. In this configuration, a key exchange between two ground stations is also possible. To this end each of the two ground stations has to establish a quantum key with the satellite. Since the space terminal has access to both keys, it can transmit a logical combination of the keys, which can then be used by either ground station or both ground stations such that they arrive at the same key. This logical combination can easily be chosen in a way that it cannot reveal any information about the key. Note that the key does not have to be generated simultaneously at both receiver stations. In principle, a quantum key exchange can be performed between arbitrarily located

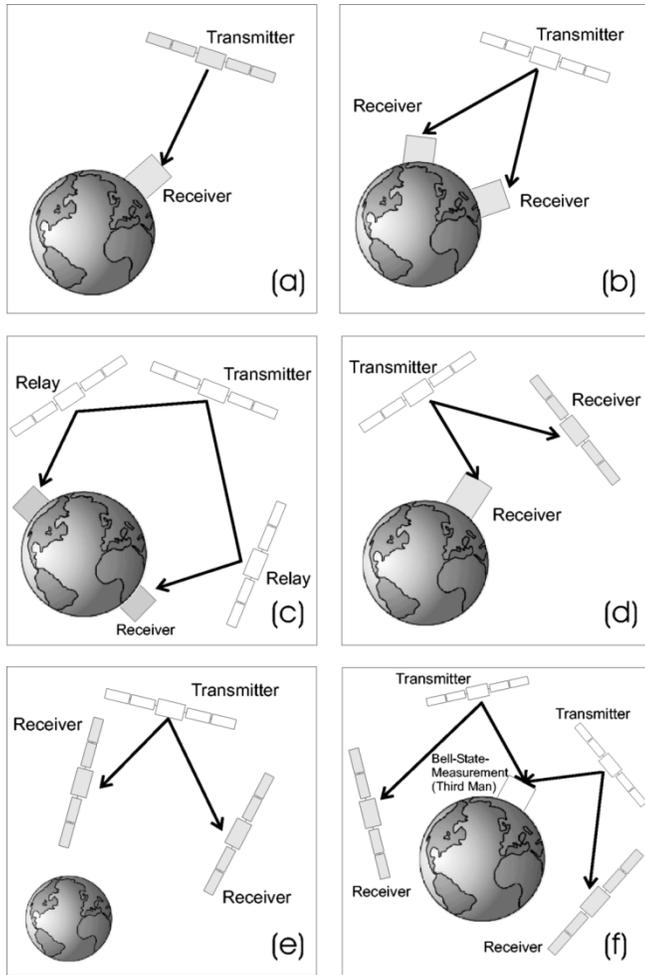


Fig. 2. Scenarios for quantum communication with a space-based transmitter terminal. Since optical space-to-Earth downlinks are less effected by atmospheric turbulence such configurations provide lower overall link attenuations and thus allow longer distances than the corresponding Earth-to-space links.

ground stations. This is also possible for a ground-based transmitter terminal as shown in Fig. 1(a). However, in all such scenarios based on single photons the security requirement for the transmitter terminal is as high as it is for the ground station. Only the use of entangled states sent to two separate ground stations allows instantaneous key exchange between these two communicating Earth-bound parties and also relaxes the security requirement for the transmitter module. Furthermore, more advanced quantum communication schemes will be feasible. The required shared entanglement can be established either by two direct downlinks [Fig. 2(b)] or by using additional satellite relay stations [Fig. 2(c)]. Quantum entanglement can also be distributed between a ground station and a satellite [Fig. 2(d)] or between two satellites [Fig. 2(e)]. In an even more elaborate scheme a third party, either on ground or on a satellite, might be involved, which is capable of performing a Bell-state analysis on two independent photons [Fig. 2(f)]. This allows quantum state teleportation and even entanglement swapping and could thus resemble a large-scale quantum repeater for a truly global quantum communication network. Applied to quantum cryptography, this third party might be used to control the

communication between the two other parties in a “Third Man” cryptography protocol. For example, in a polarization-based experiment, depending on whether he performs a simple polarization analysis of the independent photons or a Bell-state measurement, the “Third-Man” can communicate secretly with either of the two parties (or with both) or he can control whether the two can communicate secretly or not without knowing the content of the communication.

C. Link Requirements

The maximal acceptable link attenuation for a quantum communication system based on entangled photons is determined by the timing resolution and the dark count rates of the detectors used, as well as by the net production rate of the source. As the minimum signal-to-noise ratio (SNR), we assume the one that it is necessary for the violation of a Bell-inequality because of its relevance to establish the security of quantum cryptography (see Appendix I). With a typical overall detection efficiency $\eta_{Det} = 0.3$, a photon production rate of $P = 5 \cdot 10^5 \text{ s}^{-1}$, an estimated total background count rate¹ of $S = 10^3 \text{ s}^{-1}$ and a coincidence timing window of $\Delta\tau = 5 \cdot 10^{-9} \text{ s}$, the link efficiency should obey

$$\eta_{\text{link}} \geq 6.66 \dots \cdot 10^{-7} \quad (1)$$

when following the calculations presented in Appendix I. Roughly speaking, a total link efficiency of $\eta_{\text{link}} = \eta_{\text{link1}} \eta_{\text{link2}} \approx 10^{-6}$ (−60 dB) is necessary.

