



Performance Analysis of Continuous Variable Quantum Key Distribution Over Free Space Optical Channel under Fog Conditions

Ibtihaj Hameed Qaddoori¹ and Shelan Khasro Tawfeeq²^{1,2} Institute of Laser for Postgraduate Studies, University of Baghdad, Baghdad, Iraq.

• These authors contributed equally to this work

DOI: <https://www.doi.org/10.29194/NJES.29030515>

Received: Dec. 16, 2025

Revised: Feb. 4, 2026

Accepted: Feb. 23, 2026

Published: Sep. 20, 2026

Abstract

Quantum key distribution (QKD) provides secure keys with information-theoretic security ensured by the principles of quantum mechanics. The flexibility and efficient deployment of free-space optical (FSO) quantum key distribution systems can make them highly advantageous. Despite the benefits of free-space transmission, there is still a chance of running into unfavorable weather conditions like fog. According to this study, free-space continuous variable (CV) QKD systems may be applicable when fog is present. Using attenuation based on the Kim and Kruse empirical visibility models, the performance of the models that explain the relationship between fog attenuation and air visibility is examined in order to evaluate its impact on the secure key rate (SKR) at wavelengths of 850 and 1550 nm. A comparative analysis between the two wavelengths is carried out to highlight their suitability under different weather conditions. Based on the results, 1550 nm performs better in foggy situations, reaching an SKR of 1.389379 bits/symbol, because of lower scattering losses, whereas 850 nm achieves a longer range of 12 km in clear air because of smaller diffraction divergence. The results demonstrate that wavelength selection plays a critical role in enhancing the robustness of CV-QKD systems that operate over FSO links. In addition, optimizing reconciliation efficiency (β) under thick-fog conditions greatly improved the SKR, indicating that 1550 nm operation has the ability to achieve reliable and secure quantum communication. Results show that varying β from 0.90 to 1.00 for both 850 nm and 1550 nm produces SKR enhancement of (0.63-0.80 bits/symbol) and (0.97-1.13 bits/symbol), respectively.

Keywords: Continuous Variable Quantum Key Distribution, Secure Key Rate, Reconciliation Efficiency.**Corresponding author:** Provide the corresponding author information and publisher here. E-mail address: ibtihaj.hameed2202p@ilps.uobaghdad.edu.iq

1. Introduction

Alice and Bob, two authorized faraway parties, can share a common key over a potentially eavesdropped quantum channel using QKD [1]. This method protects the key exchange from eavesdropping assaults by utilizing the Heisenberg uncertainty principle and the concepts of quantum physics [2]. QKD is separated into two groups according to the shapes of its quantum states. One is connected to discrete variables, such as a single photon's polarizations; these are known as discrete-variable QKD (DV-QKD) protocols, and they require a dedicated single photon source and counter in order to encode the information on the single photon's discrete variable. The standard DV-QKD famous protocols are SARG04, B92, and BB84 [2]. The second one, referred to as continuous-variable QKD (CV-QKD) protocols, encodes information on the conjugate quadratures of the optical field and is related to the CV of quantized electromagnetic field. Ralph, Hillery, and Grosshans and Grangier (GG02) [2] describe the widely used standard protocols for CV-QKD. CV-QKD procedures use balanced intradyne detection methods with light sources that are not at the single-photon level, particularly those with a coherent-state (CS). Therefore, as compared to DV-QKD, this approach offers the advantages of higher detection efficiency, higher secure key rate, and longer transmission distance [1,3]. Coherent state-based CV-QKD is quickly gaining popularity since it works with current telecommunication equipment. CV-QKD, for instance, can use a commercial continuous-wave laser in conjunction with a coherent receiver [4]. CV-QKD techniques can be classified as discrete

modulation (DM CV-QKD) or continuous Gaussian modulation (GM CV-QKD) based on the modulation strategy. In the former, such as with GMCS or GG02 protocols, Gaussian modulation is carried out for both the amplitude and phase quadratures. The latter relies on discrete modulation of the quadratures, such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) [5,6]. GM CV-QKD stands out as a cornerstone methodology, providing important advantages in terms of security, robustness and operational efficiency. This approach influences the continuous nature of quantum variables, allowing for an information-dense encoding process compared to discrete methods [4].

Using an FSO channel or optical fiber, the CV-QKD initiates the quantum states with a secret key [2]. If a line-of-sight (LOS) link can be established between the transmitter and reception sites, FSO can be easily deployed in a matter of hours, much like optical fiber channels, which both provide enormous bandwidth for data transfer [7]. The light polarization remains almost constant during propagation because FSO is less sensitive to polarization than a fiber channel [1]. Establishing QKD links across land and sea surfaces can be greatly aided by free-space QKD.

