Detection Methods in CV-QKD System: A Systematic Literature Review

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Continuous Variable Quantum Key Distribution (CV-QKD) aims to strengthen communications security by using quantum mechanics to protect encryption against eavesdropping. In this context, the effective detection of quantum states is a crucial factor for the performance and security of CV-QKD systems. In order to provide a current and concise overview of the detection methods used in experimental CV-QKD setups, 42 articles published between 2019 and 2024 were selected and analyzed. As a result, trends were identified, such as the temporal evolution of publications and the predominant detection method. In summary, CV-KD detection studies have shown an upward trend over the last five years and are promising for the future of communications security.
Keywords: Systematic Literature Review. Quantum Key Distribution. Continuous Variable. Detection.

Security is crucial in a digital environment increasingly threatened by sophisticated attacks [1]. In this context, Continuous Variable Quantum Key Distribution (CV-QKD) emerges as a technology that promises to shape the future of communication, guaranteeing the protection of cryptographic keys through the principles of quantum mechanics [2]. Using the unique properties of quantum states, CV-QKD offers cryptography theoretically immune to interception, surpassing traditional methods [3]. Considering the growing complexity of cyber threats, CV-QKD represents an advanced solution for ensuring secure communication.

Although CV-QKD systems have been extensively studied [4], there is a gap in the literature regarding reviews that focus specifically on detection methods. Efficiently detecting quantum states is crucial to the efficacy of CV-QKD systems, where homodyne and heterodyne detection methods are particularly highlighted [5]. While homodyne detection is recognized for its sensitivity and precision, heterodyne detection is known for its speed and robustness [6]. This study aims to fill the gap in the literature by reviewing detection methods in detail, offering a critical analysis intended to provide an overview of this topic for future studies.

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This paper is structured as follows: Section 2 details the research methodology. Section 3 presents the results. Section 4 summarizes the conclusion of our study.

Materials and Methods

Review Method

The method used is a systematic literature review (SLR), which is defined as a protocol-driven comprehensive review and synthesis of data focusing on a topic or related key questions [7]. Hereinafter, the essential aspects of an SLR are defined, such as the research questions that will guide the study, the search strategy adopted, and the exclusion criteria that will delimit the selection of articles [8,9].

Research Questions

The five research questions presented in Table 1 will guide this study. Therefore, the answers presented later will satisfy the objective of this review.

Search Strategy

The search strategy involves an automated search utilizing a search string to ensure a systematic approach, as recommended by previous research. Four digital libraries are used here: IEEE Xplore, Scopus, arXiv, and Google Scholar. A comprehensive search string incorporates Quantum Key Distribution, Continuous Variable, and Detection. Variations of "CV" and equivalent terms used for methods are included, along with specifications for Detection in Homodyne or Heterodyne. The final search string is: "QKD" AND ("CV" OR "Continuous Variable" OR "Continuous-Variable") AND "Detection" AND ("Homodyne" OR "Heterodyne") AND ("Method" OR "Technique" OR "Implementation" OR "Design"). Adapted search strings for each database are provided in Table 2.

Study Selection

The four exclusion criteria used to select the primary studies are shown in Table 3.

Selection Process

Figure 1 shows a workflow of the selection process, from selecting the digital libraries to extracting the data needed to answer the research questions. The blue hexagons indicate the number of articles filtered after each of the five stages shown in the image.

Threats to Validity

This review aims to analyze studies on detection methods used in experimental setups of CV-QKD systems. It is worth noting that potential biases were not considered in the selection of studies and that the search was not conducted through a manual analysis of all journal article titles. Consequently, some relevant articles on

Table 1. Research questions on literature review.

ID	Research Question
RQ1	Which journal is the most significant concerning publications on QKD detection methods?
RQ2	Which kind of detection methods are the most used in CV-QKD systems?
RQ3	What are the advantages of the detection method(s) discussed in the article?
RQ4	What methods of Digital Signal Processing (DSP) are researchers selecting?
RQ5	Which model of the interferometer is most often used in experimental CV-QKD setups?