The link attenuation is also important for determining the number of photon pairs that can be received within a certain time window. This could be crucial in scenarios where the links are only available for short times as is for example the case in uplinks to low orbiting LEO satellites.

III. LINK ATTENUATION

The overall link efficiency of 10^{-6} , corresponding to a maximum attenuation of 60 dB, imposes quite a strong restriction on the various space scenarios. In the following, we will investigate the link attenuation for optical free-space links involving space infrastructure. The attenuation factor calculated includes the effect of beam diffraction, of attenuation and turbulence-induced beam spreading caused by the atmosphere, of receive aperture diameter, of losses within the telescopes acting as antennas, as well as antenna pointing loss. Effects not included in this factor are the detection efficiency of the photon-counter modules (~ 3.5 dB per detector) and reflective and absorptive losses at optical components (typically ~ 3 dB per individual photon link), which add up to an overall detection efficiency of ~ 6.5 dB per photon link. One may take these losses into account when calculating specific total link budgets. Fig. 3 summarizes the scenarios considered based on satellites in geostationary orbit (GEO) and in low earth orbit (LEO). Such satellites may serve

¹This includes the dark counts from the detector (50 s^{-1}) and additional background contributions from sunlight eventually reflected by the ISS (950 s^{-1}). Our estimate is based on an 0.1 nm bandwidth spectral filtering at the receiver site and on a sufficiently narrow field of view of the receiver telescope [32]. To avoid the significantly higher background radiation from the sky during the day the assumed background rate can only be achieved at nighttime.

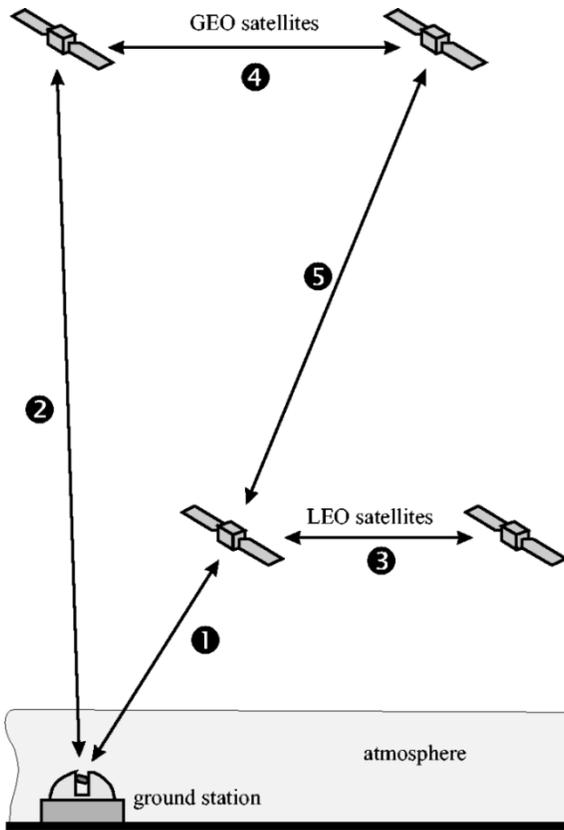


Fig. 3. Summary of links involving Earth-based ground stations and LEO satellites or GEO satellites.

as a platform for transmitters or receivers. We presently do not envision the use of passive relays, e.g., retroreflectors or mirrors, because of the high link loss they would introduce and because of the difficulty to implement a point-ahead angle.²

A. Satellite-Ground Links

1) *Ground-LEO or LEO-Ground Links:* For the case of a LEO-based transmitter or receiver (Link 1 in Fig. 3), link attenuation poses no problems. Even for quite small telescopes onboard the LEO satellite, the attenuation factor is well below 60 dB for all cases. Fig. 4 is a contour plot of the link attenuation as a function of transmitter and receiver aperture diameter (D_T , D_R) for the ground-to-LEO uplinks operated at a wavelength of $\lambda = 800$ nm. Two additional vertical scales give the link distance L for 30 cm receive telescope aperture as well as for the receive telescope aperture for a link distance of $L = 500$ km (For the equation and further parameters used to arrive at Fig. 4—and also at some subsequent figures—see Appendix II.). The lines of equal attenuation are separated by 5 dB. The corresponding plot for LEO-to-ground downlinks is shown in Fig. 5. One notes that the attenuation is much larger for the uplink than for the downlink. This is caused by the pronounced influence of atmospheric turbulence for the uplink, where the turbulent layers are close to the transmitter. In contrast, for a downlink the effect of the

²The point-ahead angle denotes the difference angle between transmit and receive direction of the telescope. Its occurrence is a consequence of the movement of the satellite together with the finite velocity of light of the signal propagation.

