Link technology for all-optical satellite-based quantum key distribution system in C-/L-band

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***Abstract*—Satellite based quantum key distribution (QKD) enables the delivery of keys for quantum secure communications over long distances. Maturity of the technology as well as industrial interest keep increasing. So does the technology readiness of satellite free-space optical communications. A satellite QKD system comprises a quantum communication subsystem and a classical communication subsystem (public channel). Both are implemented with free-space optics. Thus, in satellite QKD system design, there are strong synergies that should be exploited as much as possible and lead to an all-optical satellite QKD system. In this paper, we present a system like this locating all optical channels in ITU DWDM C-band. We focus on the overall conceptual design and the setup of the optical channels for quantum and classical signal transmission. The system description addresses the breadboards of a transmitter laser terminal (Alice terminal), a receiver laser terminal, (Bob terminal), the public channel implementation, the interfaced QKD system and the deployed encryption system. The design basis for the Alice terminal is the laser terminal development OSIRISv3. The design basis for the Bob terminal is the ground station development THRUST. The later contains an adaptive optics correction to enable single mode fiber coupling. This enables the interfacing to almost arbitrary quantum receivers such as the Bob modules used in the described experiment. The public channel is composed of a bi-directional 1 Gbps IM/DD system and a MODEM that implements a proprietary waveform optimized for free-space channels.**

The system was experimentally analyzed in a field test in the framework of the German initiative QuNET which addresses the use case of quantum secure communication for authorities. The results of the experiment are used to model a feasible LEO satellite-ground link. Performance indicators such as quantum bit error rate and secure key rate of a potential mission are estimated analytically.

Keywords—quantum key distribution, satellite communications, secure communications, free-space optical communications, laser terminal, QBER

I. Introduction

Several of today's secure communications channels are threatened by the upcoming quantum computer. Specifically, communication sessions based on widely used asymmetric encryption methods like RSA for key sharing are immediately challenged. Thus, the security of key sharing is under attack. Quantum key distribution is one technology that can solve this. It gives the security system the functionality of securely distributing keys between two partners that cannot be tapped without the parties not revealing the eavesdropper [1]. Typical fiber-based systems are limited to a few hundred kilometers

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and even the currently most sophisticated laboratory demonstrations only achieve 509 km [3]. These distances are useful for metropolitan networks or mid-range intercity backbones. For large-scale networks, a large number of trusted nodes would be needed. Satellite-based quantum key distribution (QKD) gives a solution to this problem since the satellite can, depending on the orbit, access any point on earth and thus enables a global QKD network. In the following we show a system architecture and ground demonstration of such a system that can be the basis for a future satellite QKD development. On a currently technically feasible and practical system, the deployed QKD system would be of prepare and measure kind, the employed protocol a variant of the well-established BB84 protocol [4] and the satellite would act as a single trusted node. Several demonstrations till now showed feasibility of QKD with aeronautical and satellite nodes [5][6][7][8][9]. To obtain compatibility to fiber networks for large scale deployment and integration into a future quantum network comprising fiber and free-space links, it is straightforward to use wavelengths in DWDM C-band. These wavelengths are used for the quantum channel as well as all other channels that are needed for implementation of the QKD protocol, i.e. also the data communication, sync channel and PAT (Pointing, Acquisition and Tracking) channel. Having all these channels in C-band gives the complete system compatibility with the fiber network. Furthermore, optics terminal design is easier (and thus cheaper and more robust) since design is done only for one wavelength. This gives the motivation to develop an all-optical C-band free-space system for satellite QKD. The system is experimentally analyzed in a field test, e.g. by measurement of the end-to-end loss and the quantum bit error rate (QBER) contributors and secure key rate of a potential mission is estimated analytically.

This demonstration was conducted in the framework of the German QuNET initiative. The initiative addresses secure communications between authorities. Therefore, a demonstration testbed was setup between the building of the Federal Ministry of Education and Research (BMBF) and the Federal Office for Information Security (BSI) in Bonn, Germany. A quantum secure video conference call was demonstrated using this setup [1].

