Satellite-to-ground QKD Feasibility Analysis for High Altitude Rural Areas: A Case Study in Greece

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***Abstract*—This paper is focused on the QKD deployment options for mountain communities based on LEO satellite-to-ground downlinks. The satellite QKD usecase for Vovousa village in Zagori is considered in this paper, providing simulation results for infrastructure deployment options that can support the implementation of LEO satellite DS-BB84 QKD protocol. SKR analysis is provided using an already available key rate calculator, allowing for up to 50kbps key rates with 1.2m receiver apertures in OGS. The use of small sized-OGS as the receiver located in village is also explored, showing ~3kbps SKR.**

Keywords—satellite-to-ground QKD, LEO, DS-BB84 QKD, Quantum Communication Infrastructure (QCI), Optical Ground Station (OGS)

I. Introduction

Private and secure communication is of fundamental importance in modern societies. Traditional public-key cryptography relies on the computational intractability of certain mathematical functions. In contrast, Quantum Key Distribution (QKD)—which was proposed in the mid-1980s [1]— counters the threat posed by quantum computers on the widely used asymmetric encryption and will lead to long-term secure communication. QKD enables two distant users who do not initially share any information to produce a common, random sequence of secret bits, called a secret key. QKD consists of the establishment of secret keys in a way that is "information theoretically secure" [2]. This means that the security of QKD protocols can be proven mathematically, based on direct information-theoretic arguments [3], eliminating the need for computational assumptions.

The Quantum Key Distribution (QKD) landscape has significantly evolved in the last two decades, culminating in technologically mature systems, that are offered commercially by an ever-increasing eco system [4]. The transition from single point-to-point links to large QKD networks has mirrored this trend, starting form the first proof-of-principle QKD networks [5] to impressive technology demonstrations that span over large countries and even offer intercontinental QKD links via satellite [6]. Although remarkable progress in QKD has been performed [4], one of the most important problems is photon loss in the fiber channel, so that the distance of peer-to-peer fiber-based QKD transmission with reasonable key rates is about a thousand km [7]. This seems to be a limitation to applying the QKD technology on a global scale. The driving force for linking QKD testbeds across Europe [8] and realizing intercontinental quantum-secured communications is the use of satellite-to-ground QKD [9].

In the field of wireless QKD several milestones have been reported in the literature. Long-distance Free Space Optical (FSO)-QKD over Qinghai Lake has been demonstrated in 2017, showing successful QKD over a 53Km link in daylight conditions [10]. High-dimensional QKD experiment over a noisy 10.2 km metropolitan free-space channel to successfully show an advantage in noise resistance has been demonstrated in Vienna in 2023 [11]. In the era of satellite QKD, Space-to-ground QKD experiment using a small payload (57.9 kg) between the Tiangong-2 space lab and the Nanshan ground station has been reported in 2018 [12], implementing polarization-encoded Decoy-State BB84 (DS-BB84). By 2020, the QKD with the Micius satellite and the compact ground station had been demonstrated in many Chinese cities, including Beijing, Jinan, Weihai, Lijiang, and Mohe with Kbps-scale sifted key rates [13].

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In parallel to the technology developments and research milestones in the field of FSO-QKD and Satellite-QKD, the preparation phase of National QCIs is currently running feasibility analysis for the space segments [14, 15] and preliminary efforts for the development of optical ground stations. While the fiber distribution network has been selected to be the main deployment option for delivering symmetric quantum keys to the end nodes/users, the unavailability of exploitable deployed fibers dedicated for QKD requires to explore alternative deployment options for selected usecases. The digital divide, being an infrastructure divide, puts more pressure on mountain villages where telecom infrastructure companies have no interest in investing to bring the necessary infrastructure [16]. To cope with the limited infrastructures, mountain communities have promoted the use of wireless connectivity resources to ensure access to broadband internet connectivity [17]. Beyond classical communications, entering the era of future quantum internet these mountain communities can exploit the optical wireless links at single-photon regime accessing the quantum information resources. Leveraging the development of mega-constellation satellites, where about 100,000 satellites will be launched into Low Earth Orbit (LEO) in the next decade [18], the plan for quantum onboard payloads in these satellites [19] will give the opportunity to mountain communities to easily access these quantum resources.

