Analysis and Qiskit-based Simulation for QKD Satellite-to-Ground Systems with BB84 Protocol

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Outline

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- Satellite-to-Ground QKD Systems
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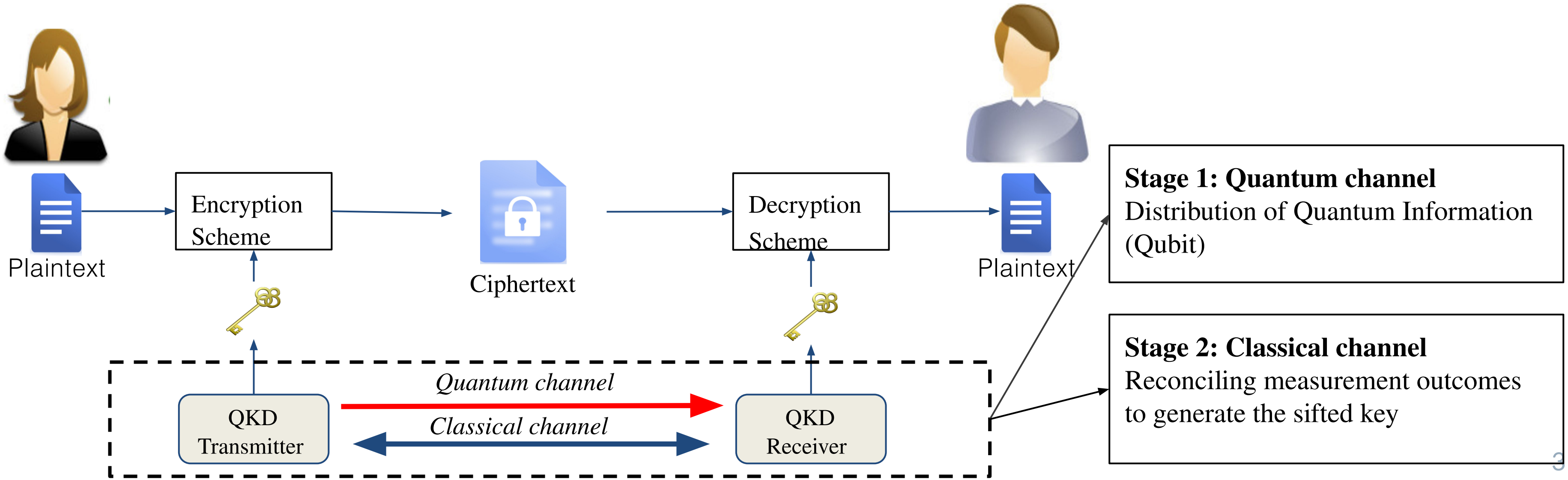
Quantum Key Distribution (QKD)

- QKD is a promising method to ***distribute secure keys*** secretly between legitimate users
  - It bases on the laws of quantum physics.
  - First QKD protocol proposed by C. Bennett and G. Brassard in 1984, i.e., ***BB84 Protocol***
  - Some of best-known Japanese companies have been working on various QKD projects, e.g., Toshiba, NEC, and NTT



Satellite-to-Ground QKD Systems : Motivation

QKD can be implemented through <u>*terrestrial networks*</u> or <u>*satellite (non-terrestrial) platforms*</u>.

Conventional QKD systems mainly rely on optical fibers

>> Inflexible for mobile users and limited in transmission distance …

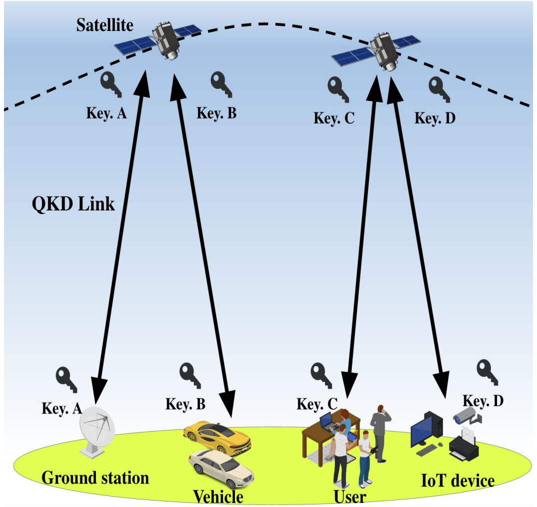
Challenge:

Limited support for global QKD services and scalable networks, particularly for mobile users

Solution:

Use satellite-based approaches for QKD systems, which offer flexible deployment and can cover wide geographic areas.

>> Enables support for applications such as mobile users and devices (e.g., self-driving cars) by providing secure communication by QKD.



