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Tooba Angabeen

NED University of Engineering and Technology

Roohi Zafar

NED University of Engineering and Technology

Muhammad Kamran

kamran@cloud.neduet.edu.pk

NED University of Engineering and Technology

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Performance Analysis of Relativistic Quantum Key Distribution for Deep-Space Optical Communication

Tooba Angabeen¹ , Roohi Zafar¹ , Muhammad Kamran^{*2} 

¹ Department of Physics, NED University of Engineering and Technology, University Road, Karachi 75270, Sindh, Pakistan

² Department of Computer Science and Information Technology, NED University of Engineering and Technology, University Road, Karachi 75270, Sindh, Pakistan

*Corresponding author(s). E-mail(s):
kamran@cloud.neduet.edu.pk

Abstract

Quantum key distribution (QKD) is a method for securely exchanging keys based on quantum mechanics. QKD has been thoroughly examined for terrestrial and near-Earth satellite applications; however, forthcoming deep-space links are anticipated to experience considerable relativistic effects. Quantum states can be altered in these circumstances by relative motion between terminals and by gravitational effects, which may affect entanglement, measurement outcomes, and overall security. The effectiveness of entanglement-based quantum key distribution (QKD) in relativistic motion is investigated in this work, with particular attention to deep-space optical communication. The quantum channel model includes Wigner rotations due to Lorentz transformations, polarization mixing due to Doppler shift, and redshift due to gravity. This method gives us new ways to analyze the quantum bit error rate (QBER), quantum entanglement fidelity, Bell inequality violation, and secret key rate. Our numerical simulations show that when the relative velocity becomes high enough, the polarization correlations start to break down significantly. This leads to more errors in the quantum bits, making it harder to generate a secure secret key. Even though quantum nonlocality persists at these speeds, relativistic effects make it much harder to actually extract a secure key.

Keywords: Free-Space Optical Communication, Quantum key distribution, Spatial Modes, Atmospheric Turbulence.

1 Introduction

Quantum key distribution (QKD) offers provably secure communication by exploiting uniquely quantum phenomena such as superposition, entanglement [1–3], and measurement induced disturbance [4, 5]. Among QKD protocols, entanglement-based schemes such as the Ekert E91 protocol are especially powerful because they allow security verification through Bell inequality violation [6–8], linking cryptographic security directly to quantum nonlocality. Over the past decade, satellite-based QKD [9–11] has demonstrated quantum communication across thousands of kilometers. However, extending quantum communication to interplanetary or deep-space missions introduces new physical regimes. Spacecraft, satellites, and planetary

stations may move at significant fractions of the speed of light relative to each other, and photons may traverse regions with varying gravitational potential[12, 13]. Under such conditions, relativistic effects alter the polarization states used to encode quantum information [14–16]. Lorentz transformations introduce Wigner rotations that change the polarization basis observed by moving receivers. In addition, Doppler shifts and gravitational redshift modify photon frequency and temporal modes, effectively contributing to decoherence. Despite their growing relevance, these relativistic effects are largely absent from conventional QKD security analyses. This study establishes a quantitative connection between relativistic physics and quantum cryptographic security by developing a unified relativistic framework for entanglement-based QKD performance evaluation [17, 18]. We show that relativistic motion acts as a fundamental noise source that degrades entanglement and imposes an upper limit on secure key generation [19–21].

