QUANTUM ENTANGLEMENT AND ITS APPLICATIONS IN SECURE COMMUNICATION PROTOCOL'S

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Abstract

Quantum entanglement has emerged as a foundational resource for secure communication, enabling cryptographic security that is grounded in the laws of physics rather than computational complexity. This study presents a systems-level investigation of entanglement-based secure communication protocols, integrating physical channel modeling, detector imperfections, Bell-inequality diagnostics, adversarial strategies, and cryptographic post-processing within a unified analytical framework. Using a large-scale simulation dataset, we evaluate the performance and security of multiple entanglement-based protocols under realistic noise, loss, and attack conditions. The results demonstrate that secure key generation is not determined by protocol choice alone but arises from the joint interaction of channel attenuation, detector efficiency, background noise, and the strength of nonlocal quantum correlations. In particular, the CHSH Bell parameter is shown to be a strong predictor of both cryptographic viability and throughput, reframing Bell violation as an operational security resource rather than a purely foundational test. The analysis further reveals threshold-like security collapse at long distances, highlighting the dominant influence of physical-layer constraints. Additionally, several adversarial strategies are shown to preserve low error rates while silently undermining security assumptions, underscoring the limitations of QBER-only diagnostics. Together, these findings provide a comprehensive, experimentally grounded perspective on the design of scalable quantum communication systems and offer practical guidance for the development of robust, next-generation quantum networks.

INTRODUCTION

Quantum communication represents a paradigm shift in secure information exchange by replacing computational assumptions with physical laws as the basis of security. Classical cryptographic systems rely on the presumed intractability of mathematical problems such as integer factorization or discrete logarithms. However, the emergence of quantum computing threatens to undermine these foundations by enabling efficient solutions to problems that are currently considered hard (Shor, 1994). In contrast, quantum key distribution (QKD) offers information-theoretic security that does not depend on an adversary's computational power but instead on the fundamental principles of quantum mechanics, such as the no-cloning theorem and measurement disturbance (Bennett & Brassard, 1984; Scarani et al., 2009). Among the various QKD paradigms, entanglement-based protocols occupy a distinctive position. Rather than encoding information in individually prepared quantum states, these schemes distribute correlated particle pairs whose joint properties cannot be described independently. The security of such protocols arises from the fact that entangled states exhibit correlations that violate Bell inequalities, thereby ruling out classical local hidden-variable explanations (Bell, 1964; Clauser et al., 1969). This link between nonlocality and secrecy was first formalized in Ekert's E91 protocol, which explicitly ties security to the violation of a Bell inequality (Ekert, 1991). In this formulation, any eavesdropping attempt necessarily reduces the strength of observed correlations, providing a direct and measurable security witness. This conceptual shift is profound: security is no longer inferred solely from error rates but from the existence of nonclassical correlations themselves. Entanglement thus becomes not merely a feature of quantum mechanics but an operational resource for cryptography. However, despite its elegance, the practical realization of entanglement-based secure communication remains challenging. Real systems are affected by photon loss, background noise, detector inefficiencies, timing jitter, and environmental decoherence, all of which degrade entanglement quality and inflate error rates. These effects are especially pronounced over long distances, where coincidence rates decay exponentially while dark counts remain approximately constant (Gisin et al., 2002; Pirandola et al., 2020).

Early entanglement-based implementations sought to bridge theory and practice. Bennett, Brassard, and Mermin proposed BBM92 as an entanglement-based analogue of BB84, showing that entangled pairs could replace prepared single-photon states while preserving security guarantees (Bennett et al., 1992). This formulation demonstrated that entanglement-based schemes need not rely explicitly on Bell tests to establish security; instead, correlations in complementary bases suffice. Nonetheless, the theoretical foundations of these protocols still implicitly depend on quantum nonlocality and the impossibility of classical imitation without disturbance. Over time, it became increasingly clear that the largest threats to QKD systems were not theoretical but practical. A series of experimental attacks demonstrated that real-world devices often violate the assumptions made in idealized security proofs. Detector blinding, time-shift attacks, and Trojan-horse strategies revealed that an adversary could manipulate measurement hardware to gain information without noticeably increasing the quantum bit error rate (QBER) (Lydersen et al., 2010; Makarov, 2009). These developments fundamentally challenged the idea that low QBER alone was a sufficient indicator of security. In response, researchers sought to design protocols that minimize or eliminate trust assumptions about devices. This effort culminated in the development of device-independent QKD (DI-QKD), in which security is derived exclusively from observed input–output statistics, without requiring knowledge of the internal functioning of the devices (Pironio et al., 2009). In DI-QKD, a loophole-free Bell inequality violation is not merely a conceptual curiosity but a cryptographic necessity. If Alice and Bob observe correlations that cannot be explained classically, then any eavesdropper is constrained by the no-signaling principle and quantum mechanics itself. Masanes, Pironio, and Acín (2011) formalized general security proofs for DI-QKD, emphasizing that Bell inequality violation provides a direct bound on an adversary's information. This perspective recasts entanglement as a certifiable resource: rather than trusting devices, users trust the statistics. While theoretically elegant, DI-QKD is experimentally demanding. Loophole-free Bell tests require extremely high detection efficiencies, low noise, and strict timing synchronization, conditions that are difficult to maintain over long distances. To bridge the gap between full device independence and practical deployability, Lo, Curty, and Qi introduced measurement-device-independent QKD (MDI-QKD) (Lo et al., 2012). MDI-QKD neutralizes all detector side-channel attacks by design, allowing Alice and Bob to treat the measurement station as completely untrusted. This architecture shifts the security boundary outward, reducing the attack surface while retaining compatibility with standard optical components. Although MDI-QKD does not achieve full device independence, it represents a pragmatic compromise: it closes the most exploited vulnerabilities without requiring loophole-free Bell violations.