For instance, it can link communication terminals between islands, buildings in cities, and mountains [8]. Since absorption, scintillation, and scattering are the primary elements influencing FSO communication links, they are susceptible to air turbulence and route loss from precipitation, fog, and clouds. Fog is regarded as a severe weather phenomenon that can restrict sight to a few meters and, in

the worst situations, cause considerable attenuation of up to 480 dB/km [2]. Link outputs may result from this high attenuation since it lowers link availability [7]. Optical signal attenuation can even approach 480 dB/km and 130 dB/km in thick and moderate continental fog [9]. In foggy conditions, Mie scattering predominates, leading to optical attenuation [10]. However, because signals move in open spaces and the weather is typically unpredictable, fog can occasionally present a challenging scenario [8].

In [2,4], free-space QKD over an actual atmospheric channel was thoroughly reviewed. A few empirical models have been put out in the literature to simulate fog attenuation. The simulation results indicate that the scattering effect of fog particles is related to the transmission wavelength. With lower operating wavelength, the greater the fog attenuation, and that the wavelength window of 1550 nm is more appropriate for the FSO system. In [9] an analysis of the influence of fog on transmission performance objectives such as bit error rate and quality factor of FSO system with different operating wavelengths are presented. A transmission distance of 1.8 km at a visibility of 1.5 km can be accomplished in an experiment of FSO QKD employing CV in foggy conditions, as shown in [8]. The results indicate that FSO CV-QKD systems may be useful in the presence of fog. A unified model for fog attenuation in FSO communication links is derived in [7] by taking into account and analyzing fog measurement data. When the performance of the suggested model is compared to that of other well-known alternative models, it outperforms them by more than 9 dB on average RMSE. In [11], field tests were carried out with a self-developed FSO terminal at a data rate of 2.5 Gbps under varying turbulence levels and meteorological conditions, experimental outcomes show close agreement with the model's predictions, and provide a reliable reference for performance evaluation and link planning of urban FSO systems.

This article examines the GM CV-QKD horizontal link on Earth's surface and focuses on using free space as the transmission medium while accounting for the difficulties presented by fog-induced atmospheric attenuation, which may impair the functionality of QKD systems that uses FSO communication. The fog effects on SKR and coherent state transmission in free-space for GM CV-QKD were examined. We also look at whether free-space CV-QKD is feasible in a foggy environment. Using Kruse and Kim attenuation models, the performance of free-space CV-QKD systems at various visibility levels was assessed numerically. The findings suggest that CV-QKD devices could be used in foggy conditions. Additionally, by evaluating the system's SKR, the FSO channel's performance under various fog conditions was examined. Our findings demonstrate how link physical length and weather visibility affect performance behavior. The main scientific contribution of this work is to study how improving reconciliation efficiency enhances the SKR under thick fog conditions at 1550 nm, while other studies have given less attention to the impact of reconciliation efficiency under such conditions. Besides, the attenuation models were investigated by MATLAB, while the SKR values are found using VPItoolkit™ QKD. 850 nm and 1550 nm, the two wavelengths most frequently used in FSO communications, are the subjects of the analysis. The study's goal in creating this system model is to increase the system's reconciliation efficiency, which will enhance quantum communication performance.

The paper is structured as follows: Section 2 provides an overview of the GM CV-QKD protocol and its guiding principles. The formula for calculating SKR based on the acquired transmittance characteristic is described in Section 2.1. Section 2.2 discusses the function of reconciliation efficiency and how it affects the overall performance of the system. The attenuation models, which are used

to describe air losses under various weather circumstances, are explained in Section 3. The results and discussion are presented in Section 4. Section 5 reviews the main points concluded from this paper.

2. GM CV-QKD Protocol

Consider Alice and Bob, two distant parties separated by distance z , serving as a transmitter and a receiver. They are roughly at the same elevation, h , on Earth's surface.

GM CS CVQKD protocol architecture, based on polarization coding over a free-space fog channel, is depicted in Fig. 1. It can be briefly explained as follows:

A train of coherent state pulses is created at Alice's side using a coherent optical source. For each signal pulse, Alice selects two values at random for the orthogonal quadrature P_A and the in-phase quadrature X_A . Two separate random number generators (RNGs) are used to accomplish this, and they generate zero-mean Gaussian distributed random variables (RVs) N [13],

$$N = \mathcal{N}(0, V_{mod}) \quad \dots(1)$$

where V_{mod} is Alice's modulation variance. The weak optical pulses are modulated by an in phase-quadrature (IQ) modulator, which introduces quantum signal pulses (QSPs) utilizing Gaussian RVs. Alice has now completed preparing the GMCS QSPs $|X_A + P_A\rangle$. Through the foggy atmospheric channel, Alice uses the transmitter telescope to relay her coherent states to Bob. To achieve coherent detection, the necessary local oscillator (LO) optical signal is split using a balanced beam splitter (BBS) after being locally created. Bob then uses heterodyne detection to measure the two orthogonal components concurrently without the need for extra random basis selection. The final keys are subsequently generated by Alice and Bob using parameter estimation, data reconciliation, and privacy amplification across a public channel that has been authenticated [13,14].