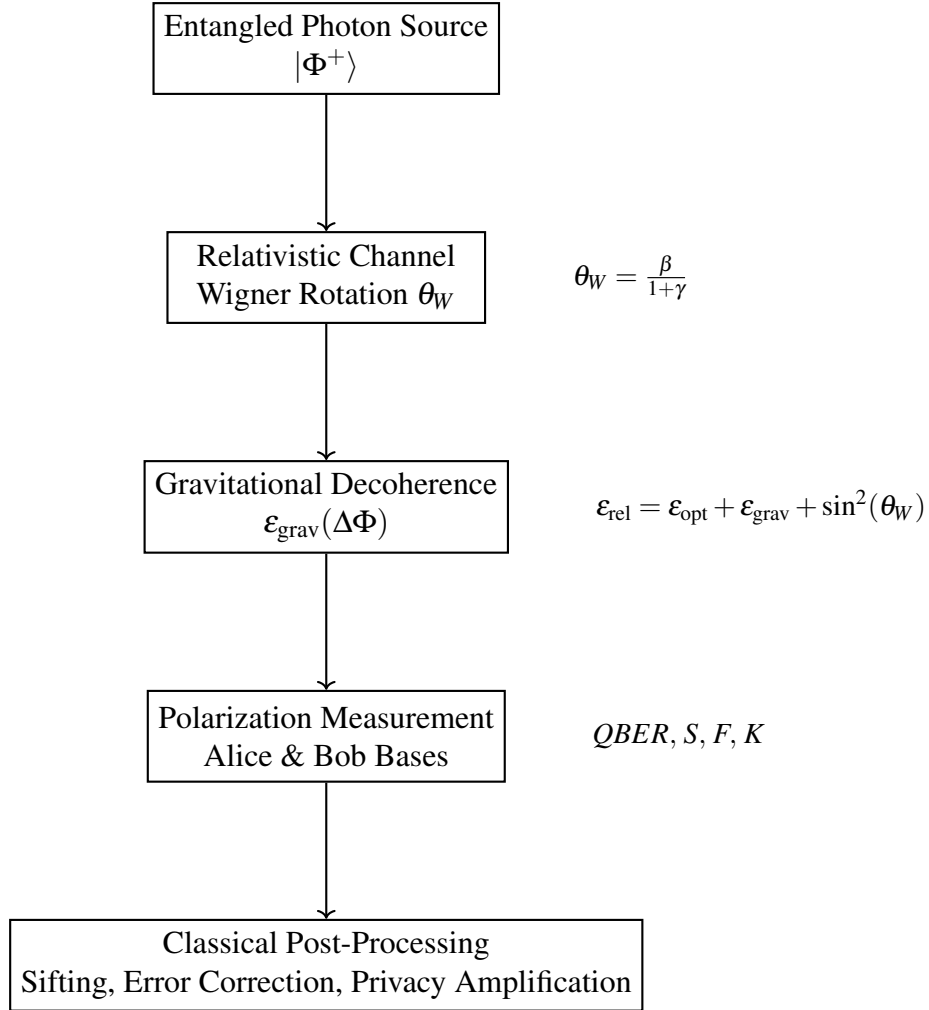


Figure 1: System architecture of relativistic entanglement-based QKD incorporating Lorentz-induced polarization rotation, gravitational decoherence, quantum measurement, and classical security processing.

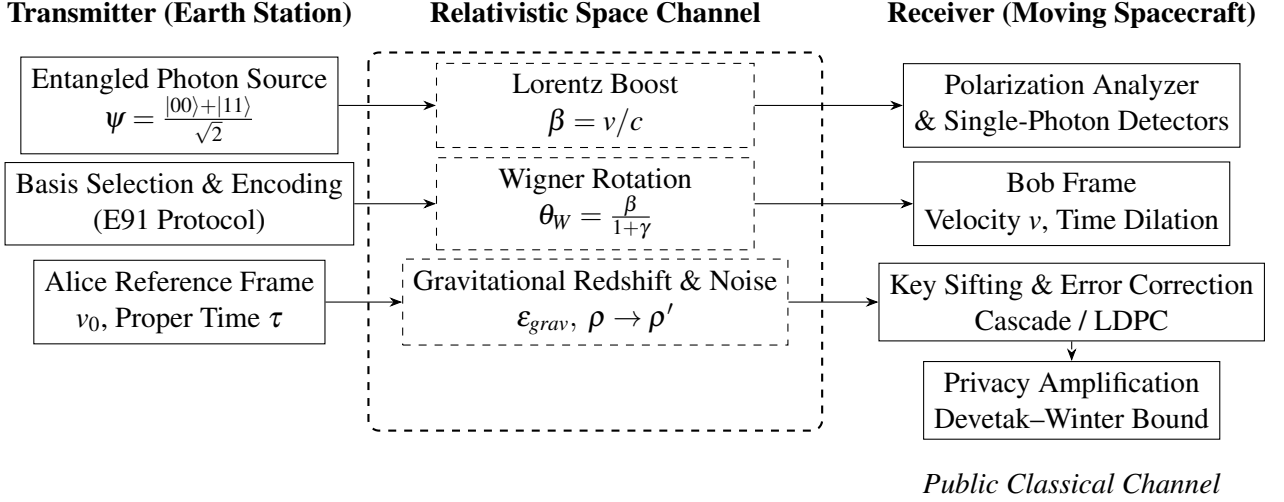


Figure 2: Relativistic entanglement-based QKD architecture for deep-space optical communication, illustrating Lorentz boost, Wigner rotation, gravitational effects, detection, and classical post-processing.