Inspired by this vision, in this paper we present a feasibility analysis based on satellite links for establishing QKD links to a mountain village called Vovousa which is in East Zagori, Greece. Leveraging the LEO-to-ground QKD downlink for accessing the onboard quantum resources, we provide a design analysis and a detailed performance evaluation study under realistic assumptions for QKD system architecture. Different deployment scenarios including small-sized Optical Ground Stations (OGSs) and large diameter apertures, different single photon counting technologies at 1550nm have been included in the presented analysis for the proposed infrastructure.

The remainder of the paper is structured as follows: Section 2 introduces the proposed infrastructure for providing access to quantum resources in mountain communities. Section 3 focuses on the system assumptions used in this work as input to satellite-to-ground simulation platform. In section 4 the simulation results are presented, and different deployment options are discussed. Section 5 concludes this work.

II. Proposed Architecture and Deployment

Figure 1 illustrates the proposed OGS infrastructure used for delivering quantum keys in Vovousa village. We chose Avgo peak (N39°55′32.3″, E21°5′45.7″) at an attitude of 2177m for placing the OGS implementing LEO-to-satellite QKD downlink. The measurement of background noise radiance levels using the Sky Quality Meter (SQM) device for neighboring regions [20] implies that the levels of background noise from light pollution are acceptable for QKD applications in this mountain region. The OGS can be located on Avgo peak allowing for Line-of-Sight (LOS) connection with the center of Vovousa village. The Avgo mountain's peak can then communicate with the small village's (Vovousa) via terrestrial FSO-QKD system for delivering symmetric quantum keys to the community. The terrestrial FSO-QKD link interconnecting the Avgo mountain's peak, and the village will be part of our next study extending this work.

Fig. 1. Vovousa Village and the mountain peak of Avgo

As a redundancy deployment option for the successful implementation of a satellite link with the Avgo peak, a portable ground station can be installed in the center of the Vovousa village to increase the availability of the QKD link for the cases where the visibility conditions for the mountain's peak are poor. Following the demonstration of feasibility of satellite-to-ground QKD with compact ground stations in many Chinese cities [13], feasibility studies of using small-sized QKD optical terminals have been conducted through the literature showing the strong potential of the small-size OGS to be used as infrastructure gateways for establishing LEO-to-ground QKD downlinks [21]. In our analysis we selected the installation of a mini-OGS close to the stone bridge of Vovousa Zagori at an attitude of 1050m (N39°56′13.3″, E21°2′58.2″).

III. System Architecture and Simulator Assumptions

We selected for our analysis the prepare-and-measure (one-way) scheme and the efficient BB84 protocol with decoy and vacuum states (vacuum, decoy, and signal). Decoy-state protocol, a one-way quantum key distribution protocol, works the same way as BB84, however it adds a precedent step which adds another degree of freedom. This adds another choice taken by Alice when sending every signal pulse to Bob, as well as another level of complexity for the eavesdropper to analyze. Decoy-State BB84 (DS-BB84) QKD is the best understood and most widely studied scheme and protocol, and it also has the advantage that complete general security proofs are available, which have also been widely scrutinized for correctness [22]. In our analysis, we selected the LEO orbit which is an orbit that is relatively close to Earth's surface. Recently significant efforts have been devoted to implementing efficient tracking systems of LEO satellites from ground stations [23]. To overcome the limited coverage time, LEO satellites often work as part of a large combination or constellation, of multiple satellites to give constant coverage [24].