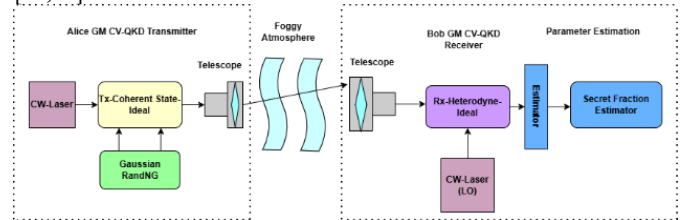


Figure 1. Schematic representation of the GM CV-QKD scheme in foggy FSO channel. CW-laser: continuous wave laser, Tx-Coherent State: coherent state transmitter, Rx-Heterodyne: heterodyne receiver, LO: local oscillator

2.1.SKR in GM CV-QKD

The asymptotic limit of the SKR computation, which assumes Gaussian modulation with security under collective attacks, is defined as [15],

$$SKR = \beta I_{AB} - S_{BE}, \quad \dots(2)$$

where I_{AB} represents the mutual information between Alice, the transmitter, and Bob, the receiver, and β is the reconciliation efficiency. The estimated knowledge of an eavesdropper, Eve, is denoted as S_{BE} (Holevo bound).

Alice and Bob's mutual information is connected to the signal's signal to noise ratio (SNR) by [16].

$$I_{AB} = \frac{1}{2} \log_2(1 + SNR), \quad \dots (3)$$

And SNR can be expressed by,

$$SNR = \left(1 + \frac{\frac{1}{2}TV_{mod}}{1 + \frac{1}{\mu}\xi_n}\right) \dots (4)$$

where ξ_n is the excess noise, T is the total transmittance, which includes detection and coupling efficiency, and $\mu=1, 2$ for homodyne or heterodyne detection, respectively. When Eq. (4) is substituted in Eq. (3) [16],

$$I_{AB} = \frac{\mu}{2} \log_2 \left(1 + \frac{\frac{1}{2}TV_{mod}}{1 + \frac{1}{\mu}\xi_n}\right) \dots (5)$$

More precisely, the Beer-Lambert law [17] provides the transmittance.

$$T = \exp(-\gamma L) \dots (6)$$

where the transmission distance is denoted by L . Because of this, the GM CV-QKD protocol's SKR is highly dependent on T , and fog-induced degradation results in poorer SKR generation performance. Two wavelengths that are frequently utilized in free-space devices, such as 850 and 1550 nm, will be used in SKR simulations because they fall within atmospheric transmission windows where scattering predominates and absorption is minimal.

2.2. Reconciliation Efficiency in GM CV-QKD

How well the two parties fix mistakes to create a shared secret key is known as reconciliation efficiency in GM-CV-QKD. Because it has a direct effect on the final SKR, it is essential for performance. High reconciliation efficiency for GM-CV-QKD is theoretically possible but difficult to sustain in practice because of things like variable SNR and system flaws [18]. Two crucial methods for error correction and privacy amplification are direct reconciliation (DR) and reverse reconciliation (RR). These methods are crucial for guaranteeing that the quantum key generated between Alice, the sender, and Bob, the recipient, is secure, identical, and impervious to possible eavesdropping. Alice initiates the process in DD (Eq. (7)) by transmitting her encoded quantum states to Bob over the quantum channel. The received states are then measured by Bob. Bob and Alice have different roles in the reconciliation process in RR (Eq. (8)). [14] provides the length of the secure key.