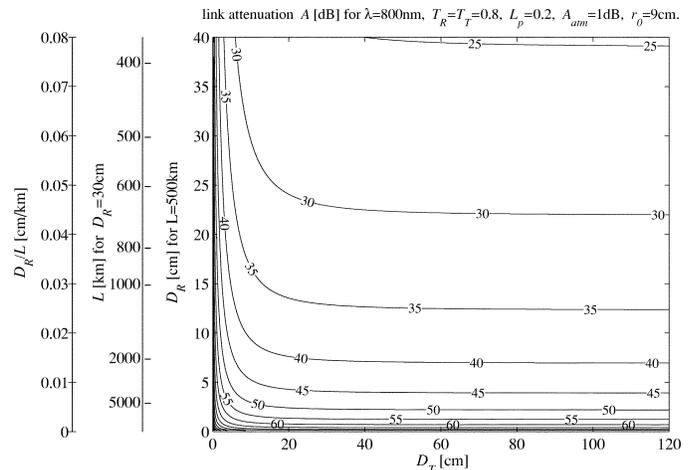


Fig. 4. Contour plot of link attenuation A (in dB) as a function of transmitter and receiver aperture diameter (D_T , D_R) and link distance L for ground-to-LEO uplinks at $\lambda = 800$ nm.

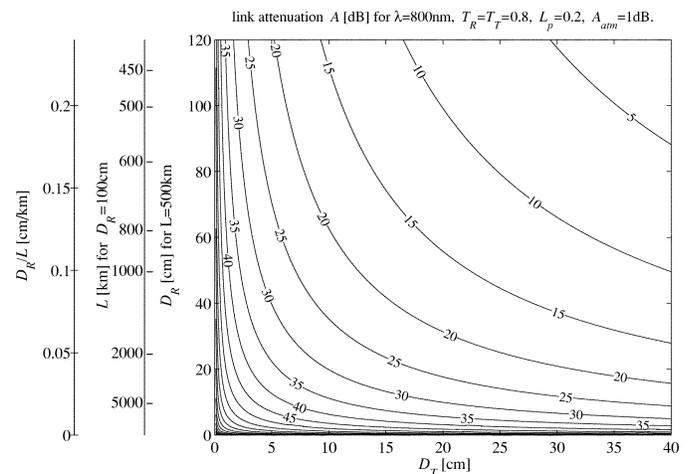


Fig. 5. As Fig. 4 but for LEO-to-ground downlinks.

turbulent layer close to the receiver is negligible to first order. Another consequence of turbulence is that increasing the transmitter aperture for the uplink beyond 40 cm hardly decreases the link attenuation (see Fig. 4). This effect could be mitigated by employing adaptive optics.

In the case of links connecting a LEO and a ground station, the possible duration for communication is comparatively short (e.g., a few minutes) and the angular velocity with which the telescope at the ground station has to be moved to track the satellite along its orbit is high. For all ground-to-space links the possibility of communication is weather dependent. While for clear weather and sufficient altitude of the ground station the uplink attenuation caused by the atmosphere is mainly determined by turbulence-induced beam spread,³ clouded skies will make any link impossible. This influence increases at low elevation angles typical for LEO-to-ground links. This lengthens the propagation path within the atmosphere.

2) *Ground-GEO or GEO-Ground Links:* The long distance in links between GEO and ground (Link 2 in Fig. 3) results in

³For a diffraction limited telescope of 20 cm diameter and a link distance of 500 km, some 20 dB attenuation have to be expected [33].

TABLE I
 LINK ATTENUATION FOR VARIOUS SPACE SCENARIOS

800 nm	ground-based receiver	LEO receiver	GEO receiver
ground based transmitter		27.4 dB	64.5 dB
LEO transmitter	6.4 dB	28.5 dB	52.9 dB
GEO transmitter	43.6 dB	52.9 dB	53.9 dB

For the numerical calculation the default parameter values given in Appendix III have been taken at a wavelength of 800 nm.

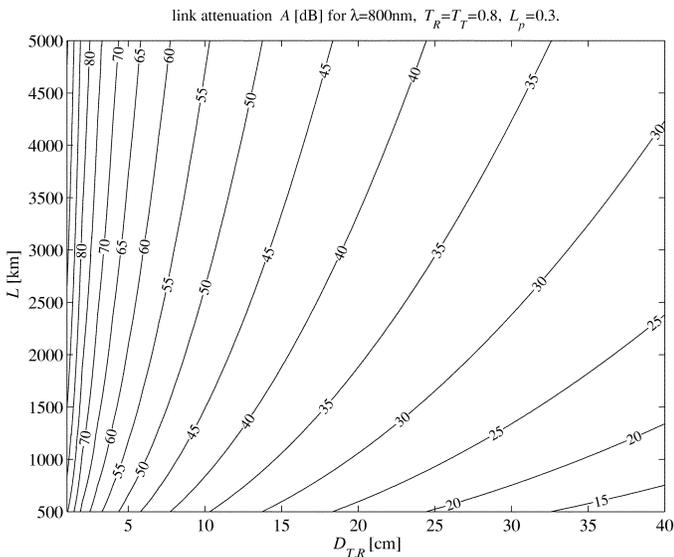


Fig. 6. As Fig. 4 but for LEO-to-LEO links.

a relatively high attenuation. As a consequence, with a ground station aperture of $D = 100$ cm and a GEO terminal aperture of $D = 30$ cm one will be able to meet the 60 dB requirement in a downlink, but not in an uplink (compare Table I of Section V).