II. System Design

The overall system includes a QKD system, a data communication system and a cryptographic system. The overview block diagram is depicted in Figure 1. The experiment setup comprises two parties: authority 1 and authority 2. Authority 1 comprises the Alice Unit, which is also the transmitter side of the quantum channel, and a consumer device (the user). Authority 2 comprises the Bob Unit, which is the receiver side of the quantum channel, and also a user. Two free-space optical terminal, one on each side, act as transmitter and receiver antennas of the optical signals, which implement the pointing, acquisition and tracking function. Communication modules are included to implement the public channel for the QKD protocol post-processing data and for data transmission for the video conference.

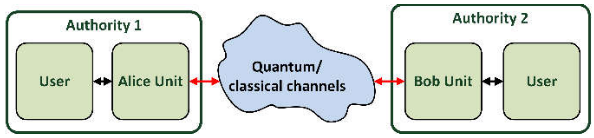

Figure 1. Overview of experimental setup. Red lines: optical interfaces; black lines: electrical interfaces.

The transmission direction of the quantum channel goes for Alice to Bob which would also be the downlink channel in the case of a satellite-ground scenario. The wavelength plan foresees four downlink wavelengths in C-band and two uplink wavelengths in L-band as shown in Figure 2. This scheme follows the CCSDS standard O3K for LEO downlinks which is currently under development [10]. The standard essentially foresees downlink wavelengths for data transmission in C-band and uplink beacon wavelength in L-band. The wavelengths are chosen so that the weak quantum signal (1546.92 nm) has minimum interference with the strong DATA/Beacon signal.

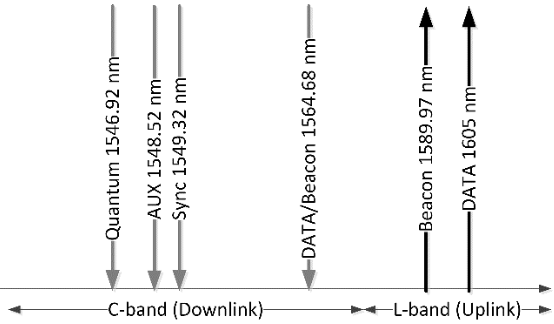

Figure 2: Wavelength plan of experiment setup

A more detailed look into the Alice Unit is shown in Figure 3 which denotes also the satellite unit. Interface to the free-space channel is the Alice Terminal that resembles the actual free-space laser terminal, i.e. the antenna. The red arrows denote optical interfaces, i.e. free-space optics (FSO) or fiber, and the black arrows denote electrical interfaces (like coax or Ethernet). The Alice Terminal comprises the FSO technology like the PAT subsystem and the data receiver front end (RFE) and is further described in chapter III. The receive data signal goes from the RFE in the Alice Terminal to the MODEM. The transmit data signal goes from the MODEM to the TX Laser which is directly modulated by the help of a driver board in the MODEM. The TX Laser is the laser source for the data and PAT channel in downlink direction (Alice→Bob) and its signal is led to the multiplexer (MUX). The Alice module interfaces the QKD signal and its sync signal also to the MUX. Furthermore, an auxiliary laser source (AUX) is connected to the MUX which is used for channel measurements and monitoring. The MUX combines all transmit wavelengths and interfaces to the Alice terminal. The Alice module is connected to the crypto box for key delivery, i.e. the crypto box is the key consumer. The crypto box comprises here the cryptographic system for encryption/decryption as well as the key management system. The data stream that goes over the MODEM and eventually over the FSO channel contains the user data and QKD public channel data. The whole stream goes through the crypto box, i.e. the user data and the QKD public channel are encrypted.