2 SYSTEM MODEL AND ASSUMPTIONS

We consider a deep-space optical communication link in which polarization-entangled photon pairs are distributed between two observers, Alice and Bob[22–25]. The entangled photon source is located in Alice’s local inertial frame, while Bob is in uniform inertial motion with velocity v along the optical axis[26–29]. Key assumptions:

1. The E91 entanglement-based QKD protocol is employed.
2. Photons propagate through free space without atmospheric turbulence
3. Relativistic effects are modeled using special relativity (Lorentz boosts) and weak-field gravitational redshift.
4. Finite-key effects are neglected (asymptotic key analysis)
5. Alice and Bob do not share identical reference frames
6. The simulated velocity range extends beyond current spacecraft capabilities. This extended range is intentionally chosen to identify fundamental theoretical security limits imposed by relativistic physics, rather than to model present-day mission parameters.

The final assumption is central to this study: the shared entangled state must be transformed between relativistically related frames before measurement.

3 RELATIVISTIC QUANTUM COMMUNICATION MODEL

3.1 Lorentz-Induced Wigner Rotation

Under a Lorentz boost with relative velocity v , photon polarization does not remain invariant. Instead, it undergoes a Wigner rotation, a relativistic transformation arising from the non-

commutativity of Lorentz boosts[30–32]. Let

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}, \quad \beta = \frac{v}{c} \quad (1)$$

The Wigner rotation angle for polarization states is approximated as

$$\theta_W = \frac{\beta}{1 + \gamma} \quad (2)$$

This rotation produces a mismatch between Alice’s preparation basis and Bob’s measurement basis, acting as an intrinsic relativistic noise source[33]. Equation 2 represents the small-velocity approximation of the exact Wigner rotation angle given in Appendix A

3.2 Relativistic Noise Model

We model the total relativistic noise as

$$\epsilon_{\text{rel}} = \epsilon_{\text{opt}} + \epsilon_{\text{grav}} + \sin^2(\theta_W) \quad (3)$$

where:

- ϵ_{opt} — optical system imperfections
- ϵ_{grav} — decoherence due to gravitational redshift
- $\sin^2(\theta_W)$ — polarization mixing due to relativistic motion

This unified noise model directly connects relativistic physics to QKD performance[34–37].

4 RELATIVISTIC QBER AND ENTANGLEMENT DEGRADATION

4.1 Quantum Bit Error Rate

The relativistically modified QBER for the E91 protocol becomes

$$\text{QBER} = \frac{1}{2} [1 - (1 - 2\epsilon_{\text{rel}}) \cos(\theta_{AB} + \theta_W)] \quad (4)$$

This behavior reveals that both relativistic decoherence[38–40] and basis rotation increase bit errors as shown in Fig.4.

4.2 Entanglement Fidelity

Fidelity between the shared state and the ideal Bell state is

$$F = 1 - \epsilon_{\text{rel}} \quad (5)$$

indicating continuous entanglement degradation as relativistic effects[41, 42] grow as shown in Fig.6.

