Overview of Physical Channel Modeling in CV-QKD Systems

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Abstract: Continuous-Variable Quantum Key Distribution (CV-QKD) is a promising solution for secure quantum communication, offering compatibility with standard optical components and potential for high key generation rates. However, practical deployments face critical challenges due to imperfections in the physical communication channel. These include optical attenuation, excess noise, polarization disturbances, residual phase noise, and crosstalk from coexisting classical channels, all of which impact the system's secure key rate (SKR). This work provides a comprehensive analysis of physical channel modeling in CV-QKD systems, focusing on how different models capture transmittance degradation and excess noise. We begin with the standard lossy bosonic channel and extend the discussion to more specific models addressing polarization effects, nonlinear interference in DWDM networks, phase fluctuations in LLO-based architectures, propagation impairments in free-space optical (FSO) links, and modulation-induced distortions, including discretized Gaussian modulation and multi-carrier OFDM schemes. We further examine the limitations and applicability of these models in realistic scenarios, considering finite-size effects, time-varying channel conditions, and calibration inaccuracies. These insights contribute to the development of more accurate security analyses and performance optimization strategies for CV-QKD systems deployed in practical environments.
Keywords: Physical channel modeling. Quantum communication channels. Continuous-variable quantum key distribution.

1. Introduction

The security of modern communications, traditionally based on the computational hardness of mathematical problems, faces a critical challenge with the advent of quantum computing and algorithms such as Shor's algorithm [1]. In this emerging context, Quantum Key Distribution (QKD) has become a foundational technology, offering information-theoretic security grounded in the fundamental principles of quantum mechanics, particularly the Heisenberg Uncertainty Principle and the No-Cloning Theorem [2].

QKD enables two legitimate parties, commonly referred to as Alice and Bob, to establish a shared secret key that can subsequently be used for encrypted communication with perfect secrecy, such as through the One-Time Pad protocol [3, 4].

Among the various QKD implementations, Continuous-Variable Quantum Key Distribution (CV-QKD) has received considerable attention [5]. Unlike discrete-variable QKD (DV-QKD), which typically requires single-photon detectors—often costly and inefficient—CV-QKD encodes information in the continuous quadratures of the optical field (e.g., amplitude and phase), leveraging coherent detection methods compatible with commercially available optical components [4]. This compatibility offers several practical advantages, including high quantum efficiency, the potential for elevated secret key rates over short distances, and the ability to coexist with classical communication systems on a single fiber through Wavelength Division Multiplexing (WDM) [6].

The robustness and practical performance of a CV-QKD system are critically dependent on the accuracy of the physical channel model and the effectiveness of strategies for mitigating the imperfections introduced by the channel [7]. The coherent optical channel—whether implemented via fiber or free-space optics (FSO)—is inherently non-ideal and introduces various disturbances that can adversely affect the Secure Key Rate (SKR), thereby compromising the system's security [6, 4].

This paper aims to present a comprehensive analysis of physical channel models used in CV-QKD systems, with a particular focus on coherent optical communication channels. We investigate how different physical and mathematical formalisms describe the behavior of these channels, accounting for critical effects such as attenuation, thermal noise, Gaussian excess noise, and optical losses. Furthermore, the study evaluates the capacity of these models to effectively capture and manage such imperfections, thereby providing a solid theoretical foundation for the design and optimization of practical CV-QKD systems.

2. Coherent Optical Channels in CV-QKD

At the core of Continuous-Variable Quantum Key Distribution (CV-QKD) lies the encoding of secret information onto the quadratures of a quantum state of light, typically coherent states that resemble high-quality laser light [8]. The most widely studied encoding scheme is Gaussian Modulated Coherent States (GMCS), in which the position ($\hat{X}$) and momentum ($\hat{P}$) quadratures follow a Gaussian distribution with zero mean and variance V_A [9].

To decode these states, the receiver (Bob) employs coherent detection techniques—namely, homodyne or heterodyne detection [2]. Both methods require a strong local oscillator (LO) to interfere with the weak quantum signal, amplifying it and enabling quadrature measurements limited only by shot noise [8]. The method by which the LO is delivered to the receiver represents a critical architectural choice in system design.

Transmitted Local Oscillator (TLO)

In the TLO scheme, the LO is generated by Alice and transmitted alongside the quantum signal over the same public optical channel. This approach ensures phase stability between the signal and LO, which is essential for coherent detection [10, 11]. However, transmitting a strong classical LO introduces potential security vulnerabilities. Notably, it enables side-channel attacks such as LO calibration attacks or manipulations of the LO's intensity and polarization, which adversaries can exploit to extract information or destabilize the system [10].

Local Local Oscillator (LLO)

In contrast, the LLO scheme generates the LO locally at Bob's side using an independent laser [9]. This architecture eliminates the attack surface associated with LO transmission, making it more secure and suitable for practical applications [10].

However, it also introduces technical challenges, primarily the need to compensate for phase noise and frequency drift between the independent lasers of Alice and Bob. These factors are a significant source of excess noise and may affect the system's overall performance [10].