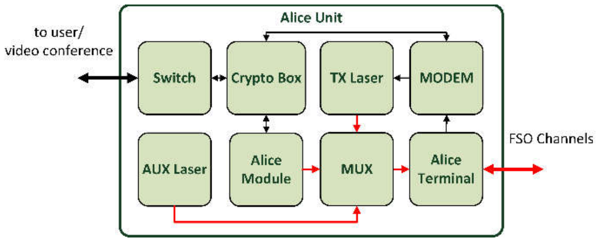

Figure 3: Block diagram of Alice Unit (satellite unit). Red lines: optical interfaces; black lines: electrical interfaces.

The Bob Unit is shown in Figure 4. In a satellite system, this Bob Unit would denote the ground station unit. The red arrows denote optical interfaces (FSO or fiber) and the black arrows denote electrical interfaces (like coax or Ethernet). Like the Alice Terminal, the Bob Terminal comprises the PAT subsystem sensor unit, the RFE, the adaptive optics unit and the fiber coupling unit and is also further described in chapter III. The receive data signal goes from the RFE in the Bob Terminal to the MODEM (same as in the Alice Terminal). The transmit data signal goes from the MODEM to the TX Laser/Modulator. Unlike in the case of the Alice Unit, the TX laser is not modulated directly but externally with an intensity modulator. The TX Beacon is the laser source for the PAT channel (uplink direction). The TX laser signal and TX beacon signal are interfaces separately to the Bob Terminal. The Bob Terminal receives the QKD signal, the sync signal, the DATA/PAT signal of the Alice Terminal and the AUX signal. The DATA/PAT signal are received by free-space sensors in the Bob Terminal. The QKD, sync and AUX signal are guided to the demultiplexer (DEMUX). A power sensor is used to monitor the in-fiber power of the AUX channel, thus providing a measurement of the fiber coupling efficiency and the end-to-end loss. Like the Alice module, the Bob module is connected to the crypto box for key delivery and the encrypted data stream contains the user data and the QKD public channel data.

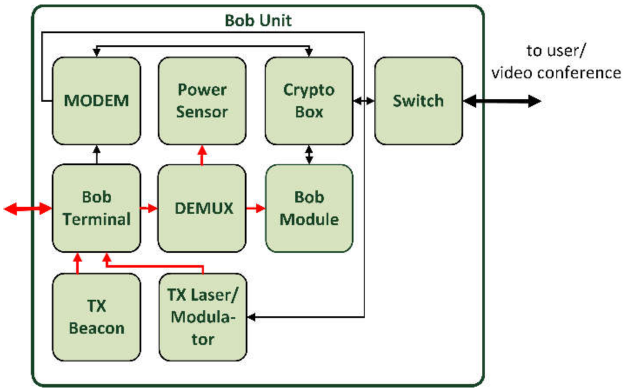

Figure 4: Block diagram of Bob Unit. Red lines: optical interfaces; black lines: electrical interfaces.

III. Free-Space Terminals

A. *Alice Terminal*

In the satellite QKD scenario, the Alice terminal would be the transmitter terminal in LEO-ground downlink. In this ground campaign it is also the transmitter terminal (with respect to the quantum channel). It is responsible for sending the quantum and synchronization signals for the QKD systems, the data signal for the public channel, the beacon signal for the PAT and an auxiliary signal for channel measurements and monitoring. A picture of the terminal is given in Figure 5. Coarse pointing is achieved through mounting the terminal on a combination of a goniometer and a rotation stage. The whole assembly is mounted on a tripod which ensures day-to-day pointing stability.

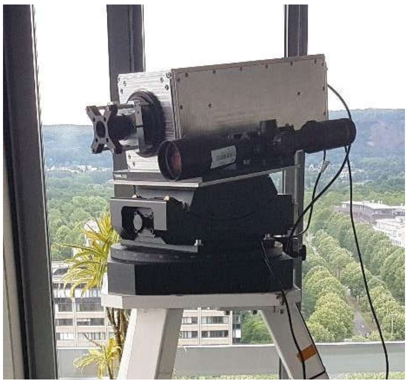

Figure 5: Picture of Alice terminal mounted on the CPA (goniometer and rotation stage) and a tripod with external rifle scope.