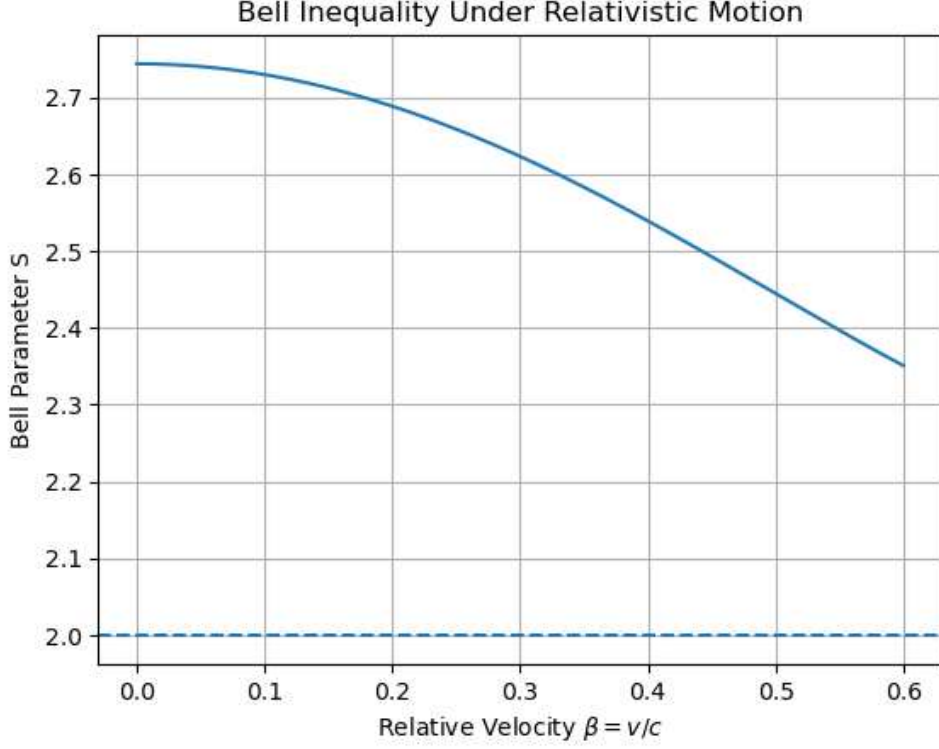


Figure 3: The CHSH Bell parameter S can be expressed as a function of the normalized relative velocity $\beta = v/c$. Relativistic Wigner rotation and gravitational noise reduce quantum correlations, causing the Bell inequality violation to approach the classical bound $S = 2$. The violation collapses near the critical velocity $\beta_{\text{crit}} \approx 0.309$.

4.3 BELL INEQUALITY UNDER RELATIVISTIC MOTION

The CHSH Bell parameter becomes

$$S = 2\sqrt{2}(1 - 2\varepsilon_{\text{rel}}) \quad (6)$$

Bell violation persists ($S > 2$) until relativistic noise exceeds a threshold as shown in Fig.3.

4.4 SECRET KEY RATE ANALYSIS

Using the Devetak–Winter bound:

$$K = 1 - H(\text{QBER}) - H(\varepsilon_{\text{rel}}) \quad (7)$$

where $H(x)$ is the binary entropy function. Simulations show a security breakdown near $v/c \approx 0.309$, where $K \rightarrow 0$ as simulated in Fig.5.

5 MATHEMATICAL FRAMEWORK FOR RELATIVISTIC ENTANGLEMENT-BASED QKD

5.1 Physical Scenario

Two observers:

