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研究課題名（和文）Satellite-based Free-Space Optical Quantum Key Distribution (QKD) Systems for Secured Wireless Networks

研究課題名（英文）Satellite-based Free-Space Optical Quantum Key Distribution (QKD) Systems for Secured Wireless Networks

研究代表者

Ａｎｈ・Ｔ　Ｐｈａｍ（Pham, T. Anh）

会津大学・コンピュータ理工学部・教授

研究者番号：８０４０４８９６

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研究成果の概要（和文）：本プロジェクトは非コヒーレント検波を適用することで衛星CV-QKDの新しい設計を提示した。また衛星ベースのFSOシステムの設計と応用に関する課題に取り組んだ。次にLEO衛星とGEO衛星を利用した量子もつれに基づく新しいFSO/QKDシステムを提案した。そして既存のGEOとLEO衛星を利用した日本のQKDネットワークの事例について実現可能性を調査した。またGEO衛星を秘密鍵源としLEO衛星を複数の無線ユーザの中継ノードとするグローバル規模のFSO/QKDネットワークの新しい設計を提案した。最後に、既存のQKDプロトコルに比べてスペクトル効率が高い新しい変調信号ベースのQKDプロトコルを提案した。

研究成果の学術的意義や社会的意義
本研究は5G以降の無線ネットワークパラダイムにおいて自動運転車両など遠隔通信においての安全な無線通信をサポートする衛星ベースのFSO通信の設計と開発を提案する。計算技術の急速な進歩により数学的複雑さに基づく従来の鍵配送プロトコルはすぐに危険にさらされる可能性がある。量子物理学の法則を利用する量子鍵配送は固定ネットワークで実証済みで実装を備えた有望な方法とされている。私たちはFSOとHAPSの光無線技術に基づく無線ネットワーク用の量子鍵配送システムの提案を目指している。私たちは信頼性が高く効率的な鍵配送方法を実現するために基礎理論とシステム、プロトコル設計の問題の両方に重点を置いている。

研究成果の概要（英文）：First, we presented a new design for satellite CV-QKD by applying non-coherent detection for the entanglement-based scheme. We also worked on issues related to the design and applications of satellite-based FSO systems. Second, we proposed a novel entanglement-based FSO/QKD system that uses LEO and GEO satellites. We then investigated the feasibility of a case study for the Japan QKD network using the existing GEO and LEO satellite constellations. Thirdly, we proposed a novel design for a global-scale FSO/QKD network based on a GEO satellite as the secret key source and LEO satellites as relay nodes for multiple wireless users. Finally, we proposed a novel modulation signaling-based QKD protocol that employs eight phases of the optical carrier, which exhibits increased spectral efficiency compared to existing protocols.

研究分野： Information networks

キーワード： Quantum key distribution　Free-space optics　Satellite communications　Security attack　BBM92 Protocol

１．研究開始当初の背景

One of the major concerns in communication networks is security, i.e., the capability that allows entities to communicate with confidentiality, integrity, and authentication. The present security technologies rely on classical cryptography, which includes two major schemes: asymmetric (public key) and symmetric cryptography [1]. Nevertheless, these classical methods may soon become vulnerable due to the advancement of computer hardware, computational algorithms, and especially the recent research and development of quantum computers [2]. Emerging as a promising security method, quantum key distribution (QKD) has recently been studied intensively. The fundamental motivation behind the QKD method is that according to Shannon's theory of information-theoretic security [3], perfect security can be achieved when the long key is used only once. Therefore, with a secured method of key distribution, it is possible to achieve unconditional security in communication networks.

Originally, QKD was proposed to be implemented in fiber networks, the fiber-based QKD has been extensively studied and many implementations have been commercialized over the past few decades. This solution is, however, only applicable for fixed stations with fiber connectivity. Practically, there are many applications and scenarios in which secure users cannot be connected by optical fiber, including mobile stations, such as ground vehicles (ships, trains, self-driving cars, and trucks, etc.), unmanned aerial vehicles (UAVs) in the next-generation wireless networks, and fixed stations where installation of fiber is not favorable, such as base stations in high-density 5G networks or some remote areas (islands or mountainous areas). In these cases, a wireless QKD method is needed. Therefore, free-space optical (FSO)-QKD, which allows the transmission of optical signals over the atmosphere, is considered an effective solution. In 2017, the National Institute of Information and Communications Technology (NICT) published a report outlining the roadmap of quantum network technologies, in which the QKD for securing mobile UAVs, satellites wireless networks are expected to be one of the key challenging R&D issues in the coming decade [4].