There are three main subsystems that constitute the free-space QKD system discussed in this paper: the Quantum Transmitter (QTx), the Quantum Receiver (QRx), and the OGSs. The space-suitable QTx is hosted in the satellite payload, and it comprises a polarization encoder, operating at 1550 nm emitting around -76.5 dBm average power corresponding to μ=0.7 photons/pulse at 250MHz clock rate. The QTx encodes single photons according to the DS-BB84 QKD protocol and a Quantum Random Number Generator (QRNG) that provides random bits to the polarization encoder. The OGSs incorporate the optical telescope assisted

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by Adaptive Optics (AO) systems which allow for efficient free-space-to-fiber coupling of quantum, classical and beacon signals. The QRx contains a fiber-based polarization analysis module for the quantum signals connected to four SNSPDs. Figure 2 shows a schematic of the proposed system architecture considered in this work.

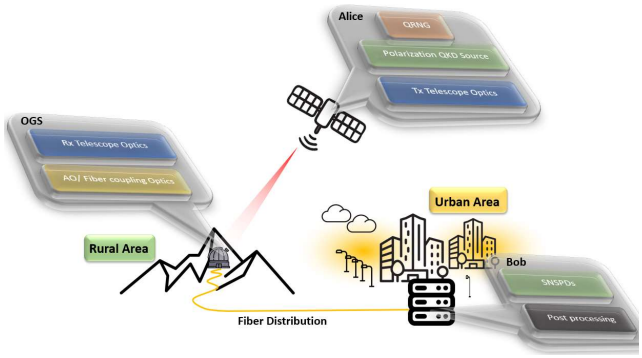

Fig. 2 System architecture of the proposed BB84-QKD satellite downlink including QTx, OGS and QRx blocks.

In support of the feasibility analysis presented in this work, the satellite-to-ground simulator which was recently presented [25] has been used. In the key rate calculator, the atmospheric link modelling was used, including the geometrical loss, pointing loss, atmospheric transmission losses, additional losses induced by turbulence, night-time sky background radiance, and fiber coupling efficiency parameters for the LEO-to-ground transmission scenarios. Additionally, for the DS-BB84 QKD, the finite key size effect has been considered for the protocol modelling.

A single satellite pass was set as the baseline, assuming that the LEO satellite reaches a high enough elevation angle of almost 90 degrees, while the key rates were compared for different OGS infrastructure parameters and detection systems. For the first scenario of OGS located in the Avgo mountain peak, three different receiver telescopes have been considered with different receiver aperture diameters. To provide field deployment options, we have considered three types of optical telescopes that are commercially available, and they have been deployed in real OGS infrastructures. Aside from the type of optical telescopes, two different types of 1550nm single photon detectors were also considered in our analysis for detecting 1550nm photons in the OGS: Superconducting Nanowire Single Photon Detectors (SNSPDs) and Single-Photon Avalanche Diodes (SPADs).

For the second scenario of using small-sized optical terminals for establishing LEO-to-ground QKD link directly in Vovousa village, we used a 280mm diameter receiver telescope combined with SNSPDs for increased system detection efficiency. Table 1 summarizes the input parameters used in our analysis for both scenarios that were studied.

Table 1. System assumptions and parameters.

Symbol	Parameter	Value
λ	quantum channel wavelength	1550 nm
f	Emission rate	250 MHz
N_t	Transmitted block size	10^{10} bits
H_{sat}	Satellite orbit altitude	550 km
D_{Tx}	Tx telescope aperture diameter	0.3 m
D_{Rx}	Rx telescope aperture diameter	0.28/0.6/0.8/1.2 m
a	Obscuration ratio	~0.34/0.4/0.4/0.47
f/x	Focal ratio	~f/10/7/6.85/8
η_{sys}	Tip-tilt Optical transmittance	0.9
H_{OGS}	OGS Altitude	2177 m
ε	Min. elevation angle	20°
σ_p	Pointing error variance	1 μrad
η_{Bob}	Detector's setup loss	2 dB
C_n^2	Refractive index structure parameter	$1.7 \times 10^{-14}\ m^{-2/3}$
H_{rad}	Background solar radiance	$1.5 \times 10^{-5}\ W/m^2 sr\ \mu m$
p_0	Outage Probability	1%
Ω_{FOV}	Receiver's FOV	100 μrad
λ_{pass}	Filter's spectral passband	0.2 nm
η_{filter}	Filters efficiency	0.7
μ	Mean signal photon/pulse	0.7
ν	Mean decoy photon/pulse	0.1
ε_s	Smoothing parameter	9×10^{-11}
ε_{pe}	Parameter Estimation	7.7×10^{-11}
ε_{ec}	Error correction parameter	8×10^{-11}
η_{SNSPD}	SNSPDs detection efficiency	0.85
DCR_{SNSPD}	SNSPDs dark count rate	10 cps
τ_{dead_SNSPD}	Dead time SNSPD	30 ns
η_{SPAD}	SPADs detection efficiency	0.15
DCR_{SPAD}	SPADs dark count rate	300 cps
$\tau_{dead\ SPAD}$	Dead time SPAD	20 μs
t_{gate}	Effective gate time window	1 ns
e_0	Error probability for noise counts	50%