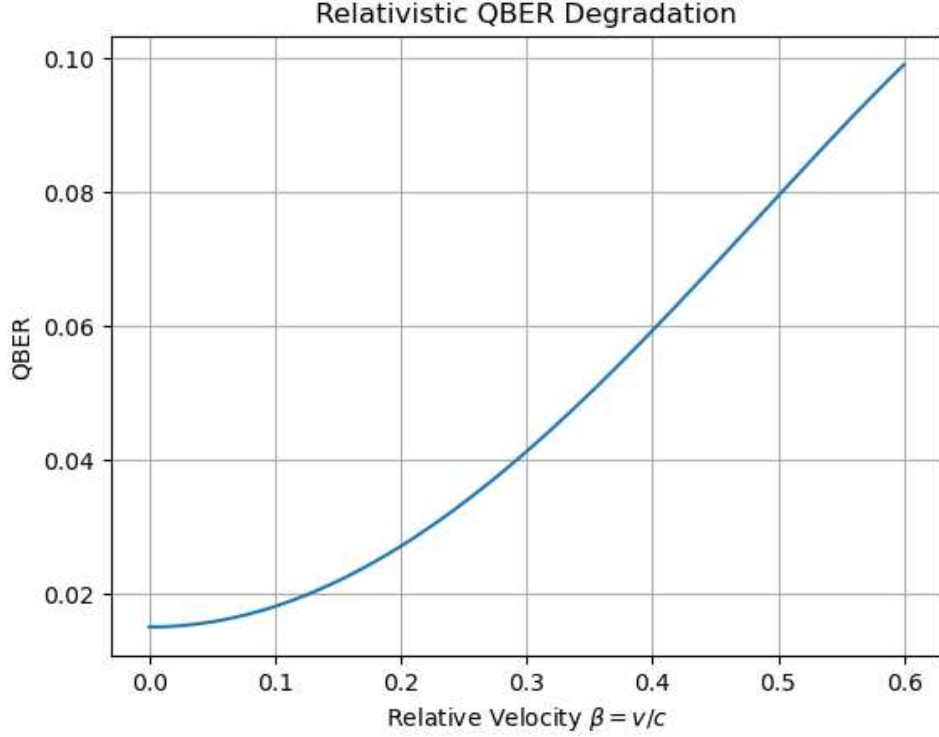


Figure 4: Quantum bit error rate (QBER) as a function of relativistic velocity. Polarization basis mismatch caused by Wigner rotation increases error probability, pushing the system toward the QKD security threshold.

- Alice on a spacecraft (gravitational potential Φ_A)
- Bob on a satellite (gravitational potential Φ_B)
- Relative velocity v along the photon propagation axis

We assume:

- Weak-field Schwarzschild metric
- Polarization-entangled photon pairs
- Non-identical local reference frames

This frame mismatch is the core relativistic effect[43–45].

5.2 Initial Bell State

From 1 and 2 we have,

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B) \quad (8)$$

where,

$$\rho_0 = |\Psi^-\rangle\langle\Psi^-| \quad (9)$$

5.3 Lorentz Transformation and Wigner Rotation

Polarization rotation operator:

$$R(\theta_W) = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \quad (10)$$

Relativistically transformed state:

$$\rho_{\text{rel}} = (I \otimes R) \rho_0 (I \otimes R^\dagger) \quad (11)$$

5.4 Gravitational Redshift

$$\zeta = \sqrt{\frac{1 + \frac{2\Phi_A}{c^2}}{1 + \frac{2\Phi_B}{c^2}}} \quad (12)$$

$$\varepsilon_g = 1 - \zeta \quad (13)$$

The gravitational decoherence term is modeled phenomenologically to capture redshift-induced phase mismatch, rather than derived from a full quantum field treatment in curved spacetime. Total relativistic noise:

$$\varepsilon_{\text{tot}} = \varepsilon_g + \sin^2 \theta_W \quad (14)$$

Mixed density matrix:

$$\rho_{\text{tot}} = (1 - \varepsilon_{\text{tot}}) \rho_{\text{rel}} + \varepsilon_{\text{tot}} \frac{I}{4} \quad (15)$$

6 NUMERICAL AND SIMULATION KEY RESULTS AND FINDINGS

Simulations combined as shown in Fig.7 reveal the following relativistic effects:

- Monotonic growth of the quantum bit error rate (QBER) with relative velocity v
- Smooth decay of entanglement fidelity F
- Persistent but weakening violation of the CHSH Bell parameter S
- Existence of a relativistic security threshold, beyond which secure key generation fails

Numerical modeling evaluated relativistic QKD performance over $0 \leq \beta \leq 0.6$.

As shown previously in Fig.3, the CHSH Bell parameter decreases with relativistic velocity and collapses near the classical bound $S=2$, signaling a breakdown of quantum nonlocality[46–49].