２．研究の目的

The project's goal is to study the fundamental theory as well as the development of satellite-based FSO-QKD systems, as illustrated in Fig. 1. We especially focus on tackling both system and protocol design challenging issues to extend the limit the transmission distance and the secret key rate. In particular, the proposed research project has the following three purposes:

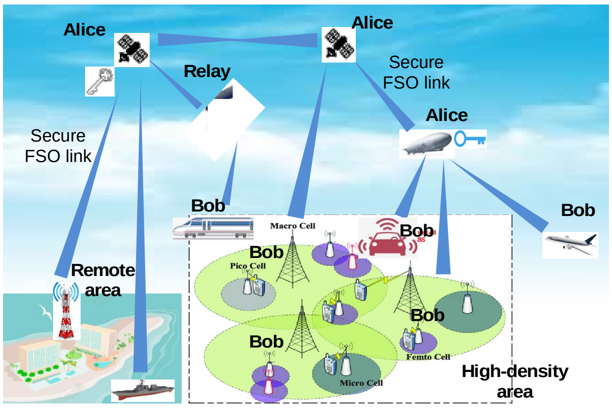

Fig. 1: Satellite-based HAP-assisted FSO-QKD system.

- First, the project aims to propose high-performance and reliable satellite-based FSO-QKD networks, which are expected to provide high secret key rates and long transmission distances in various deployment scenarios. Especially we aim to propose relay-assisted systems using the high-altitude platform (HAP), as shown in the figure, so that quantum keys can be reliably distributed to moving stations, including airplanes, UAVs, trains, and self-driving cars.
- Secondly, the project also aims to prove the feasibility of the proposed FSO-QKD systems by comprehensively analyzing their security performance under the effects of various physical layer impairments.
- Finally, the proposal of security performance improvement methods and novel protocol designs for FSO-QKD systems is also a target of this project. More specifically, the proposed methods and protocols would help to reduce the quantum bit error rate (QBER) and increase the secret-key rate.

３．研究の方法

There are two major approaches in the proposal which are unique comparing with other research in terms of both *underlaying FSO system* and the *system implementation*.

First, regarding the underlaying optical system, when the first QKD protocol, widely known as BB84 protocol, was proposed by Bennett and Brassard [5], there was no discussion on how the system can be implemented. As the legitimate sender (Alice) and receiver (Bob) achieve the secret-key sharing by using randomly generated signals encoded by two pairs of orthogonal states, over the years, there exist two major implementation methods of QKD protocols, namely discrete variable (DV) and continuous variable (CV). In DV-QKD systems, the key information is encoded onto the discrete state of a single photon, such as the phase or polarization [1]. The encoded photons are then transmitted over the quantum channel and detected by a single-photon receiver. It is worth noting that DV-QKD ideally use single photon but practically uses weak optical signal for encoding and single-photon receiver, which is bulky, expensive, and requires a cooling system. In contrast, CV-QKD systems encode the key information on the continuous variables of coherent states conveyed by the amplitude and/or phase of weakly modulated light pulses [6]. Compared to DV-QKD, CV-QKD is less expensive, working at room temperature, and much easier to implement as it is compatible with the standard optical telecommunication technologies and enables higher key generation rates by using heterodyne/homodyne detection instead of the single-photon counters.

Regarding the system implementations of FSO-QKD systems, both terrestrial and satellite-based applications have been considered. The QKD implemented on satellites is treated as one of the most promising solutions to realize a global quantum communication network. To test the feasibility of satellite-based free-space optical QKD, many experimental works have been performed on the ground in the past decade [6-11]. In 2017, the first demonstration of QKD from a ground transmitter to a moving aircraft has been reported with distances between 3-10 km and generated secure keys up to 868 kilobytes in length [11]. Later, BB84 was successfully implemented over satellite links from Micius to ground stations in China and Austria. The keys were combined, and the result was used to transmit images and video between Beijing, China, and Vienna, Austria [12]. In *these previous works*, however, it is obvious that there is a tradeoff between the secure key rate and the transmission distance (i.e., the length of optical fiber or FSO link) of developed QKD systems. More specifically, high secure key rate can only achieve with short transmission distance and vice versa. Therefore, one of the most challenges in design and implementation new QKD systems that can support ***both high secure key rate and long transmission distance***. Also, there is a need in proposing effective solutions for distributing the quantum key to various types of users in various deployment scenarios.

Our proposal addresses both issues by proposing novel *satellite-based with HAP-assisted FSO-QKD systems*. The proposal includes both system design by introducing new relaying methods and protocol design focusing on *improving the system key rate, transmission system and secrecy capabilities*. The originality and contributions of this project are as follows.

