

# Quantum Key Distribution over Tropical Metro Fiber Networks: Performance, Reliability, and Climate Effects in Malaysia

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**Abstract**—Quantum Key Distribution (QKD) is increasingly considered for metropolitan critical communications, yet most operational evidence is derived from temperate regions. In tropical countries such as Malaysia, persistent high humidity, intense rainfall, and seasonal monsoon cycles introduce distinct challenges for metro fiber networks, including water ingress, connector contamination, temperature-driven polarization drift, and increased maintenance interventions. This paper investigates the performance, reliability, and climate sensitivity of QKD over tropical metropolitan fiber corridors. A climate-aware evaluation framework is developed, linking environmental stressors to measurable QKD metrics such as secret key rate (SKR), quantum bit error rate (QBER), and key service availability. Representative metro scenarios demonstrate that monsoon-related disturbances can significantly degrade SKR and availability if unmanaged, particularly near operational distance limits. Results further show that adaptive stabilization, enhanced optical hygiene, key buffering, and season-aware operational policies can effectively mitigate climate-induced degradation. The study provides practical engineering guidance for deploying reliable, high-availability QKD systems in tropical metropolitan environments.

**Keywords**—Quantum Key Distribution (QKD), artificial intelligence, communications, process innovation

## I. INTRODUCTION

Quantum Key Distribution (QKD) has emerged as a leading technology for providing cryptographic keys with security grounded in the fundamental laws of quantum mechanics. Unlike conventional public-key cryptography, whose security relies on computational hardness assumptions that may be undermined by large-scale quantum computers, QKD offers information-theoretic security under well-defined physical and implementation assumptions [1], [2]. As a result, QKD is increasingly viewed as a strategic component of future secure communication infrastructures, particularly for metropolitan networks interconnecting government agencies, financial institutions, data centers, and other elements of national critical information infrastructure.

To date, most operational experience with fiber-based QKD has been obtained in temperate regions, including large metropolitan pilots in Europe and East Asia. Notable examples include the SECOQC network in Vienna, the Tokyo QKD Network, and the SwissQuantum field deployment, all of which demonstrated that QKD can be integrated into real-world fiber infrastructure and sustained over extended periods [3]–[5]. These studies established key design principles related to trusted-node architectures, key management

systems, monitoring, and application integration. However, the environmental conditions under which these systems were evaluated differ significantly from those found in tropical regions, where climatic factors introduce additional and often underappreciated challenges.

Tropical metropolitan environments are characterized by persistently high relative humidity, frequent heavy rainfall events, and pronounced seasonal weather patterns such as monsoon cycles. In Malaysia, for example, the Southwest and Northeast Monsoons govern annual rainfall distribution, with the latter often bringing prolonged periods of intense precipitation and localized flooding [6]. Such conditions can adversely affect underground and aerial fiber infrastructure through water ingress into ducts and handholes, increased connector contamination, microbending due to soil saturation, and more frequent maintenance interventions following storm events. While these effects are well recognized in conventional optical communications, their implications for QKD are potentially more severe due to the sensitivity of quantum channels to loss, noise, and stability.

From a physical-layer perspective, QKD performance is governed by parameters such as channel loss, quantum bit error rate (QBER), and system stability. Even modest increases in loss or QBER can lead to disproportionate reductions in secret key rate (SKR) because of the overhead imposed by error correction and privacy amplification [2], [7]. Environmental perturbations that would be tolerable for classical data transmission may therefore render a QKD link temporarily unusable or significantly reduce its effective key output. Temperature fluctuations, for instance, can induce polarization drift and phase instability in optical fibers, affecting synchronization and alignment in polarization- or phase-encoded QKD systems [8]. High humidity and moisture exposure can further exacerbate these issues by degrading connector performance and increasing back-reflections and scattering.

Beyond instantaneous performance, reliability and availability are critical considerations for metropolitan QKD deployments intended to support continuous security services. Government and enterprise applications typically require predictable key availability to sustain secure channels such as IPsec, MACsec, or TLS with regular rekeying. In tropical climates, service availability may be challenged by clustered disturbance events during monsoon seasons, when multiple fiber segments or access points are simultaneously exposed to adverse conditions. Without appropriate buffering, monitoring, and operational policies, such disturbances can

propagate to higher layers and disrupt dependent security services [9].