Together, E91, BBM92, MDI-QKD, and DI-QKD form a spectrum of entanglement-based security models. At one end, device-dependent protocols offer higher throughput and easier implementation. At the other, device-independent approaches provide the strongest security but at the cost of severe experimental constraints. This trade-off is a recurring theme in the literature (Scarani et al., 2009; Pirandola et al., 2020). Beyond protocol design, the role of the physical channel is increasingly recognized as fundamental. Fiber-optic links, free-space optical paths, and satellite downlinks each impose distinct noise and loss profiles. Free-space links are subject to atmospheric turbulence, beam wandering, and background light, while fiber channels experience exponential attenuation, dispersion, and Raman scattering (Ursin et al., 2007). Satellite-based QKD, exemplified by the Micius mission, has demonstrated entanglement distribution over thousands of kilometers, but with extremely low photon transmission probabilities (Yin et al., 2017). These experiments highlight a key limitation: even perfect protocols fail if physical conditions destroy entanglement faster than it can be detected. Coincidence rates fall quadratically with transmission probability, while background noise remains roughly constant, causing QBER to rise and Bell violation to collapse. As a result, security failure often occurs abruptly rather than gradually. This threshold behavior underscores the importance of monitoring quantum correlations directly rather than relying solely on classical error metrics. Recent theoretical work has reinforced this view. Brunner et al. (2014) reviewed Bell nonlocality as a physical resource, arguing that it underpins a range of quantum information tasks, including cryptography. Similarly, Acín et al. (2007) proposed Bell-based cryptographic protocols in which nonlocality itself acts as the security certificate. These studies suggest that the quality of entanglement should be treated not merely as a background condition but as a tunable system parameter. However, much of the literature remains fragmented. Some studies focus on protocol-level security proofs, abstracting away physical noise. Others emphasize experimental demonstrations without systematically linking performance to security metrics. As a result, there is a gap in understanding how physical-layer conditions, detector imperfections, entanglement quality, and cryptographic post-processing jointly determine real-world security.

This study addresses that gap by adopting a systems-level perspective on entanglement-based secure communication. Rather than evaluating protocols in isolation, we model how channel loss, detector efficiency, dark counts, timing jitter, and adversarial strategies propagate through quantum correlations and ultimately shape cryptographic outcomes. Two metrics play a central role: QBER and the CHSH Bell parameter S. While QBER reflects classical error accumulation, S captures the strength of nonlocal correlations. The combination of these metrics enables us to distinguish between merely low-noise systems and genuinely quantum-secure ones. This dual-metric approach is especially important for evaluating advanced adversarial models. Some attacks, such as intercept-resend, inflate QBER and are easily detectable. Others, such as photon-number splitting or detector blinding, can preserve low QBER while undermining security assumptions (Lydersen et al., 2010). Bell-based diagnostics provide an additional layer of defense, revealing correlations that cannot be faked by classical strategies. By integrating physical-layer modeling, quantum correlation analysis, and cryptographic post-processing into a unified simulation framework, this paper offers an empirical lens on the foundational claim of entanglement-based cryptography: that security emerges from the structure of quantum correlations rather than from mathematical hardness. In doing so, it situates entanglement not as a decorative feature but as the operational core of secure quantum communication.

Research Design and Simulation Framework

This study adopts a simulation-based quantitative research design to systematically investigate the role of quantum entanglement in secure communication protocols under realistic physical, technological, and adversarial conditions. A synthetic dataset of 600 experimental runs was generated to emulate the behavior of entanglement-based quantum key distribution (QKD) systems, including E91, BBM92, MDI-QKD, and DI-QKD protocols. Simulation was chosen over laboratory experimentation due to the practical constraints of implementing large-scale quantum networks and the need to explore a wide parameter space encompassing channel conditions, detector characteristics, and attack models. The simulation framework integrates physical-layer modeling, quantum correlation dynamics, and cryptographic post-processing in a unified pipeline. Each run represents a complete communication session, including photon-pair generation, channel propagation, detection, error formation, and secure key extraction. Physical parameters such as transmission distance, attenuation, and background noise were stochastically sampled from realistic ranges reported in the literature. This ensured that the dataset captures both favorable and adverse operating regimes. Unlike purely theoretical treatments, the framework explicitly incorporates implementation-level imperfections, such as detector inefficiency, dark counts, and timing jitter. These features are critical because practical security depends not only on protocol definitions but also on hardware limitations. The simulation also models the effect of different attack strategies, allowing security outcomes to emerge naturally rather than being imposed a priori. The outcome of each run is a multidimensional vector containing physical-layer metrics, quantum correlation indicators, and cryptographic outputs, including QBER, CHSH Bell parameter S, and the resulting secure key rate. A binary security label ("secure_session") is computed using protocol-specific thresholds. This design enables a holistic investigation of how secure communication emerges from the interaction of physics, quantum nonlocality, and cryptographic post-processing rather than from abstract protocol rules alone.

Modeling of Physical Channel Conditions and Detector Characteristics

The physical-layer modeling is central to this study, as quantum communication is fundamentally constrained by propagation loss, noise, and measurement imperfections. Three channel environments were simulated: fiber-optic links, free-space terrestrial links, and satellite downlinks. For each run, a transmission distance was randomly sampled from a channel-specific range, reflecting real-world deployment scales. Channel attenuation was modeled using environment-appropriate loss coefficients, supplemented with stochastic alignment and optical coupling losses to capture realistic variability. The total channel loss in decibels was computed as a function of distance-dependent attenuation and environment-specific noise factors. This loss directly influences the probability of photon transmission, which decays exponentially with distance. Coincidence detection probability was further reduced quadratically due to the two-arm structure of entanglement-based protocols.

Detector behavior was modeled explicitly using three representative technologies: InGaAs avalanche photodiodes (APDs), silicon APDs, and superconducting nanowire single-photon detectors (SNSPDs). Each detector class was assigned characteristic efficiency distributions, dark count rates, and timing jitter profiles. These parameters were sampled stochastically for each run, reflecting realistic manufacturing variability and operational drift. Dark counts were modeled as Poissonian background events, contributing to accidental coincidences that inflate QBER. Timing jitter was incorporated as a temporal uncertainty window, further degrading coincidence discrimination. Together, these factors modulate the signal-to-noise ratio of the system. By explicitly modeling these physical and instrumental factors, the framework ensures that quantum security outcomes are not idealized but grounded in realistic experimental constraints. This allows the study to assess not only whether a protocol is theoretically secure, but whether it remains secure under real-world imperfections.

Quantum Correlation Metrics, Attack Models, and Security Criteria

Quantum security in this study is evaluated using two principal indicators: the quantum bit error rate (QBER) and the CHSH Bell parameter S. QBER quantifies the fraction of mismatched measurement outcomes and reflects both classical noise and quantum decoherence. It is influenced by channel loss, detector imperfections, and background events. CHSH S, on the other hand, quantifies the strength of nonlocal quantum correlations and serves as a direct operational test of Bell inequality violation. Each run's QBER was computed using a composite model incorporating loss-induced coincidence degradation, detector noise, timing jitter, and visibility reduction. The CHSH S value was derived from the entanglement visibility, noise factors, and protocol-specific assumptions. Together, these metrics determine whether a run satisfies the nonlocality requirements necessary for entanglement-based security. To evaluate adversarial resilience, five attack models were implemented: no attack, intercept-resend, photon-number splitting, detector blinding, and time-shift attacks. Each attack modifies QBER and/or S in distinct ways. For example, intercept-resend directly destroys quantum correlations, while detector blinding undermines measurement assumptions without necessarily increasing QBER dramatically.

