

Satellite-Based Quantum Key Distribution: Protocols, Network Architectures, and Continuous-Variable Implementation Challenges

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Abstract: Losses and attenuation are the main limitations to implementing secure quantum networks based on fiber or free-space optical links over long distances. A hybrid satellite-ground approach offers an effective solution to overcome these constraints and achieve higher key transmission rates. This article presents a systematic review of publications on satellite quantum communication, providing an overview of quantum key distribution with satellites, the use of satellite networks with emphasis on commonly adopted orbits, and the role of satellites in such architectures. Special attention is given to the implementation of continuous-variable QKD (CV-QKD) in satellite-based channels, highlighting its challenges and potential for integration into future satellite-based quantum networks

Keywords: Quantum Key Distribution. Satellite. Satellite-based QKD. Free-Space Optics. Continuous-Variable QKD

Abbreviations: QKD, Quantum Key Distribution. DV-QKD, Discrete-Variable Quantum Key Distribution. CV-QKD, Continuous-Variable Quantum Key Distribution. SatQKD, Satellite-based Quantum Key Distribution. FSO, Free-Space Optics. GEO, Geostationary Orbit. LEO, Low Earth Orbit. SNR, Signal-to-Noise Ratio. PATS, Pointing Acquisition and Tracking Subsystem. LO, Local Oscillator. SKR, Secure Key Rate. QPSK, Quadrature Phase-Shift Keying.

1. Introduction

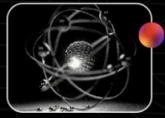
Despite the predominance of classical systems in everyday applications such as television, the internet, and GPS, advances in quantum communication are transforming the telecommunications sector, particularly in data security. Quantum Key Distribution (QKD) enables encrypted information exchange with enhanced security and is being tested in projects such as satellite communications to protect data against interception, even by agents with advanced technology.

A systematic review is a research method that analyzes the literature on a topic using explicit criteria for searching and synthesizing information. This approach minimizes bias, consolidates evi-

dence, and identifies gaps in knowledge [1]. The process involves three steps: (1) planning (defining objectives and selection criteria), (2) execution (filtering studies and extracting data), and (3) analysis and synthesis [2]. In rapidly evolving areas such as satellite-based quantum optical communication, where studies are abundant but dispersed, this methodology is essential for mapping the state of the art, guiding future research, and validating scientific results.

2. Methodology

This study conducted a targeted search on QKD in satellite communications using LENS.org, Web of Science, and IEEE Xplore. The search focused on experimental and space-oriented applications,

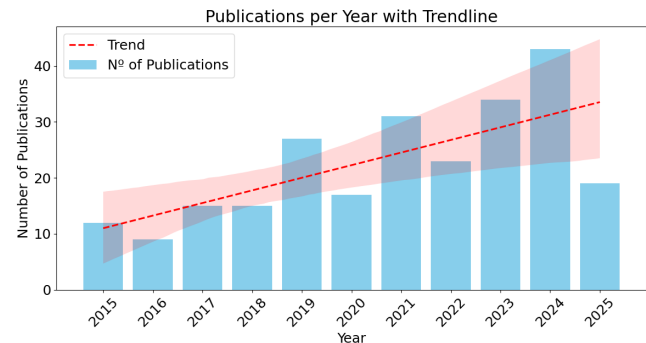


considering journal and conference articles published between 2015 and 2025. The initial results included 266 records from LENS.org, 116 from Web of Science, and 52 from IEEE Xplore. Python scripts were used to remove duplicates and correct metadata inconsistencies. The query applied was:

("quantum key distribution" OR "QKD" OR "CV-QKD" OR "continuous variable QKD") AND ("satellite" OR "space-based" OR "space-to-ground" OR "inter-satellite" OR "orbital" OR "LEO" OR "GEO" OR "space link" OR "optical space link" OR "SAT-QKD") AND ("experiment" OR "demonstration" OR "implementation" OR "field trial") NOT ("fiber" OR "terrestrial network" OR "optical fiber").