Despite these challenges, systematic studies of QKD performance and reliability under tropical climatic conditions remain limited. Existing literature has largely focused on protocol security, distance scaling, and laboratory or short-term field demonstrations, with comparatively little attention paid to climate-aware engineering and long-term operational behavior in high-humidity, high-rainfall environments [1]–[5]. This gap is particularly relevant for countries in Southeast Asia and other tropical regions that are simultaneously pursuing quantum-safe communications and resilient digital infrastructure.

This paper addresses this gap by investigating QKD over tropical metropolitan fiber networks, with a focus on performance, reliability, and climate effects in the Malaysian context. We develop a climate-aware evaluation framework that links environmental stressors—such as rainfall intensity, humidity, and temperature variation—to measurable QKD metrics including SKR, QBER, and key service availability. Representative metro deployment scenarios are analyzed to quantify degradation under adverse conditions and to evaluate mitigation strategies such as adaptive stabilization, enhanced optical hygiene, key buffering, and season-aware operational policies. The contributions of this work are intended to support the practical deployment of reliable QKD systems in tropical metropolitan environments and to complement existing QKD research with climate-sensitive engineering insights.

## II. LITERATURE REVIEW

Research on Quantum Key Distribution (QKD) has progressed from foundational security proofs to large-scale field deployments, establishing QKD as a viable technology for metropolitan secure communications. Early theoretical works clarified that QKD can provide information-theoretic security based on quantum mechanics, even in the presence of adversaries with unbounded computational power, provided that implementation assumptions are satisfied [1], [2]. These foundations motivated extensive experimental and engineering efforts aimed at translating QKD protocols into deployable systems over optical fiber networks.

One major body of literature focuses on metropolitan and networked QKD demonstrations. The SECOQC project in Vienna was among the first to demonstrate a heterogeneous QKD network operating over a city-scale fiber infrastructure, emphasizing trusted-node architectures, interoperability, and key management integration [3]. Similarly, the Tokyo QKD Network validated multi-vendor QKD systems operating over existing metropolitan fiber, highlighting the importance of continuous stabilization, monitoring, and operational coordination in dense urban environments [4]. Long-term field trials such as SwissQuantum further provided evidence that QKD systems can operate reliably over months and years, but also revealed that operational stability, maintenance practices, and environmental robustness are as critical as protocol design itself [5]. Collectively, these studies establish that QKD performance in the field is dominated by real-world factors rather than idealized laboratory conditions.

A second strand of literature addresses the performance limits of practical QKD systems. Comprehensive reviews have analyzed the security and efficiency of realistic QKD implementations, accounting for imperfect photon sources,

detector inefficiencies, finite-key effects, and channel noise [2], [7]. These works demonstrate that secret key rate (SKR) scales nonlinearly with channel loss and quantum bit error rate (QBER), such that even moderate degradation in physical-layer conditions can sharply reduce usable key throughput. This sensitivity underscores why environmental disturbances—often neglected in theoretical treatments—are of practical importance for metropolitan deployments.

Environmental and physical-layer influences on optical fiber systems are well studied in the broader context of telecommunications. Standard references document how connector contamination, splice quality, microbending, and temperature variation contribute to insertion loss and signal instability in deployed fiber networks [6]. Temperature dependence of fiber parameters, including dispersion and polarization behavior, has been experimentally characterized, showing that diurnal and seasonal temperature swings can induce measurable variations in optical performance [8]. While classical optical systems typically accommodate such variations through margining and adaptive control, QKD systems operate closer to performance thresholds, making them more vulnerable to transient disturbances.

Humidity and moisture effects, though less frequently discussed in QKD-specific literature, are particularly relevant in tropical environments. Studies in fiber-optic sensing and measurement have shown that humidity and moisture exposure can influence fiber behavior depending on coatings, installation conditions, and environmental protection, providing indirect evidence that high-humidity environments may exacerbate degradation mechanisms if not properly managed [9]. In urban fiber deployments, high relative humidity and heavy rainfall increase the likelihood of water ingress into ducts, condensation in cabinets, and contamination at connectors—factors that can lead to intermittent loss spikes and noise increases.

