Research Progress: Design of Blind Reconciliation for Satellite-based Quantum Key Distribution Systems

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Outline

I. Introduction

II. Proposed Design and Current Result

III. Directions of Extension

IV. Conclusion

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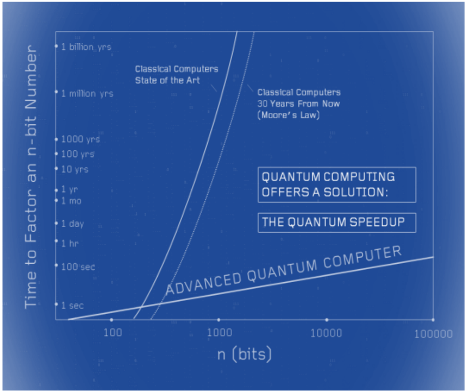
Internet of Vehicles (IoV)

- **Internet of Vehicles:** the network of vehicles and related entities
- **Applications:** speed warning, self-driving cars, vehicle tracking,...
- These applications can directly affect human safety.

Security becomes more and more important for the future IoV systems.

Figure: The Internet of Vehicles and its applications.

A Growing Threat from Quantum Computers



Quantum computers, utilizing the power of qubits, can increase the computational power exponentially.

This makes quantum computers, in principle, can **solve certain mathematical problems (e.g. factoring) much faster than classical computers.**

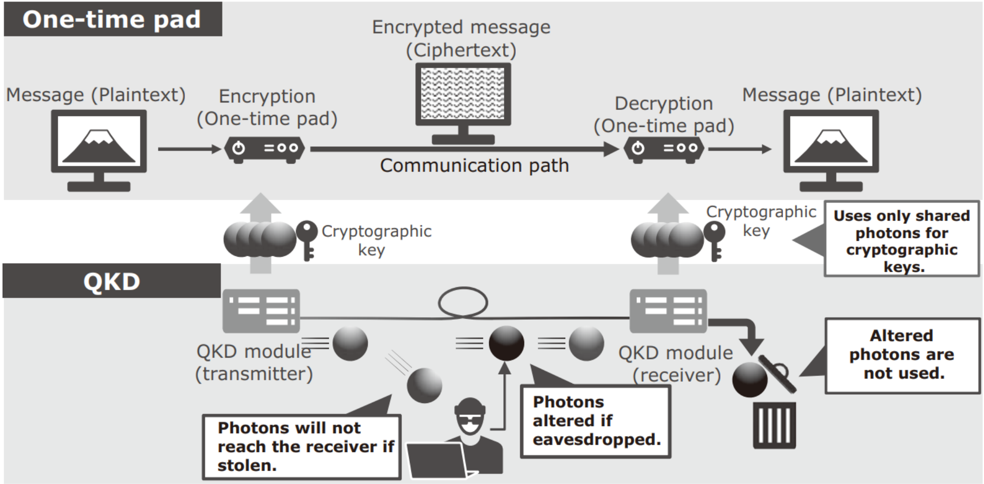
- These mathematical problems are the foundation for many modern cryptosystems, such as RSA. $\Longrightarrow$ *Pose a growing threat to today's security infrastructure.*

With the advance of quantum computers recently, many people believe that conventional cryptography schemes will soon be compromised.

➡ **Research efforts on quantum-safe solutions become more and more important.**

Quantum Key Distribution (QKD)

Quantum key distribution (QKD): *a key distribution protocol based on quantum mechanics*



Free Space Optical (FSO)-based Satellite QKD Systems

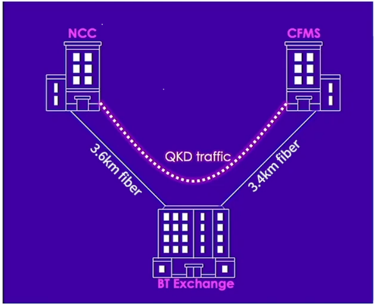


Figure: Optical fiber QKD systems.

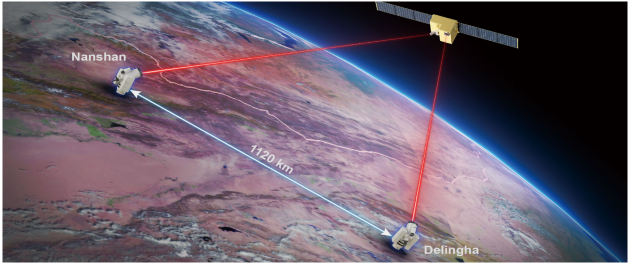


Figure: *Micius*, the world's first quantum satellite experiment

- Have been widely commercialized
- Can not support mobile users

- Can support mobile users via the FSO channel
- Provide global coverage using satellites

➡ **FSO-based satellite QKD systems are potential approaches for secured wireless applications.**

