

Optimal Start-Stop Elevations for Satellite-to-Ground Quantum Key Distribution

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ABSTRACT

Satellite-to-ground quantum key distribution (S-QKD) has emerged as a practical solution to extend the reach of quantum secured communication networks to a global scale. Recent lower earth orbit (LEO) satellite-to-ground demonstrations show the capability of S-QKD to securely connect users around the world over distances which are well beyond the reach of current fiber-based QKD systems. Given the limited satellite visibility duration (typically a few minutes), technological improvements to the quantum source and receiver are also starting to be realised, in terms of clock-rate and insertion loss, to increase the amount of secure key generated within a single satellite overpass. However, due to the dynamic nature of the channel in S-QKD, more efforts are needed to enable efficient use of these resources onboard satellites and on the ground. This work studies the impact of the channel between a LEO satellite and an optical ground station (OGS) on the secure bit rate, where the link loss and satellite visibility duration varies due to the overpass geometry and the specification of source and receiver. A method to plan a QKD session between a LEO satellite and an OGS is proposed which allows efficient use of the QKD resources on each end of the link by estimating the optimal QKD start-stop points within an overpass. Using an efficient decoy-state BB84 protocol and typical LEO based satellite-to-ground link specification, we carry out simulations to study how the proposed method can guide the S-QKD network operators and users to wisely plan the QKD session within any relevant satellite overpass and only perform QKD at certain times within the overpass to maximise the secret key.

Keywords: Satellite, Quantum Key Distribution, Lower Earth Orbit, Optical Ground Station, Free-space Optics, Laser Communication, Telemetry, Tracking and Control.

1. INTRODUCTION

Quantum key distribution (QKD) relies on the fundamental properties of quantum particles to generate and distribute encryption keys between parties.¹ The mechanism is proven to be secure against attacks by quantum computers, which threaten traditional cryptography schemes. Despite recent breakthroughs in increasing link distance through twin-field QKD,^{2,3} the limited operation range of fiber-based QKD technology is a major obstacle in enabling global coverage. Satellite QKD (S-QKD) has emerged as a practical solution to the range problem. Recent demonstrations (field-trials)⁴⁻⁶ show the capability of S-QKD to securely connect users around the world over distances which are well beyond the reach of current fiber-based QKD systems.

A promising form of S-QKD is when it is performed between a satellite in the lower earth orbit (LEO) and an optical ground station (OGS). Although a LEO satellite can scan almost the entire earth in one day, it is visible from any one point on earth for a few minutes only (typically less than 10 minutes). Maximizing the secret key that is generated within this limited time-window (within a single satellite overpass) is essential for creating a global quantum secured network. This requires realization of high clock-rate QKD sources, high transmission efficiency and low jitter receivers;⁷ and effective mitigation of the atmospheric beam wandering and coarse misalignment.^{8,9} Whilst it is important to improve the capability onboard the satellite and at the OGS side, it is also important to use these resources efficiently.

The dynamic nature of the optical link between a LEO satellite and an OGS can result in more than 10 dB channel loss variation within the overpass, which is typically higher at lower elevation angle of the satellite due to higher link distance, i.e. at the beginning and end of the satellite overpass. Due to the presence of lower

signal-to-noise ratio, this start and end part of the optical link duration results in higher QBER and degrades the accuracy of QKD parameter estimation, reducing the overall secret key. Therefore, it is useful in some cases to either ignore the raw key material gathered from certain lower satellite elevations or only begin QKD after satellite has reached a certain optimal elevation. Choosing optimal start and stop times for a QKD session within a satellite overpass frees up significant proportion of the satellite visibility duration, which may be utilized for other tasks, such as channel estimation and alignment, and/or simply not doing anything to save power.