IV. Results and Discussion

Fig. 3 illustrates the calculated Secure Key Rate (SKR) during a single satellite pass at 1550 nm over Avgo OGS assuming the use of SNSPDs in the quantum receiver terminals. For this ideal case, the satellite was visible with an elevation higher than 20◦ elevation for approximately 5 min and 30 s. The analysis assumes the implementation of the DS-BB84 protocol and tip tilt correction for the telescope to Single Mode Fiber (SMF) coupling. The end-to-end loss including the fiber coupling and the system detection

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efficiency has been calculated over the satellite pass. From Fig. 2, it is evident that larger apertures have the capability to generate key volumes that are almost doubled than those achieved by smaller-sized receivers since the end-to-end losses are almost the same, within 5 dB range for all three apertures. Indicatively, using a receiver aperture of 1.2m, SKR up to 50kbps can be achieved.

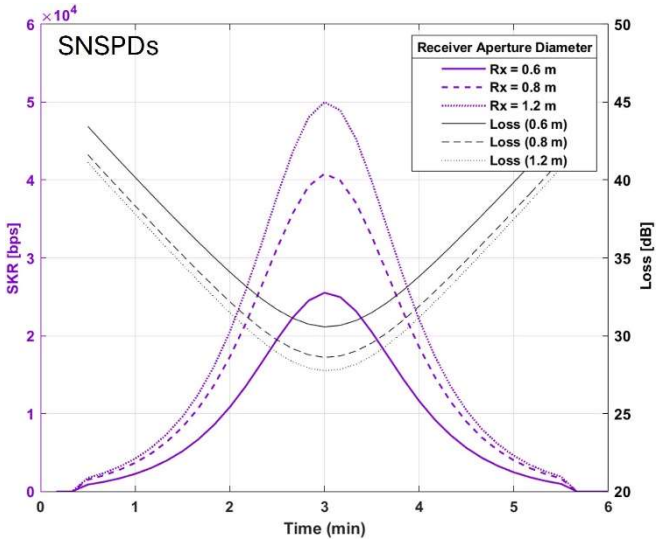

Fig. 3 Calculated SKR and end-to-end loss for a single satellite pass considering different receiving aperture diameters using SNSPDs.

To further investigate the performance of the different receiver aperture diameters, we calculated the SKRs values for a single satellite pass assuming the use of SPADs in the receiving terminals. The results are graphically depicted in Fig. 4 considering, once more, tip tilt correction. The trend remains that larger apertures can achieve maximum values approximately double compared to those achieved with smaller telescope apertures. Even with smaller aperture sizes (0.6m diameter receivers) LEO QKD downlinks can be feasible, however the communication time window remains reduced to approximately two and a half minutes, since the increased coupling losses combined with the low SPAD efficiencies do not allow for positive SKRs for low elevation angles. Therefore, the overall volume of distilled key bits remains limited.

Finally, Fig. 5 illustrates the calculated SKR during a single satellite pass at 1550 nm over a small-sized OGS (0.28 m aperture) located in the village of Vovousa. The use of 0.28 m telescope aperture diameter has been selected for the OGS located in rural environment, since experimental studies employing the same or similar sized telescopes have been presented throughout the literature [13], [26]. Moreover, satellite tracking as well as receiver assemblies for fiber coupling have been demonstrated for these kinds of astronomical commercial-off-the-shelf telescopes [27].

