Study of the Quantum Channel between Earth and Space for Satellite Quantum Communications

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Abstract. In this work there are studied the conditions for the effective quantum communications between a terminal on Earth and the other onboard of an orbiter. The quantum key distribution between a LEO satellite and a ground station is studied in particular. The effect of the propagation over long distances as well as the background during day or night is modeled, compared and discussed in the context of key generation and exchange.

Keywords: Quantum cryptography – Satellite optical communications – single photon transmission.

1 Introduction

The quantum limit is the natural frontier for space communication. With a quantum channel the information is encoded in the state of a single entity, in the following a photon. On Earth, this was extended to links with length of about one hundred kilometres. In the case of fibre links, this is due to the signal attenuation in the fibre; in the case of free-space link the losses are due to atmospheric turbulence and absorption. Free-space optical terminals exploiting satellite-based relays are the only resource that can enable global scale quantum key distribution, since single photon propagation is for the main part in vacuum with no turbulence or absorption, and just a small part of the path is through the atmosphere. Several proof-of-principle experiments have been carried out recently: among these the feasibility of single-photon exchange between a satellite and an optical ground station was demonstrated in 2008 [1].

2 Signal and Noise in the Quantum Channel

Several aspects of the space quantum channel deserve careful attention in order to provide a complete picture of a quantum space link.

Signal Attenuation. The main factor limiting the performance of free-space optical communication is atmospheric turbulence, both for terrestrial horizontal links or for links between ground and satellites. Turbulent eddies whose size is large compared to the size of the beam induce a deflection of the beam (beam wandering), while

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smaller-scale turbulent features induce beam broadening. In other words, observing a beam which propagates through turbulent atmosphere at different time instants, one can see a broadened beam randomly deflected in different directions. When integrating the observation over a time-scale longer than the beam-wandering characteristic time, the global effect is a broadening of the beam. For a Gaussian beam of waist w_0 and intensity I_0, the long-term intensity distribution is described by [2]:

$$< I(r, L) >= I_0 e^{-2r^2/w_{LT}^2}$$

where:

$$w_{LT}^2 = w_{ST}^2 + 2 < \beta^2 >$$

w_{LT} is the long-term beam width, w_{ST} is the short-term one and β is the instantaneous beam displacement from the unperturbed position.

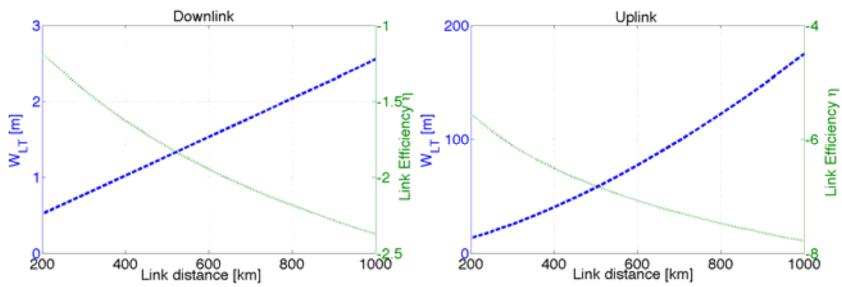

Fig. 1. Beam width w_{LT} and link efficiency for the uplink and the downlink

The results are shown in Fig. 1 for the uplink and the downlink. For the uplink, the beam first propagates through the turbulent atmosphere and then, aberrated, in vacuum, resulting in a large broadening (around 100 m diameter at 500 km). For the downlink, the beam propagates through turbulence only in the final stage, and the spreading is much less (around 1 m at 500 km). Therefore, the attenuation is much stronger in the uplink (more than 50 dB for a 30-cm diameter telescope) compared to the downlink (around 10 dB).