The terminal is based on a modular design, intended for a space-borne free space optical communication system [12]. It features a lightweight aluminum alloy construction with titanium inserts providing the interface between glass optics and the aluminum chassis. In order to eliminate the need for adjustable kinematic optics, the components are aligned to the optical bench through the use of precision alignment pins.

The functional block diagram is shown in Figure 6. The optical system features a Galilean telescope with an input aperture of 30 mm and magnification of about 2. The beams are reflected by a fine-steering mirror (FSM) and a folding mirror. The transmit signals from the DWDM MUX are coupled into the optical bench with an off-the-shelf single mode fiber collimator with 3.6 mm beam diameter which results in an ex-aperture full beam divergence of 330 microradians. A chromatic beam splitter is used to couple the transmit beam to the FSM and telescope (Coupling block). The two receive signals (tracking beacon and data channel uplink) are separated by another chromatic mirror (Coupling block) and focused on a 4-quadrant detector and a receiver front end respectively by focusing lenses.

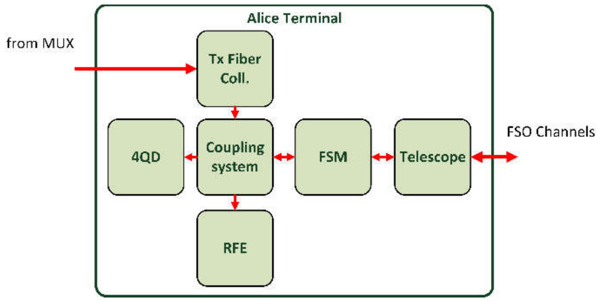

Figure 6: Optical block diagram of Alice terminal. 4QD: 4-quadrant diode; FSM: Fine Steering Mirror; RFE: Receiver Front End. The coupling system comprises two chromatic filter for beam combination and beam separation. Red lines: optical interfaces; black lines: electrical interfaces.

In order to compensate for angular alignment errors between both terminals and external disturbances introducing jitter to the system active optical components are used. A 4-quadrant-diode is the main optical reference which measures the beam displacement from the calibrated position. To facilitate this, a dedicated beacon signal (L-band) modulated at 10 kHz is sent by the Bob terminal. The beacon signal, received by the 4QD (4-quadrant diode) is digitized with a 24-bit 4-channel simultaneously sampling analog-to-digital converter. The signal is processed in the digital domain by a 32-bit micro-controller and the calculated angular displacement is sent over an RS-485 connection to the control system.

The receiver and transmit beams all go over the FSM [13] allowing a manipulation of the beams in both directions. The FSM features a clear aperture of 20 mm, ±1° mechanical stroke and pointing jitter of < 1 microradians and is therefore precise enough for the targeted beam stabilization. The FSM features the ability to measure deflections of the mirror platform using a set of eddy-current-sensors (ECS). The combination of a 4QD (sensor) and FSM (actuator) allows the system to track the incoming beacon signal in closed loop mode. The tracking system with control loop is a special implementation and implemented with two nested control loops – a slow, outer loop, which uses the 4QD as a sensor and a fast, inner loop, which uses the ECS. The control system software runs on a 32-bit microcontroller based embedded system. The characterization of the FSM mechanical system shows an eigenfrequency of about 120 Hz. A digital notch filter is used to suppress this frequency range so that it not excited by any control command. It allows for a cascaded control design where the dynamics of the mirror are considered. The use of an observer model generates the input for a mirror state feedback loop with the advantage to reach high control bandwidths. In order to facilitate the required bi-directional classical communication, the terminal is equipped with a commercial off-the-shelf optical receiver front end.

B. Bob Terminal

The Bob terminal is the receiver station in the satellite QKD scenario. The optical bench as used and developed in the current experiment can be seen as the potential back plane of an optical ground station telescope. A picture of the Bob terminal is shown in Figure 7. It shows the terminal in action during the field test (cover removed). The Bob terminal serves four main functions: (1) Transmit "uplink" L-band beam that served as a beacon for tracking at Alice terminal, (2) Transmit “uplink” L-band beam for data transmission, (3) Receive "downlink" beam in C-band to support tracking and public channel data transfer and (4) Receive QKD system signals (quantum and sync channel in C-Band) and couple them into the single mode fiber.