B. Satellite-Satellite Links

While from a technological point of view a satellite-to-satellite link is the most demanding configuration it offers highly attractive prospects for scientific experiments. It allows one to cover, in principle, arbitrarily large distances and might thus also be a possibility for further novel fundamental tests on quantum entanglement.

We calculated the attenuation factor as a function of both transmitter and receiver aperture diameter for a LEO-LEO link (Link 3 in Fig. 3). Fig. 6 displays the attenuation for a wavelength of 800 nm as a function of the satellite distance L and telescope diameters D_T and D_R , assumed to be equal for both terminals. We conclude, that the 60-dB limit poses no problem for LEO-LEO links with reasonable link distance.

For GEO-GEO links (Link 4 in Fig. 3), the attenuation can be read off Fig. 7, where again equal telescope apertures have been assumed. For a distance of $L = 45000$ km, an attenuation of $A = 55$ dB would result for $D_T = D_R = 30$ cm.

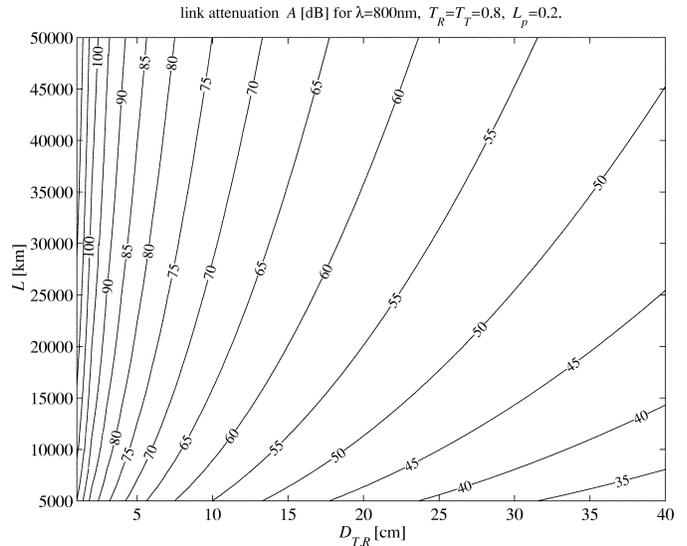


Fig. 7. As Fig. 4, but for GEO-to-GEO links.

IV. TECHNOLOGICAL PREREQUISITES FOR ENTANGLEMENT IN SPACE

For performing the quantum communication experiments aforementioned, the following minimum hardware is required: a transmitter terminal to generate and transmit the entangled particles and one or more receiver terminals suited for single-photon manipulation and detection. We briefly outline their main features.

A. Transmitter, Receiver, and Relay Modules

A transmitter module comprises a photon source for entangled photon pairs (including passive or active manipulation of single qubit-states), a module for timing synchronization with the receiver station and a channel for classical communication. Present entangled photon sources rely on laser-pumped spontaneous parametric down conversion [34]. This technology is very likely capable of being miniaturized to a size suitable for satellite modules. Elsewhere, we have demonstrated a compact and stable source for entangled photon pairs that could be operated outside the shielded laboratory environment [29].

A receiver module comprises one or more optical input channels, each of which allows independent manipulation of qubits such as the rotation of photon polarization or the modulation of an interferometric phase. Additionally, it has to be equipped with single-photon detectors at each input port, a receiver module for timing-synchronization, and a classical channel for communication with the transmitter. Depending on whether active (remote) control of optical elements for qubit manipulation is possible or not (via, e.g., a polarizer or a retarder), we distinguish between *active* and *passive* receiver modules. Passive manipulation only requires a static setup of linear optics components. Typically, beam splitters in the input ports would randomly distribute incoming photons to differently oriented retarders, polarizers or beam splitters, where a manipulation and successive detection of single photons takes place. This kind of passive receiver module has

recently also been suggested by Rarity *et al.* in a space-suited system for single-photon QKD [35]. For active control of single qubit manipulation, an additional information concerning the arrival time (i.e., a timing synchronization) is required. More advanced quantum communication schemes, such as quantum dense coding or quantum teleportation, require at some stage of the protocol the projection of independent photons in a joint Bell state, i.e., a Bell-state measurement. Up to now, efficient achievement of this projection is only possible by means of two-particle-interferometry [6].⁴ This requires that the arrival time difference of two photons at the two input ports of a beam splitter has to be less than their coherence time (typically 0.5 ps) [37].