$$K_{DR} = I(A; B) - I(A; E) \dots (7)$$

$$K_{RR} = I(B; A) - I(B; E) \dots (8)$$

3. Attenuation Models for Fog

Based on actual measured visibility values, empirical models are typically employed to forecast the attenuation effect of fog on laser transmission. Mie scattering theory serves as the primary foundation for this attenuation type. The researchers' first empirical model for calculating fog attenuation was proposed by Kruse [9], which uses Eq. (9) to represent the attenuation coefficient [8],

$$\gamma = \frac{3.912}{V} \left(\frac{\lambda}{550}\right)^{-q} \dots (9)$$

where q is the size distribution parameter of scattered particles that relies on visibility, γ is the air attenuation coefficient, V is the measured visibility value in kilometers, and λ is the optical wavelength in nanometers. Kim and Kruse models [9], are well known, widely used in literature and recommended by ITU-R for FSO attenuation modelling. Newer models such as, Al-Naboulsi and Ijaz models [7], are not recommended in this study because they are designed for very dense fog with visibility below 1 km. This article studies the performance of CV-QKD across wider range of visibility (0.2-20 km). The Kruse model allows for the following common values of q to be determined [9],

$$q = \begin{cases} 1.6, & V \geq 50 \text{ km} \\ 1.3, & 6 \text{ km} \leq V < 50 \text{ km} \\ 0.585V^{1/3}, & V \leq 6 \text{ km} \end{cases} \dots (10)$$

Visibility, which is more practical and convenient in the limited wavelength range of 785-1550 nm, is related to the formula for computing the attenuation coefficient using the Kruse model. Kruse model is not suitable to be applied in limited visibility situations (less than 6 km), accordingly Kim introduced a model that improves the accuracy in limited visibility by changing the value of q [15] and predicts visibilities < 500 m, the 550 nm and the 1550 nm will be muted at the same level [7,11].

$$q = \begin{cases} 1.6, & V \geq 50 \text{ km} \\ 1.3, & 6 \text{ km} \leq V < 50 \text{ km} \\ 0.16V + 0.34, & 1 \text{ km} \leq V < 6 \text{ km} \\ V - 0.5, & 500 \text{ m} \leq V < 1 \text{ km} \\ 0, & V < 500 \text{ m} \end{cases} \dots (11)$$

The fog-induced attenuation that can vary from several decibels per kilo meter (dB/km) to hundreds of dB/km is strongly related to specific visibility. The visibility is (roughly) a distance where the 550 nm collimated light beam is attenuated to a fraction (5%, or sometimes 2%) of an original power. It is measured regularly near the airports, for example. Once the visibility statistics are known, the attenuation statistics can be obtained provided the relation between these two quantities is known [11]. Hence the performance of CV-QKD should be discussed under different visibility conditions. The analysis of the measurements data shows a reciprocal relationship between the signal attenuation and the visibility. The signal attenuation increases as the visibility decreases.

4. Results and Discussion

4.1. Spatial Distribution of GM CV-QK Signal

CV-QKD over a foggy channel is a difficult problem because attenuation affects the transmitted quantum signal quality. This can impact the received signal's spatial dispersion and complicate the process of establishing a secure key between the two parties, particularly in challenging situations or over great distances [14].

Using both the Kim and Kruse attenuation models, Fig. 2 shows the spatial intensity distribution of the GM CV-QKD signal at Bob's side under various visibility conditions. Each subplot represents a distinct weather condition: clear air ($V=20,000\text{m}$), light fog ($V=1900\text{m}$), moderate fog ($V=500\text{m}$), and heavy fog ($V=200\text{m}$). The received beam retains a strong and well-focused Gaussian profile in clear air, suggesting good transmittance and low optical attenuation. A large decrease in peak intensity and a wider, weaker distribution are the results of scattering and absorption, which greatly attenuate the beam power as fog density rises. In the circumstances of thick and moderate fog, where the normalized intensity decreases by several orders of magnitude, this decline is very noticeable.

Because of its lower estimated attenuation under the same vision, the Kim model typically forecasts slightly higher received intensities than the Kruse model. This suggests that the Kim model may reflect more optimistic propagation scenarios and has a tendency to be less conservative. These findings generally support the idea that fog-induced attenuation significantly restricts the optical channel transmittance, which lowers the system's possible SKR.

