A Proposal of Satellite-based FSO/QKD System for Multiple Wireless Users

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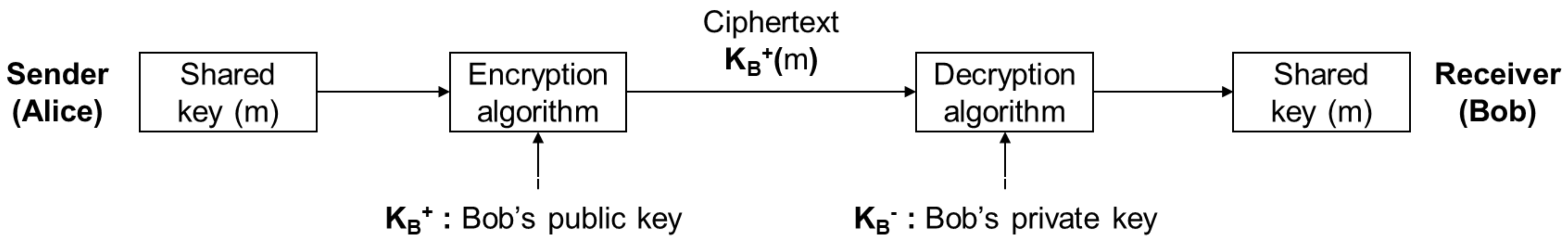
Contents

Quantum Key Distribution (QKD)

In network security, how can two users share secret keys in a secure manner?

- Conventional approach is *Public-Key Cryptography (PKC)*



  - The security of PKC relies on mathematical complexity

→ Becomes vulnerable to advances in computational technologies (e.g., quantum computing, DNA computing)

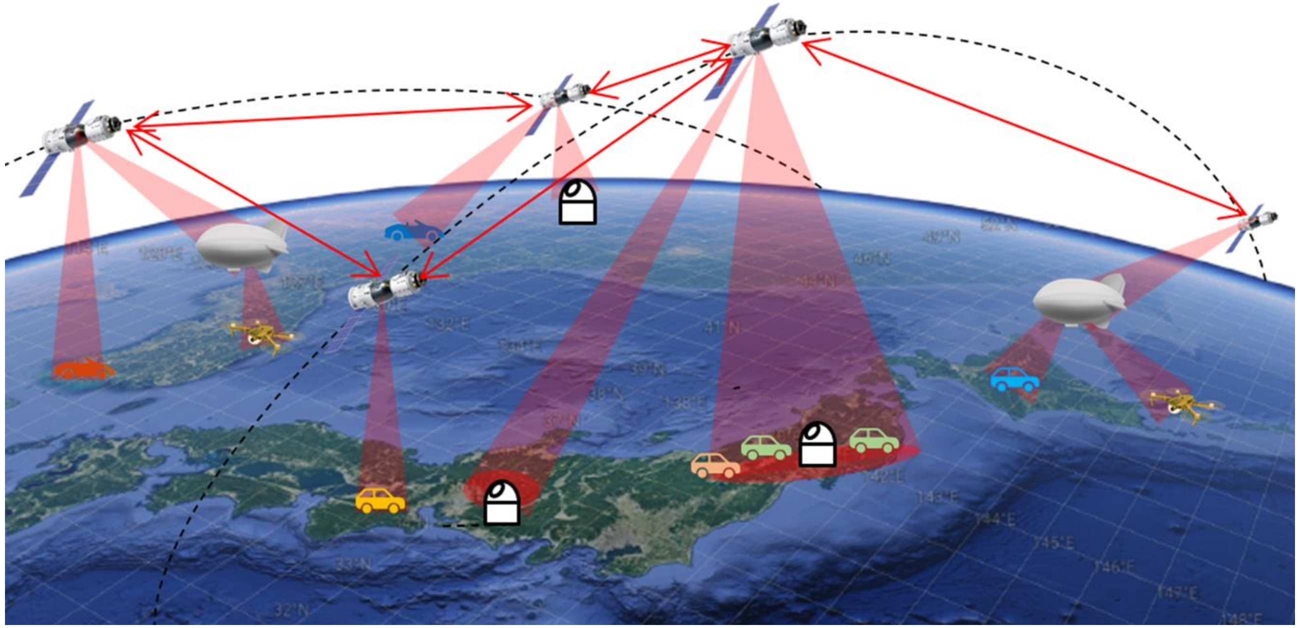
- To solve this issue, a promising solution is *Quantum Key Distribution (QKD)*
  - It is based on the laws of physics to distribute secret keys between two legitimate users
  - Possible unconditional security can be achieved

Satellite-based QKD Systems: Overview

- QKD can be implemented over *optical fiber* and *free-space optics (FSO)* (terrestrial or satellite)
- Conventional QKD systems mainly focus on
  - Optical fiber: for fixed users, inflexibility
  - Terrestrial FSO: limited distance (several kilometers)

→ Difficult to support global QKD services, large-scale networks, especially for mobile users (e.g., autonomous cars, UAVs)