A relay module would redirect and/or manipulate qubit states without actually detecting them. Possibilities for its implementation range from a simple retroreflector to a more sophisticated relay-satellite (e.g., for deep-space communications), where the entanglement of photons establishing the quantum channel between ground station and deep-space satellite could be purified. We emphasize, that a relay can not serve as an amplifier. This is a consequence of the quantum no-cloning theorem [38].

B. Existing Optical Space Technology

Optical transceivers for space-to-ground links or intersatellite links are almost state of the art. The major design parameters for the transmission subsystem are laser wavelength, modulation format, data rate, and reception technique. Of equal importance is the subsystem required for beam pointing, link acquisition, and automatic mutual terminal tracking (PAT). Because of the very narrow widths of the communication beams involved, PAT asks for highly sophisticated protocols and for electromechanic and electrooptic hardware meeting exceptional technological standards. Major parameters entering the link capacity are telescope size, optical transmit power, link distance, and receiver sensitivity. Other aspects are mass, volume, and power consumption of the terminal. Examples for existing space laser communication links include ESA's intersatellite link Semiconductor Laser Intersatellite Link Experiment (SILEX) and a satellite ground link, which was only recently realized between the GEO satellite ARTEMIS and ESA's optical ground station OGS at Tenerife.

Photon sources and detectors presently implemented in such classical space laser communication systems can, in general, not be directly employed in quantum communication systems. However, the experience available may serve as a starting point for the development of space qualified components needed for quantum space experiments. The available optical communication technology could of course be applied to provide the classical channel that is always necessary in parallel to the quantum channel. One would also make synergistic use of some of the optics employed for PAT and employ one and the same telescope as antenna for both the classical and the quantum channel, which is a novel way of quantum-classical-multiplexing.

⁴Recently, another scheme based on the nonlinear couplings has been suggested to achieve a full discrimination of all four Bell states although with low efficiency [36].

C. Proof-of-Principle Experiments

The establishment of entanglement in space and, subsequently, its use for fundamental quantum physics experiments and quantum communication applications necessitates certain experimental stages:

Stage I: Creation and detection of qubits (here: single photons) via an optical space link. From an application point of view this achievement would already allow to perform QKD based on single photons.

Stage II: Establishment of entanglement (i.e. nonclassical correlations via shared entangled particles) between the communicating parties. This includes the ability to detect single qubits synchronously at the spatially separated locations of the communicating parties. At this stage already the most fundamental experiment in quantum physics, demonstration of a violation of Bell's inequality can be performed. It also makes possible further experiments such as QKD based on entangled qubits.

Stage III: Bell-state analysis of independent qubits. For the case of photons, the most efficient scheme relies on two-photon interferometry at a beam splitter. Technically speaking, the arrival time of the photonic qubits at the receiver module has to be synchronized such that photon wavepackets overlap at the beam splitter within their coherence length. If this problem is solved, all advanced quantum communication and computation protocols such as quantum-state teleportation or quantum dense coding can be implemented.

The selection of an experimental scenario, in which all of these stages can be performed, requires a tradeoff between link attenuation and experimental flexibility. It has been shown above that the total link attenuation of the experimental setup must not exceed some 60 dB, assuming today's quantum-optics technology. Presently, without the use of quantum memories, entanglement can only be shared when more than one link is available. For the symmetric case of two equally long quantum links (one transmitter and two receivers), this limits the maximal single-link attenuation (between one transmitter and one receiver) to approx. 30 dB. Although space-to-space links have the attractive advantage of not being influenced by the Earth's atmosphere, we have to discard them at present due to the expected disproportionate technological and financial effort as compared to alternative schemes with at least one of the communication terminals on ground. Since two links should be established, it is therefore most reasonable to place the transmitter module in space, while the receiver modules stay in easily accessible ground-based laboratories. Most envisioned quantum experiments require higher flexibility at the receiver due to active polarization control or data analysis. Also, the atmosphere causes a larger footprint in an uplink than in a downlink, due to the higher influence of turbulence. With such perspectives it becomes obvious that in a first proof-of-principle experiment one should place the transmitter module into space and the receiver module(s) on Earth. Because of their relative stationarity, terminals placed on GEO satellites do not require such a highly sophisticated pointing, acquisition and tracking (PAT) systems as those on a LEO satellite. They would also

allow for long-duration experiments. On the other hand, the link attenuation and cost are significantly larger for GEO links compared to LEO links. Therefore, when trading GEO-based against LEO-based systems, we would rather accept the more complex PAT system and the limited connection time per orbit and suggest to use a LEO platform for the transmitter terminal for first proof-of-principle experiments.