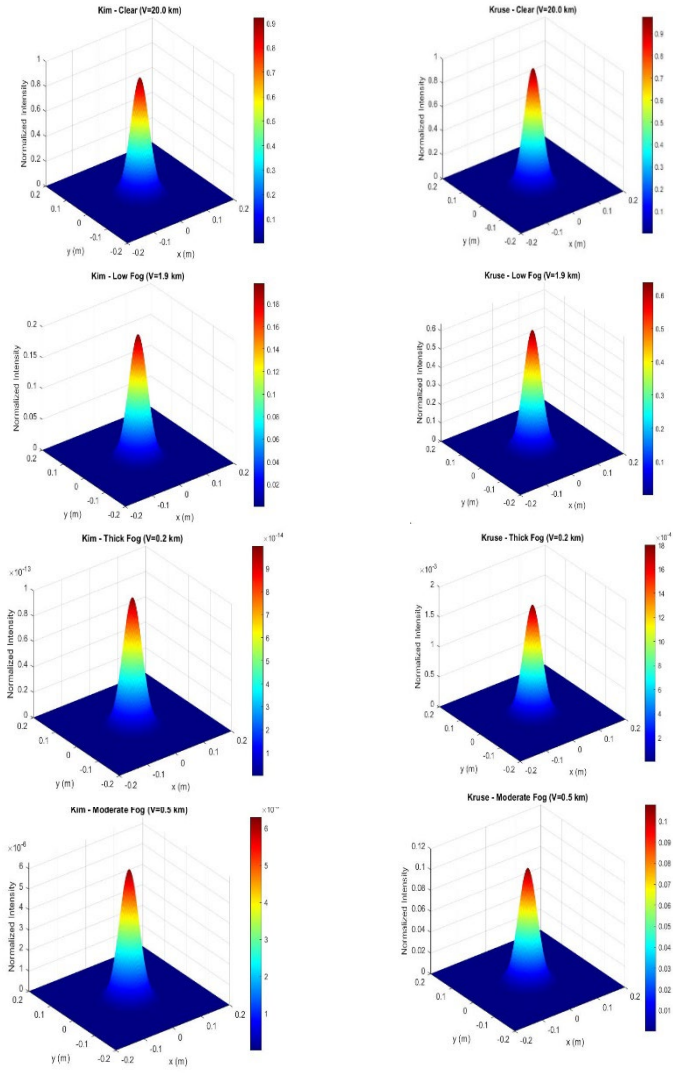


Figure 2. Spatial distribution of the received GM CV-QKD signal over FSO channel under varying fog conditions using Kim and Kruse models.

4.2. Attenuation Effects on SKR

In this section, we used VPItoolkit™ QKD to give simulation results for various performance indicators for the GM CV-QKD system depicted in Fig. 1. The parameters in Table 1 and their associated values were taken into consideration. Specifications of real-world QKD systems are used to determine transmitter and receiver parameters [14].

Table 1. Parameters modelled CV-QKD system with FSO quantum channel.

Parameter	Value
Wavelength (nm)	850, 1550
Symbol Rate (MHz)	250
Modulation Variance (SNU)	5
Wind Speed (m/s)	21
Beam Launch Radius (m)	0.02
Receiver Aperture Radius (m)	0.1
Receiver Excess Noise (SNU)	0.01

First, a MATLAB code was used to compute the atmospheric attenuation coefficients for both 850 nm and 1550 nm operating wavelengths using the Kim and Kruse empirical visibility models in Eqs. (10) and (11). Table 2 lists four visibility regions according to ITU-R budget was made possible by the software environment, which also included the computed fog-induced losses to examine their effect on system's approach, which guaranteed a physically

consistent the recommendation [20]. The performance of the GM performance. The theoretical attenuation results from Kim and Kruse models were directly applied to the VPItoolkit™ QKD using this hybrid MATLAB-VPI CV-QKD system over an FSO channel was then simulated using the attenuation values that were acquired and entered into VPIphotonics as input parameters. Accurate modeling of the optical link framework. This allowed for a realistic assessment of how various visibility levels and wavelengths affect the achievable SKR.

Fig. 3 illustrates the variation of SKR with the propagation distance at wavelengths of 1550 nm and 850 nm in various fog conditions using both the Kruse and Kim attenuation models.

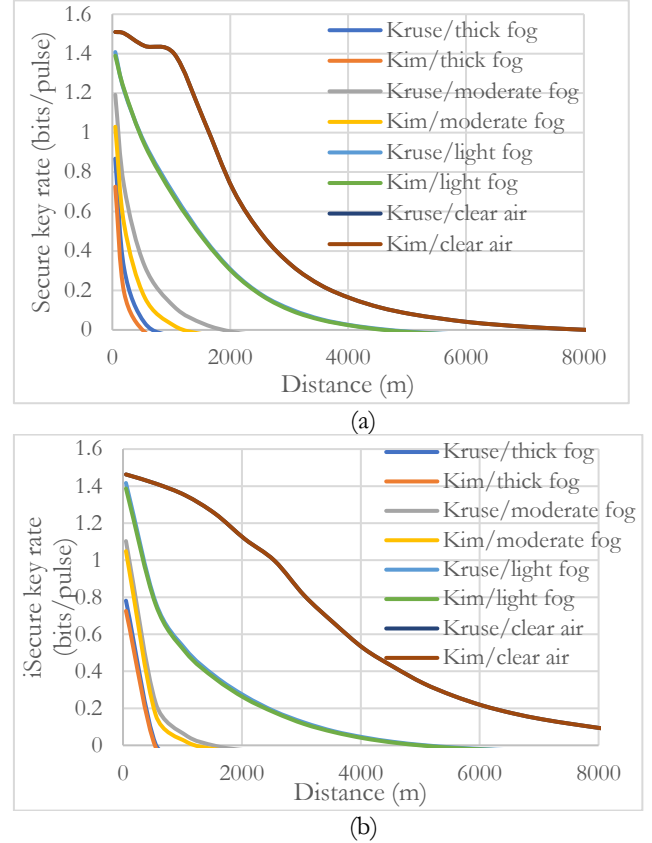


Figure 3. SKR versus distance for four visibility levels using Kruse and Kim models at (a) 1550 nm and (b) 850 nm.