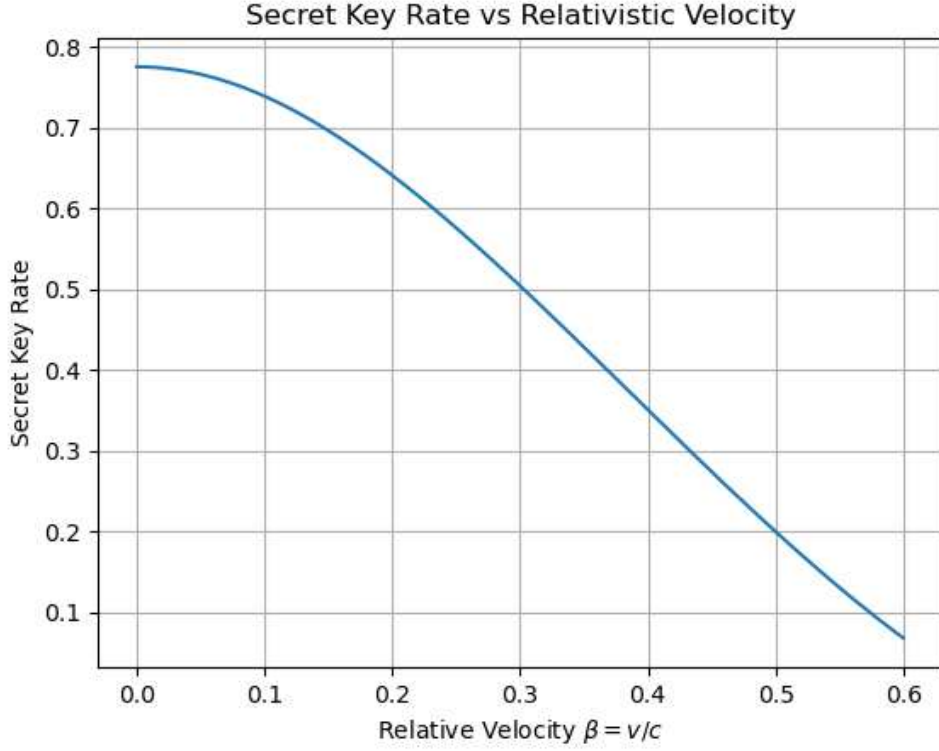


Figure 5: Secret key generation rate versus relativistic velocity. The key rate decreases as relativistic noise increases and falls to zero at the velocity where Bell violation disappears.

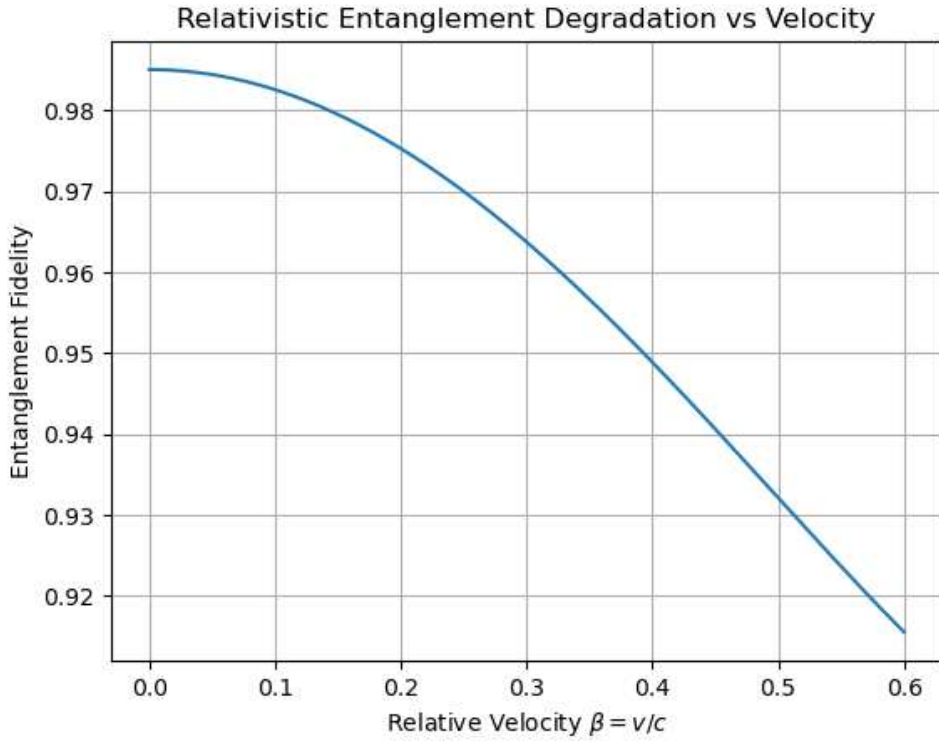


Figure 6: Entanglement fidelity is given by $F = 1 - \epsilon_{\text{rel}}$ versus relativistic velocity. Increasing relativistic motion degrades the shared entanglement due to polarization mixing and gravitational effects.