This work proposes a method to enable resource-efficient planning of time and power utilisation for a QKD session between a satellite-based transmitter and a receiver in OGS. The proposed function allows to determine an optimal QKD session “start” and “stop” time in S-QKD, where the transmitter (satellite segment) and receiver (ground segment), although visible to each other, do not start QKD until the satellite reaches a specific elevation (with reference to relevant OGS). Starting QKD at this specific satellite elevation optimizes the session time, and therefore the secret key generated within an overpass. The determination of the “start” and “stop” times of the QKD session within an overpass will rely on a number of specifications related to the satellite segment, ground segment and the free-space channel. These specifications can fluctuate over time and must be timely updated at the space and ground segments for accurate determination of the “start” and “stop” times. Furthermore, the process of “start-stop” time estimation should not be computationally intensive as the link specifications may be updated at the beginning or just before the beginning of a relevant satellite overpass.

To the best of our knowledge, efforts to address this problem are scarce. Recent field trials^{4,5,10} have conducted experiments starting QKD sessions at satellite elevations between 5° - 15° , decided based on the visibility available at the OGS and without any optimization. This leads to inefficient use of resources onboard a satellite and at an OGS facility and the secret key per overpass could be significantly lower than that achievable through a delayed start. A method to obtain optimal QKD transmission window within a satellite overpass is presented in,¹¹ which requires estimation of optimal protocol parameters a number of times (usually $\gg 1$ and scales with the number of satellite elevations investigated to find the optimal elevation) within the optimisation function for the QKD transmission window itself. Although resulting in joint optimisation of the protocol parameters and QKD transmission window, this method leads to longer times to compute the optimal start-stop elevations, and may be unusable closer to or at the beginning of the relevant overpass due to time limitation.

The method proposed in this work relies on using pre-obtained optimal protocol parameters for optimising the QKD session start-stop times and therefore, avoids estimating optimal protocol parameters multiple times during the determination of the optimal “start-stop” time for QKD session. This makes the process computationally less intensive, which could allow this process to take place closer to the start of the QKD session, considering latest specification on Alice, channel and Bob. The proposed method avoids QKD in lower signal-to-noise region of the satellite overpass to enhance the parameter estimation and thereby optimizes the secret key per overpass. A “wait” segment before the QKD session and an “avoid QKD” segment after the QKD processes are introduced where the QKD subsystem onboard satellite and on OGS can minimise power consumption by switching to standby mode. Considering a wide range of system specification, simulations are carried out to see how the proposed method can allow users to determine the optimal QKD session window within an overpass to maximise the amount of secret key per overpass.

2. THE PROTOCOL AND PARAMETER OPTIMISER

2.1 QKD protocol and parameters

Considering polarization encoding for free-space QKD, this study employs a three-intensity efficient decoy-state BB84 protocol and finite-size key analysis with composable security against collective eavesdropping attacks.¹² The protocol is referred to as T12 protocol for the remainder of this paper. Alice (transmitter) prepares weak-coherent states with fluxes; signal (u), decoy (v) and vacuum (w), which are selected randomly with probabilities P_u , P_v and $P_w = 1 - P_u - P_v$ to encode a random bit $\{0, 1\}$ over bases Z ($|H\rangle$ or $|V\rangle$ polarization state) and X ($|D\rangle$, $|A\rangle$ polarization state). The bases are also selected randomly with probabilities $P_X = 1 - P_Z$ for encoding of each quantum bit. One basis (Z) is used for key distillation, while the other (X) is used as a checking basis.

The key generation process starts with Alice selecting the polarization basis to send the quantum bit to Bob with majority (minority) probability P_Z ($P_X = 1 - P_Z$). She then encodes bit 0 or 1 with 50% probability