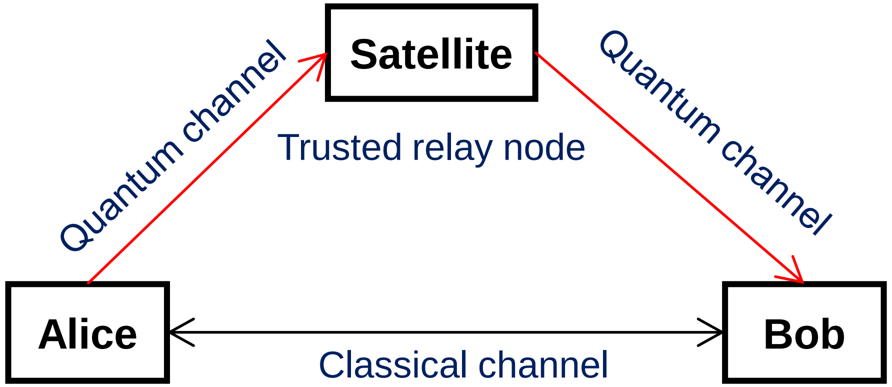
- To tackle those issues, *FSO-based satellite* has been recently considered for QKD systems thanks to flexible deployment and wide coverage area



Satellite-based QKD Systems: Implementation

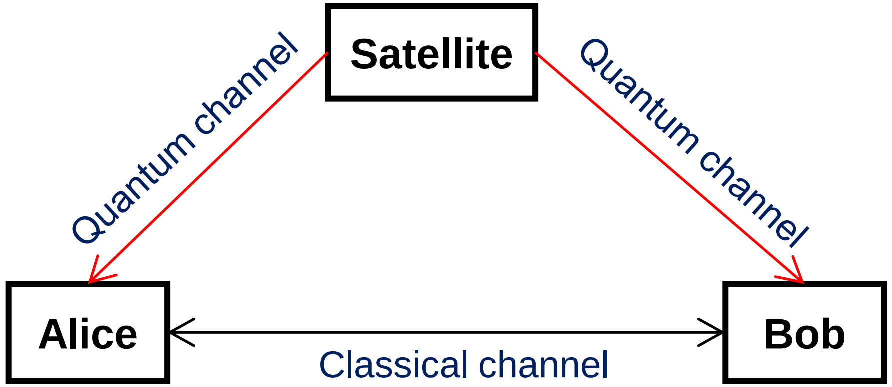
Implementation Schemes

(1) Prepare-and measure



More than one phase is needed to transmit key from Alice to Bob → complexity and inefficiency

(2) Entanglement-based



Satellite does not need to be a trusted node

➡ **Entanglement-based scheme is more efficient and more secure as Alice and Bob can settle secret keys without the involvement of the satellite**

Entanglement-based Satellite QKD: Literature Survey

- There are two main approaches to implement entanglement-based QKD
  - *Discrete-variable (DV)*: Entangled photon-pairs are sent and then detected by single-photon detectors
  - *Continuous-variable (CV)*: Two-mode entangled states created from laser are sent and then detected by coherent detectors
- Both DV and CV-QKD have recently studied for satellite-based QKD
  - [1], [2] considered DV-QKD for entanglement-based satellite QKD

  → Low key rate and incompatibility with standard optical communication technologies
  - [3], [4] addressed CV-QKD for entanglement-based satellite QKD

  → Complexity (require a sophisticated phase stabilized local light for coherent detection)

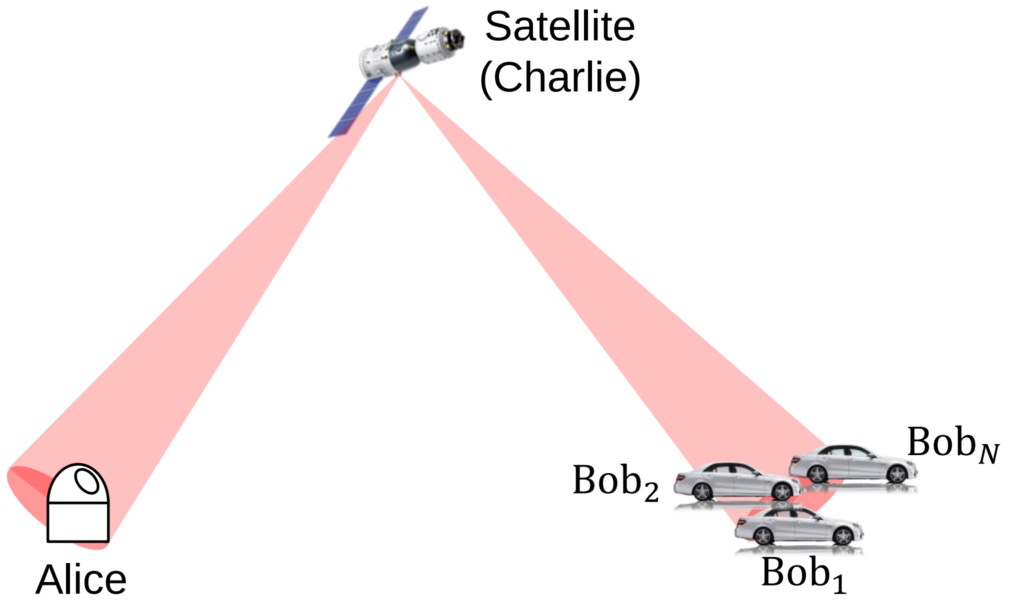
  And all of them just considered a pair of users (between Alice and Bob)