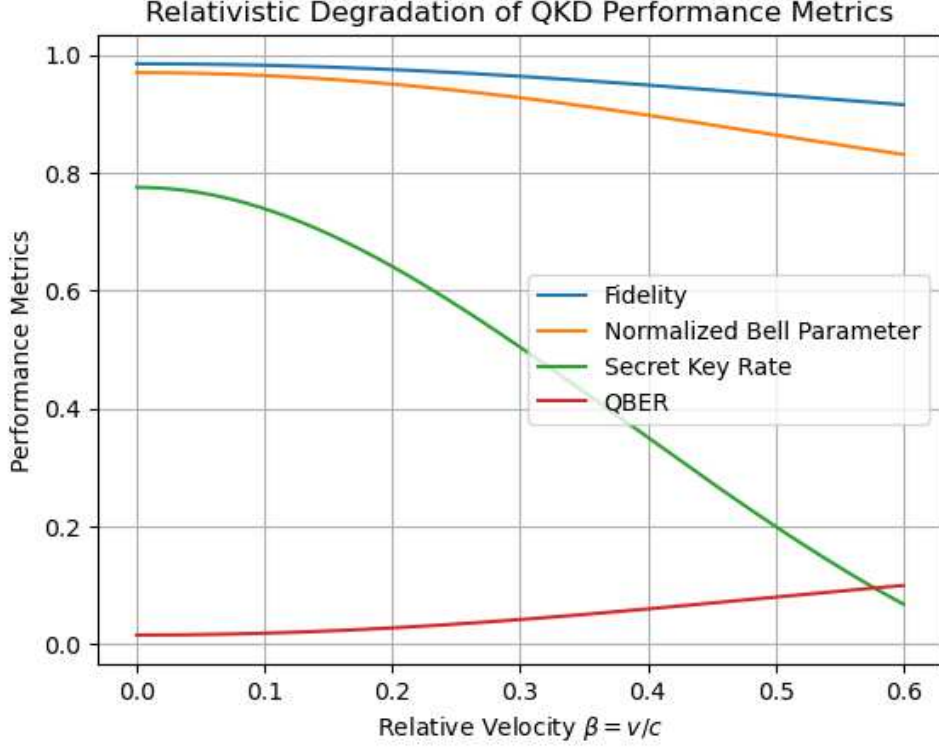


Figure 7: Simultaneous degradation of entanglement fidelity, normalized Bell parameter, secret key rate, and increase in QBER with relativistic velocity. The figure illustrates how relativistic motion imposes a fundamental security limit on deep-space quantum key distribution.

7 Discussion

The numerical analysis over the velocity range $0 \leq \beta \leq 0.6$ shows relativistic motion affects the performance of entanglement-based quantum key distribution (QKD) [50]. The results indicate that relativistic effects act as a systematic, velocity-dependent source of decoherence rather than random noise. Unlike conventional noise, this degradation arises from frame transformations and gravitational phase shifts, which cannot be fully corrected by local operations [51–54].

Due to the mismatch between the polarization conclusion reference frames of the communicating observers, the quantum bit error rate (QBER) increases with velocity. Lorentz-induced Wigner rotations mix polarization components and weaken correlations even in ideal conditions [55–57]. At the same time, gravitational potential differences introduce additional phase shifts, further reducing entanglement fidelity. An important result is the separation between the existence of quantum correlations and the ability to generate secure keys. Although Bell inequality violations remain observable over part of the velocity range, their magnitude decreases with increasing β . This means that entanglement can still exist even when the system no longer supports a positive secret key rate [58].

Simulations identify a relativistic security threshold near $\beta_{\text{crit}} \approx 0.309$, where the Bell parameter approaches the classical bound $S = 2$, QBER exceeds the security limit, and the key rate becomes zero. This limit arises from relativistic frame effects rather than hardware imperfections [59–61]. These results show that quantum nonlocality and cryptographic security are not identical resources in relativistic settings. While entanglement may persist, it may no longer be strong enough to ensure secure communication. This insight is important for future quantum networks involving satellites, spacecraft, and deep-space communication systems. This

Parameter	Behavior
Entanglement fidelity	Monotonic decay
Bell parameter (S)	Falls below 2 at $\beta \approx 0.309$
QBER	Exceeds 11% security bound
Key rate	Drops to zero beyond threshold

Table 1: Summary of numerical simulations showing the effect of relativistic motion on QKD performance over the range $0 \leq \beta \leq 0.6$. Key parameters include entanglement fidelity, the CHSH Bell parameter S , the quantum bit error rate (QBER), and the secure key rate

study focuses on fundamental relativistic limits and does not include finite-key effects, detector inefficiencies, or atmospheric turbulence.