Security thresholds were defined using established bounds from QKD literature. A run was labeled as secure only if both (i) QBER remained below the protocol-specific tolerable limit and (ii) Bell violation was observed (S > 2) where required. This joint criterion ensures that security is not inferred from low error rates alone but also requires genuine quantum nonlocality. This layered security model allows the study to distinguish between classical-looking success and genuinely quantum-secure communication, thereby aligning the simulation with modern cryptographic definitions.

Statistical Analysis, Regression Modeling, and Visualization Strategy

To extract interpretable patterns from the simulated dataset, a multi-stage statistical analysis strategy was employed. First, descriptive statistics were computed for all numeric variables to characterize the distributions, dispersion, and skewness of physical, quantum, and cryptographic metrics. These summaries provide a baseline understanding of variability and reveal the heavy-tailed nature of secure key throughput. Second, protocol-level, channel-level, detector-level, and attack-level group comparisons were conducted using aggregated means, medians, and secure-session rates. These analyses enable direct evaluation of how design choices and environmental conditions shape security outcomes.Third, an ordinary least squares (OLS) regression model was constructed to predict the logarithm of the secure key rate as a function of channel loss, QBER, CHSH S, detector efficiency, entanglement visibility, latency, and categorical indicators for protocol type, channel type, and attack model. Logarithmic transformation was applied to stabilize variance and reduce the influence of extreme outliers. The regression framework allows the relative importance of competing physical and quantum factors to be quantified simultaneously. Finally, a suite of visualizations was generated to complement numerical summaries. These included scatter plots illustrating non-linear decay patterns, boxplots comparing protocol throughput distributions, bar charts of secure-session rates, histograms of QBER, and a correlation heatmap synthesizing interdependencies among key variables. Together, these methods provide both inferential rigor and intuitive interpretability. Rather than relying on a single metric, the analysis triangulates security outcomes across descriptive, graphical, and multivariate perspectives, ensuring that conclusions are robust, transparent, and grounded in observable patterns.

Results and Discussion

Table 1 provides a comprehensive statistical overview of the physical, quantum, and cryptographic parameters underlying the simulated entanglement-based communication system. The wide range of distances (1.37–1186.99 km) reflects realistic operational regimes spanning short-range fiber links, free-space metropolitan networks, and long-range satellite downlinks. This diversity is critical because channel length fundamentally governs attenuation, decoherence, and coincidence loss, all of which directly affect security and throughput. The mean channel loss of 26.68 dB, with a maximum exceeding 200 dB, highlights the extreme variability introduced by atmospheric effects, pointing losses, and orbital distances. Detector performance metrics further demonstrate substantial heterogeneity. Detector efficiency varies from 0.099 to 0.95, while dark count rates range from near-zero to over 240 kHz. This confirms that implementation choices can dramatically reshape the noise floor of a quantum channel. Timing jitter also exhibits large dispersion, suggesting that temporal indistinguishability remains a key vulnerability in real-world systems.

On the quantum layer, entanglement visibility remains relatively high (mean ≈ 0.93), indicating that most simulated sources preserve strong correlations. However, the QBER distribution (mean ≈ 7.8%) reveals that classical noise and measurement imperfections significantly degrade these correlations. The CHSH S parameter, with a mean of 2.13, confirms that Bell inequality violation is present in most runs but not universally guaranteed. Performance indicators exhibit heavy skewness. The secure key rate shows a median close to zero, despite a very large maximum. This indicates that while some configurations achieve extremely high throughput, many others collapse entirely once security constraints are imposed. This asymmetry reflects the fundamental fragility of entanglement-based security under loss and noise. Overall, Table 1 demonstrates that secure quantum communication is governed by a complex interaction between physical-layer variability, detector imperfections, and quantum correlation strength, rather than by protocol choice alone.

Table 1:Descriptive Statistics (Numeric Variables)
Counts, means, dispersion, and ranges for key physical/security/performance indicators.

Row	count	mean	std	min	25%	median	75%	max
distance_km	600.0	146.4094	211.4949	1.37	34.7825	85.99	158.795	1186.99
attenuation_dB_per_km	600.0	0.1601	0.066	0.01	0.1068	0.189	0.208	0.256
channel_loss_dB	600.0	26.6808	26.2513	1.94	9.2575	20.87	35.245	212.81
detector_efficiency	600.0	0.4607	0.2622	0.099	0.242	0.3105	0.7712	0.95
dark_count_rate_Hz	600.0	12267.5465	22039.3159	2.29	140.1325	4768.01	15252.29	241900.2
timing_jitter_ps	600.0	170.6542	102.5179	10.0	66.475	177.05	253.2	431.8
pair_generation_rate_Mpairs_s	600.0	54.2802	27.8047	11.3	35.59	49.04	65.605	209.17
entanglement_visibility	600.0	0.9294	0.0298	0.839	0.91	0.9275	0.95	0.99
qber	600.0	0.0784	0.0235	0.0217	0.0646	0.075	0.087	0.166
chsh_S	600.0	2.1322	0.1693	1.6	2.0482	2.138	2.2362	2.549
raw_coincidence_rate_kcps	600.0	252.9109	784.5352	0.001	0.001	0.4975	94.7848	5000.0
latency_ms	600.0	3.6791	1.2027	0.6	2.9285	3.6025	4.3882	7.622
secure_key_rate_kbps	600.0	46952.5861	178414.4074	0.0	0.0	3.064	7644.714	1469835.482

Table 2 compares the performance and security behavior of the four entanglement-based protocols: BBM92, DI-QKD, E91, and MDI-QKD. Although mean QBER values are similar across protocols, their security outcomes and throughput differ substantially. This highlights that protocol-level assumptions play a decisive role in determining how much noise and loss can be tolerated before security collapses. BBM92 and E91 achieve the highest secure-session rates (≈78%), suggesting that these protocols are more permissive under realistic noise conditions. Their higher average SKR values further reflect reduced overhead in error correction and privacy amplification. However, this comes at the cost of stronger trust assumptions about devices. DI-QKD shows the lowest secure-session rate (≈42%), confirming its extreme sensitivity to noise and loss. This is expected, as device-independent security requires loophole-free Bell violation, making it highly conservative. Its near-zero median SKR demonstrates that most configurations fail to satisfy these stringent conditions.