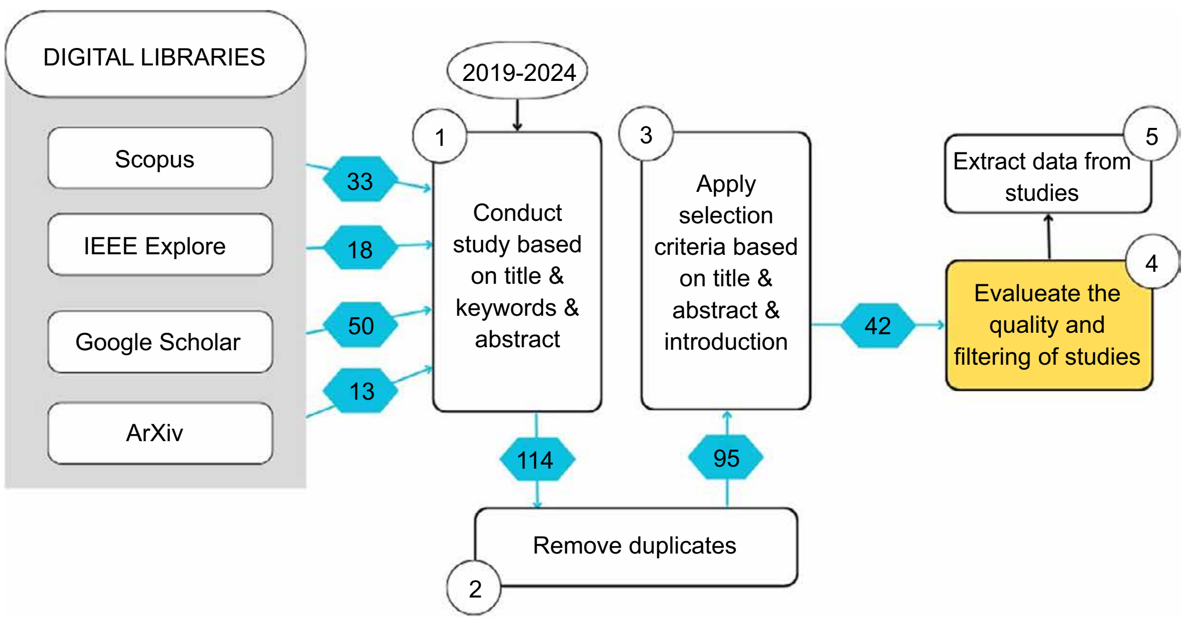
Table 2. Search string according to the database.

Database	Search String
IEEE Xplore	"All Metadata": "QKD") AND ("All Metadata": "CV" OR "All Metadata": "Continuous Variable" OR "All Metadata": "Continuous-Variable") AND ("All Metadata": "Detection") AND ("All Metadata": "Homodyne" OR "All Metadata": "Heterodyne") AND ("All Metadata": "Method" OR "All Metadata": "Technique" OR "All Metadata": "Implementation" OR "All Metadata": "Design"
Scopus	"QKD" AND ("CV" OR "Continuous Variable" OR "Continuous-Variable") AND "Detection" AND ("Homodyne" OR "Heterodyne") AND ("Method" OR "Technique" OR "Implementation" OR "Design")
arXiv	AND all= "QKD"; AND all= "CV" OR "Continuous Variable" OR "Continuous-Variable"; AND all= "Detection"; AND all= "Homodyne" OR "Heterodyne"; AND all= "Method" OR "Technique" OR "Implementation" OR "Design"
Google Scholar	"QKD" AND ("CV" OR "Continuous Variable" OR "Continuous-Variable") AND "Detection" AND ("Homodyne" OR "Heterodyne") AND ("Method" OR "Technique" OR "Implementation" OR "Design")

Table 3. Exclusion criteria on literature review.

ID	Exclusion Criteria
EC1	Article not written in English
EC2	Article published before 2019 (5 years ago)
EC3	Article does not cover CV-QKD systems only
EC4	Article does not cover a detection method in detail

Figure 1. Workflow of the selection process.



detection from conference proceedings or journals may have been missed. In addition, the analysis includes studies from conference proceedings, as experience reports are often published in these.

Results and Discussion

Research Question 1

This literature review includes 42 primary studies on CV-QKD systems detection methods. Question 1 is "Which journal is the most significant in terms of publications on QKD detection methods?". Figure 2 (a) presents a distribution of these studies across different years to illustrate the emerging interest in this topic over time, while Figure 2 (b) displays the most significant detection methods journals. It is noted that, although the number of publications is still in its early stages, the number of studies focused specifically on detection methods for CV-QKD systems has shown an increasing trend over the last five years.