- The use of satellite is a promising way of extending the deployment of range of QKD. Although, full-scale verifications of satellite-based free-space QKD have been reported, their performance suffers from the impact of atmospheric conditions, including absorption, scattering, and atmospheric turbulence appearing in atmospheric channels. Different from the conventional systems with direct connection from satellites, we propose *high-altitude platforms (HAP) assisted relays* for performance improvement of satellite-based FSO QKD systems. Here, HAP plays a role as a relay station, which receives the quantum key from the satellite, amplifies (or generates), and then forwards the key to ground stations.
- Other contributions of this project are the proposals of novel methods and protocol design for security performance improvement of free-space QKD systems. The performance improvement methods and protocols can be employed to overcome the challenges in practical deployment of free-space QKD systems. Also, the novel mathematical models derived in this project can be used for designing and determining the optimum values of system's parameters for free-space QKD systems.

４．研究成果

The project results are reflected in four major achievements, as follows. First, we presented a new design concept for satellite CV-QKD by applying non-coherent detection for the entanglement-based scheme based on the BBM92 protocol. The BBM92 protocol is the most popular entanglement-based QKD protocol, which was recently used in Micius's satellite-based QKD system to provide secret keys for ground stations. We model and analyze the performance of the proposed system in the context that a satellite distributes secret keys to two legitimate users. The analytical results are derived by considering the channel loss, atmospheric turbulence-induced fading, and receiver noises. The Gaussian beam model is considered to evaluate the impact of geometrical spreading on the signal received by legitimate users and the possibility of being eavesdropped on. Based on the design criteria for the system and analytical results, we can find suitable parameters for the transmitter and the receivers to properly achieve the QKD function for distributing secret keys between two legitimate parties. In addition, we have also worked on several issues related to the design and applications of satellite-based FSO systems, including hybrid FSO/RF systems, error control, and improvement using advanced hybrid ARQ techniques.

We also proposed a novel entanglement-based FSO/QKD system that uses LEO and GEO satellites. FSO/QKD systems using low-Earth orbit (LEO) satellites and EB scheme have been proposed previously. The LEO satellite benefits from the low channel loss; however, its coverage is limited. While a geosynchronous satellite (GEO) satellite with an altitude of 35,786 km can solve the coverage problem, the system needs a high path loss and limited key rates. Therefore, combining GEO and LEO satellites becomes a promising solution for the global-scale QKD network. Our proposal focuses on designing a system that can support multiple wireless users, which opens the potential to establish a global-scale QKD network. Based on the design criteria for the proposed system, we investigate the feasibility of a case study for the Japan QKD network using the existing GEO satellite and LEO satellite constellation to provide QKD service for legitimate users in Japan. Furthermore, the secret key performance of the proposed system is studied based on the design criteria of transmitters and receivers considering the unauthorized receiver attack (URA) and beam-splitting attack (BSA). We aim to design the transmitted signal to prevent URA and propose a simple scheme that allows legitimate users to detect BSA. In addition, we also work on issues related to the design and applications of satellite-based FSO systems, including hybrid FSO/RF systems, error control, and improvement using advanced hybrid ARQ techniques.

In addition, we proposed a novel design framework for a global-scale FSO/QKD network based on a GEO satellite as the secret key source and LEO satellites as relay nodes for multiple wireless users. The non-coherent CV-QKD protocol inspired by the BBM92 protocol for the EB scheme was employed. The system performance was analyzed, considering the spreading loss, atmospheric attenuation, and turbulence. Based on the design criteria for the proposed system, we investigated the case study for the Japan QKD network, considering the two prevalent attacks of URA and BSA. We proposed a multiple-access method to improve the total secret key performance. We also proposed a simple, yet effective BSA detection method based on legitimate users' statistical observation of sift probability.

Finally, we proposed a novel modulation signaling-based QKD protocol that employs eight phases of the optical carrier, therefore named octa-phase shift keying QKD (8PSK-QKD). The proposed QKD protocol shares two key bits simultaneously and exhibits increased spectral efficiency compared to existing modulation signaling-based QKD protocols. To inspect the potential of the system, the 8PSK-QKD system is compared with the quadrature phase shift keying-based QKD (QPSK-QKD) and subcarrier intensity modulation binary phase shift keying-based QKD (SIM/BPSK-QKD) systems. Results reveal the proposed system outperforms the SIM/BPSK-QKD and QPSK-QKD.

The result of the project has been disseminated in many different forums, including publications in reputable transactions, journals, international conferences, and in the public domain of the Internet (project website). The result of this 3-year project has been published in thirteen (13) journal articles and fifteen (15) conference papers. All publications are accessible in the public domain for the more detailed results of the project.

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
インド	IIT Roorkee	Dept. of Elec. and Commun. Engi.		
インド	IIT Indore	Department of Electrical Engi.		
ベトナム	Hanoi Univ. of Science and Technology	School of Electrical and Electronic Eng.		
ベトナム	Posts & Telecommu. Institute of Technol.	Wireless Communications Department		