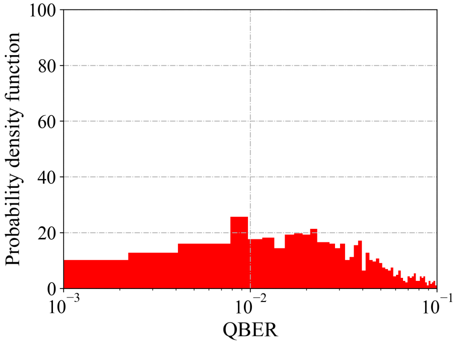
Challenging Issues: Uncertainty Channel

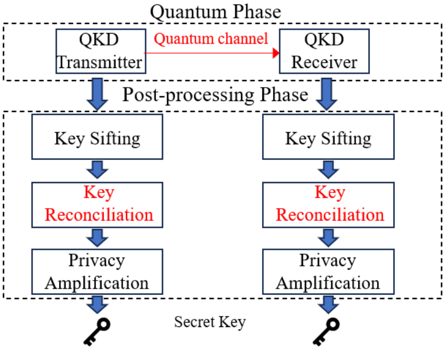
Uncertainty Channel:

- **Cause:** Adverse issues (such as, cloud coverage) and the mobility of satellite
- Lead to **fluctuating quantum bit-error rate (QBER)**

In general, QKD protocols always include a step in the post-processing phase to correct errors, namely **key reconciliation**.

$\Longrightarrow$ *It is necessary to have a proper design of key reconciliation for satellites QKD systems.*

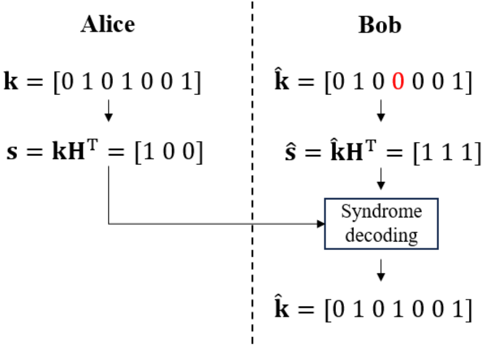




Key Reconciliation based on Error Correction Code

- **Key reconciliation:** Both users (Alice and Bob) try to correct the errors in their keys while minimizing the information leakage
- One of the main approaches is using the syndrome-based error correction codes
- **Low-density parity-check (LDPC) code** is widely considered thanks to its capacity-approaching performance and low-decoding complexity

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$



Existing Approaches and Motivations

There are three main approaches

1. **Fixed-rate Reconciliation:** A fixed code rate is used to reconcile all blocks
   $\Longrightarrow$ **Fixed-rate** KR may be *inefficient over turbulence FSO channels.*
2. **Adaptive-rate Reconciliation:** Based on estimated QBER, choose the best code rates among a set of code rates to reconcile
   - If the reconciliation fails, both sides discard their sifted keys.
   - To estimate the QBER, Alice and Bob will reveal a portion of sifted keys (10-25%)

   $\Longrightarrow$ This leads to *the reduction of the final key rate performance.*
3. **Blind Reconciliation:** If the reconciliation fails, incremental information will be sent to help decoding

Blind reconciliation is a potential approach for key reconciliation of satellite-based QKD systems.

However, to the best of our knowledge, blind reconciliation has not been considered for satellite-based QKD systems.

Our Goal

We propose a design of blind reconciliation and analyze its performance for satellite-based QKD systems.

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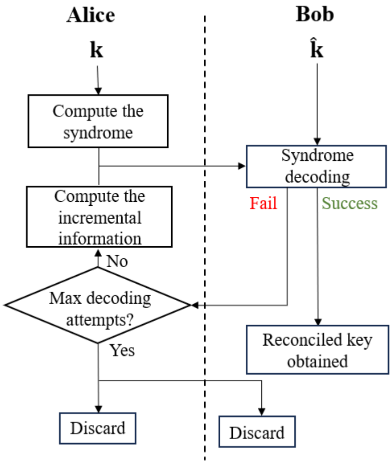
Flow Diagram of Blind Reconciliation



Proposed Structure of Rate-Compatible LDPC Code Family

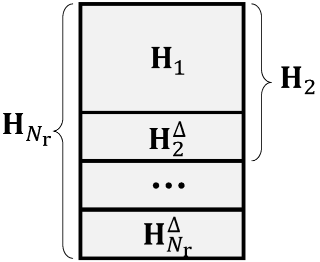


Figure: Proposed structure

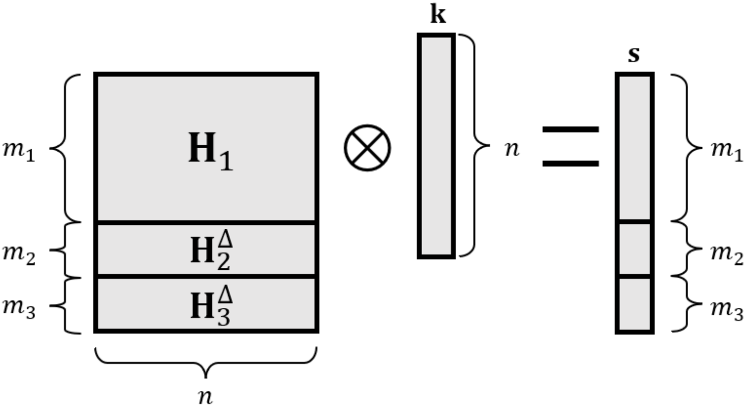
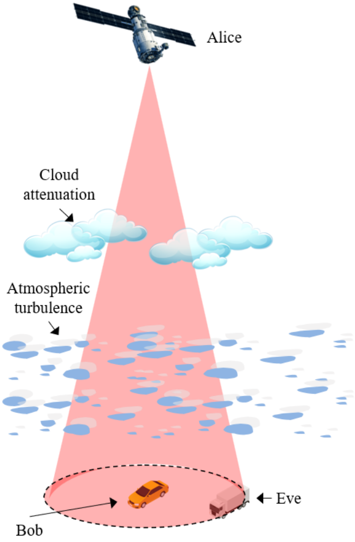