Table 2. Attenuation values according to Kim and Kruse models for 1550 nm and 850 nm wavelengths.

Weather Condition	Visibility (Km)	Kruse parameter q	Kim parameter q	Wavelength= 1550 nm		Wavelength= 850 nm	
				Kruse attenuation (dB/km)	Kim Attenuation (dB/km)	Kruse attenuation (dB/km)	Kim Attenuation (dB/km)
Thick fog	0.2	0.34211	0	13.722	19.56	16.854	19.56
Moderate fog	0.5	0.46431	0	4.8362	7.824	6.3922	7.824
Thin fog	1.9	0.72456	0.644	0.97189	1.0565	1.502	1.5556
Clear air	20	1.3	1.3	0.051	0.051	0.11	0.11

An important finding from the SKR plots versus distance is that, in clear air, the 850 nm wavelength achieves a little higher SKR value and a longer transmission distance than the 1550 nm wavelength.

This could be because of the wavelength's higher detector efficiency, higher optical intensity, and lower beam divergence. In fog, that benefit gained from 850 nm operating wavelength is negated by high wavelength-independent attenuation (as in the Kim model) and enhanced scattering losses, resulting in equivalent SKR or lower performance at the 1550 nm wavelength. This highlights that 1550 nm is still the best option for foggy FSO QKD systems because of its lower Mie scattering, which dominates the propagation loss and makes the effect of beam divergence in fog conditions relatively insignificant, whereas 850 nm can only operate competitively in clear weather. This inversion in performance shows that the empirical parameters of the Kim and Kruse models favor shorter wavelengths when visibility is below a few kilometers, even if theoretically 1550 nm frequently performs better. Thus, the attenuation coefficient is the primary regulating factor that connects atmospheric visibility to SKR degradation, as shown by the combined MATLAB–VPI simulation. Another finding is that the Kruse and Kim models differ clearly at 1550 nm in thick and moderate fog levels, but at 850 nm only in moderate fog levels.

Since the SKR depends on both the channel transmittance and β , increasing β provides an efficient way to make up for channel deterioration where larger β values directly result in higher SKR generation rates, particularly in low SNR regimes that are typical of foggy situations.

To further examine the influence of β , more simulations were carried out for different values of β as shown in Fig. 4, in which the two plots are under thick fog condition, using the Kim fog attenuation model. Thick fog is selected as the worst-case scenario for system performance evaluation. Since the Kim model, in contrast to the Kruse model, provides wavelength-independent attenuation coefficients for a given visibility condition, that is, the attenuation stays the same for both 1550 nm and 850 nm wavelengths under identical fog density, it was selected for the two wavelength simulations. This enables a fair and isolated evaluation the effect of β on SKR. It is clear that 1550 nm continuously maintains greater SKR values and transmission distances, proving its benefit in extreme weather conditions. The findings demonstrate that SKR improves noticeably with increasing β at all fog levels and wavelengths.

In the high-loss conditions (moderate and deep fog), the advantage of improved reconciliation is noticeable. This enhancement shows that reconciliation process optimization in the post-processing stage can greatly increase the operating range and reliability of GM CV-QKD systems in real-world FSO situations.

Therefore, 1550 nm is the ideal working wavelength for improved GM CV-QKD performance in foggy areas (such as Iraqi climates with frequent winter fog), especially in thick fog situations. Choosing 1550 nm as the operating wavelength to provide improved reliability, longer secure transmission distances, and greater key generation rates is the first practical design advice for GM CV-QKD systems in Iraqi foggy regions. Second, with the use of error reconciliation optimization ($\beta \rightarrow 1$), adaptive modulation variance, and real-time channel estimation. Even in extremely attenuating weather, these techniques can reduce fog-induced losses, increase communication range, and preserve secure key generation.