Figure 7: Picture of Bob terminal without cover during field experiment. The optical bench is mounted on a similar CPA and tripod as the Alice terminal in Figure 5.

The block diagram of the system is shown in Figure 8. The aperture of the main telescope is 4" diameter and was selected to be large enough so that it would be larger than the expected phase distortions in the downlink. The tilt of the received downlink beam induced by the atmospheric channel is then corrected using a piezo-driven FSM. After that, part of the downlink beam power is picked off for a wavefront sensor (WFS) that is used for characterization of atmospheric turbulence induced wavefront distortion. All the remaining wavelengths in the downlink are propagated unaffected. The beam is then shaped before being reflected from a deformable mirror (DM). There, higher-order phase distortions caused by optical turbulence in the channel are corrected. After that, downlink and uplink beams are chromatically divided.

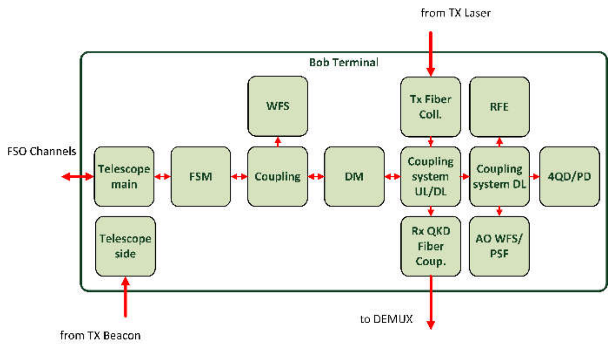

Figure 8: Block diagram of the optical setup of the Bob terminal. FSM: fine-steering mirror; WFS: wavefront sensor; DM: deformable mirror; UL: Uplink; DL: Downlink; RFE: receiver front end; AO WFS: adaptics optics WFS; PSF: point spread function; 4QD: 4-quadrant-diode; PD: power diode

In the uplink direction, the signal from the TX Laser (data stream) is collimated out of the fiber and recombined with the downlink path. The signal from the beacon laser (TX Beacon) is interfaced to a dedicated smaller side telescope which was necessary to obtain far field condition of this beam at the Alice terminal since the link distance in the campaign was only 300 m. As both the uplink and the downlink beams are reflected off the DM, the uplink beam wavefront is this way also "pre-compensated". Assuming the channel reciprocity, the channel distortion "flattens out" the propagated wavefront and thus stabilizes the uplink signal reception at the Alice terminal.

The downlink beam is chromatically separated from the uplink beam in the coupling system UL/DL. The QKD signals are guided towards the QKD fiber coupling. The remaining downlink signals are separated by the coupling system DL and transmitted and propagated towards downlink measurement instruments. There, the 4QD is responsible to feed tracking controller with system pointing error that in a closed-loop drives the FSM. This allows for beam stabilization essential for fiber coupling. Part of the downlink signal is also used for optical power measurements using a free-space photodiode (PD) and part for the public channel RFE. Part of the power is then used for a point spread function camera observing the received focal spot (PSF), facilitating the alignment process as well for observing correct functionality of the system. The majority of the downlink beacon power, however, is used for the adaptive optics WFS. It is based on the Shack-Hartmann wavefront sensing principle, where the entrance pupil is sampled by an array of lenses (lenslet array) with a detector (a camera) placed in its. The resulting image is shown in Figure 9 showing an array of focal spots. The tilt of the wavefront in a section of the pupil is then represented by the movement of the respective focal spot in the WFS image out of its central position. The WFS image is taken at frame rates between several hundred Hz to several kHz to ensure control bandwidth higher than that of the atmospheric distortions. The matrix of the individual spot positional offsets is therefore processed in a dedicated real-time computational platform and fed at high rates to the DM that is shaped accordingly. This results in a flat wavefront arriving at focusing lens and so in high fiber coupling efficiency necessary to support very low QKD signal power levels.