Once again, for the analysis presented below the implementation of the DS-BB84 protocol and SNSPDs for signal detection has been assumed. From Fig. 4, it is evident that that small-sized receivers, located in such environments, can effectively operate, yielding SKRs of several thousand of bits per second even the end-to-end losses are almost at 40 dB. However, for the case of the 0.28m aperture diameter telescope, employing SPAD as detector units renders the

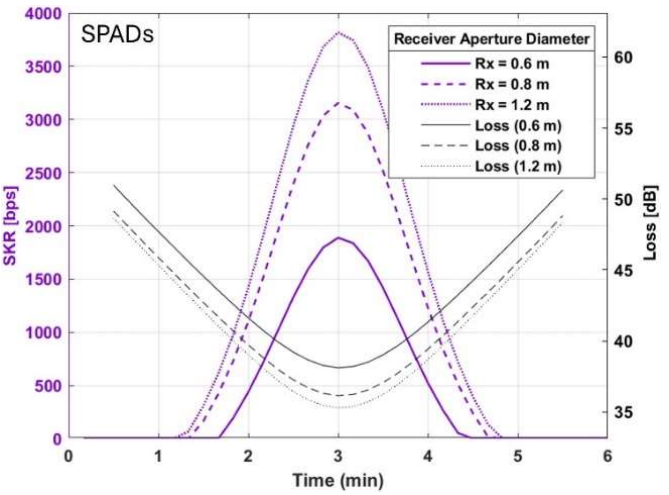

Fig. 4 Calculated SKR and end-to-end loss for a single satellite pass considering different receiving aperture diameters using SPADs

QKD downlinks unfeasible, due to the increased overall end-to-end loss.

V. Conclusions

The feasibility of LEO satellite-to-ground QKD links for mountain village was presented in this work, focusing on different grades of optical telescopes of OGS installed at an altitude of 2177m. The performance of QKD downlinks has been evaluated for 1550nm, assuming SPADs and SNSPDs for the detection of single photons. SKRs of up to 50 kbps scale were achieved for the case of DS-BB84 QKD protocol

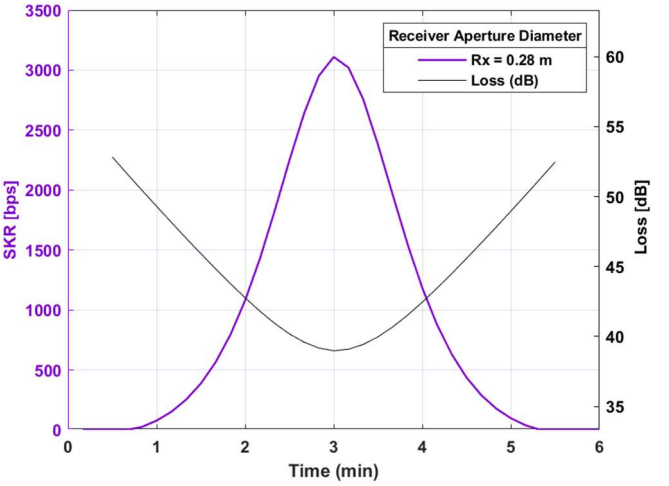

Fig. 5 Calculated SKR and end-to-end loss for a single satellite pass using SNSPDs and a 0.28 m aperture receiver.

using SNSPDs, while acceptable SKRs of approximately 4kbps were calculated for the case of using low complexity SPADs for detecting single photons. The use of a small sized-OGS equipped with a 0.28 m aperture receiver was also explored as a deployment option for establishing QKD link directly to the Vovousa Zagori village, allowing for SKR up to 3 kbps in the case of using SNSPDs. The presented results denote the strong potential of using satellite QKD technology as an infrastructure option allowing the mountain communities for accessing the QKD resources available in the sky via future quantum satellite constellations.

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