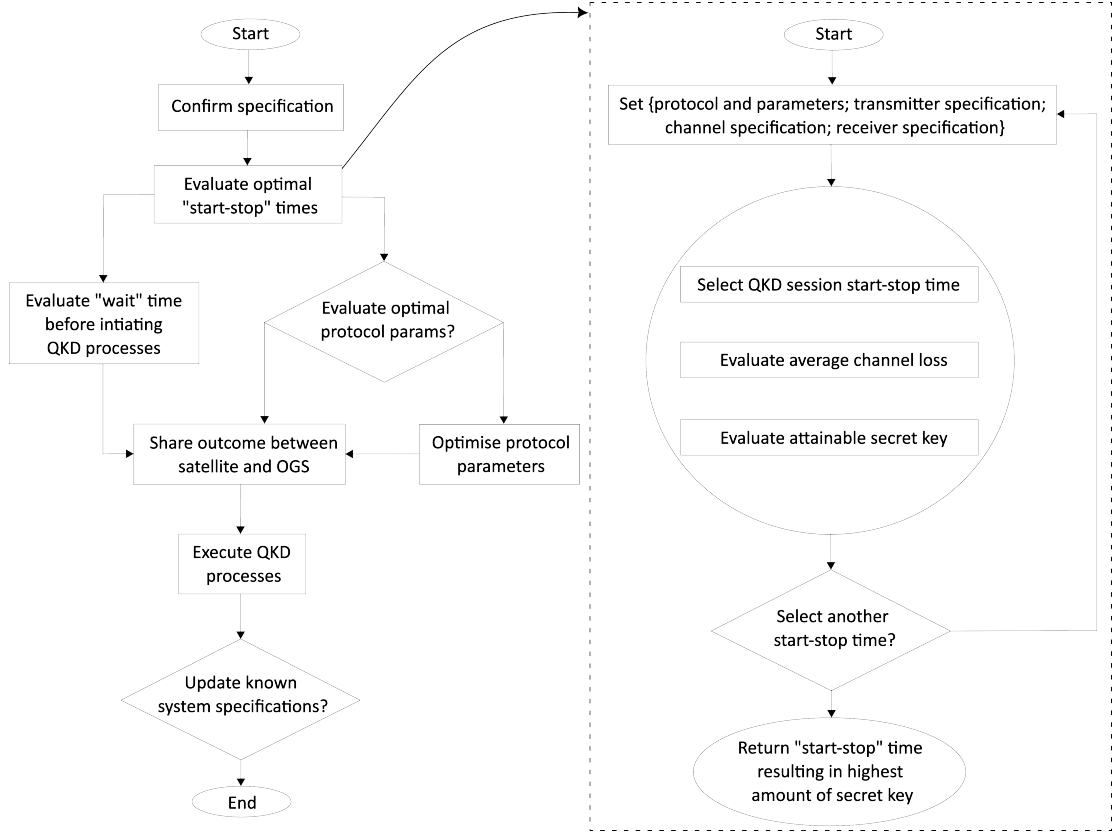


Figure 1. A flow-chart of the proposed function.

and prepares a phase-randomized weak-coherent state with intensity u , v , or w , and probability P_u , P_v or P_w , respectively. Bob chooses basis X or Z with same probabilities as Alice to measure the quantum state using two threshold detectors in each basis. Depending on which detector clicks, Bob decodes the bit value 0 or 1. Following detection of N quantum states, post-processing of detection event material begins, where sifting, error-correction and privacy amplification takes place before secret key is distilled. The post-processing takes place over an authenticated public channel using classical communication techniques. Sifting is a process where Bob shares his bases and associated timestamps of detected signal and decoy counts with Alice, who then shares the bases and classes of these counts along with the bit value in the X basis, decoy and vacuum classes of Z basis. Through this process Alice and Bob form sifted key material from the matched Z basis signal states. This is followed by an error correction stage using the well-known Cascade algorithm, then finally privacy amplification including randomness extraction to hash the error-corrected key to a reduced size that is provably secure.