V. PERSPECTIVES AND LIMITS OF SPACE-AIDED QUANTUM COMMUNICATIONS

We determined the typical attenuation for the links indicated in Fig. 3. The values listed in Table I were calculated using (7) for wavelengths of 800 nm, assuming telescope apertures characteristic for present day optical space technology. Furthermore, calculations have been performed for a wavelength of 1550 nm. The first wavelength seems reasonable because the best single-photon detectors exist for 800 nm, while the second wavelength is mainly used in standard telecom systems. Applying this wavelength may thus increase compatibility and reduce development effort because commercial off-the-shelf components are available. However, the total link attenuation is slightly increased for $\lambda = 1550$ nm due to the higher beam divergence at larger wavelength, although the atmospheric absorption and the influence of turbulent air is slightly decreased compared to 800 nm. For each link the default parameters are specified in Appendix III.

Based on present-day technology and assuming reasonable link parameters, it seems feasible to achieve enough entangled photons per receiver pair to demonstrate a quantum communication protocol. For example, assuming a LEO-based transmitter terminal, a simultaneous link to two separate receiving ground stations and a (conservatively estimated) total link attenuation of approx. 51 dB,⁵ one can expect a local count rate of approximately 2600 per second in total at each of the receiver terminals. The number of shared entangled photon pairs is then expected to be approximately 4 per second. For a link duration of 300 s, this accumulates to a net reception of 1200 entangled qubits. One can expect erroneous detection events on the order of 7 per 100 s, which yields a bit error of approximately 2%. This would already allow a QKD protocol between the two receiver stations. It is thus clear, that a demonstration of basic quantum communication protocols based on quantum entanglement can already be achieved today.

All proposed setups are based on the utilization of entangled photon pairs as carriers of quantum information. Given state-of-the-art technologies present in today's quantum optics labs we can specify some practical limitations for the preparation and detection of entangled qubits.⁶

The rate of information transfer is limited by the maximal number of photons or entangled photon pairs that can be created and detected. Typical standard repetition rates for pulsed laser

sources able to create (entangled) qubit states are of the order of $10^6 - 10^7$ s⁻¹, which will be reduced to only a few thousands per second by effects such as optical filtering, finite coupling efficiency and finite detection efficiency. Additionally, one has to take into account transmission losses, which can limit the qubit transmission drastically. Also, state of the art detector systems have low dynamic ranges over a maximum of six orders of magnitude⁷ and a maximal detection rate of some MHz.⁸ Further development both of source and detector technology will lead to additional improvements of the qubit rates.

In the present paper, we propose various scenarios for entanglement-assisted global and space-based quantum communication. While this in itself is already an interesting and outstanding experimental challenge, there are various specific novel opportunities which such a technology would offer. First and from a technological perspective foremost is the possibility to establish a secure and efficient communication using the methods of entanglement based quantum cryptography. As we explained above, that way one could not only establish a secure communication link between two arbitrary locations on Earth. It would also be possible to establish secure communication from Earth to satellites or between satellites. This would certainly increase the security of satellite remote control, which at present is a highly sensitive area and, thus far, an unsolved technical problem.

Another very important aspect is the fact that resources for communication in space are usually very limited, rare and expensive, particularly in view of the necessity of low power consumption. There we expect that quantum communication provides a natural goal, where one utilizes the ultimate limit of transmitting one bit of information per photon. Actually, this could even be increased if one would exploit photon states in higher dimensional Hilbert-spaces, where one photon can carry more information than one bit [40]. This might be particularly useful in deep space communication, where both communication time and energy resources are even more limited and where efficient communication is absolutely mandatory. One might conceive that the ultimate application of novel ideas in quantum communication complexity might some day provide a unique means to reduce the resources necessary for the transmittal of certain information. Finally, we mention that the distribution of quantum entanglement over astronomic scales will allow the test of quantum mechanics, particularly via violation of Bell's Theorem over novel distances larger by several orders of magnitude than existing experiments. This will make the issues of quantum nonlocality even more directly obvious than today. One might even conceive that in future manned missions to other planets, say to Mars, one could actually have human observers who decide to perform these experiments in the sense that the decision, which parameter is measured is made by human observers in the last instance when the entangled photons are already on their way. This would eliminate any hidden possibility of crypto-determinism, except the last resource namely that even human decisions are deterministic. Furthermore, as it has always been the

⁵Note again, that without quantum memories, quantum entanglement can only be shared when more than one link is available. For the symmetric case, i.e., two equally long quantum links involving one transmitter and two receivers, this limits the maximal single link attenuation between one transmitter and one receiver to approximately 30 dB. Here, we assume a loss of 25.5 dB for each of the downlinks.

⁶A more detailed analysis on link duration and qubit transmission rates for specific experimental scenarios is presented in [39].

⁷The highest dynamic range of about six orders of magnitude is achieved with Si avalanche photodiodes (APDs), whereas systems based on InGaAs up to now reach only three to four orders of magnitude.

⁸Some tens of kHz in the case of InGaAs.

case in physics, we expect that novel ideas will emerge as soon as such systems have been placed in space and are safely operating.