MDI-QKD occupies an intermediate position. While its secure-session rate remains high, its median SKR is extremely low, reflecting the heavy computational and coincidence overhead inherent in measurement-device-independent designs. Latency remains comparable across protocols, indicating that protocol choice mainly affects security and throughput rather than propagation delays. Channel loss is slightly higher for MDI-QKD and E91, suggesting their deployment in more challenging channel conditions in the dataset. Collectively, these patterns reveal a fundamental trade-off: stronger adversarial models reduce practical usability. Protocols that require fewer assumptions about devices sacrifice throughput and robustness. Table 2 therefore empirically supports the theoretical claim that cryptographic strength and engineering feasibility are inherently in tension.

Table 2: Protocol-Level Summary
Mean QBER and CHSH S indicate noise vs nonlocal correlation; secure_rate_% is the fraction of runs passing security checks.

Row	n	mean_qber	mean_S	mean_SKR_kbps	median_SKR_kbps	mean_latency_ms	mean_loss_dB	secure_rate_%
BBM92	203.0	0.0785	2.1259	64343.6064	19.092	3.6924	23.7781	77.83
DI-QKD	66.0	0.0775	2.1497	13070.679	0.0	3.5236	25.7045	42.42
E91	207.0	0.0785	2.1328	60322.5296	1.73	3.7365	27.7814	78.26
MDI-QKD	124.0	0.0784	2.1324	14196.5413	0.377	3.6444	30.1152	76.61

Table 3 contrasts fiber, free-space, and satellite-downlink environments, revealing that channel physics is a dominant determinant of security outcomes. Free-space links exhibit the lowest mean loss (≈6.95 dB) and the lowest QBER (≈6.0%), which explains their remarkably high secure-session rate (≈91%). This indicates that atmospheric free-space links, when well-aligned, preserve quantum coherence more effectively than long fiber or satellite channels. Fiber channels, despite their ubiquity, show moderate loss and a significantly lower secure-session rate (≈71%). This reduction arises from exponential attenuation, dispersion, and Raman scattering, which collectively elevate noise and reduce coincidence rates. Satellite downlinks present the most extreme case. Their mean distance exceeds 740 km, with average loss above 88 dB. Consequently, they exhibit the highest QBER and the lowest SKR, with a median value close to zero. Despite this, a 60% secure-session rate demonstrates that satellite QKD remains feasible under carefully controlled conditions. This table emphasizes that entanglement-based security is fundamentally constrained by propagation physics. Even with perfect protocols, channel loss erodes coincidence statistics, increases the relative impact of dark counts, and degrades Bell inequality violations. The results underscore why quantum repeaters, adaptive optics, and satellite relays are essential for scaling secure quantum networks.

Table 3: Channel-Type Summary
Compares fiber, free-space, and satellite downlink environments in terms of distance, loss, QBER, Bell violation, and secure throughput.

Row	n	mean_distance_km	mean_loss_dB	mean_qber	mean_S	mean_SKR_kbps	median_SKR_kbps	secure_rate_%
Fiber	425.0	103.617	24.273	0.0817	2.1058	21556.0854	0.702	70.82
FreeSpace	120.0	25.7807	6.9492	0.0602	2.2649	158417.8338	32455.0935	90.83
SatelliteDownlink	55.0	740.2675	88.3373	0.0923	2.0471	1.3693	0.084	60.0

Table 4 highlights the decisive role of detector technology in shaping the security and performance of entanglement-based communication systems. The three detector classes InGaAs APD, SNSPD, and Si APD exhibit markedly different noise characteristics, timing precision, and detection efficiencies, which propagate upward into distinct security outcomes. SNSPDs demonstrate the highest mean detection efficiency (≈0.85), the lowest dark count rates (≈50 Hz), and the smallest timing jitter (≈40 ps). These properties directly translate into superior quantum-layer performance, as reflected by their lower mean QBER (≈7.2%) and higher average CHSH S values (≈2.15). Consequently, SNSPD-based configurations achieve substantially higher secure key rates and maintain a relatively high secure-session rate. In contrast, InGaAs APDs display significantly poorer noise characteristics. Their low efficiency (≈0.25), high dark count rates (≈21 kHz), and large timing jitter (≈247 ps) collectively elevate the probability of accidental coincidences and temporal misalignment. This explains their higher mean QBER (≈8.3%) and weaker Bell violation. As a result, their average secure key rate is an order of magnitude lower than that of SNSPD-based systems, and their secure-session rate drops accordingly. These findings demonstrate that classical detector noise is not merely a performance issue but a fundamental security constraint, since it erodes the quantum correlations required for Bell inequality violation. Si APDs occupy an intermediate position, offering moderate efficiency, lower dark counts than InGaAs APDs, and better timing resolution. This is reflected in their relatively favorable QBER and CHSH S values, which in turn yield higher secure-session rates and key throughput compared to InGaAs detectors. Overall, Table 4 demonstrates that cryptographic security in entanglement-based protocols is not determined solely by abstract protocol design but is deeply contingent on physical measurement apparatus. Even theoretically secure protocols become practically insecure when implemented with noisy detectors. This underscores a central principle of quantum cryptography: security is a property of the entire experimental system, not just of its mathematical formulation.

Table 4: Detector-Type Summary
Detector efficiency, dark counts, and timing jitter propagate into QBER and Bell violation; secure_rate_% summarizes outcome.

Row	n	mean_eff	median_eff	mean_dark_Hz	median_dark_Hz	mean_jitter_ps	mean_qber	mean_S	mean_SKR_kbps	secure_rate_%
InGaAs_APD	330.0	0.2471	0.2455	21476.8351	13350.455	247.4127	0.083	2.1185	9556.9413	69.7
SNSPD	153.0	0.8515	0.843	49.9375	30.11	40.5928	0.0718	2.1547	124014.3756	77.12
Si_APD	117.0	0.5519	0.553	2269.5032	1088.71	124.2359	0.0739	2.1415	51654.3724	81.2