2.2 Protocol parameter optimisation

A parameter optimisation routine is performed with the objective of maximizing the output secure key length, for simulations performed using the T12 protocol (see Ref¹² for details of the secure key length calculation). The optimiser inputs include the bounds for the protocol parameters that need optimising (including photon fluxes u , v and w and their associated encoding probabilities as well as the probability of encoding in each basis) and the fixed system specifications (including average channel loss, S-QKD session duration (overpass duration), clock-rate, dark count rate, intrinsic quantum bit-error rate (QBER), photon detection efficiency (PDE), detector dead-time, total excess loss at the receiver). The vacuum flux (w) is set to 1×10^{-4} and given $P_Z = 1 - P_X$ and $P_w = 1 - P_u - P_v$, some degrees of freedom are removed to simplify the optimization process. This leaves five parameters u , v , P_u , P_v and P_X , to be optimized within practical system constraints, which is achieved using the Constrained Optimization BY Linear Approximation (COBYLA) method.

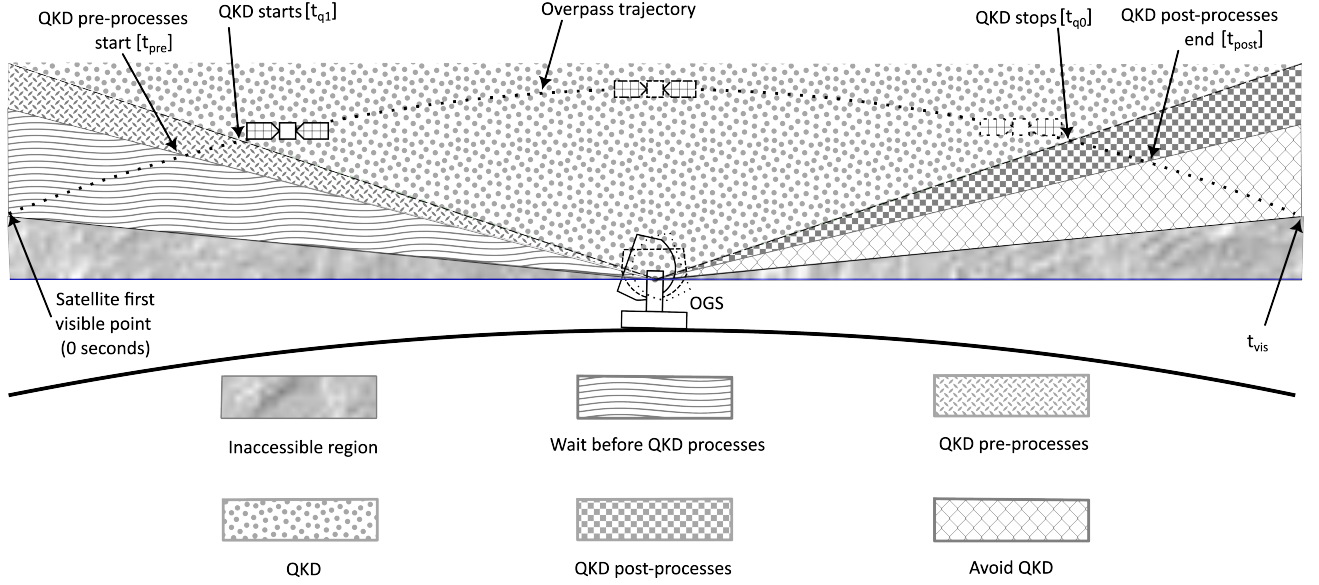


Figure 2. A view of sky above an OGS, sectorized to show the regions for QKD and other processes.

3. THE PROPOSED QKD SPECIFIC TT&C FUNCTION

In a LEO satellite-to-ground QKD link, the orbiting satellite and the OGS are visible to each other for a limited amount of time. Generally, processing the sifted and error corrected QKD data in large blocks leads to larger amount of secret key due to the finite-size effects. Therefore, conducting QKD over entire satellite visibility duration may seem an apparent choice. However, the channel loss variation throughout the visibility period can result in lower amount of secret key if QKD is not avoided in the regions of the satellite overpass presenting higher channel loss. Telemetry, tracking and command (TT&C) subsystem i) allows satellites to share important health and status information with ground stations, ii) allows ground station(s) to accurately determine the location and trajectory of the satellite and iii) enable satellite control and maintenance from the ground. We propose a satellite-to-ground QKD specific TT&C function to determine optimal “start” and “stop” times within an overpass of a satellite above an OGS, which minimises the secret key degradation. Based on the estimated “start-stop” times, the overall visibility and estimated QKD pre- and post-processing times, we also estimate a “wait” duration at the beginning of the overpass and an “avoid QKD” window towards the end of the overpass so as to use the available resources efficiently for power conservation.