➡ **A simpler approach that is compatible with standard communication technologies and can support multiple users is needed**

[1] J. Yin, Y.-H. Li, L. Shengkai et al., "Entanglement-based secure quantum cryptography over 1,120 kilometres," Nature, vol. 582, pp. 1–5, Jun. 2020.
[2] S.-K. Liao, W.-Q. Cai, J. Handsteiner et al., "Satellite-relayed intercontinental quantum network," Phys. Rev. Lett., vol. 120, Jan. 2018, Art. no. 030501.
[3] N. Hosseinidehaj, Z. Babar, R. Malaney et al., "Satellite-based continuous-variable quantum communications: State-of-the-art and a predictive outlook," IEEE Commun. Surv. & Tut., vol. 21, no. 1, pp. 881–919, 2019.
[4] D. Dequal, L. Trigo Vidarte, V. Roman Rodriguez et al., "Feasibility of satellite-to-ground continuous-variable quantum key distribution," npj Quantum Inf., vol. 7, no. 1, Jan. 2021, Art. no. 3.

Goals

1. **Design an entanglement-based satellite QKD system with simple, low-cost implementation, and compatibility with standard communication technologies for multiple users**
   - Applying SIM/BPSK FSO system with dual-threshold (DT)/direct detection (DD) receivers based on BBM92 QKD protocol [5]
2. **Investigate performance results**
   - Total key-creation rate, the number of users

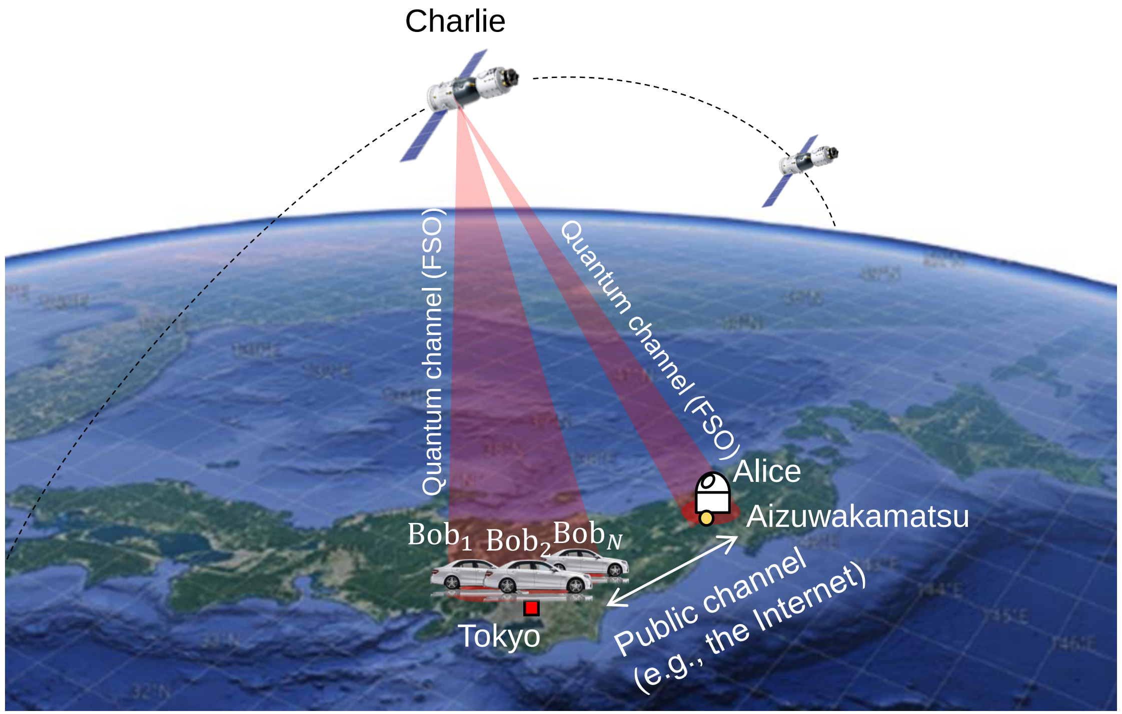


[5] M. Q. Vu, H. D. Le and A. T. Pham, "Entanglement-based Satellite FSO/QKD System using Dual-Threshold/Direct Detection," ICC 2022 - IEEE International Conference on Communications, 2022, pp. 3245-3250

Our System Implementation

- **Considered system scenario**
  - Charlie transmits signal simultaneously to both Alice and Bob *via FSO channel*
  - Alice and Bob detect received signal and then confirm via public channel to *create the secret key*
  - Eavesdropers (Eve) are *within the satellite's beam footprint* trying to *collect secret keys*