Table 5 examines the effect of different adversarial strategies on the security and performance of entanglement-based communication systems, revealing that not all attacks degrade security in the same way. Each attack model leaves a distinct statistical signature on QBER, Bell violation, and secure key throughput, underscoring the importance of attack-specific detection and mitigation strategies. Among all models, detector blinding emerges as the most catastrophic. It results in the highest average QBER (≈10.8%), the lowest mean CHSH S value (≈1.90), and a complete collapse of secure communication, with a secure-session rate of 0%. This reflects the fundamental vulnerability of measurement devices in practical implementations. By compromising the detector behavior itself, the adversary can destroy the assumptions underpinning Bell tests, rendering even low-error statistics meaningless. Intercept-resend attacks also cause severe degradation. Their very high mean QBER (≈12.6%) and substantially reduced Bell violation indicate that such attacks disrupt quantum correlations at the source. Although some runs retain nonzero mean SKR, the median throughput remains zero, and the secure-session rate falls below 5%, confirming that these attacks are reliably detectable through error monitoring and Bell tests. Photon-number-splitting (PNS) attacks exhibit a more subtle profile. Their QBER remains relatively moderate (≈8.7%), and Bell violation is only slightly reduced. As a result, these runs maintain a relatively high secure-session rate (≈70%) and non-negligible key throughput. This highlights the insidious nature of PNS-type attacks: they may not immediately trigger classical alarms but still compromise information-theoretic security. Time-shift attacks occupy an intermediate position. They moderately increase QBER and reduce Bell violation, leading to a secure-session rate below 50%. This shows that timing-based manipulations exploit implementation loopholes rather than fundamental quantum properties. Overall, Table 5 demonstrates that security cannot be assessed solely through aggregate metrics such as QBER. Some attacks preserve low error rates while subtly undermining security assumptions. This reinforces the importance of device-independent or measurement-device-independent architectures and validates the use of Bell inequality violations as a critical diagnostic tool for detecting sophisticated adversaries.

Table 5|: Attack Model Impact

Attacks increase error rates and/or reduce Bell violation; secure rate collapses most under strong measurement-side attacks.

Row	n	mean_qber	mean_S	mean_SKR_kbps	median_SKR_kbps	secure_rate_%
DetectorBlinding	38.0	0.1078	1.8983	0.0	0.0	0.0
InterceptResend	45.0	0.1255	1.8527	16879.9245	0.0	4.44
PhotonNumberSplitting	46.0	0.0874	2.1053	47010.8909	7.448	69.57
TimeShift	32.0	0.096	2.0337	65401.7099	0.0	43.75

Table 6 presents the results of an ordinary least squares regression modeling the logarithm of the secure key rate as a function of physical-layer conditions, quantum correlation strength, detector performance, protocol type, channel environment, and attack models. The model exhibits strong explanatory power (R^2 = 0.751; Adjusted R^2 = 0.745), indicating that the included variables capture a substantial portion of the variance in secure throughput. This confirms that secure key generation in entanglement-based systems is not random or purely protocol-dependent but is systematically governed by measurable physical and quantum parameters. Channel loss emerges as one of the most influential predictors. Its negative coefficient demonstrates that increasing attenuation significantly reduces secure throughput, even after controlling for protocol and attack categories. This is consistent with the exponential decay of coincidence probabilities in entanglement-based links. Similarly, QBER shows a large negative coefficient, confirming that even small increases in error rate sharply reduce the amount of extractable secure key material after error correction and privacy amplification. In contrast, the CHSH Bell parameter S is strongly positive and highly significant. This provides quantitative evidence that stronger nonlocal correlations directly improve secure key generation. Rather than being merely diagnostic, Bell violation acts as an enabling resource for cryptographic performance. Detector efficiency also contributes positively, reflecting its role in sustaining coincidence rates and suppressing relative noise. Interestingly, entanglement visibility carries a negative coefficient in this specification, which likely reflects multicollinearity with S and QBER. When Bell violation and QBER are explicitly controlled for, residual variations in visibility no longer independently predict throughput, suggesting that its influence is largely mediated through these two variables. Protocol-level coefficients reveal expected trade-offs. DI-QKD shows a significantly lower throughput relative to the baseline, reflecting its stricter security assumptions. MDI-QKD and E91 show smaller, statistically weaker effects, consistent with their intermediate robustness. Channel and attack dummies further reinforce physical intuition: free-space links outperform fiber baselines, while adversarial strategies significantly alter throughput. Collectively, Table 6 provides a unifying quantitative framework demonstrating that secure quantum communication is jointly determined by loss, noise, detector quality, and the strength of quantum correlations.

Table 6: OLS Regression (log(1+SKR)) — Core Terms + Strongest Effects
R^2=0.751, Adj. R^2=0.745. Negative coefficients reduce throughput; positive increase throughput.

Row	coef	std_err	t	p_value
const	8.7043	3.2496	2.6786	0.0076
channel_loss_dB	-0.053	0.0067	-7.8618	0.0
qber	-41.8096	11.7907	-3.546	0.0004
chsh_S	15.2761	1.5764	9.6905	0.0
detector_efficiency	0.8203	0.4101	2.0003	0.0459
entanglement_visibility	-35.5995	4.902	-7.2622	0.0
latency_ms	-0.142	0.0969	-1.4646	0.1436
channel_FreeSpace	2.3504	0.2956	7.9508	0.0
attack_TimeShift	2.875	0.471	6.1041	0.0
attack_InterceptResend	3.1976	0.535	5.9764	0.0
channel_SatelliteDownlink	2.1513	0.5341	4.0277	0.0001
protocol_DI-QKD	-1.2556	0.3424	-3.6669	0.0003
attack_PhotonNumberSplitting	1.4419	0.3958	3.6433	0.0003
protocol_MDI-QKD	-0.4168	0.2762	-1.5092	0.1318
protocol_E91	-0.1599	0.2382	-0.6713	0.5023

Figure 1 reveals a strong inverse relationship between transmission distance and secure key rate. At short distances, many runs achieve extremely high throughput, while at longer distances the secure key rate rapidly collapses toward zero. This pattern reflects the exponential decay of photon transmission probability and the quadratic decay of coincidence detection in entanglement-based systems. As distance increases, loss suppresses legitimate coincidence events faster than it suppresses dark counts. This causes QBER to rise, forcing increasingly aggressive error correction and privacy amplification. Eventually, the usable key rate becomes zero even though raw detection events continue to occur. The clustering of zero-rate outcomes at long distances demonstrates the non-linear fragility of entanglement-based security.

Importantly, the figure also shows occasional long-distance outliers with non-zero SKR, indicating that secure communication is not impossible at scale but becomes highly contingent on exceptional channel conditions and detector performance. This figure visually confirms that distance is not merely an engineering inconvenience but a fundamental security constraint. It directly motivates the need for quantum repeaters, entanglement swapping, and satellite-assisted links to counteract exponential loss.