Research Question 2

Question 2 is, "Which detection methods are the most used in CV-QKD systems?" As illustrated in Figure 3, the most used method in the selected studies was homodyne detection (42.9%), followed by heterodyne detection (35.7%), studies covering both (19%) and dual-threshold/heterodyne detection (DT/HD) (2.4%). As a result, the percentage of the two main detection methods used was closely aligned, differing by just 7.2%.

Figure 2. Distribution of selected studies over (a) the years and (b) journal publications.

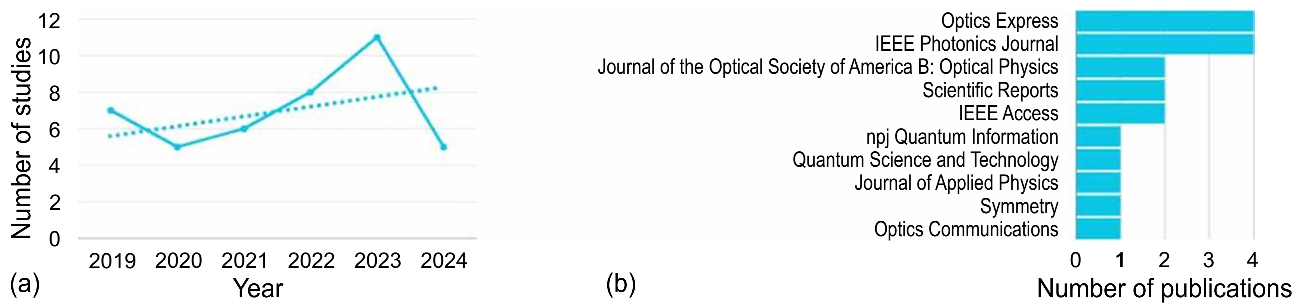
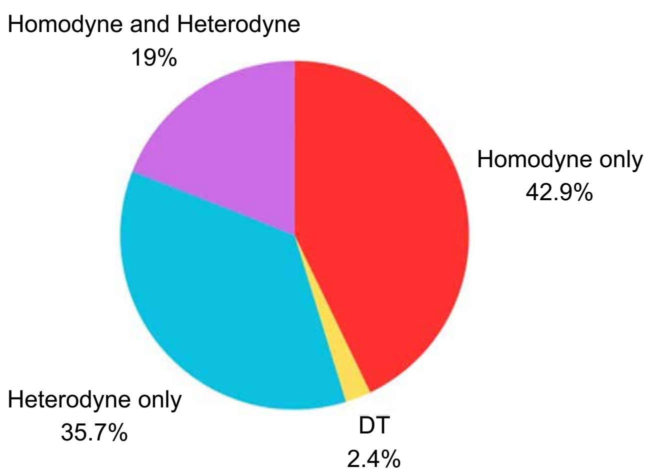


Figure 3. Distribution of detection methods of selected studies.



Research Question 3

Question 3 is "What are the advantages of the detection method(s) discussed in the article?". The selected studies agreed that the CV-QKD systems primarily utilize homodyne and heterodyne detection methods. The main advantages described by the selected studies for each of these methods are summarized by homodyne detection, heterodyne detection and Dual-threshold/ heterodyne detection (DT/HD).

Homodyne Detection

This method is more straightforward to implement and more efficient, allowing the measurement of one quadrature component at a time by randomly selecting phase shift of $\theta = 0$ or $\theta = \pi 2$ for each incoming mode [4]. It facilitates straightforward extraction of phase information from the quantum states transmitted between Alice and Bob [10], and it uses standard optical components, making it practical for real-world applications [11]. It effectively manages noise, crucial for maintaining key distribution integrity over long distances and in fluctuating environments [12]. The method enables higher key rates than discrete-variable systems by extracting more information from quantum states. Its high sensitivity and ability to achieve a high signal-to-noise ratio (SNR) benefit long-distance communication. Also in this category, variations such as balanced homodyne detection [13,14], parametric homodyne detection [15], and time-division dual-quadrature homodyne detection (TDDQHD) [16] have been adopted by the selected studies.