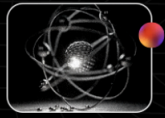
After automated and manual screening, 245 relevant publications remained. Figure 1 shows the annual distribution of satellite-based QKD research, with a linear trendline confirming steady growth. Most (79.2%) address satellite-based QKD, whereas only 6.8% specifically examine CV-QKD protocols. The remainder cover broader theoretical discussions or less-defined approaches. These results underscore the predominance of satellite-based QKD research, with CV-QKD emerging as a promising subfield. All references in subsequent sections were drawn from this systematic search.

Figure 1: Annual distribution of publications from 2015 to 2025 with linear trendline



3. Quantum Key Distribution Protocols

Quantum key distribution protocols are classified into discrete variable (DV-QKD) and continuous variable (CV-QKD) schemes, differing in their implementation requirements and operational principles. DV-QKD protocols encode information in the polarization, phase, or time-bin degree of freedom of single photons, requiring expensive single-photon detectors [3], whereas CV-QKD uses coherent states with quadrature modulation, enabling high-efficiency homodyne or heterodyne detection and leveraging existing telecommunications infrastructure for enhanced scalability [4]. The foundational DV-QKD protocol, BB84, encodes information in the polarization states of photons, allowing communicating parties (Alice and Bob) to detect eavesdropping (Eve) through quantum superposition principles and No-cloning theorem [5, 6]. Enhanced with decoy-state methods, this protocol has demonstrated robust satellite implementations resistant to photon number-splitting attacks [3, 7, 8, 9].



A critical challenge in satellite-mediated QKD involves establishing trust in the orbital platform, which typically relays signals between ground stations without direct connection [3]. While conventional BB84 requires treating the satellite as a trusted node, measurement-device-independent (MDI) protocols circumvent this limitation by having the satellite (Charlie) perform Bell measurements on quantum states from both parties before broadcasting results [10, 11]. This approach enables secure key establishment without relying on Charlie's integrity, although atmospheric turbulence in free-space optics poses implementation challenges [10]. Nevertheless, multiple studies have confirmed the feasibility of MDI-QKD [11, 12, 13], including satellite-based CV-QKD demonstrations [14].

Entanglement-based protocols represent another significant advancement, with extensive theoretical [15, 16, 17, 18, 19, 20] and experimental [21] developments. In these schemes, Charlie distributes entangled photon pairs to Alice and Bob, who perform measurements and basis reconciliation via authenticated channels. The BBM92 protocol extends BB84 by incorporating entanglement measurements, eliminating reliance on Charlie's trustworthiness [16].

4. Satellite-based Quantum Key Distribution Networks

With advances in quantum technologies, satellite communication is becoming essential for the realization and scalability of future quantum networks [7]. Although they have their own limitations, especially related to complications involving the link, positioning, and distribution of satellites, functional applications of quantum key distribution are already known in the literature [3, 8, 14, 22].

The use of satellites in QKD depends on factors such as the distance between ground stations, the number of satellites available, and the protocol adopted. The last one is particularly critical, as it influences and adapts to the other parameters.

Hybrid ground-space integration offers a promising solution to mitigate high attenuation in fiber channels and atmospheric losses in free-space optical (FSO) links. China has demonstrated this approach with an integrated quantum network combining fiber and satellite-to-ground links, achieving a 4,600 km range and a key rate of 47.0 kbps in 2021 [3].

A major challenge in such systems is maintaining alignment between moving satellites. Studies from Australia and Singapore indicate that with a residual pointing error of 10 μ rad, operation is feasible up to 400 km; however, the Pointing, Ac-

quisition, and Tracking Subsystem (PATS) experiences Signal-to-Noise Ratio (SNR) limitations beyond 150 km due to weak tracking-beacon signals [23].