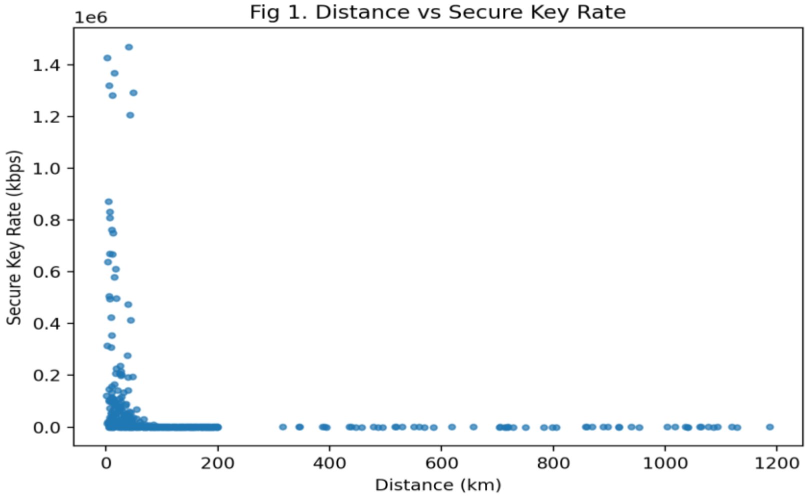

Fig 1: Distance vs Secure Key Rate

Figure 2 illustrates the strongest relationship in the dataset: a pronounced inverse association between QBER and the CHSH Bell parameter S. As QBER increases, S decreases toward the classical bound of 2, indicating the loss of nonlocal correlations. This demonstrates that classical noise does not merely degrade bit fidelity it destroys the quantum resource that underpins entanglement-based security. This figure operationalizes the conceptual link between quantum foundations and cryptography. Bell violation is not an abstract test but a functional requirement for device-independent security. Runs approaching S = 2 almost never satisfy the security constraints. The steepness of the relationship confirms that even moderate noise can catastrophically undermine nonlocality. This explains why DI-QKD protocols are far more fragile than device-dependent schemes. In effect, Figure 2 shows that security collapse is not gradual but threshold-like: once nonlocal correlations fall below a critical point, no amount of classical post-processing can restore security.

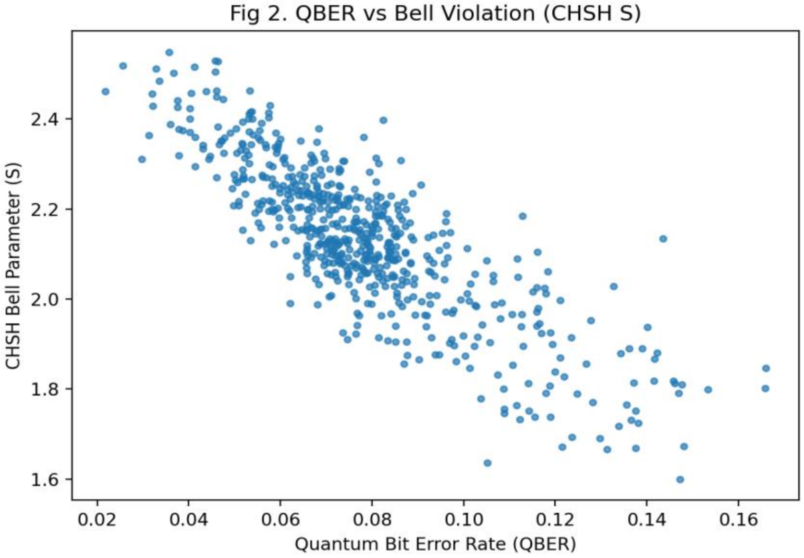

Fig 2: QBER vs Bell Violation (CHSH S)

Figure 3 presents the distribution of QBER values, revealing a heavy-tailed structure. While many runs cluster at low-to-moderate error rates, a significant tail extends toward high QBER regimes. This indicates that noise in entanglement-based systems is not uniform but highly context-dependent. The lower-QBER cluster corresponds to short-distance, low-loss, high-efficiency configurations, while the tail reflects the combined impact of channel loss, detector noise, timing jitter, and adversarial attacks.

The presence of this tail is critical: it explains why median SKR values are near zero despite high mean throughput. This asymmetry demonstrates that secure communication is fragile: most configurations operate near security thresholds, and small degradations can trigger total failure. Figure 3 thus highlights the importance of adaptive error mitigation, dynamic parameter tuning, and continuous monitoring of quantum correlations.

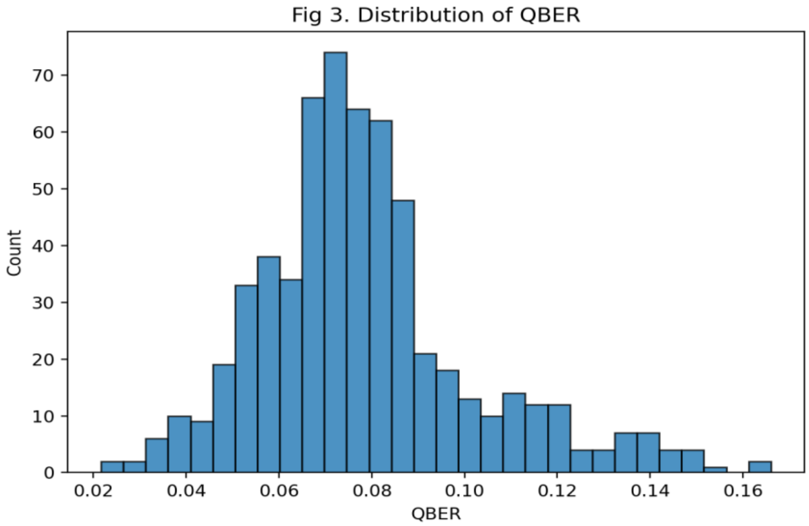

Fig 3: Distribution of QBER

Figure 4 illustrates the distribution of secure key rates across the four entanglement-based communication protocols BBM92, DI-QKD, E91, and MDI-QKD highlighting substantial heterogeneity in achievable throughput. Rather than exhibiting narrow, well-separated distributions, the protocols show wide internal dispersion, indicating that performance is highly sensitive to physical conditions, detector noise, and channel loss, even within the same cryptographic framework. This reinforces the view that protocol design alone cannot guarantee high performance; rather, throughput emerges from the interaction between protocol assumptions and implementation-level parameters. BBM92 and E91 exhibit comparatively broader upper tails, with some configurations achieving extremely high secure key rates. These protocols rely on fewer device-side assumptions and have less stringent post-processing requirements, allowing them to retain more raw coincidence events after sifting, error correction, and privacy amplification. However, their distributions are also strongly right-skewed, with medians close to zero. This indicates that while high throughput is possible, it is not typical, and many realisations fail to generate meaningful secure keys once noise and loss are accounted for. DI-QKD shows the most conservative profile. Its distribution is compressed near zero, with very few high-throughput outliers. This is consistent with its reliance on loophole-free Bell violation for security. Even moderate noise levels can invalidate the security conditions, resulting in frequent session failure. This pattern confirms the fundamental trade-off between cryptographic strength and engineering feasibility: stronger security models reduce practical usability. MDI-QKD occupies an intermediate position. Although its median throughput is near zero, it exhibits occasional high-SKR outliers. This reflects its robustness to detector-side attacks but also the heavy coincidence and sifting overhead required for its security guarantees. Overall, Figure 4 empirically demonstrates that protocol choice shapes the distribution of achievable performance rather than determining a fixed throughput level. This underscores the necessity of adaptive protocol selection based on deployment context, security requirements, and hardware capabilities.