Heterodyne Detection

This method enables the simultaneous measurement of both quadratures [4], enhancing the amount of information extracted and improving the key generation rate [10,11,17,18]. It offers better noise resilience and increased robustness against specific eavesdropping attacks [4]. Heterodyne detection also avoids security risks related to local local oscillator (LLO) manipulation, which can concern homodyne setups [19]. Furthermore, it is compatible with existing coherent optical telecommunications infrastructure, facilitating easier integration into current systems [20].

Dual-Threshold/Heterodyne Detection (DT/HD)

Implementing a DT/HD receiver improves the receiver's sensitivity compared to dual-threshold/ direct detection (DT/DD), thereby offering the advantage of reducing quantum bit errors. In the selected study, this detection method was used to strengthen the reliability and viability of satellite EB/CV-QKD/FSO systems, which utilizes the continuous-variable (CV) method for quantum state representation and the entanglement-based (EB) scheme for QKD implementation. Furthermore, these systems are expected to contribute to global security in the upcoming sixth-generation (6G) wireless communications [21].

Research Question 4

Question 4 is "What methods of Digital Signal Processing (DSP) are being selected by researchers?". According to the selected studies, the DSP methods being used by researchers include real-time polarization calibration, phase compensation, data synchronization [22], clock synchronization, static and dynamic equalization, frame synchronization, pulse shaping [4], error correction, privacy amplification [17], real-time phase feedback and quadrature remapping [13]. Besides, improvements in algorithms and numerical methods are being explored to enhance the proposed protocol's performance, including using neural network models to predict secure key rates quickly and accurately [23]. It also adopted the use of optimized high-pass filters (HPFs) to manage noise and intersymbol interference (ISI), as well as machine learning frameworks for phase carrier recovery [24]. Lastly, a pilot-tone-assisted frequency locking algorithm was used to ensure phase and frequency coherence between the transmitter and receiver's laser signals, thereby enhancing the reliability of the CV-QKD system [25].

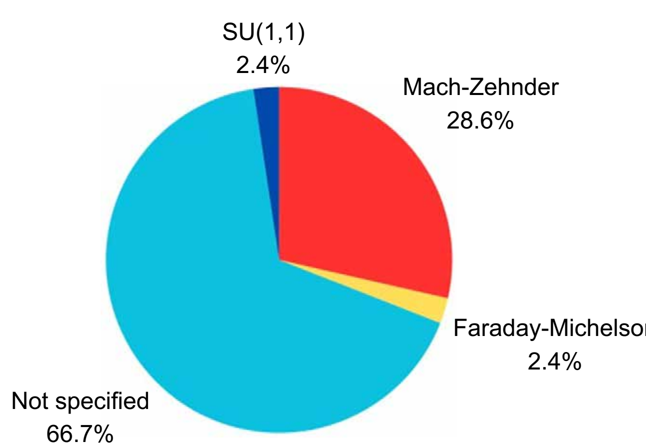
Research Question 5

Question 5 is "Which interferometer model is most often used in experimental CV-QKD setups?". Figure 4 shows the distribution of the three interferometer models used in the CV-QKD experimental setups. As shown in the figure, most articles did not explicitly specify the interferometer model used (66.7%). Among the models specified, the most used was Mach-Zehnder (28.6%), followed by Faraday-Michelson (2.4%) [16] and SU(1,1) (2.4%) [15]. Accordingly, some potential reasons for the Mach-Zehnder interferometer being the most widely used in CV-QKD systems may include its high sensitivity, flexibility in configuration, ability to measure specific changes, and lower sensitivity to external disturbances. Besides, its ability to effectively manipulate and measure the quantum states allows the necessary phase and polarization adjustments required for secure key distribution [22].

Conclusion

In summary, this systematic literature review analyzed 42 articles based on exclusion criteria to fill the gap of review articles focusing specifically on detection methods in CV-QKD experimental setups. The results, guided by the research questions, revealed a growing trend in publications in the area over the last five years. Among the detection methods adopted in the selected studies, the homodyne emerged as the most widely used,

Figure 4. Distribution of interferometer models of selected studies.



while the Mach-Zehnder interferometer was the most common in experimental implementations. In addition, the digital signal processing (DSP) methods used by researchers and the advantages associated with each detection technique were identified. Future research should focus on integrating these detection methods into real communication scenarios to improve the safety and effectiveness of CV-QKD systems.

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