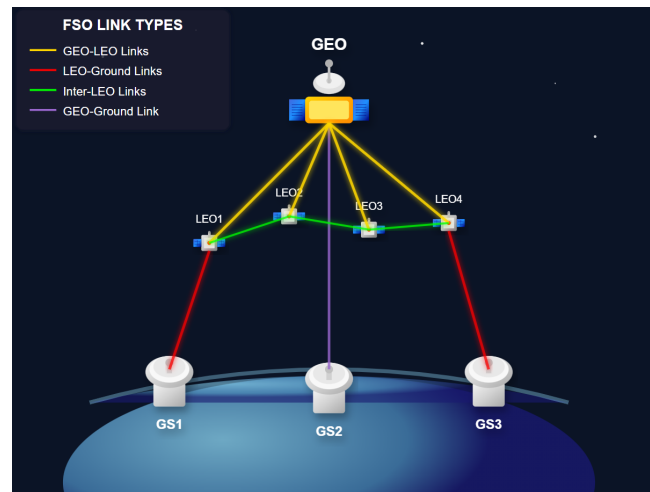
The successful implementation of satellite-based QKD systems fundamentally depends on the alignment between orbital mechanics and quantum communication requirements. Different orbital configurations present distinct advantages for QKD applications, with altitude, inclination, orbital period, and coverage characteristics directly influencing protocol selection, link performance, and system viability.

These parameters critically determine key distribution efficiency, as quantum communication performance exhibits strong dependence on satellite elevation, access duration, and ground station visibility windows. A systematic evaluation of orbital dynamics reveals how specific orbital regimes optimize different aspects of QKD implementations.

4.1. Low Earth Orbit

Low Earth Orbit (LEO) satellites (500-1,200 km altitude) are crucial for quantum communications, as demonstrated by China's Micius satellite [24, 25]. However, these systems face significant signal attenuation (20-30 dB downlink, up to 69 dB uplink) [26], with atmospheric turbulence causing transmittance fluctuations that impair protocol efficiency [18, 27]. Their Earth proximity offers

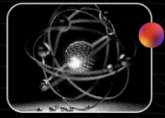
Figure 2: Schematic diagram of the communication between a constellation of satellites and earth stations.



Yellow lines represent optical links between the GEO satellite and LEO CubeSats, which are interconnected by green lines. The red line indicates the link between an LEO and the ground stations (GSs), while the purple line shows the link from the GEO to the GSs.

advantages including reduced diffraction losses [28], relaxed pointing requirements, and simplified adaptive optics needs [29].

The BB84 protocol remains the preferred PM-DV-QKD choice due to its simplicity and proven security [28], typically implemented in S/C bands where single-photon detectors perform optimally [28]. Operational challenges include intermittent coverage with brief access windows (minutes per day) [3, 30] and demanding tracking requirements due to orbital motion [31]. While finite-size effects impact key rates, their effect is less pronounced in LEO [24].



4.2. Geostationary Orbit (GEO)

GEO satellites, located at an altitude of 35,786 km, have complementary characteristics that can be valuable for global quantum networks. This configuration allows permanent connections between the satellite and fixed ground stations, eliminating the complexity of handover between multiple satellites in LEO constellations.

Experiments with Micius have shown that with each handover in LEO, the system requires precise telescope realignment, new negotiation of QKD parameters, and interruption of the quantum key stream [3, 25]. With the extended visibility of the GEO orbit, this problem would be mitigated, allowing continuous data accumulation [24], coverage also simplifies network management by reducing tracking complexity.

This operational difference is particularly relevant in CV-QKD, where link stability is crucial for error correction and privacy amplification protocols allowing the implementation of advanced post-processing schemes that require prolonged iterative exchanges between parties [32]. They offer the advantage of maintaining a continuous connection for extended periods, allowing extended QKD operations, and provide 24/7 availability without orbital restrictions [30].

A GEO system can point to a target user on demand in a short time, without the orbital con-

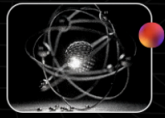
straints imposed on a LEO system by orbital mechanics [30]. Measurements of quantum-limited signals from a geostationary satellite can show total losses of 69 dB [26].

5. Satellite-Based CV-QKD: Challenges and Approaches

Satellite-based CV-QKD employs space-qualified optical communication hardware, enabling high-speed operation with IQ modulators and coherent receivers, making it a scalable and cost-effective option for global quantum networks [16, 24, 27, 33, 34].