APPENDIX I LINK REQUIREMENTS

The accidental coincidence rate is given by

$$C_{\text{acc}} = S_1 S_2 \Delta\tau \quad (2)$$

where S_1, S_2 are the background count rates of the two detectors and $\Delta\tau$ is the timing resolution for the electronic registration of a twofold coincidence event. As the minimum SNR, we assume that required for violating a Bell-inequality, since this guarantees at the same time the security of certain quantum cryptography schemes [41]. For the case of polarization-entangled photons this necessitates a twofold coincidence visibility of at least 71%, corresponding to a SNR of 6:1.⁹ Below that ratio a local realistic modeling of the observed correlations is possible thus allowing unobserved eavesdropping.¹⁰ Therefore, in order to discriminate the signal from the background coincidences, the coincidence rate C_0 must be at least six times larger than C_{acc} .

The coincidence detection rate is determined by the total coincidence efficiency η_{link} , which is the product of the individual efficiencies for the two qubit links

$$\eta_{\text{link}} = \eta_{\text{Link1}} \eta_{\text{Link2}}. \quad (3)$$

The detected signal coincidences C are given by the product

$$C = P \eta_{\text{link}} \eta_{\text{det1}} \eta_{\text{det2}} \quad (4)$$

where P is the pair production rate of the source and $\eta_{\text{det1}}, \eta_{\text{det2}}$ are the detection probabilities. In order to achieve a violation of Bell's inequality, the signal coincidences must exceed the limit $C_0 = \text{SNR} \cdot C_{\text{acc}}$, which leads to the following limit for the total link efficiency

$$\eta_{\text{link}} \geq \text{SNR} \frac{C_{\text{acc}}}{P \eta_{\text{det1}} \eta_{\text{det2}}} = \text{SNR} \frac{S_1 S_2 \Delta\tau}{P \eta_{\text{det1}} \eta_{\text{det2}}}. \quad (5)$$

APPENDIX II MODELING THE LINK ATTENUATION

We define the link attenuation factor A as the ratio of the mean transmit and receive power P_T and P_R [43] measured at the entrance and the exit of the transmit and the receive telescope, respectively. Thus losses due to single photon detection efficiency and optical elements such as filters, polarizers or retarders are not included in this number. Then the attenuation factor A of a one-way free-space link is thus given by

$$A = \frac{L^2 \lambda^2}{D_T^2 D_R^2} \frac{1}{T_T (1 - L_P) T_R} \quad (6)$$

where L is the link distance, λ the wavelength, and D_T and D_R the diameters of the transmit and receive telescope. With T_T and

⁹The visibility, in terms of the signal S and the noise N , is defined by $(S - N)/(S + N)$.

¹⁰Note, that phase-coded entanglement results in slightly higher requirements to show that no local realistic model describes the corresponding correlations [42].

T_R we denote the transmission factors (≤ 1) of the telescopes, L_P is the pointing loss due misalignment of transmitter and receiver. This basic relationship applies (i) if the receiver is in the transmitter's far field, i.e. $L \geq D_T^2/\lambda$, (ii) if the transmit telescope is diffraction limited, and (iii) if there is no influence of the atmosphere.

Influence of Atmosphere

Atmospheric effects on propagation at optical beams can be divided into three categories: absorption, scattering, and turbulence [44], [45]. While absorption and scattering mainly depend on wavelength and visibility conditions, the net impact of atmospheric turbulence additionally depends on elevation angle and direction of transmission [46]. The main effect of atmospheric turbulence is an enlarged beam divergence, resulting in a reduced amount of signal power collected by the receive telescope. Further turbulence-induced effects are beam-wander, loss of coherence, scintillation and pulse distortion and broadening¹¹ [47]. The effect of turbulence is in general quite different for a space-to-ground link and a ground-to-space link. In a space-to-ground link the light propagates through vacuum for the most of the distance first before being disturbed by the atmosphere, whereas for a ground-to-space link the beam spreading effects of turbulence take place at the beginning of the propagation, causing a strongly enhanced divergence.

Ground-to-Space Links

For ground-to-space links we therefore modify (6) to take into account an additional attenuation by the atmosphere and the influence of turbulence. The diffraction-limited divergence caused by the aperture diameter of the transmit telescope is increased when the beam passes the turbulent atmosphere. The influence of the atmosphere can be taken into account by the so-called *Fried parameter*, r_0 , which can be interpreted as an "effective aperture" [46]. We will assume that the divergence due to turbulence adds quadratically to the divergence of the telescope [33]. The attenuation factor may then be approximated by

$$A = \frac{L^2 (\theta_T^2 + \theta_{\text{atm}}^2)}{D_R^2} \frac{1}{T_T (1 - L_P) T_R} 10^{\frac{A_{\text{atm}}}{10}} \quad (7)$$

where A_{atm} is the attenuation of the atmosphere, given in dB. The divergence angle resulting from the transmit telescope is assumed to be

$$\theta_T = \frac{\lambda}{D_T} \quad (8)$$

and the turbulence causes the additional divergence

$$\theta_{\text{atm}} = \frac{\lambda}{r_0}. \quad (9)$$

This calculation probably underestimates the turbulence effect,¹² but our model is considered to be suitable to calculate a lower-bound estimation for the attenuation factor.