Background noise. As regards the expected background noise in the uplink, during day-time the main contribution is given by sunlight reflection on the Earth surface into the telescope field-of-view. We calculated this contribution to be between 10^7-10^9 photons per second (for a 1 nm of bandwidth). During night-time the main sources of noise are moonlight reflection from the Earth surface, which we calculated as six-orders of magnitude less than it is in day-time (around 10^1-10^3 photons per second) and light pollution from human activities.

We show that the signal-to-noise ratio is proportional to:

$$SNR = \frac{\epsilon_S}{\epsilon_N} \propto \frac{\eta_0}{w_{LT}^2 (IFOV)^2 \Delta\nu \Delta t}$$

where η_0 comprises the detection efficiency, the pointing losses and the atmospheric attenuation, (IFOV) is the telescope field of view and Δt is the detector gating time. In first approximation the SNR does not depend on the radius R of the receiving telescope. The results show that during day-time it is impossible to achieve a SNR higher than 1. During night-time a good SNR can be obtained both for the uplink (~15 dB) and the downlink (~20 dB), provided that a strong filtering is implemented.

3 Key Generation Rate

The expected key generation rates results a function of the link distance for different configurations (uplink, downlink) during night-time for different quantum key distribution protocol.

In most practical quantum communication experiments, single photons are implemented with weak coherent pulses, which have a non-zero probability of multi-photon emission. On such multi-photon pulses Eve could perform a photon-number-splitting attack (PNS)[3]. In the case of high-loss channels, like the ground-to-satellite one, multi-photon pulses are more likely to survive the channel attenuation and get to Bob's detector than single-photon pulses. The probability of tagged bits in the key, for which Eve can have information without introducing any perturbation, is very high. In the case of the BB84 protocol, a worst-case estimate is taken on the fraction of tagged bits, assuming that all multi-photon pulses are correctly intercepted by Eve. In this case the only way to guarantee security is to reduce the probability of having multi-photon pulses, reducing the source mean photon number. This results in the impossibility to establish a BB84 uplink to a LEO satellite, while for the downlink the results are much better (see Fig. 2).

A better estimate of the fraction of tagged bits can be obtained using weak pulses with different mean photon numbers, the decoy-state technique [4]. Such technique mitigates the need to have a very low intensity source, so that a meaningful key generation rate can be achieved even in the uplink (Fig. 2). Assuming a three-intensities decoy state protocol (vacuum, $\mu = 0.27$, $\mu' = 0.4$) a key generation rate of 10^{-6} can be obtained for an uplink to a satellite orbiting at 350 km (see Fig. 2). The cut-off distance for un uplink is around 300-400 km (depending on the QBER).

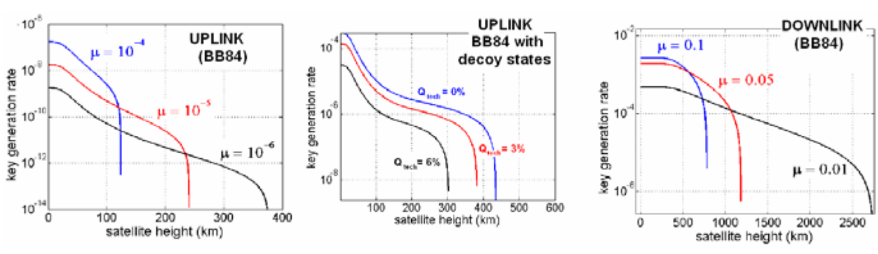

Fig. 2. Key generation rate for uplink (BB84 with and without decoy states) and downlink (BB84). For the uplink, it is possible to establish a QKD channel only using the decoy-state technique and the cut-off distance is around 300-400 km.

The establishment of an entanglement-based link between a LEO satellite and Earth is also investigated. In this case the most important parameter is the SNR [4]: only achieving a 6:1 SNR Bell inequalities can be violated.. We show that a configuration with one local receiver and the other to or from a LEO satellite is feasible. The configuration with two downlinks [5] is also be feasible, but with very strict hardware requirements.

In conclusion, satellite technology is expected to provide the means for the extension of quantum communication on the global scale.

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