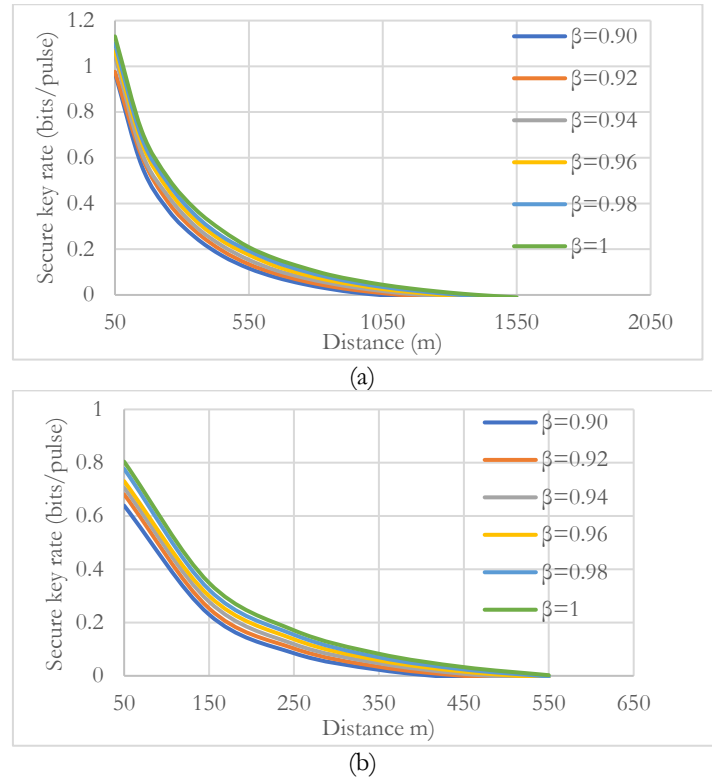


Figure 4. Secret key rate versus transmission distance at different reconciliation efficiencies under thick fog at (a) 1550 nm (b) 850 nm.

5. Conclusions

In this paper, the GM CV-QKD system operating over the FSO channel in foggy conditions is thoroughly investigated. In order to assess system robustness over four weather regimes: clear air, light fog, moderate fog, and thick fog, the analysis took into account two operational wavelengths, 1550 nm and 850 nm, as well as the empirical fog-attenuation models developed by Kim and Kruse. According to the simulation results, 850 nm's reduced diffraction divergence and higher received optical power allowed it to reach longer transmission distance of 12 km in clear air. However, due to its superior transmittance in dense atmospheric media and reduced scattering losses, 1550 nm outperformed 850 nm in foggy conditions, maintaining higher SKR values (1.389379-0.86 bits/symbol) and longer secure distances (0.6-4.6 km). The Kim attenuation model has smoother, wavelength-independent attenuation behaviour in low visibility, provides a realistic basis for foggy channel modelling, which makes it more appropriate for studying the impact of β on SKR improvement where the transmission distance can be enhanced from 1 km to 1.4 km in 1550 nm and from 0.35 km to 0.55 km in 850 nm. However, a comparison of the Kruse and Kim models showed that both anticipate a similar qualitative trend. Effective reconciliation methods are crucial, as evidenced by performance studies conducted under the worst-case thick fog scenario, which showed that boosting β and optimizing channel estimates greatly improve SKR. These findings provide practical guidelines for deploying robust QKD systems in regions with frequent fog, such as Iraq, recommending 1550 nm operation coupled with adaptive post processing techniques.

6. References:

- [1] S.Y. Shen, M. W. Dai, X.T. Zheng, Q. Y. Sun, G. C. Guo, and Z. F. Han, " Free-space continuous-variable quantum key distribution of unidimensional Gaussian modulation using polarized coherent states in an urban environment ", Phys. Rev.