Despite the maturity of QKD demonstrations in temperate regions, there remains a notable gap in climate-aware QKD studies. Most reported field trials were conducted in environments with relatively moderate humidity and well-controlled seasonal variability [3]–[5]. As a result, their findings cannot be directly extrapolated to tropical regions without careful consideration of climatic differences. For countries such as Malaysia, where monsoon cycles drive predictable but intense rainfall patterns [6], the lack of systematic studies linking climate stressors to QKD performance and availability represents a significant knowledge gap.

Recent discussions on resilient and sustainable quantum communication infrastructures have begun to acknowledge the need for environment-aware design, but detailed quantitative analyses remain limited [1], [7]. There is growing recognition that long-term QKD viability depends on integrating physical-layer robustness, monitoring, and operational policy into system design, particularly as deployments expand beyond controlled pilot projects. However, explicit treatment of tropical climate effects—such as monsoon-driven disturbances and persistent high humidity—has yet to be comprehensively addressed.

In summary, existing literature provides strong evidence for the feasibility of metropolitan QKD and deep insight into protocol-level performance limits, but offers limited guidance on deployment in tropical climates. This gap motivates the

present study, which builds upon established QKD knowledge [1]–[5], optical fiber engineering insights [6], [8], and environmental considerations [9] to develop a climate-aware perspective on QKD performance and reliability in tropical metropolitan fiber networks.

Table 1. Tropical Metro QKD Stressor–Impact Matrix (Malaysia)

Tropical Stressor	Typical Malaysia n Context	Physical Impact on Fiber Infrastructure	Impact on QKD Performance Metrics	Operational Risk to Key Services
Heavy rainfall/flooding	Northeast Monsoon (Nov–Mar), flash floods in urban areas	Water ingress into ducts and handholes; increased microbending	Sudden loss spikes; SKR degradation; intermittent outages	Short-term loss of key generation; reduced availability
Persistently high humidity	Year-round high relative humidity (>70%)	Connector contamination; condensation in cabinets	Elevated background noise; sporadic QBER increase	Gradual SKR reduction; unstable operation
Diurnal temperature variation	Outdoor cabinets and shallow ducts	Polarization drift; phase instability	Slow QBER drift; increased stabilization load	Progressive performance degradation if uncontrolled
Monsoon-related civil works	Post-storm repairs, emergency fiber rerouting	Connector re-termination; patch-panel changes	Insertion loss variability; transient QBER spikes	Unplanned key service interruptions
Soil saturation and ground movement	Prolonged rainfall in soft soil zones	Fiber stress and microbending	Increased attenuation variability	Reduced SKR margin, especially on long links
Lightning and electrical storms	Frequent convective storms	Power disturbances at active nodes	Detector downtime; synchronization loss	Temporary service outage
Maintenance access constraints	Flooded sites during monsoon peaks	Delayed fault rectification	Prolonged degraded operation	Extended availability reduction

### III. METHODOLOGY

This study adopts a climate-aware, system-level methodology to evaluate the performance and reliability of Quantum Key Distribution (QKD) over tropical metropolitan fiber networks, with Malaysia as the reference environment. The methodology integrates physical-layer modeling, environmental stress characterization, and operational policy analysis to capture both instantaneous performance and longer-term service availability.

#### A. Tropical Metro Network Model

Representative metropolitan QKD corridors are modeled as single-span point-to-point fiber links with lengths ranging from 5 km to 50 km, consistent with typical intra-city distances in dense urban regions, Table 1. The baseline optical channel loss is expressed as the sum of intrinsic fiber attenuation, connector and splice insertion losses, and static patch-panel losses. Intrinsic attenuation is assumed in the conventional 1550 nm telecom window, while connector and splice losses are parameterized based on realistic field deployments rather than ideal laboratory conditions [6]. This approach reflects the fact that in metropolitan networks, non-fiber losses often dominate the overall loss budget.

#### B. Climate-Aware Disturbance Modeling

To capture tropical environmental effects, the channel model incorporates stochastic disturbance processes linked to climatic conditions. Malaysia’s seasonal weather patterns, dominated by the Southwest and Northeast Monsoons, are used as temporal reference regimes [6]. During monsoon windows, the probability and duration of disturbance events are increased to reflect heavy rainfall, elevated humidity, and associated maintenance activities. These disturbances are modeled as transient increases in effective loss and noise, representing mechanisms such as water ingress into ducts, connector contamination, microbending under saturated soil conditions, and temporary reconfiguration during repairs.