- **Protocol implementation**
  - Satellite CV-QKD using non-coherent detection (realized by *dual-threshold/direct detection* (DT/DD) receivers) for the entanglement-based scheme based on *BBM92 protocol* [5]



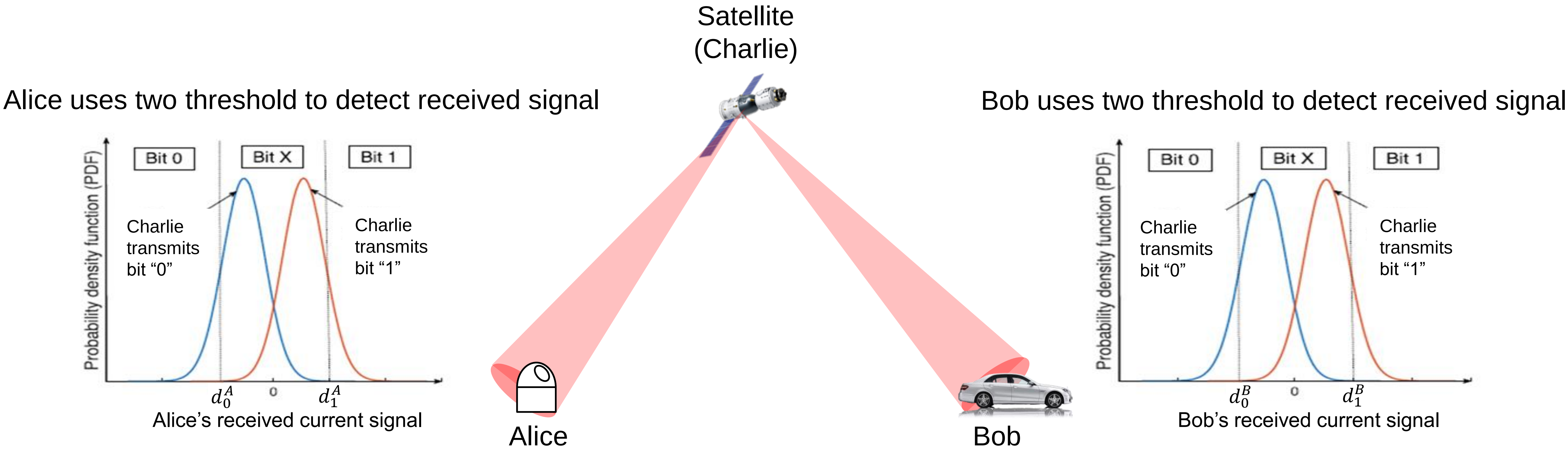
Satellite-based QKD system for multiple users

[5] M. Q. Vu, H. D. Le and A. T. Pham, "Entanglement-based Satellite FSO/QKD System using Dual-Threshold/Direct Detection," ICC 2022 - IEEE International Conference on Communications, 2022, pp. 3245-3250

Protocol Implementation: BBM92 with DT/DD

- The idea of the protocol proposal: mimic the key transmitting/decoding of BBM92 protocol [6]
- Implement on standard FSO system with non-coherent detection

Charlie transmits SIM/BPSK modulated signal to Alice and Bob with small intensity modulation depth (0<δ<1)