CV-QKD protocols may have a practical advantage in free-space applications, especially in satellite-based channels, because a homodyne detector, in which the signal is coupled to an intense, narrow-band local oscillator (LO) beam, intrinsically filters out background radiation at non-coincident wavelengths [26], this suggests that CV-QKD can operate in strong stray light conditions and potentially during the day, which for discrete variable protocols would require additional filtering, increasing attenuation and complexity [29].

CV-QKD in FSO and satellite-to-ground links has been investigated theoretically [24], detailed analyses address the feasibility of CV-QKD with Gaussian modulation in uplink scenarios, considering practical factors such as atmospheric turbu-



lence and pointing errors under dynamic and time-varying orbital parameters [32].

Studies also analyze satellite-to-ground CV-QKD in the downlink scenario, which is more favorable for the transmission [33, 35], preliminary experiments were carried out on signal transmission in FSO and satellite-to-ground links [24]. More recent proposals include the use of optical phase-shift keying (QPSK) signaling and dual heterodyne/threshold detection receivers to increase the reliability and feasibility of satellite entanglement-based FSO-CV-QKD systems [34].

One of the main challenges of CV-QKD is its lower robustness to transmission losses compared to DV-QKD [32]. With current homodyne detectors, positive secure key rates (SKR) can be achieved only for losses not exceeding 20–25 dB, which is very challenging in satellite-to-ground links [29]. For comparison, positive secure key rates with channel losses exceeding 69 dB (over fiber) have been demonstrated with DV-QKD [29].

Satellite-to-ground links are characterized by strongly variable channel attenuation (fading) [18], atmospheric turbulence induces phenomena such as beam wandering and beam broadening, which increase the average link loss [33] to higher orbits, key generation is affected by finite size effects, due to the limited number of symbols exchanged in a single satellite pass for high-loss channels [26], these can be mitigated by achieving

higher transmission rates or considering multiple satellite passes [24].

Although CV-QKD employs standard telecom components, the need for a phase-stabilized local oscillator can raise implementation costs [27]. Atmospheric turbulence is stronger in the uplink, where the signal is affected early in the channel [33], whereas in the downlink most of the path is in vacuum, reducing turbulence effects [7, 35].

Simulations indicate that uplink QKD in the Micius orbit remains highly challenging and is more feasible in lower orbits [32]. To enhance uplink CV-QKD performance, optimization of orbital parameters, beam spot size, receiving aperture, and modulation variance has been proposed [32].

Segmenting the satellite pass and extracting keys from each segment, rather than from the entire pass, improves robustness against channel noise and enables secure key generation even under active collective attacks; this approach also mitigates fading, increasing the secure key rate and enabling communication with higher-altitude satellites [26].

The use of squeezed states extends CV-QKD operation to higher loss and noise levels under given security assumptions, though compression must be optimized for collective-attack scenarios [18]. CV-QKD with discrete modulation offers lower implementation requirements, acceptable key rates, and compatibility with existing in-



frastructure. In satellite-to-ground links, where payload weight is critical, the homodyne protocol with QPSK shows greater tolerance to excessive noise [33, 34].

6. Conclusion

The coexistence of classical and quantum applications in different satellite orbits demonstrates the potential for faster and more secure global communication. While GEO satellites offer broad coverage for QKD over long distances, LEO satellites stand out for their low latency, essential for real-time applications.

Hybrid integration, as demonstrated by the Micius fiber-optic network, is already a reality and is expected to expand as satellite constellations evolve. The most promising solution for global quantum networks may lie precisely in the synergistic integration of these two approaches, combining the high transmission rate of LEO satellites with the continuous coverage provided by GEO satellites [32].

This integration will, however, require significant advances on several fronts, including the development of dedicated QKD satellites, more robust protocols for operation in high-attenuation conditions, and the standardization of interfaces between the ground and space segments. The studies analyzed suggest that, with appropriate investment and technological development, satellite-based quantum networks could become an opera-

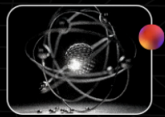
tional reality within the next decade, thus revolutionizing the secure communications landscape on a global scale.

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