¹¹Turbulence-induced pulse distortion and broadening might actually impose an upper limit to the spectral bandwidth in the pulsed downconversion schemes.

¹²In comparison to the values presented in [48] the divergence obtained with our model is lower by a factor of 1.5. However, we do not know the exact turbulence conditions assumed in [48]. Also, the experimental results of the ARTEMIS-OGS downlink are slightly worse than our calculations would predict.

TABLE II
PARAMETERS FOR GROUND—LEO AND LEO—GROUND LINKS
(DEFAULT VALUES ARE UNDERLINED)

link distance	L	<u>500</u> to 1400 km
ground aperture	D_T, D_R	<u>1</u> m
LEO aperture	D_T, D_R	20 to <u>30</u> cm
wavelength	λ	800 nm, <u>1550</u> nm
telescope transmission factor	$T_T = T_R$	<u>0.8</u>
pointing loss	L_p	<u>0.2</u>
atmospheric attenuation	A_{atm}	<u>1</u> dB
Fried parameter	r_0	<u>9</u> cm, 20 cm

TABLE III
PARAMETERS FOR GROUND—GEO AND GEO—GROUND LINKS

link distance	L	\geq <u>36 000</u> km
ground aperture	D_T, D_R	<u>1</u> m
LEO aperture	D_T, D_R	20 to <u>30</u> cm
wavelength	λ	800 nm, <u>1550</u> nm
telescope transmission factor	$T_T = T_R$	<u>0.8</u>
pointing loss	L_p	<u>0.2</u>
atmospheric attenuation	A_{atm}	<u>1</u> dB
Fried parameter	r_0	<u>9</u> cm, 20 cm

TABLE IV
PARAMETERS FOR LEO—LEO LINKS

link distance	L	<u>2 000</u> km
aperture	$D_T = D_R$	20 to <u>30</u> cm
wavelength	λ	<u>800</u> nm, 1550 nm
telescope transmission factor	$T_T = T_R$	<u>0.8</u>
pointing loss	L_p	<u>0.3</u>

APPENDIX III DEFAULT PARAMETERS

For the altitude of the LEO satellite we assume 500 km, which thus represents the lower limit of the link distance. For an elevation angle of, e.g., 15° , the link distance is of some 1400 km.¹³

Geostationary satellites have an altitude of 36 000 km. Again, the link distance may be larger, depending on the elevation of the satellite (for the ARTEMIS-OGS link the link distance is 41 229 km).

The baseline for the ground aperture is 1 m because this is the telescope diameter of ESA's optical ground station at Tenerife (OGS). Telescopes with a diameter of 20 to 30 cm are small and light enough to be operated even onboard a small LEO satellite. Larger telescopes are feasible, especially for GEO satellites.

We assume the transmission factors T_P, T_R of the involved telescopes to be 0.8. The pointing loss is $L_P = 0.2$ for all links except for the LEO-LEO link, where we assume $L_P = 0.3$ to take into account the—possibly—high relative velocity of the satellites that might result in reduced tracking accuracy.

The assumption of an atmospheric attenuation of $A_{atm} = 1$ dB applies for excellent sight conditions (no haze, fog, or clouds) and is valid only in certain wavelength regions.

A recently obtained estimate for the Fried parameter, valid for the optical ground station at Tenerife (OGS), is $r_0 = 90$ mm for a wavelength of 800 nm in case of weak turbulence [33].

¹³Note that for low elevation angles the influence of the atmosphere is increased, a fact not taken into account by the model used here.

TABLE V
PARAMETERS FOR LEO—GEO LINKS

link distance	L	<u>35 500</u> km
aperture	$D_T = D_R$	<u>20</u> to 30 cm
wavelength	λ	800 nm, <u>1550</u> nm
telescope transmission factor	$T_T = T_R$	<u>0.8</u>
pointing loss	L_p	<u>0.2</u>

TABLE VI
PARAMETERS FOR GEO—GEO LINKS

link distance	L	<u>40 000</u> km
aperture	$D_T = D_R$	<u>20</u> to 30 cm
wavelength	λ	800 nm, <u>1550</u> nm
telescope transmission factor	$T_T = T_R$	<u>0.8</u>
pointing loss	L_p	<u>0.2</u>

For the calculations presented we have assumed wavelengths of 800 nm and of 1550 nm. Tables II–VI summarize the link characteristics.

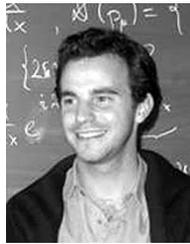
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Prof. Zeilinger has received many awards, among them are an Honorary Professorship at the University of Science and Technology of China, memberships in the German Order Pour le Mérite and various academies, and the Senior Humboldt Fellow Prize of the Alexander von Humboldt-Stiftung.