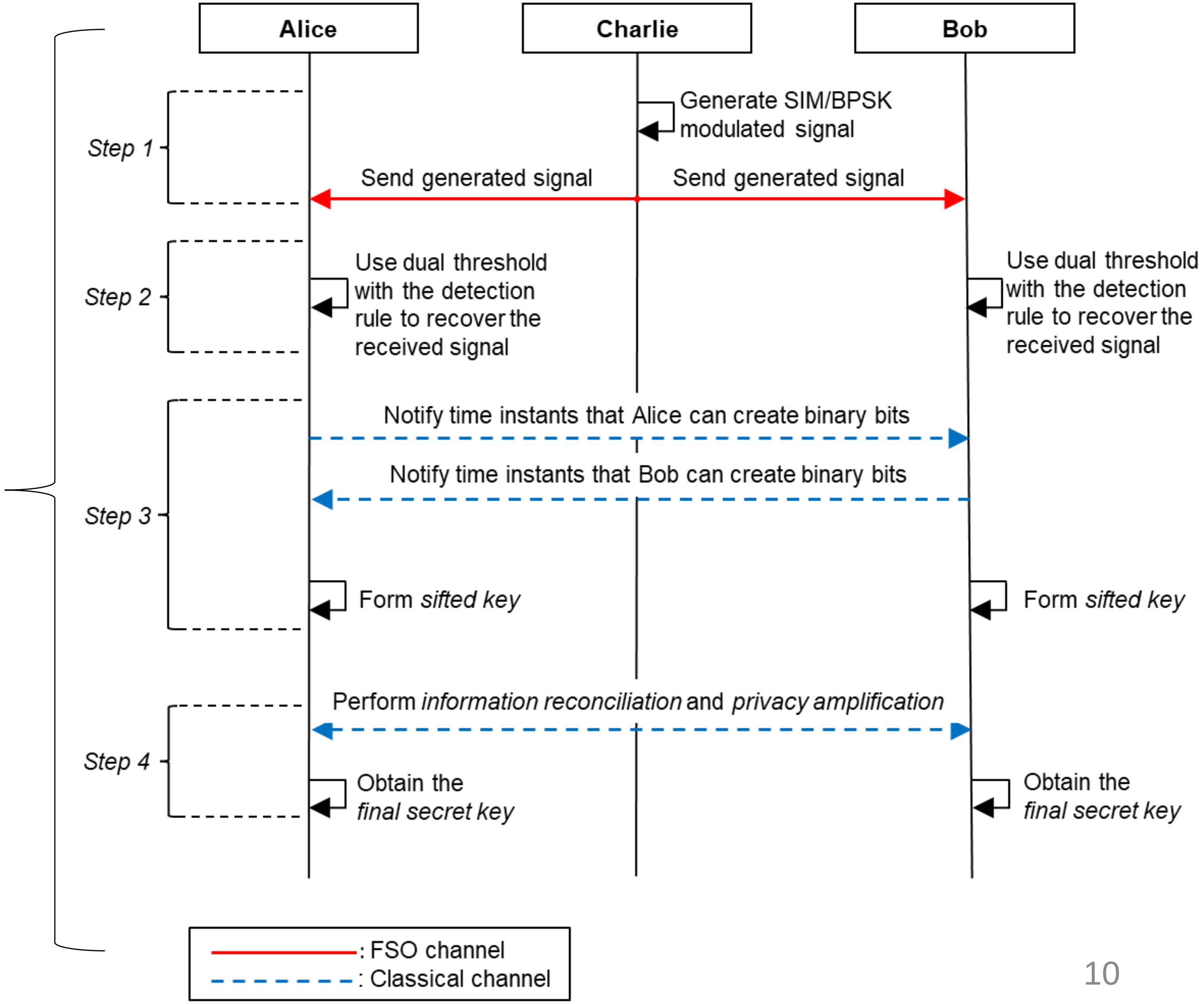


[6] C. H. Bennett, G. Brassard, and N. D. Mermin, “Quantum cryptography without Bell’s theorem,” Phys. Rev. Lett., vol. 68, pp. 557–559, Feb. 1992.

Protocol Implementation: Flowchart

Our protocol includes 4 steps

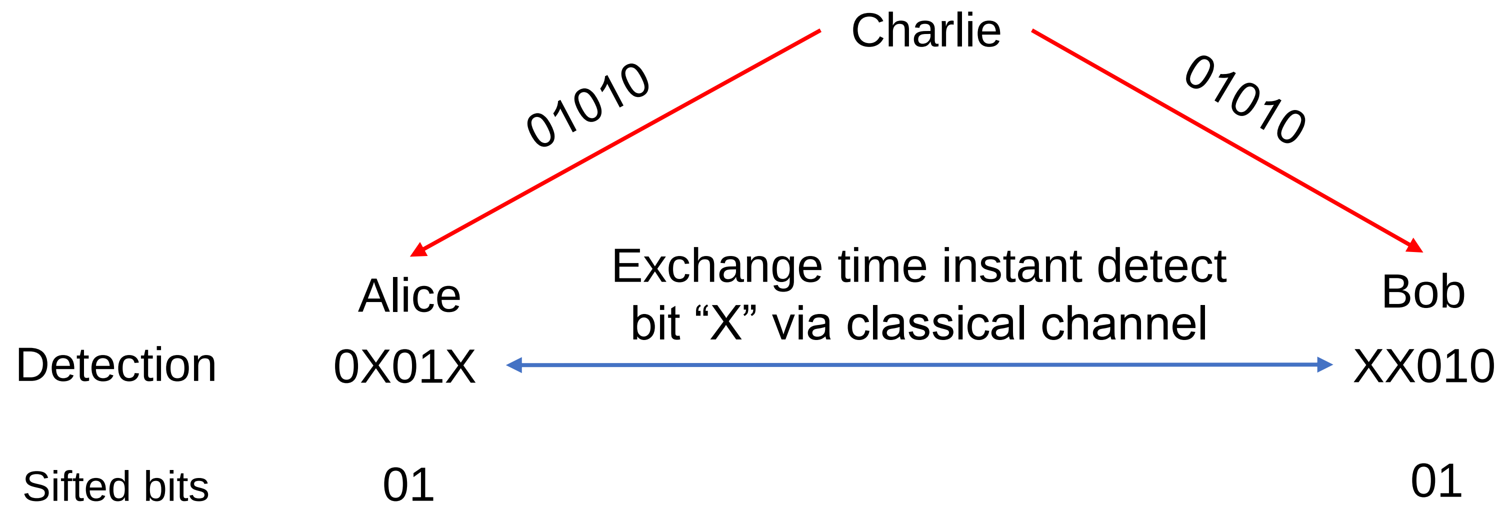
The key issue for simple and low-cost implementation comes from *the non-coherent detection (realized by dual-threshold/direct detection)*