A flowchart of the proposed function is shown in Fig. 1. The first process is the confirmation of system and optical link specifications for the relevant/up-coming satellite overpass for secret key generation. The QKD specific characteristics of the transmitter onboard satellite can change over-time. The characteristics of the channel between the satellite and the OGS evolve continuously due to changes in overpass geometry. In addition, without active correction the orbital altitude gradually decreases over time due to atmospheric drag associated with solar activity. Therefore, this process of finding optimal “start-stop” elevations for the QKD session should take place as near as possible in time to the relevant satellite overpass to ensure effectiveness.

The second process determines the QKD session start and stop times (associated to specific satellite rise and descend elevation angles within the overpass) which is likely to result in the highest secret key based on a fixed set of pre-obtained optimal parameters for efficient decoy-state BB84 protocol¹² (or one could also assume use of different protocol such as the one proposed in¹³). This process starts by (1) setting the protocol parameters and the transmitter, channel and receiver specifications. The fixed set of protocol parameters used in this process can be the pre-obtained optimal protocol parameters for a variety of satellite-to-ground QKD links comprising different telescope sizes on either ends of the link, different overpass geometries and orbit altitudes. In addition to (1), the QKD “start-stop” time determination process uses the following specifications as a minimum: (2) the source clock-rate, (3) intrinsic quantum bit-error rate (iQBER), (4) average channel loss between the “start” and “stop” times, (5) receiver insertion loss, (6) single-photon detection efficiency, (7) detector dark count rate,

(8) average expected background count rate between “start” and “stop” times, (9) detector dead-time, (10) after-pulse probability and (11) considered session duration, i.e. the time between “start” and “stop”. Having defined these specifications, the next step is evaluation of attainable secret key amount for which we use the security analysis presented in.¹² The “session duration” (11) is varied and the secret key is evaluated within a loop for a range of session durations ($<$ visibility duration). The process returns the session duration, i.e. a “start” and “stop” time for the QKD session resulting in the largest secret key.

The third process calculates the “wait” time for the satellite segment before QKD processes can be initiated. This process will consider the overall visibility duration, the recommended “start-stop” times by the second process and the time taken by other necessary housekeeping tasks before the establishment of QKD link between the satellite and the OGS. These pre-processes could include tasks, such as spatial alignment, temporal alignment and polarization reference frame alignment. During the “wait”, these pre-processes and the main QKD processes, such as key preparation and measurement of quantum bits, sifting, error-correction and privacy amplification, are not operational. The fourth process, which can run concurrently along the third process, can optimize the protocol parameters for the session duration (i.e. “start-stop” times) recommended in the second step. In addition to the system specifications used in second process, this process will additionally require inputs such as, (1) bound for each protocol parameter, (2) constraints due to reconfigurability at transmitter and receiver, (3) optimization method, and (4) number of iterations to be used. This way, the protocol parameter optimisation will only need to run once, avoiding multiple runs of parameter optimisation in the second process. Following these processes, the satellite and OGS can be updated on 1) the “wait” time, 2) QKD (and pre-processes) start time, 3) QKD (and post-processes) stop times and the relevant QKD session takes place. Following this, the fifth process, if required, is to update system specifications so that the optimal protocol parameter set can be updated for future.