3. Critical Channel Parameters

The performance of a Continuous-Variable Quantum Key Distribution (CV-QKD) system, typically quantified by the Secure Key Rate (SKR), is fundamentally constrained by two critical channel parameters: channel transmittance (T) and excess noise (ε) [12]. The SKR denotes the amount of secure key material that can be generated per unit time, usually expressed in bits per symbol or bits per second [12].

The relationship between the transmitted and received signals in a CV-QKD channel can be approximated by a simplified linear model:

$$y = tx + n,$$

where y denotes the received signal, x is the transmitted signal, t represents the channel transmittance, and n accounts for both channel-induced noise and intrinsic system noise [5].

Channel Transmittance (T)

Channel transmittance characterizes the efficiency with which the quantum signal propagates through the transmission medium. It is influenced by the physical properties of the medium—such as the quality and length of optical fibers—or, in the case of free-space optics (FSO), by atmospheric conditions (e.g., fog, rain, and turbulence) and alignment precision [12]. Lower transmittance implies greater signal attenuation, reducing the amount of quantum information reaching Bob and consequently diminishing the SKR.

In optical fiber channels, transmittance is often modeled as:

$$T = 10^{-\alpha d/10},$$

where α is the attenuation coefficient in dB/km and d is the transmission distance in kilometers [10].

Excess Noise (ε)

Excess noise encompasses all noise contributions beyond the fundamental quantum shot noise [12]. This includes technical imperfections, environmental fluctuations, and possible eavesdropping strategies. Minimizing excess noise is critical for CV-QKD performance, as it can be exploited by an eavesdropper (Eve) to extract information from the quantum channel [5]. Therefore, accurately estimating and mitigating excess noise is essential for maintaining system security and achieving a positive SKR.

4. Sources of Physical Channel Imperfections

Several physical-layer imperfections contribute to excess noise and affect channel transmittance in

CV-QKD systems. These impairments originate from both quantum and classical sources and must be carefully modeled and mitigated to ensure reliable and secure operation.

Optical Losses

Optical losses are intrinsic to any transmission medium. In fiber-optic systems, they are primarily caused by absorption and scattering. In free-space optical (FSO) channels, atmospheric attenuation—due to fog, rain, snow, and molecular absorption—can be significant [13].

Electronic Noise

Receiver-side electronic components, such as photodetectors and amplifiers, introduce electronic noise (V_{el}), which adds to the quantum signal and contributes to excess noise [7].

Shot Noise and Thermal Noise

Shot noise is a fundamental quantum noise arising from the discrete nature of photons and serves as a reference level for CV-QKD system sensitivity. Thermal noise, generated by thermal agitation of electrons in electronic components, can also degrade system performance [14]. Any noise above the shot noise level is typically categorized as excess noise.

Temporal and Spectral Leakage

Imperfect modulators and synchronization mechanisms can cause time-domain diffusion and spectral leakage. These imperfections manifest as unintended residual modulation and photon leakage, resulting in measurable excess noise [12].

Polarization Disturbance

In fiber-based systems, random birefringence in standard single-mode fibers (SSMF) causes unpredictable variations in the state of polarization (SOP) of the quantum signal. These fluctuations can introduce cross-polarization interference and increase noise [12].

Photon Leakage

Photon leakage occurs when photons from high-power channels—such as the local oscillator (LO) or reference tones—leak into the low-power quantum signal path. This leakage introduces noise and potential crosstalk, particularly in shared-fiber architectures [6].

Crosstalk in Coexisting Networks

Coexistence of CV-QKD with high-power classical channels in dense wavelength-division multiplexing (DWDM) networks introduces significant challenges. Classical signals, with photon flux orders of magnitude higher than quantum signals, can induce nonlinear effects such as four-wave mixing (FWM) and stimulated Raman scattering (SRS), leading to crosstalk and fluctuations in LO power [15]. These phenomena directly impact the SKR [15].

Phase Noise

In local oscillator-based (LLO) CV-QKD systems, where the LO is generated locally at the receiver, phase and frequency offsets between Alice's and Bob's lasers introduce residual phase noise. This is a major source of excess noise and must be carefully modeled [10].

Modulation-Induced Noise

In multi-carrier schemes such as orthogonal frequency division multiplexing (OFDM), practical limitations like IQ imbalance and intermodulation distortion can degrade quantum state preparation [14]. Additionally, discretization of ideal Gaussian modulation—commonly implemented as Discretized Polar Modulation (DPM)—may introduce parameter estimation bias, leading to overestimation of excess noise and underestimation of SKR if not properly calibrated [16].

5. Physical Channel Modeling in CV-QKD

Accurate mathematical modeling of the physical channel is essential for the analysis, simulation, and optimization of CV-QKD systems. Channel models aim to capture how the imperfections described earlier affect the propagation of quantum signals and ultimately the secure key rate (SKR).