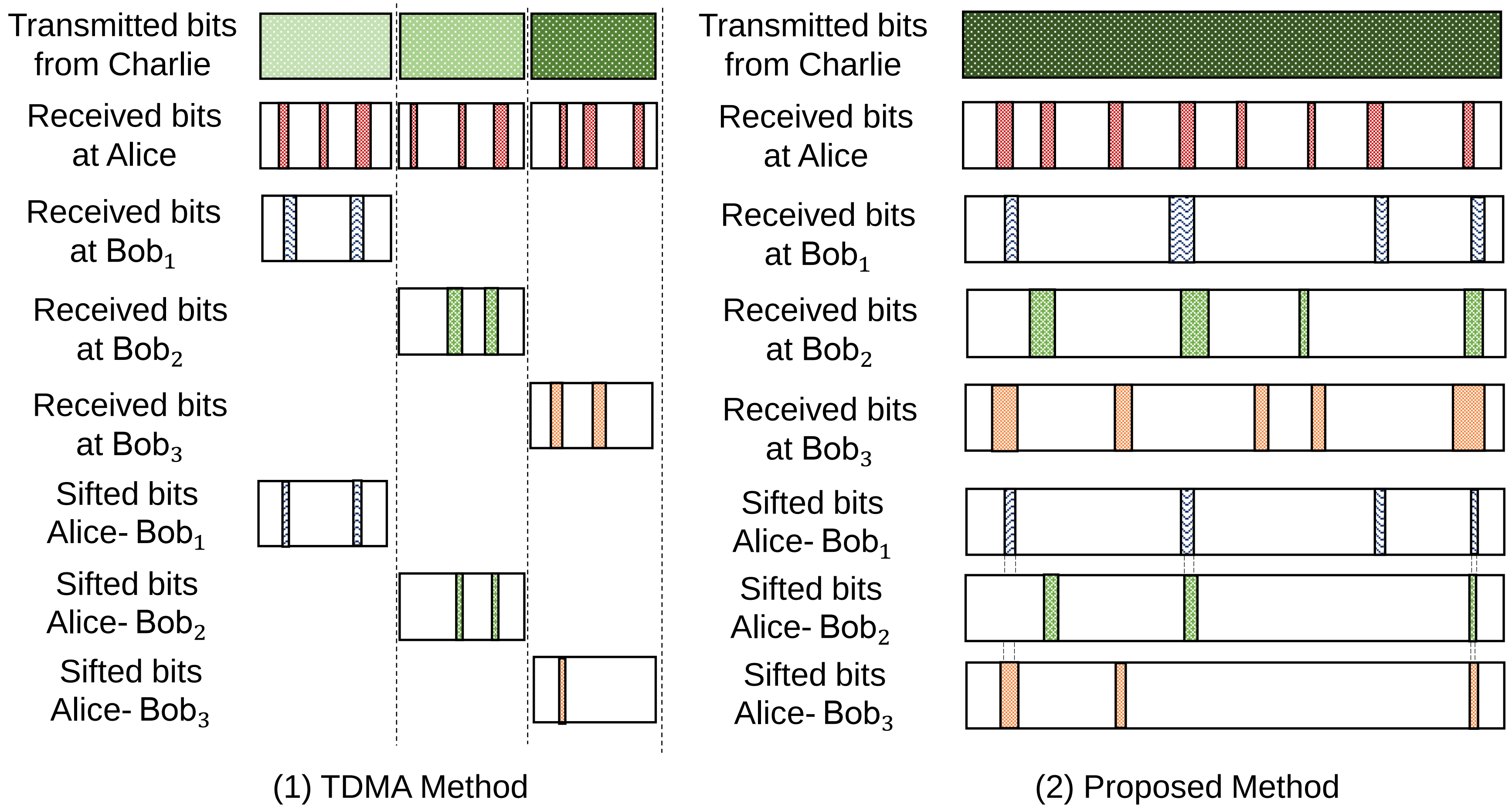
Protocol Implementation: An Example

- An example of the proposed protocol

Satellite (Charlie)			**Alice**			**Bob**			Sifted bits
Time	Bit	Signal	Time	Threshold	Bit	Time	Threshold	Bit	
t_0	0	i_0	t_0	d_0^A	0	t_0	d_0^B	X	*discarded*
t_2	1	i_1	t_2	d_1^A	X	t_2	d_1^B	X	*discarded*
t_3	0	i_0	t_3	d_0^A	0	t_3	d_0^B	0	0
t_4	1	i_1	t_4	d_1^A	1	t_4	d_1^B	1	1
t_5	0	i_0	t_5	d_0^A	X	t_5	d_0^B	0	*discarded*