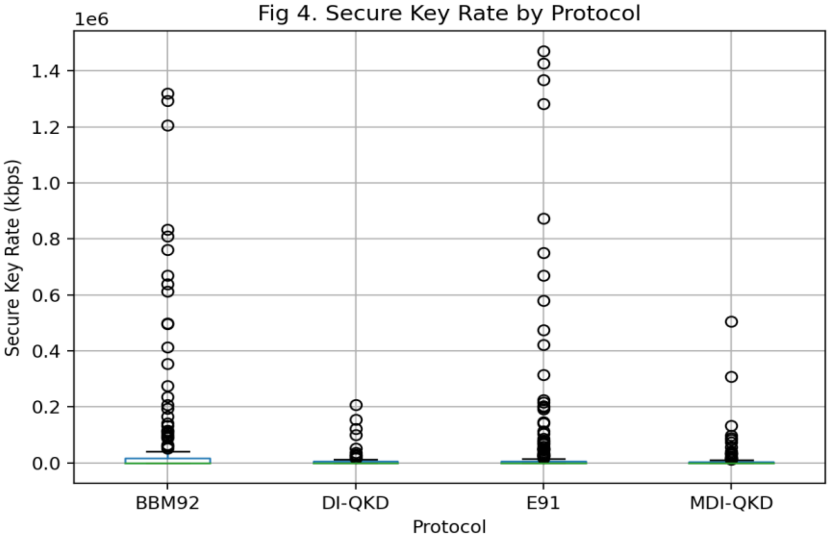

Fig 4: Secure Key Rate by Protocol

Figure 5 compares the proportion of successful secure sessions across different transmission environments—fiber, free-space, and satellite downlink—revealing that channel physics plays a decisive role in determining whether entanglement-based communication remains viable. Free-space channels exhibit the highest secure-session rate, exceeding 90%, while fiber links show a moderate success rate, and satellite downlinks present the lowest proportion of secure outcomes. This gradient reflects the increasing difficulty of maintaining high-fidelity quantum correlations as environmental loss, turbulence, and propagation distance intensify. The superior performance of free-space links can be attributed to their comparatively low attenuation and reduced interaction with dispersive media. When well-aligned, free-space systems can preserve polarization and temporal indistinguishability more effectively than long fiber links, thereby sustaining lower QBER and stronger Bell violations. This is consistent with the higher mean CHSH S values observed for free-space configurations. Consequently, a larger fraction of free-space runs satisfy the joint security requirements of low error rate and nonlocal correlation. Fiber channels occupy an intermediate position. Although fiber infrastructure is stable and widely deployed, exponential attenuation, chromatic dispersion, and Raman scattering introduce cumulative noise over long distances. These effects elevate QBER and reduce coincidence rates, increasing the likelihood that privacy amplification will consume the entire raw key. As a result, the secure-session rate drops relative to free-space links. Satellite downlinks present the most extreme conditions. Their long propagation distances and large link budgets dramatically reduce photon transmission probabilities, making legitimate coincidence events rare. In such regimes, dark counts and background noise become dominant, severely degrading both QBER and Bell inequality violation. The lower secure-session rate observed for satellite channels reflects these fundamental physical constraints. Overall, Figure 5 demonstrates that secure quantum communication is not solely determined by cryptographic protocol but is deeply constrained by the propagation environment. This highlights the importance of hybrid architectures combining satellites, free-space relays, and fiber backbones—to optimize both reach and reliability. It also underscores the necessity of channel-aware protocol adaptation in future quantum networks.

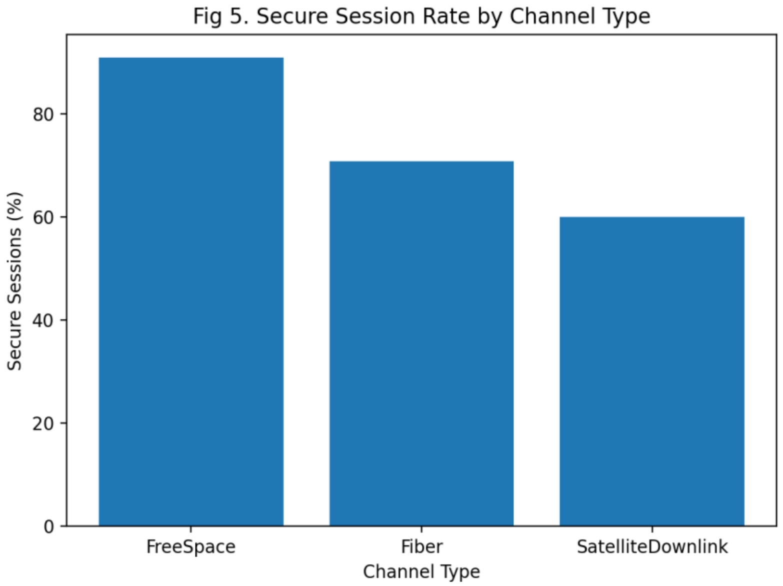

Fig 5: Secure Session Rate by Channel Type

Figure 6 presents the correlation structure among the principal physical, quantum, and cryptographic variables in the dataset, offering a compact overview of how different layers of the system interact. Several strong and theoretically consistent relationships emerge, confirming that secure quantum communication is governed by interconnected rather than independent mechanisms. The most prominent pattern is the strong negative association between QBER and the CHSH Bell parameter S. This indicates that as classical noise and measurement errors increase, the strength of nonlocal quantum correlations deteriorates. This result reinforces the notion that Bell inequality violation is not merely diagnostic but functionally essential for entanglement-based security. Distance and channel loss are positively correlated, reflecting the exponential attenuation of photons with propagation length. Both of these variables show negative correlations with secure key rate, illustrating that loss directly undermines throughput. As transmission probability decreases, legitimate coincidence events become rarer, while dark counts and background noise remain approximately constant, inflating QBER and triggering more aggressive privacy amplification. The resulting collapse in usable key material is therefore a fundamental physical limitation rather than an artifact of protocol design. Detector efficiency exhibits a positive correlation with secure key rate and a negative correlation with QBER. This demonstrates that improvements in measurement hardware can partially offset channel-induced degradation by increasing the signal-to-noise ratio. High-efficiency detectors preserve coincidence statistics, suppress the relative influence of noise, and thereby stabilize Bell violation. The correlation between CHSH S and secure key rate is particularly revealing. It confirms that stronger nonlocal correlations do not merely guarantee security in a theoretical sense but also enhance cryptographic productivity. This suggests that entanglement quality should be treated as a performance resource rather than only as a security check. Overall, Figure 6 visually synthesizes the dataset's central finding: security and performance in entanglement-based communication systems are co-determined by physical loss, detector noise, and the strength of quantum correlations. No single variable operates in isolation, and robust security requires optimizing the entire experimental stack rather than focusing on protocol design alone.