5.1. Lossy Bosonic Channel

The most fundamental and widely adopted model for representing optical channels in CV-QKD is the lossy bosonic channel, often referred to as a linear attenuation channel. This model assumes that the optical signal undergoes linear attenuation, while the added noise is Gaussian and originates from either vacuum fluctuations or a thermal reservoir [5]. The simplified linear relation $y = tx + n$ underpins most security and performance analyses in CV-QKD.

Channel impairments are modeled via perturbations to the annihilation operators of the quantum signal and reference tones. For example, after channel propagation, the annihilation operators of the reference tone ($\hat{\alpha}'_{ref}$) and the quantum signals ($\hat{a}'_{s1}$, $\hat{a}'_{s2}$) are expressed in terms of leakage factors (h) and temporal/frequency dispersion parameters (q_{1s}, q_{2s}), allowing detailed analysis of how transmittance and excess noise are impacted [12].

5.2. Excess Noise-Specific Models

To capture the diversity of excess noise sources, specialized models are developed for distinct physical effects:

Polarization Perturbation

Channel-induced polarization rotation degrades both transmittance and excess noise performance. Dual-polarization division multiplexing (DPDM) models allow quantitative analysis of polarization extinction ratio (PER) impacts. Photon leakage between polarization modes is modeled using modified annihilation operators affected by time and frequency diffusion [12].

DWDM-Induced Crosstalk

In networks where CV-QKD coexists with classical dense wavelength-division multiplexing (DWDM) channels, nonlinear effects such as stimulated Raman scattering (SRS) and four-wave mixing (FWM) introduce stochastic fluctuations in the local oscillator (LO) power [15, 17]. Modeling these effects involves deriving the LO power evolution under fiber attenuation and classical channel interference. These fluctuations affect Bob's measurement statistics and post-processing parameter estimation, degrading SKR.

Phase Noise Modeling

Residual phase noise is a major performance-limiting factor in LLO-based CV-QKD systems. Phase noise models incorporate contributions from detector electronics, the monitored intensity of the phase reference, and the measurement noise from phase tracking [10]. Kalman filters, particularly vector Kalman filters, are commonly used to estimate and compensate for both slow and fast phase drifts and laser frequency offsets [18]. These techniques improve signal recovery under time-varying channel conditions [19].

Modulation Noise: Discretization and Multi-Carrier Effects

- **Discretized Gaussian Modulation (DPM):** Practical implementations often discretize Gaussian modulation, introducing modulation-induced fluctuations in the quadratures. These preparation noises are misattributed to channel parameters, leading to overestimation of excess noise and underestimation of SKR if not properly calibrated. The bias depends on the resolution of modulation levels [16].

- **Multi-Carrier OFDM Systems:** Imperfections such as in-phase/quadrature (IQ) imbalance and intermodulation distortion degrade the fidelity of multi-carrier quantum state preparation. Systematic models have been proposed to assess the impact of these modulation-induced impairments [14].

5.3. Model Limitations and Applicability Conditions

The accuracy and applicability of these models are bounded by several practical considerations:

Finite-Size Effects

Security proofs often assume an asymptotic regime with an infinite number of exchanged signals. However, practical implementations involve a finite number of signals, which imposes stricter requirements on block size and excess noise control [10]. Composable security analysis is essential in such scenarios [8].

Time-Variant Channels

Environmental disturbances in LLO-based CV-QKD systems can induce time-varying channel behavior, particularly over long acquisition blocks. Accurate estimation and compensation of time-varying parameters are necessary to maintain system performance [19].

Calibration Accuracy

Discretization-induced noise (e.g., from DPM) and other imperfections require precise calibration procedures. Overestimating the homodyne detection efficiency may lead to an overestimated SKR and reduce the system's secure transmission distance [20].

6. Conclusion

The security and practical performance of CV-QKD systems are deeply influenced by the characteristics of the physical communication channel. This paper presented a comprehensive overview of the critical parameters and imperfections that affect channel transmittance and excess noise, both of which directly impact the achievable SKR.

We examined the standard lossy bosonic channel model and extended the discussion to include more specific modeling approaches tailored to polarization effects, nonlinear crosstalk in DWDM networks, residual phase noise, and modulation-induced distortions. These models help to quantify how physical-layer impairments influence system security and performance under practical conditions.

Furthermore, we discussed the limitations and applicability of these models in the context of finite-size effects, time-varying channels, and calibration inaccuracies. These factors are critical when designing CV-QKD systems intended for real-world deployment, where idealized assumptions do not hold.

Looking forward, accurate and adaptive modeling of quantum channels remains an essential component in the advancement of CV-QKD technologies. Future research should focus on the integration of machine learning techniques for real-time channel estimation, robust calibration under non-stationary conditions, and composable security proofs tailored to time-dependent and discretized systems.

Ultimately, a solid understanding of physical channel behavior—supported by reliable mathematical models—is a key enabler for the secure, scalable, and efficient deployment of quantum communication systems.

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