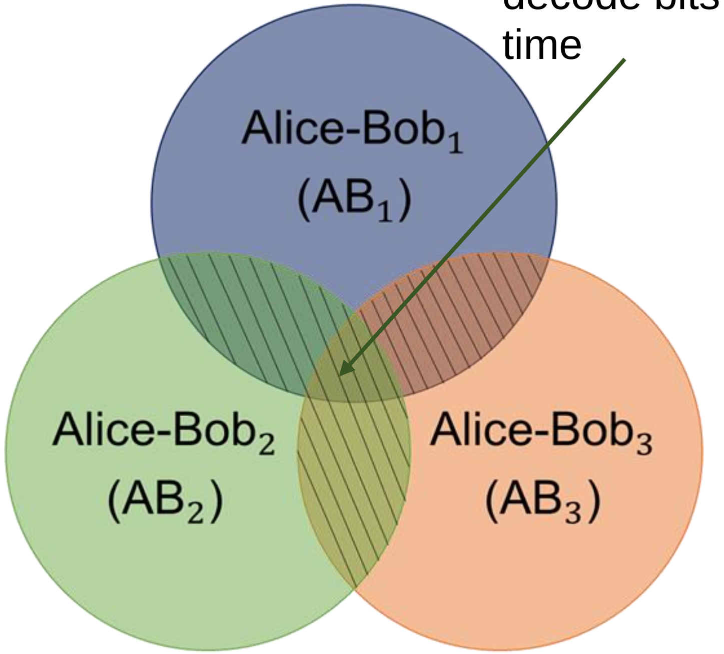
Satellite-based FSO/QKD for Multiple Wireless Users



Time Division Multiplexing Access (TDMA) vs. the proposed method for key distribution with the number of users at Bob's site = 3

Performance Analysis (1)

The overlapping region: shows the probabilities that Alice, Bob_i, and Bob_j, $j \neq i$, $j \in \{1, 2, 3\}$ can decode bits at the same time



Visualization for the relationship of sift probabilities between Alice and Bob_i , $i \in \{1, 2, 3\}$

Sift Probability:

- In TDMA system:

$$P_{AB_i}^{\text{sift}} = P_{AB_i}(0,0) + P_{AB_i}(0,1) + P_{AB_i}(1,0) + P_{AB_i}(1,1)$$

$P_{AB_i}(x, y)$ with $(x, y) \in \{0,1\}$: the probability that Alice's detected bit "x" coincides with Bob's detected bit "y"

- In the proposed system:

$$P_{AB_i}^{\text{sift}-\text{excl}} = P_{AB_i}^{\text{sift}} - \varepsilon P_{AB_i}^{\text{excl}}$$

$P_{AB_i}^{\text{excl}}$: the mutual sift probability with other users Bob_j

$$P_{AB_i}^{\text{excl}} = \sum_{j \neq i, 1 \leq j \leq N} P(AB_i \cap AB_j) + \sum_{j_1 \neq j_2 \neq i, 1 \leq j_1 \leq j_2 \leq N} P\left(AB_i \cap AB_{j_1} \cap AB_{j_2}\right) + \cdots + (-1)^{N+1} P\left(\bigcap_{i=1}^{N} AB_i\right)$$

ε: the exclusion ratio coefficient

Performance Analysis (2)

Final-key creation rate:

- We assume that there are two eavesdroppers (Eve_1 and Eve_2) who perform unauthorized receiver attacks near Alice's and Bob's sites, respectively
- After sharing the sifted key between Alice and Bob and performing error correction, Alice and Bob:
  - Estimate the information leaked to eavesdroppers
  - Exclude it through privacy amplification to obtain the final key
- Final-key creation rate can be derived as

$$R_i^f = R_i^s\{\alpha I(A;B_i) - \max[I(A;E_1), I(B_i;E_2), I(E_1;E_2)]\}$$

R_i^s: the sifted-key rate → In TDMA system: $R_i^s = P_{AB_i}^{\mathrm{sift}} \frac{R_b}{N}$