Table 1. S-QKD Link Parameters

Parameter Description	Value
Satellite orbit altitude and inclination	500 km and 90°
Satellite elevation at start of link	$10^\circ - 50^\circ$
Satellite telescope aperture	0.09 m
OGS telescope aperture	0.2/0.3/0.4 m
Source wavelength	850 nm
Source clock-rate	0.1/1.0 GHz
Minimum atmospheric absorption	50%
OGS central obstruction	30% by diameter
QKD receiver optics loss	1.25 dB
Photon detection efficiency	58%
Total dark counts	200 cps
Intrinsic QBER	0.25/2.5%
Security parameter, ϵ	10^{-10}
Error correction efficiency, f_{EC}	1.15

A TT&C system, incorporating the proposed function, will result in S-QKD key generation session planning as depicted in Fig. 2, as an example. The satellite is visible for t_{vis} seconds, limited by the capability of the OGS mount, surroundings of the OGS site and the satellite overpass trajectory. An indicator of the latter is orbit altitude and maximum satellite elevation above horizon within the overpass with reference to the OGS coordinates. For overpass time, t_o , when $0 < t_o < t_{wait}$, the QKD processes should not be running to avoid negative impact on the secret key length and for optimal resource usage. When the overpass time (t_o) reaches t_{pre} , the QKD pre-processes start, which include fine axial alignment between the satellite and OGS telescopes, the clock synchronization and polarization alignment. Next, the QKD process of qubit preparation and measurement, and sifting takes place for $t_{q0} - t_{q1}$ seconds, where, t_{q1} and t_{q0} are the start and stop times for QKD, respectively. Then the post-processes such as error-correction and privacy amplification takes place for overpass time $t_{q0} < t_o \leq t_{post}$. Any update to the system specification for planning of any future QKD sessions can

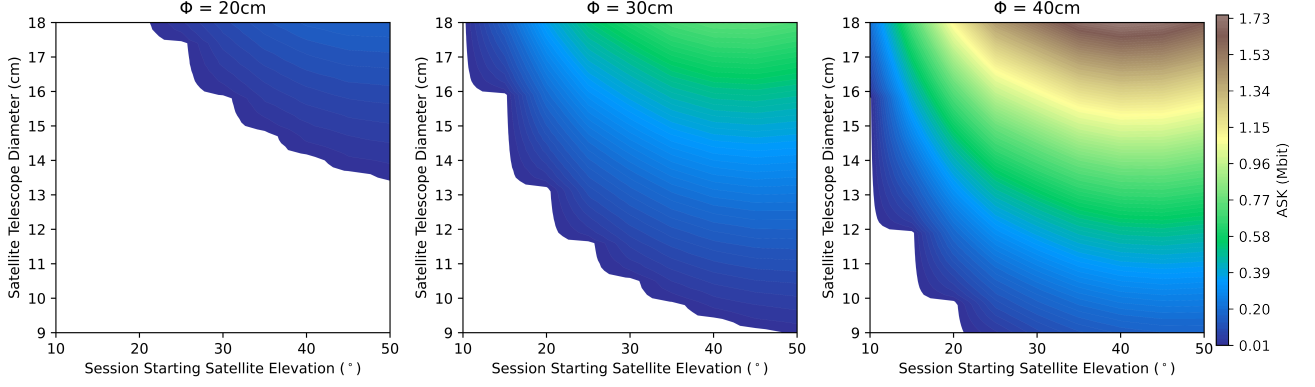


Figure 3. Impact of QKD session starting elevation on the average secret key per overpass for a 100 MHz clock-rate satellite-to-ground link deploying different diameter telescopes onboard a satellite and within an OGS.

take place for $t_o > t_{post}$. The satellite and OGS do not have line-of-sight for overpass time $t_o > t_{vis}$. In this example, the QKD process and post-processing are shown to take place just once in an overpass. However, this doesn't need to be the case. It is possible that these two processes are performed multiple times within a single overpass and within the optimal session duration between t_{post} and t_{q1} . It is also possible that these two post processes take place after several overpasses so that the privacy amplification input block size be increased to minimise the finite-key effects.