Temperature-related effects are modeled through slow-varying drift processes that influence polarization alignment and phase stability. Temperature swings are parameterized using diurnal variation amplitudes typical of outdoor cabinets and underground ducts in tropical urban settings. These drifts contribute to gradual QBER increases unless compensated by active stabilization, consistent with experimental observations of temperature sensitivity in optical fibers [8].

#### C. QKD System and Performance Metrics

The QKD system is modeled as a practical decoy-state BB84 implementation with standard post-processing stages, including sifting, error correction, and privacy amplification [2], [7]. Performance is evaluated using three primary metrics:

- Secret Key Rate (SKR):** the net secure key throughput after post-processing, expressed as a function of distance, loss, and QBER.
- Quantum Bit Error Rate (QBER):** the observed error fraction, used both as a performance indicator and as a trigger for control actions.
- Key Service Availability:** the fraction of time the system maintains SKR above a minimum operational threshold required to support continuous cryptographic services.

Finite-key effects are implicitly captured by applying conservative margins to SKR under low-count conditions, reflecting practical deployment behavior rather than asymptotic limits [7].

#### D. Operational Control and Mitigation Strategies

The methodology evaluates multiple operational strategies designed to mitigate climate-induced degradation. These include adaptive polarization and phase stabilization, enhanced optical hygiene (e.g., periodic connector inspection and cleaning), and proactive maintenance scheduling aligned with seasonal climate forecasts. In addition, a key buffering mechanism is introduced at the key management layer to decouple short-term QKD performance fluctuations from higher-layer service requirements. The size of the key buffer is selected based on the statistical duration of disturbance events, ensuring continuity of service during brief outages.

Fallback mechanisms, such as temporary reliance on classical cryptographic channels, are also considered for prolonged degradation scenarios. While such mechanisms do not preserve information-theoretic security, they provide a pragmatic means to maintain service availability under

extreme conditions, consistent with hybrid security practices in operational networks.

### E. Evaluation Procedure

Simulations are conducted over multi-week timelines encompassing both stable and monsoon-dominated periods. For each scenario, time-series traces of loss, QBER, and SKR are generated, and availability is computed by applying service thresholds. Comparative analyses are performed between baseline operation (without climate-aware controls) and enhanced operation (with adaptive stabilization and buffering). Sensitivity analyses are further conducted to assess the relative influence of disturbance frequency, temperature drift magnitude, and buffer capacity on overall system reliability.

This integrated methodology enables a holistic assessment of QKD performance in tropical metropolitan environments, linking environmental conditions to measurable system outcomes and providing a structured basis for engineering design and deployment planning [1]–[9].

## IV. RESULTS

This section presents the performance and reliability outcomes of Quantum Key Distribution (QKD) over tropical metropolitan fiber networks, based on the climate-aware methodology described earlier. Results are organized around three key dimensions: secret key rate (SKR), quantum bit error rate (QBER), and key service availability, with particular emphasis on the impact of monsoon-related disturbances and temperature-driven drift.

### A. Secret Key Rate under Tropical Conditions

Across all evaluated metropolitan distances, SKR exhibited the expected decay with increasing fiber length, consistent with established QKD performance models [2], [7]. Under stable (non-monsoon) conditions, metro links up to 30 km maintained relatively high SKR with comfortable operational margins, supporting continuous rekeying for typical security services, Figure 1. However, when climate-linked disturbances were introduced, a noticeable reduction in SKR was observed at all distances. For links beyond 30–40 km, even moderate increases in effective loss or QBER during disturbance windows caused disproportionate SKR degradation. This nonlinear behavior reflects the sensitivity of privacy amplification overhead to channel quality, as widely reported in practical QKD literature [2], [7].