→ In the proposed system: $R_i^s = P_{AB_i}^{\mathrm{sift-excl}} R_b$

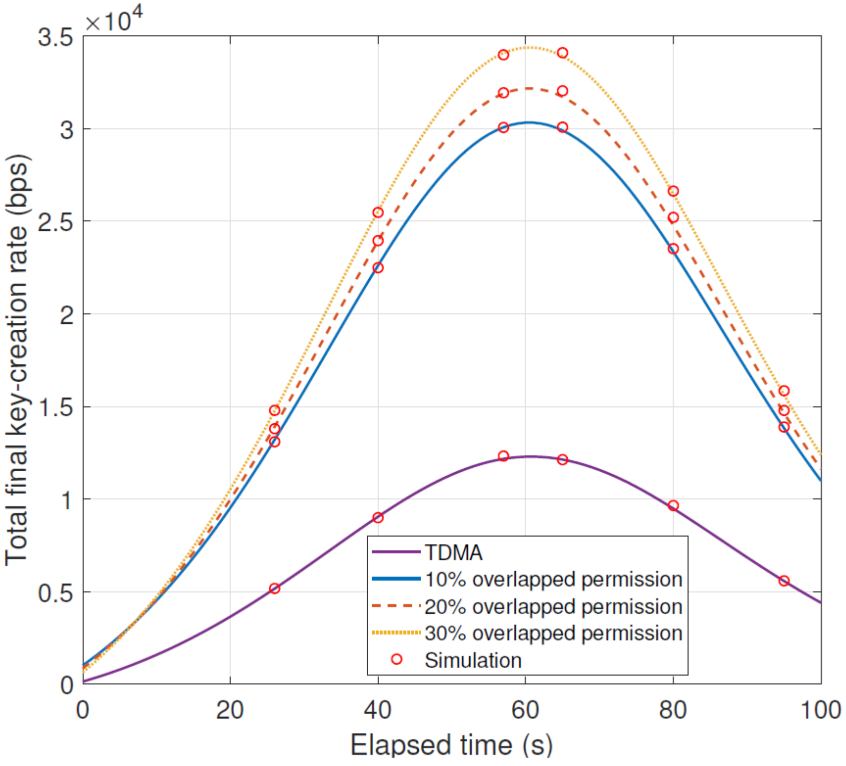
R_b: the system's bit rate

α: error correction efficiency in post-processing procedures

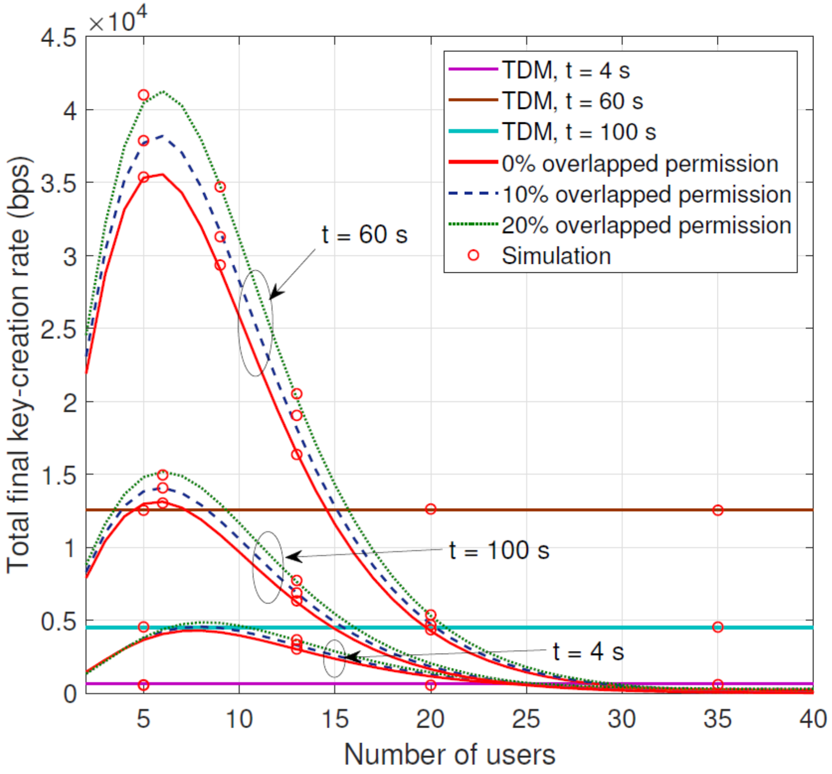
$I(X;Y), X \in \{A, B_i, E_1\}, Y \in \{B_i, E_1, E_2\}$: the amount of information shared between X and Y

Results

Results are analyzed under the impact of ***the effects of channel loss, atmospheric turbulence-induced fading, and receiver noises***



Total final key-creation rate vs. the elapsed time with the number of users =3: Proposed method vs. TDMA method



Total final key-creation rate vs. the number of users (N): Proposed method vs. TDMA method

Conclusions

- This paper proposes satellite-based CV-QKD using DT/DD to distribute secret keys to multiple users
- We analyzed the system performance regarding sift probability and total final-key creation rates for legitimate users
- The numerical results are given under the effects of channel loss, atmospheric turbulence-induced fading, and receiver noises
- The correctness of derived formulas was verified by Monte-Carlo simulations

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Thank you!

TABLE 3: System Parameters

Name	Symbol	Value
LEO Satellite (Charlie)		
Wavelength	λ	1550 nm
Bit rate	R_b	1 Gbps
Altitude	H_C	550 km
Divergence angle	θ_C	50 μrad
Transmitted power	P	30 dBm
FSO Channel		
Sun's spectral irradiance from above the Earth	Ω_v	0.2 $\mathrm{kW/m^2 \cdot \mu m}$
Wind speed	w	21 m/s
The refractive index structure parameter at the ground level	$C_n^2(0)$	$10^{-15}\mathrm{m}^{-2/3}$
Visibility	V	30 km
Alice/Bob/Eve		
Altitude	H_U	2 m
Aperture radius	a_U	5 cm
Optical bandwidth	B_0	250 GHz
Responsivity	R_e	0.9 A/W
Effective noise bandwidth	Δf	0.5 GHz
Temperature	T	298 K
Load resistor	R_L	1 kΩ
Amplifier noise figure	F_n	2