4. SIMULATION RESULTS

4.1 Channel and system specification

The channel transmission efficiency during a satellite overpass depends on several parameters such as satellite elevation angle, beam-divergence, OGS telescope size and source wavelength. In estimating the instantaneous and average channel loss for a given overpass and satellite and OGS settings, we adapt the channel model described in.⁶ For this study, we consider a 9 – 18 cm diameter telescope onboard a satellite which is assumed to be in lower earth orbit (LEO) of 500 km altitude. In order to find optimal start-stop times, we explore satellite elevation angles between 10° and 50° where the QKD session could start. The user may have access to an OGS hosting a 0.2 to 0.4 m primary mirror diameter (Φ) telescope. Such small OGSs are attractive because of their lower manufacturing and installation costs. These small OGSs may even be installed on the roof-top of an existing building or on a mobile platform.¹⁴ As a popular choice in recent field-trials^{4,5} and laboratory experiment,^{6,15} the S-QKD source wavelength is assumed to be 850 nm. We explore source clock-rates of 0.1 and 1 GHz and intrinsic quantum bit error-rate (QBER) of 0.25% and 2.5%, respectively. The key system parameters are summarized in Table 1.

4.2 Results and Discussion

Through these simulations we aim to understand how the QKD session start-stop time (i.e. the satellite elevation for starting and stopping the QKD session) varies due to i) the QKD clock-rates, ii) the size of telescope onboard the satellite and iii) the size of telescope within the OGS. The average secret key (ASK) per overpass (where an overpass could have a maximum satellite elevation between 30° to 90°) is evaluated for both the considered clock-rates and their respective intrinsic QBER and the three difference sizes of the OGS telescope. The size of the telescope onboard the satellite is varied to see how a bigger satellite could enable generation of secret keys in case when the clock-rate is low and also how such capability will increase the amount of secret key for high clock-rate QKD links.

Fig. 3 shows the amount of ASK for a 100 MHz clock-rate link. The coloured region shows the amount of secret key and the white region on the bottom left of each plot shows the cases where secret key cannot be generated for specific telescope sizes and at certain QKD session starting satellite elevations. The results show that delaying the QKD session start (or starting the QKD session at higher elevations) helps in generating

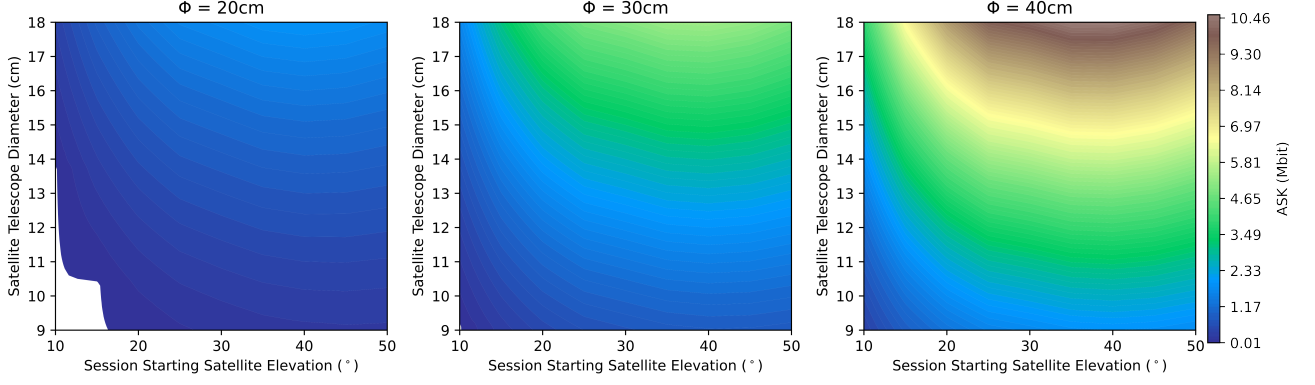


Figure 4. Impact of QKD session starting elevation on the average secret key per overpass for 1 GHz clock-rate satellite-to-ground link deploying different diameter telescopes onboard a satellite and within an OGS.