This way, the main interfaces between the Bob terminal and the rest of the system are mainly optical – free-space to Alice and fiber to QKD, but also electrical – from the integrated RFE. The optical bench is supported by dedicated self-developed on-board electronics for steering of individual mechanical elements, driven from a dedicated computer and by the aforementioned real-time computer platform for AO signal processing. A more detailed description will follow in a dedicated publication.

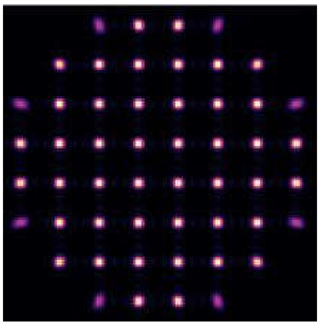

Figure 9: Example of the Shack-Hartmann Wavefront Sensor image at Bob terminal.

IV. Classical Communications

The public channel is a bidirectional FSO channel able to support a user rate of 1 Gbps. Center peace of the channel is Laser Ethernet Transceiver (LET) [11], an Ethernet-to-FSO modem developed at DLR. LET offers to the user a 1 Gbps over Ethernet MODEM that is transparent to the Ethernet channel for layer 2 and above. With regard to the FSO channel, LET encapsulates the data in a proprietary protocol that offers synchronization through the optical channel disturbances as well as data protection. The data protection is implemented as a Reed-Solomon product code with a 2-steps iterative decoding. Furthermore, it implements data interleaving able to cope with signal outages up to 10 ms each ~100 ms.

LET is implemented on a commercial Arria V FPGA which requires the use of two independent RAM banks to execute the interleaving and deinterleaving. It converts the Ethernet data into FSO data and vice versa in real time to enable live communication. It provides a latency below 250 ms and 4 ms with and without the interleavers, respectively. For the demonstration, operation without interleaver was chosen since fade length was short. Furthermore, it was possible that way to obtain an acceptable latency and thus a more agreeable channel for a videoconference.

The physical layer for the public channel was implemented with free-space receiver front ends in the Alice and Bob terminal. The transmit laser in the Alice Unit was an SFP module with direct modulation of the injection current. The transmit laser in the Bob Unit was a continuous wave laser with external intensity modulation.

During the campaign, a LET MODEM was located with each terminal and connected through an Ethernet interface to the Cypto Box (see Figure 3 and Figure 4). This channel proved itself stable and error-free towards the user for time periods of more than five minutes.

V. QKD System

The real-time prepare-and-measure QKD system used for the experiments was designed and built by Fraunhofer HHI within the QuNET project. The all-fiber design allows for the usage of different transmission channels and protocols. Alice transmitted time-phase encoded BB84 qubits with 625 MHz, using a mean photon number of $\mu = 0.5$ photons per qubit. States were prepared using a C-band continuous-wave laser, an intensity modulator, a phase modulator and a module to regulate the mean optical output power. The modulators were driven by an FPGA, which used a commercial quantum random number generator (IDQ IDQ20MC1-T) followed by a random number expansion as entropy source.

Bob used a beam splitter for the passive basis choice. Its first output was directly followed by a detector for the time basis measurement and its second output by a delay-line interferometer and two detectors for the phase basis measurement. During the experiments, we used free-running single-photon avalanche diodes (SPADs) which were connected to a time tagger with free-running clock. The clock synchronization was performed using an additional optical clock channel (sync signal in wavelength plan).

For the post-processing, a commercial software solution by the Austrian Institute of Technology was used, running two separate servers at Alice and Bob, which were fed with the transmitted qubits from Alice' FPGA and synchronized detection timestamps from the time tagger. The servers ran a key management service that provided the secret keys to a commercial AES encryptor (R&S SITLine) via the ETSI GS QKD 004 protocol.