- A, vol. 100, no. 1, Art no. 012325, 2019.
<https://doi.org/10.1103/PhysRevA.100.012325>
- [2] Y. Zhang, Y. Bian, Z. Li, S. Yu, and H. Guo, "Continuous-variable quantum key distribution system: past, present, and future", *Appl. Phys. Rev.*, vol. 11, no. 1, 2024.
<https://doi.org/10.1063/5.0179566>
- [3] M. Li, T. Wang, J. Han, Z. Yu, M. Cvijetic, H. Ye, and Y. Liu, "Free space continuous-variable quantum key distribution with practical links", *J. Opt. Soc. Am.*, vol. 37, no. 12, pp. 3782-3790, 2020. <https://doi.org/10.1364/JOSAB.405059>
- [4] S. L. Birhanu, M. Ghadimi, Y. Hai, P. Seeling, R. Bassoli, and F. H. P. Fitzek, "A Survey of Continuous Variable Quantum Key Distribution in Quantum Communication", *IEEE Access*, vol. 11, 2025. <https://doi.org/10.1109/ACCESS.2025.3610519>
- [5] A. Rani, P. Chandravanshi, J. Ramakrishnan, P. Vaity, P. Madhusudhan, T. Sharma, P. Bhardwaj, A. Biswas, and R. P. Singh, "Free Space Continuous Variable Quantum Key Distribution with Discrete Phases", *Phys. Open*, vol. 17, 2023. <https://doi.org/10.1016/j.physo.2023.100162>
- [6] K. Jaksch et al., "Composable free-space continuous-variable quantum key distribution using discrete modulation", *Quantum Physics*, vol. 1, 2024.
<https://doi.org/10.48550/arXiv.2410.12915>
- [7] M. A. Esmail, H. Fathallah, and M. Alouini, "Analysis of Fog Effects on Terrestrial Free Space Optical Communication Links", *IEEE Int. Conf. Commun. (ICC)*, 2016.
<https://doi.org/10.1109/ICCW.2016.7503780>
- [8] S. Wang, P. Huang, T. Wang, and G. Zeng, "Feasibility of continuous-variable quantum key distribution through fog", *Opt. Lett.*, vol. 46, no. 23, 2021, pp. 5873-5876.
<https://doi.org/10.1364/OL.439932>
- [9] C. Bai, J. Wang, S. Zhou, R. Rao, and T. Wang, "Performance of Free Space Optical Communication Link Under Foggy Weather Regarding Different Wavelengths", *ISAIC*, 2022, ISBN: 978-989-758-622-4, pp. 385-390.
<https://doi.org/10.5220/0011946200003612>
- [10] A. Haider et al., "A Methodology to Model the Rain and Fog Effect on the Performance of Automotive LiDAR Sensors", *Sensors*, vol. 23, no. 16, Art. no. 6891, 2023.
<https://doi.org/10.3390/s23156891>
- [11] W. Gao, K. Dong, L. Jiang, Y. Song, T. Wang, and J. Zhou, "Composite channel modeling and experimental investigation of free-space optical communications for urban scenario applications", *Opt. Express*, vol. 33, no. 20, Art. no. 42370, 2025. <https://doi.org/10.1364/OE.569650>
- [12] S. Pirandola, "Limits and security of free-space quantum communications", *Phys. Rev. Res.*, vol. 3, Art. no. 013279, 2021. <https://doi.org/10.1103/PhysRevResearch.3.013279>
- [13] N. Alshaer, T. Ismail, and H. Mahmoud, "Enhancing Performance of Continuous-Variable Quantum Key Distribution (CV-QKD) and Gaussian Modulation of Coherent States (GMCS) in Free-Space Channels under Individual Attacks with Phase-Sensitive Amplifier (PSA) and Homodyne Detection (HD)", *Sensors*, vol. 24, Art. no. 5201, 2024.
<https://doi.org/10.3390/s24165201>
- [14] X. Zheng, Q. Zhang, J. Ling, G. Guo, and Z. Han, "Free-space continuous-variable quantum key distribution under high background noise", *npj quantum inf.*, Art. no. 52, 2025.
<https://doi.org/10.1038/s41534-025-01009-w>
- [15] M. T. Sayat et al., "Improving Free-Space Continuous Variable Quantum Key Distribution with Adaptive Optics", *arXiv:2509.11759*, 2025. <https://doi.org/10.1038/s41598-026-36805-7>
- [16] T. Wang, P. Huang, Y. Zhou, W. Liu, H. Ma, S. Wang, and G. Zeng, "High key rate continuous-variable quantum key distribution with a real local oscillator", *Opt. express*, vol. 26, pp. 2794-2806, 2018. <https://doi.org/10.1364/OE.26.002794>
- [17] A. Czerwinski, "Atmospheric modeling of free-space optical transmission: Satellite downlinks and horizontal channels", *Optical and Quantum Electronics*, vol. 57, Art. no. 577, 2025.
<https://doi.org/10.1007/s11082-025-08505-5>
- [18] H. Yang, S. Liu, S. Yang, Z. Lu, Y. Li, and Y. Li, "High-efficiency rate-adaptive reconciliation in continuous-variable quantum key distribution", *Phys. Rev. A* 109, Art. no. 012604, 2024. <https://doi.org/10.1103/PhysRevA.109.012604>
- [19] I. I. Kim, B. McArthur, and E. Korevaar, "Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications", *Optical Wireless Communication Proceeding of SPIE*, vol. 4214, 2001.
<https://doi.org/10.1117/12.417512>
- [20] ITU-R, Propagation Data Required for the Design of Terrestrial Free-Space Optical Links, Recommendation ITU-R P.1817-1, International Telecommunication Union, Geneva, Switzerland, 2012.