Our Goals

1. Design a quantum channel for communication between a LEO (Low Earth Orbit) satellite and a ground station
   a. Make a transmittance model that accounts for various effects, such as beam misalignment and atmospheric turbulence.

2. Investigate the performance of channel model by applying a QKD protocol developed with Qiskit.
   a. *IBM Quantum Experience (IQX)* is used to implement *BB84* protocol using Qiskit.
   b. Simulations are conducted using *Starlink LEO satellite* date

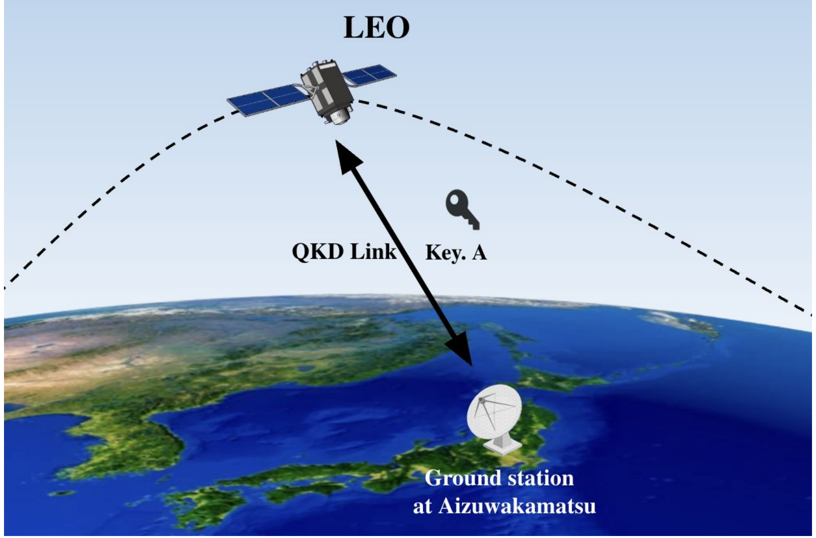
Our System Implementation

Our scenario:
P2P communication between LEO and ground station

1. LEO satellite transmits photons to Ground station(GS).
2. GS detect the photons, then create secret key.

QKD Protocol:

- Our system implements ***BB84*** QKD Protocol based on ***Qiskit***.
- Qiskit is a Python SDK developed by IBM that helps build QKD application, and is available on *IQX*



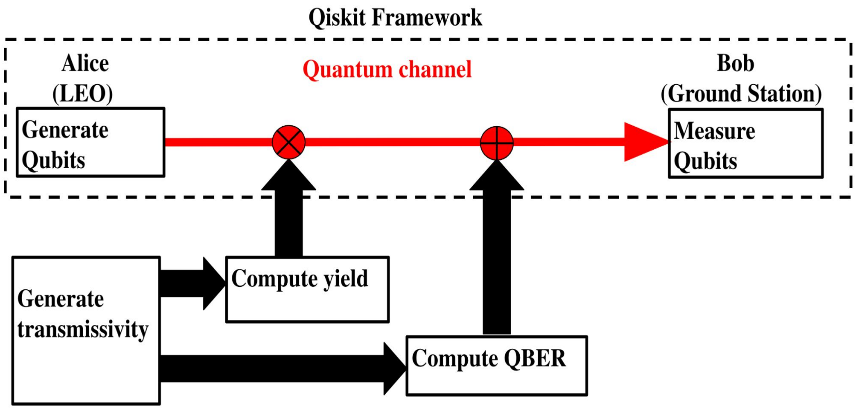
Qur Simulation Framework based on Qiskit

To investigate the performance of QKD system, a framework for simulation is built using Qiskit.

- ➢ Alice generate the Qubits and Bob measures them.

Integration of the channel model with the framework

1. Generate the transmittance of a quantum channel in a LEO satellite-to-ground link
2. Compute yield
   a. Measure probability of a detection given conditions of transmittance
3. Compute *Quantum Bit Error Rate(QBER)*
   a. Estimate the ratio of erroneous bits among detected signals at receiver based on the yield



- ➢ **These steps allow us to evaluate the performance and reliability of satellite-based quantum communication within the Qiskit framework.**

Quantum channel model

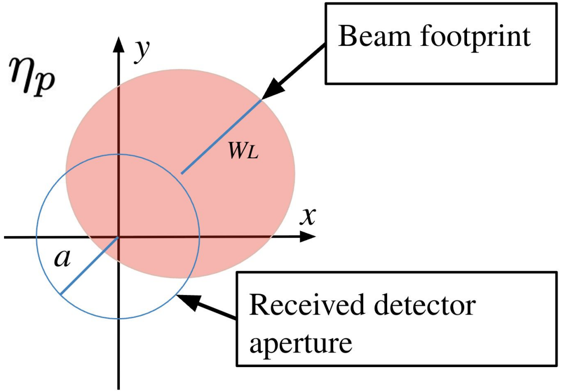
The transmittance of the quantum channel in the LEO satellite-to-ground link, taking into account the some impairments, is derived as follows.