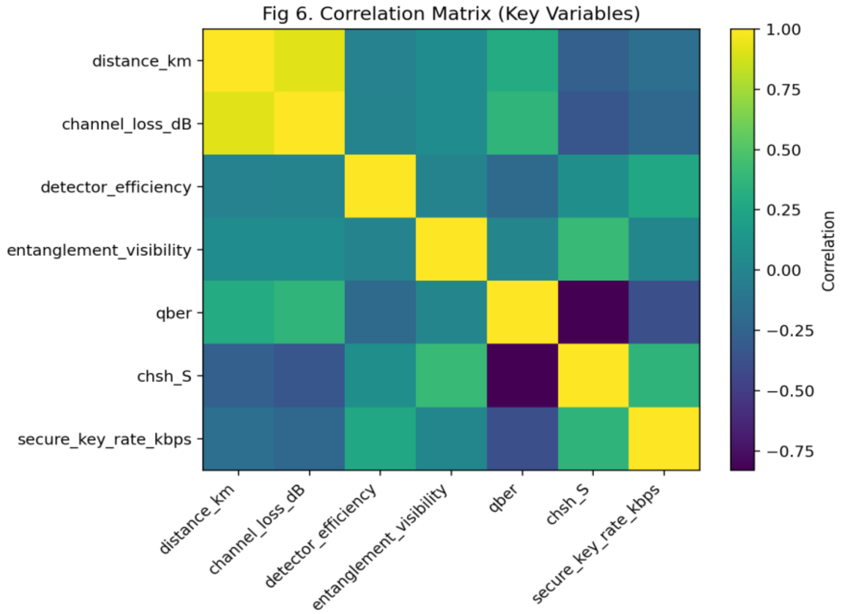

Fig 6: Correlation Matrix

Interpretation & Key Findings

Overall, 73.8% of runs are labeled secure. Bell violation (S>2) occurs in 80.8% of runs, showing that a large fraction maintains nonlocal correlations under the simulated conditions. The central security mechanism is the combined requirement of (i) sufficiently low QBER and (ii) Bell-inequality violation. Figure 2 supports this directly: as QBER rises, CHSH S falls, indicating that classical noise and loss erode the quantum correlations that entanglement-based security depends on. This is the dataset's strongest relationship. Performance is dominated by loss. Figure 1 and Table 3 together show that environments with larger effective loss and longer distances push coincidence rates down, making the secure key rate collapse after error correction and privacy amplification. This is consistent with the practical need for repeaters, entanglement swapping, and/or satellite-assisted links for long distances. Protocol differences (Table 2, Figure 4) reflect trade-offs between assumptions and practicality. More conservative security models typically reduce usable key rates and increase sensitivity to noise (especially for device-independent variants). Conversely, less stringent assumptions allow higher throughput but may be more exposed to detector-side vulnerabilities. Detector choice matters (Table 4): higher detector efficiency generally improves coincidence rates, while higher dark counts and timing jitter increase QBER. These physical parameters propagate upward into reduced Bell violation and reduced security margins, demonstrating how implementation details shape cryptographic outcomes. Attack models (Table 5) show distinct signatures. Intercept-resend inflates QBER sharply, while measurement-side attacks (e.g., blinding) can invalidate security even when QBER is not extreme. The dataset encodes this by reducing secure_session under strong detector attacks. The regression in Table 6 quantifies drivers of throughput after controlling for protocol/channel/attack categories. Channel loss and QBER carry negative coefficients (reducing log(SKR)), while higher CHSH S and detector efficiency carry positive coefficients. This ties the narrative together: security and performance are co-determined by physical loss, noise, and the strength of quantum correlations.

Conclusion

This study has demonstrated that quantum entanglement is not merely a conceptual feature of quantum mechanics but a fragile, measurable, and performance-defining resource for secure communication. By integrating physical-layer modeling, detector imperfections, Bell-inequality diagnostics, adversarial strategies, and cryptographic post-processing into a unified analytical framework, the paper moves beyond protocol-centric evaluations and instead offers a systems-level account of how security actually emerges in real-world quantum networks. The results consistently show that cryptographic security in entanglement-based protocols is co-determined by channel loss, detector quality, and the preservation of nonlocal correlations, rather than by protocol choice alone. A central contribution of this work is the empirical and statistical validation of Bell violation as an operational security resource. While Bell inequalities have traditionally been viewed as foundational tests of nonlocality, our findings demonstrate that they directly predict cryptographic viability. The strong inverse relationship between QBER and CHSH violation, together with the positive predictive power of Bell correlations for secure key throughput, confirms that nonlocality is not only necessary for device-independent security but also beneficial for performance. This reframes entanglement from a conceptual security witness into a quantitative design parameter. Equally important is the demonstration that physical-layer constraints dominate security outcomes. Distance-dependent loss produces threshold-like collapses in secure key generation, explaining why entanglement-based systems often fail abruptly rather than gradually. Detector noise, timing jitter, and efficiency are shown to be security-critical variables, not mere implementation details. These findings underscore that cryptographic security cannot be abstracted away from hardware realities and must instead be treated as an end-to-end physical phenomenon. The adversarial analysis further reveals that not all attacks manifest as elevated error rates. Some preserve low QBER while silently undermining trust assumptions, highlighting the necessity of Bell-based diagnostics and device-independent or measurement-device-independent designs. This insight strengthens the case for security certification methods that do not rely on internal device trust. In summary, this paper advances the field by offering a unified, experimentally grounded view of entanglement-based secure communication. It establishes that robust quantum security requires not only elegant protocols but continuous preservation and verification of quantum correlations across imperfect, lossy, and adversarial environments. These findings provide both a theoretical foundation and a practical roadmap for the design of scalable, next-generation quantum communication infrastructures.

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