VI. Results

The complete system was demonstrated in a videoconference between two German authorities, the Federal Ministry of Education and Research (BMBF) and the Federal Office for Information Security (BSI), both located in Bonn, Germany, in close distance and line of sight. The experiment showed the full chain of QKD implementation, key consumption and use case over a 300 m free-space link using only free-space optical channels in C-band and L-band. Furthermore, core technologies as they would be used in a satellite QKD system and ground station are demonstrated. This includes the optical bench and FSM of the Alice terminal and the AO system of the Bob terminal. Impact of noise due to atmospheric background light and channel cross-talk could be observed. Channel cross-talk can have an impact on QKD system performance but can be controlled. Therefore, satellite QKD is possible together with classical channels in C-band also when all signals share the same spatial mode. QKD was possible also during daylight conditions due to the strong spatial filtering with the single-mode fiber. The end-to-end coupling efficiency between interfaces Alice module and Bob module was between 12 and 14 dB (including also MUX and DEMUX devices).

Focus of the QKD system test was the contribution of different noise signals to the QBER. The individual QBER contributions were measured during several daytime and night time conditions. The measurements taken at dusk at 9:30 pm on July 27 2021 are shown in Table 1.

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TABLE 1: INDIVIDUAL NOISE SOURCES AND THEIR CONTRIBUTIONS TO THE QBER.

Source	QBER contribution [%]
Sync	$0.00^{+0.04}_{-0.00}$
DATA/Beacon Downlink	$0.14^{+0.01}_{-0.01}$
Beacon Uplink	$0.00^{+0.01}_{-0.00}$
AUX Downlink	$0.01^{+0.00}_{-0.00}$
DATA Uplink	$0.01^{+0.01}_{-0.01}$
Stray light	$0.01^{+0.00}_{-0.00}$
Dark counts	$0.10^{+0.00}_{-0.00}$

A. *Finding for satellite link performance*

Satellite-ground link performance can be estimated with the performance findings of the ground experiment. The potential performance of a satellite-ground link was estimated with the measured parameters and further assumed system improvements. The system then would yield a maximal tolerable channel attenuation of approx. 50 dB and the analytically calculated key rate over channel loss is shown in Figure 10. This calculation assumes ideal error correction and negligible finite size effects. The assumed system improvements are the additional usage of a narrowband bandpass filter in the receiver (10 GHz bandwidth, 25 dB suppression, 4.5 dB insertion loss), a classical receiver sensitivity of -31 dBm, and state-of-the art superconducting nanowire single-photon detectors with 1 Hz dark-count rate and 15% efficiency [14].

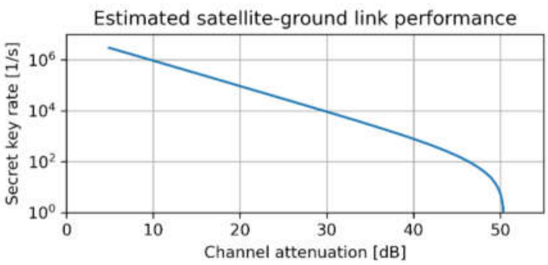

Figure 10: Estimated secret key rate over attenuation [dB] of a perspective satellite-ground system.

VII. CONCLUSIONS AND OUTLOOK

This paper describes the system concept for an all-optical satellite-based quantum key distribution system with wavelengths only in C- and L-band. The functionality of the system was demonstrated in the context of a live video conference between two authorities with 300 m free-space distance. Secure keys could be extracted during daytime and night time operation. Preliminary measurement results of the QBER in this ground campaign suggest a maximum tolerable channel attenuation of approx. 50 dB (with same assumed improvements) that would be in a satellite-ground link. Further investigations need to be done on how the different noise sources and channel cross-talk exactly deteriorate performance of the QKD system and how the noise sources can be coped with in terms of filtering, suppression or avoidance. Also, losses due to non-ideal error correction and finite size effects must be investigated. Furthermore, the relative longitudinal velocity of the satellite with respect to the ground station requires further adjustments of the quantum channel wavelength in order to compensate for Doppler shift effects on phase basis measurements. These findings shall input to the development of a full system concept of a satellite QKD system.

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