$$\eta = \eta_\ell I_\mathrm{a} \eta_\mathrm{p}$$

η_ℓ: atmospheric attenuation due to absorption and scattering
I_a: random intensity fluctuations caused by atmospheric turbulence
η_p: fluctuating received power fraction at a aperture due to pointing errors and beam divergence

$$\eta_\ell = \tau_{\mathrm{zen}}^{\sec(\theta_{\mathrm{zen}})}$$

Visibility (km)	τ_{zen}(=deterministic transmittance efficiency at zenith)
23	0.81
15	0.75
5	0.55



Performance Analysis(1): QBER

QBER, representing the mismatch probability between sifted keys, is expressed with respect to the transmittance η.

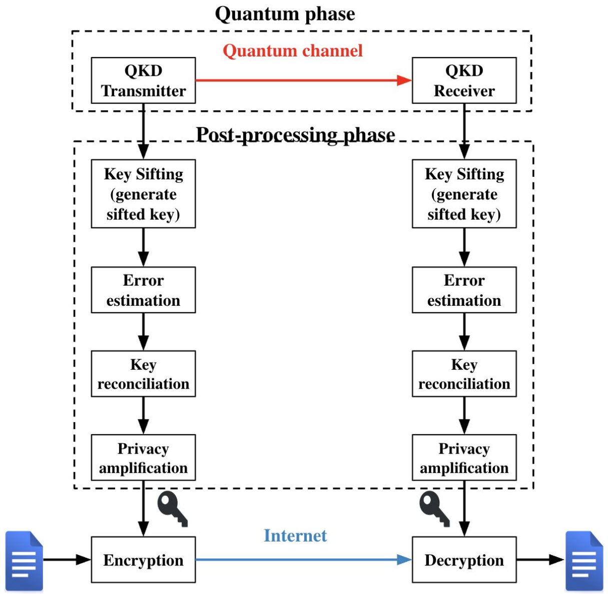
$$\overline{E}_\mu = \frac{\overline{EQ}_\mu}{\overline{Q}_\mu} = \frac{\int_0^\infty EQ_\mu(\eta) f(\eta)\,\mathrm{d}\eta}{\int_0^\infty Q_\mu(\eta) f(\eta)\,\mathrm{d}\eta}$$

$EQ_\mu(\eta)$: Conditional probability of erroneous detections per pulse, given a transmittance value η
$Q_\mu(\eta)$: Conditional probability of a detection event given the transmittance value η
$f(\eta)$: Probability density of the transmittance under atmospheric fading

Performance Analysis(2): Secret Key Rate

The SKR is defined as the average number of secret bits per second

$$\mathbf{SKR} \geq \mathcal{R}spd\left\{-\overline{Q}_{\mu} f H_2\left(\overline{E}_{\mu}\right) + \overline{Q}_1\left[1 - H_2\left(\overline{e}_1\right)\right]\right\}$$



Symbol	Description
$\mathcal{R}$	Repetition rate (pulses per second)
s	Sifting coefficient; e.g., for BB84 protocol, $s = 0.5$
p	Parameter estimation coefficient
f	Key reconciliation efficiency
d	Fraction of bits remaining after the decoy-state method
H_2	Shannon's binary entropy function
$\overline{Q}_1$	Detection event probability of single-photon pulses
$\overline{e}_1$	Error rate of single-photon pulses