Figure: An example of nested syndrome with the proposed structure.

System Model



System model:

- An LEO satellite (Alice) distributes key materials to a ground vehicle (Bob)
- We consider the BB84 protocol with dual-threshold/ direct detection.

FSO Channel Model:

- Atmospheric Turbulence
- Cloud Attenuation
- Beam-spreading loss

An adversary's car (Eve) attempts to tap the transmitted signals within the beam footprint

Performance Metric: Final Key-rate

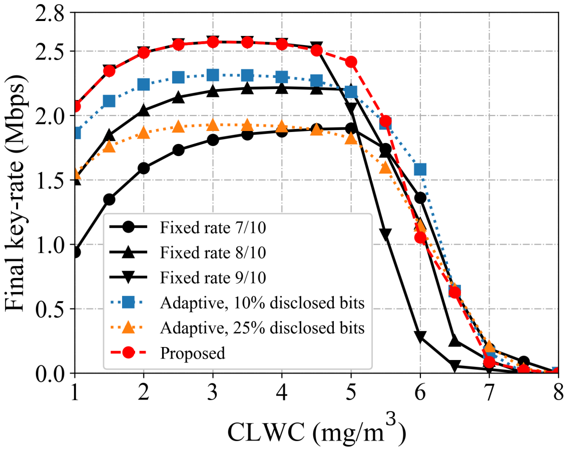
The final key rate is calculated as

$$\mathsf{KR} = \sum_{i=1}^{N_\mathsf{r}} \underbrace{\left(1 - \overline{\mathsf{FER}}_i\right)}_{\substack{\text{Prob. of}\\ \text{successful}\\ \text{reconciliation}}} \underbrace{\left(R_i - I_{AE}\right)}_{\substack{\text{Information after}\\ \text{privacy amplification}}} \underbrace{\frac{N}{R_\mathsf{b} P_\mathsf{sift}}}_{\substack{\text{Average}\\ \text{block rate}}}$$

where

- I_{AE}: mutual information between the sifted key of Alice and the information obtained by Eve
- N: block length
- R_b: the satellite's data rate
- P_sift: the sift probability.

Comparison among Other Reconcilition Methods



- The possible code rates of the blind reconciliation are $(0.9, 0.8, 0.7)$
- The performance of fixed-rate and adaptive-rate KR schemes are analyzed from the theoretical bounds

➡ The proposal design outperforms the other methods in most of the considered range.

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1. Low-latency Blind Reconciliation for Satellite-based QKD Systems

Problem: Blind reconciliation may take several communication rounds over the public channel, resulting in high processing time

This problem becomes more critical in satellite networks, which have high propagation delay. $\Longrightarrow$ significantly affects the secret key rate performance.

Directions:

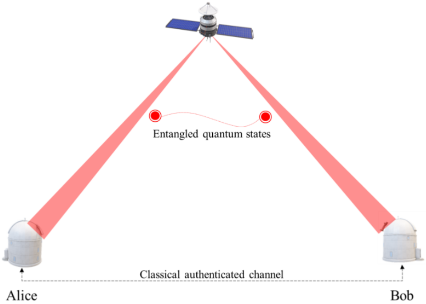
- *We would like to address a design of hybrid adaptive-blind reconciliation for low-processing time satellite-based QKD systems*
  - Integrate error estimation to the current design of blind reconciliation
  - Based on the estimated error, adaptive mechanisms will be conducted to reduce the number of communication rounds
- To confirm the effectiveness of the proposed design, it necessitates *addressing the latency-related metrics, such as the average number of communication rounds*
- We derive an analytical framework for these performance metrics and verify it with Monte Carlo simulations

2. KR Design for Entanglement-based Satellite QKD Systems

Entanglement-based (EB) satellite QKD systems: The LEO satellite (secret key source) distributes key material to Alice and Bob via two beams of entangled quantum states

- The model of quantum channels and classical channels are different from the previously considered scenario.

$\Longrightarrow$ *We investigate and optimize the performance metrics of the proposed design over the EB satellite-based QKD systems.*



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Conclusion

1. Considered a design of blind reconciliation for satellite-based QKD systems
2. Highlighted the effectiveness of the proposal compared to conventional approaches
3. Discussed the directions for the paper's extension

Thank you for your attention!