8 Conclusion

In this work, we examined how relativistic motion affects entanglement-based quantum key distribution in free-space optical communication. The system was analyzed over the velocity range $0 \leq \beta \leq 0.6$. Our results show that Lorentz-induced Wigner rotations and gravitational phase shifts gradually weaken polarization entanglement. As the velocity increases, Bell inequality violations become smaller, the quantum bit error rate (QBER) rises, and the secure key rate decreases. The analysis also reveals a relativistic security bound at the critical normalized velocity $\beta_{\text{crit}} \approx 0.309$. Beyond this point, secure key generation is no longer possible even though weak quantum correlations may still exist. This indicates that relativistic motion can set a fundamental physical limit on the operation of entanglement-based QKD systems.

These results are relevant for future quantum communication systems in space, such as satellite networks, interplanetary probes, and deep-space optical links. As quantum communication moves beyond Earth, ignoring relativistic effects may overestimate the achievable security in high-velocity or strong-gravitational-field environments. For this reason, relativistic effects should be considered in system design, security analysis, and protocol development. Future studies may investigate compensation methods, relativistic frame-alignment techniques, and alternative encoding schemes that are more robust to Lorentz and gravitational distortions.

Declarations

Funding

No specific funding was received for this work.

Conflict of interest

The author declares no conflict of interest.

Data availability

Data generated during this study are available from the corresponding author upon reasonable request.

Author contributions

All authors contributed equally.

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A Appendix

A.1 Derivation of Relativistic Polarization Rotation

Photon polarization is not invariant under Lorentz boosts. Instead, a boost induces a *Wigner rotation* due to the structure of the Lorentz group.

For a boost along the propagation direction, the rotation angle is

$$\theta_W = \arctan\left(\frac{(\gamma-1)\beta}{1+\gamma}\right) \quad (16)$$

where

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}. \quad (17)$$

For moderate relativistic velocities, this simplifies to

$$\theta_W \approx \frac{\beta}{1+\gamma}. \quad (18)$$

This angle represents the mismatch between the polarization reference frames of Alice and Bob.

A.2 Transformation of the Bell State

The initial Bell state is

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle). \quad (19)$$

The corresponding density matrix is

$$\rho_0 = |\Psi^-\rangle\langle\Psi^-|. \quad (20)$$

Applying the relativistic rotation only to Bob's photon gives

$$\rho_{\text{rel}} = (I \otimes R(\theta_W)) \rho_0 (I \otimes R^\dagger(\theta_W)), \quad (21)$$

where

$$R(\theta_W) = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix}. \quad (22)$$

Expanding this transformation leads to suppression of off-diagonal terms proportional to $\sin^2 \theta_W$, which reduces entanglement visibility[62–65].

A.3 Relativistic Noise Mixing

We model relativistic effects as a depolarizing channel acting on the rotated state:

$$\rho_{\text{tot}} = (1 - \epsilon_{\text{rel}})\rho_{\text{rel}} + \epsilon_{\text{rel}}\frac{I}{4}, \quad (23)$$

with

$$\epsilon_{\text{rel}} = \epsilon_{\text{opt}} + \epsilon_{\text{grav}} + \sin^2 \theta_W. \quad (24)$$

This formulation connects relativistic physics to an effective quantum noise model[66, 67].

A.4 Bell Parameter Degradation

For the depolarized state, the CHSH Bell parameter becomes

$$S = 2\sqrt{2}(1 - 2\epsilon_{\text{rel}}). \quad (25)$$

Bell violation requires

$$\epsilon_{\text{rel}} < \frac{1}{2} \left(1 - \frac{1}{\sqrt{2}} \right). \quad (26)$$

This condition determines the *relativistic security boundary*[68, 69].

A.5 Secret Key Rate Derivation

Using the Devetak–Winter bound[70–72], the secret key rate is

$$R = 1 - 2H_2(\text{QBER}), \quad (27)$$

where the binary entropy function is

$$H_2(x) = -x \log_2 x - (1 - x) \log_2 (1 - x). \quad (28)$$

Security vanishes when the QBER exceeds the protocol-dependent threshold (approximately 11% for entanglement-based protocols under collective attacks)[73–80].

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