Numerical Result: Raw Key Rate

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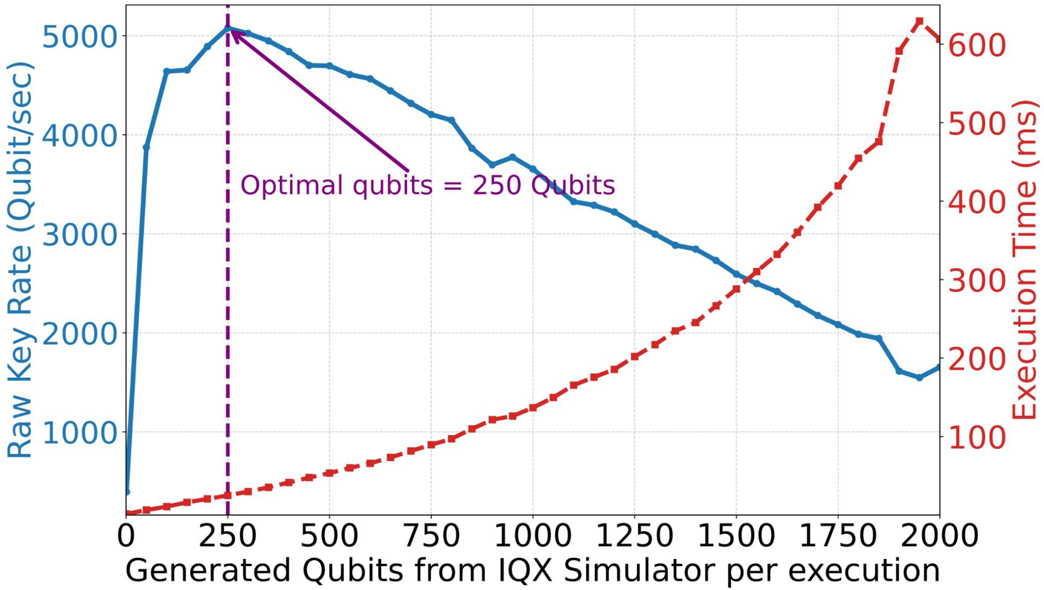
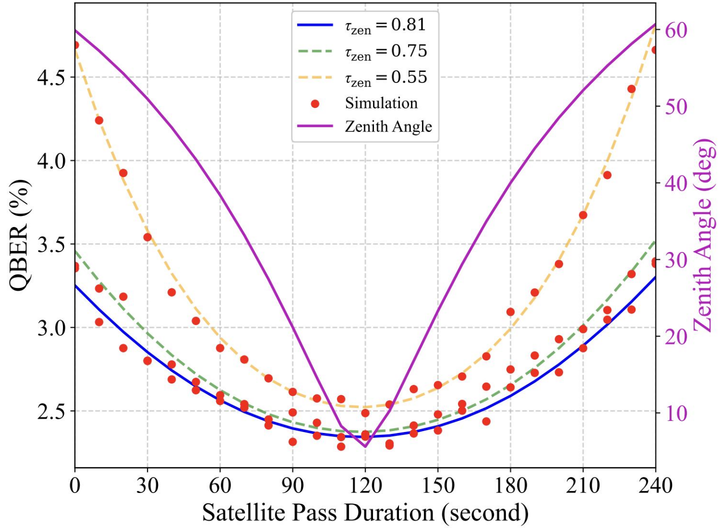
Raw key rate is simulated by specifying the number of qubits (100–2000) generated per run on IBM Quantum Experience (IQX), and the corresponding runtime was also measured.



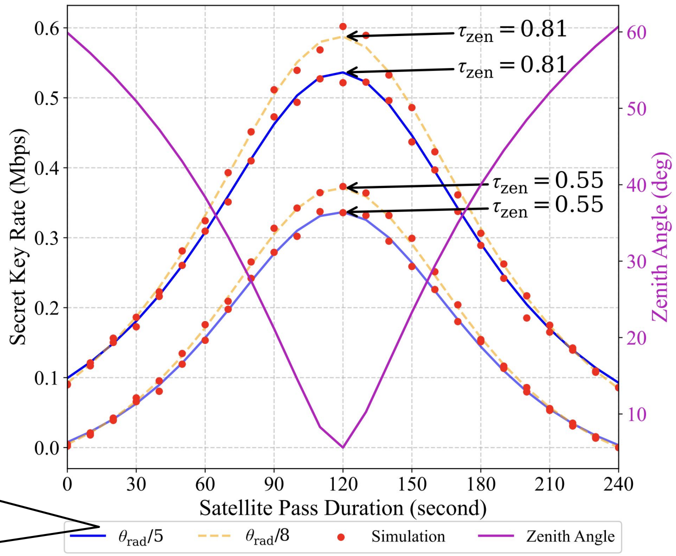
Numerical Result: QBER and Secret Key Rate

Results are analyzed under the impact of the effects of ***atmospheric attenuation***, ***turbulence-induced fading***, ***beam spreading loss, and misalignment***, using a Qiskit-based simulation to evaluate the QBER and Secret Key Rate.



QBER over the STARLINK-1293's pass duration with different deterministic transmittance efficiency.

standard deviation of horizontal and vertical beam angle-jitter



Secret Key Rate Simulation over STARLINK-1293’s Pass Duration under Varying Deterministic Transmittance Efficiencies and Beam Angle Jitter Standard Deviations

θ_{rad} : Half-divergence angle

Conclusion

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- We focused on and analysed the LEO satellite-ground-based QKD system.
- Using Qiskit, we built a simulation framework based on the BB84 protocol.
- A quantum channel model are designed and applied to the simulation framework
- The numerical results are given under the impact of the effects of atmospheric attenuation, turbulence-induced fading, beam spreading loss, and misalignment.

Thank you for your listening