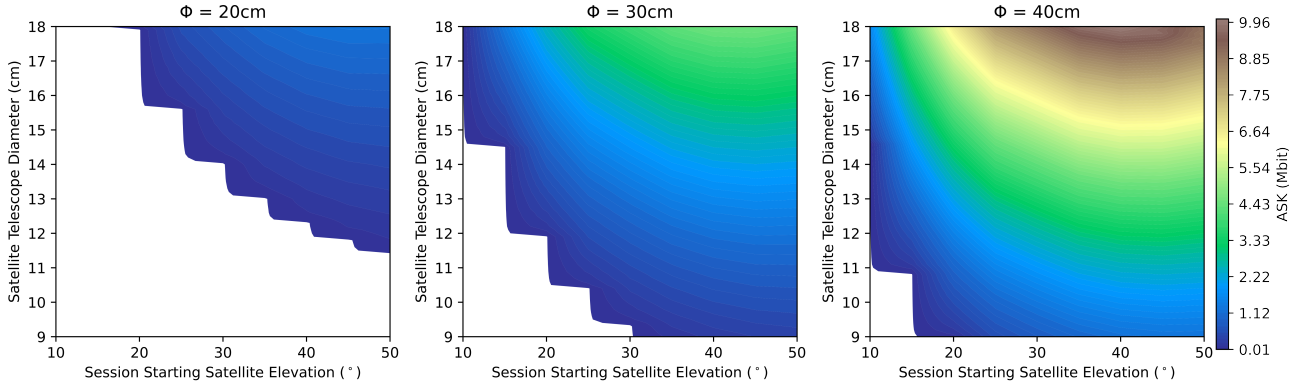


Figure 5. The sifted key from multiple overpasses can be processed as a single larger block. This plot shows the impact of QKD session starting elevation on the average secret key when processing sifted key from five identical overpasses for a 100 MHz clock-rate satellite-to-ground link deploying different diameter telescopes.

positive secret key for any size of the telescope onboard the satellite and within the OGS. We also observe that for a 40 cm diameter telescope within the OGS, the optimal satellite elevation to start the QKD session varies between 40° to 50° , depending on the size of the telescope onboard the satellite. For a 20 cm diameter telescope OGS, a telescope with higher than 13 cm diameter will be required onboard the satellite to produce positive secret key.

Fig. 4 shows simulated ASK for 1 GHz clock-rate link. The impact of increasing the clock-rate is three-fold: i) overall increase in ASK ii) the ability to produce positive secret key with smaller telescopes and iii) ability to start QKD session early within the overpass, which is indicated by the diminishing white region to the bottom-left of each plot. This is particularly useful for users accessing the QKD network through small OGS. Overall the results in Fig. 3 and Fig. 4 show that adequately delaying the start of the QKD session within an overpass, does not only increase the secret key amount but could be the only way to produce positive secret key in some cases, for example when working with lower clock-rates or smaller aperture telescopes.

We also explored the scenario where, sifted keys from multiple overpasses are stored and processed as a single large block for the 100 MHz clock-rate link. Fig. 5 shows the ASK per five overpasses for this lower clock-rate system. Such configuration will require storing sifted keys from multiple overpasses onboard the satellite as well as the OGS. The results show that much higher secret key can be produced as a result of increasing the privacy amplification input block size. However, such approach alone, does not enable the use of smaller telescopes onboard the satellite and at the OGS (20 cm diameter telescope in this case specifically).

5. CONCLUSIONS

A method to optimally conduct QKD from LEO satellite to an OGS is presented which, based on a wide range of system specification, estimates optimal satellite elevations within an overpass to start and stop the transmission and reception of quantum states. Simulation based investigation shows that the optimal satellite elevation to start-stop the QKD session can vary significantly, depending on the characteristics of the system, such as clock-rate and telescope size, and starting QKD before or after the satellite reaches a specific elevation can reduce the amount of secret key that can be generated within the overpass or even lead to sharing zero secret bit.

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