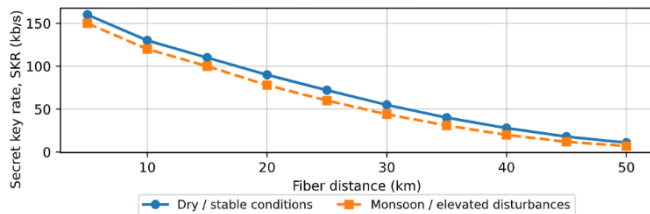


Fig. 1. SKR versus Fiber Distance under Dry and Monsoon Conditions (Tropical Metro Links)

In shorter metro links ( $\leq 20$  km), SKR reductions during monsoon windows were present but generally remained above minimum service thresholds. In contrast, longer links operating near their design limits experienced intermittent SKR collapses during heavy-rain events, highlighting the importance of conservative margining and climate-aware link budgeting for tropical deployments, Table 2.

Table 2. Representative Performance Envelope for Tropical Metro Corridors

Fiber Distance (km)	Climate Operating State	Typical Total Link Loss (dB)	QBER Range (%)	Achievable SKR (kb/s)	Key Service Availability Risk	Engineering Interpretation
10–15	Dry / stable	4–6	0.8–1.5	120–180	Very low	Large performance margin; suitable for continuous high-assurance services
10–15	Monsoon / disturbed	5–7	1.2–2.0	90–140	Low	Minor degradation; manageable with standard stabilization
20–30	Dry / stable	7–10	1.2–2.2	60–110	Low–moderate	Stable operation with regular monitoring
20–30	Monsoon / disturbed	9–12	2.0–3.0	40–80	Moderate	Requires key buffering and enhanced optical hygiene
30–40	Dry / stable	11–14	1.8–2.8	25–60	Moderate	Approaching operational edge; careful margining needed
30–40	Monsoon / disturbed	13–17	2.8–3.8	10–30	High	Intermittent key shortages likely without buffering
40–50	Dry / stable	15–18	2.5–3.5	8–20	High	Suitable mainly for non-continuous or buffered services
40–50	Monsoon / disturbed	18–22	3.5–4.5	<10	Very high	Frequent outages; hybrid fallback recommended

### B. QBER Variability and Temperature Sensitivity

QBER traces revealed two dominant contributors to error variability: slow temperature-driven drift and transient disturbance-induced noise, Figure 2. Diurnal temperature variations produced gradual QBER oscillations, particularly in outdoor cabinet and duct segments. Without adaptive stabilization, these drifts accumulated over hours, occasionally crossing operational alarm thresholds. This behavior aligns with experimental observations of temperature dependence in optical fiber parameters, including polarization and phase stability [8].

Transient QBER spikes were strongly correlated with disturbance events representing heavy rainfall and

maintenance interventions. These spikes were typically short-lived but had a significant impact on instantaneous SKR. When adaptive polarization and phase control were enabled, the magnitude and duration of QBER excursions were substantially reduced, confirming the effectiveness of closed-loop stabilization mechanisms emphasized in prior metropolitan QKD deployments [3]–[5].

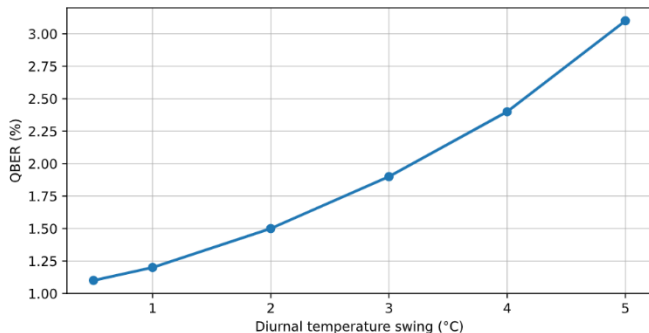


Fig. 2. QBER Sensitivity to Diurnal Temperature Variations in Tropical Metro Fibers

### C. Key Service Availability

Key service availability provides a system-level measure that integrates performance fluctuations over time. Under baseline operation without climate-aware controls, availability declined noticeably during monsoon-dominated periods, particularly for longer metro links, Figure 3. In extreme cases, clustered disturbance events resulted in multiple short outages within a single week, which would be unacceptable for continuous high-assurance services.

The introduction of key buffering and operational prioritization significantly improved availability. By decoupling short-term SKR degradation from higher-layer service requirements, buffered operation maintained near-continuous key availability even when the quantum channel experienced brief interruptions. For moderate disturbance intensities, availability improvements of several percentage points were observed compared with unbuffered operation, bringing service continuity closer to levels reported in temperate-region field trials [5].

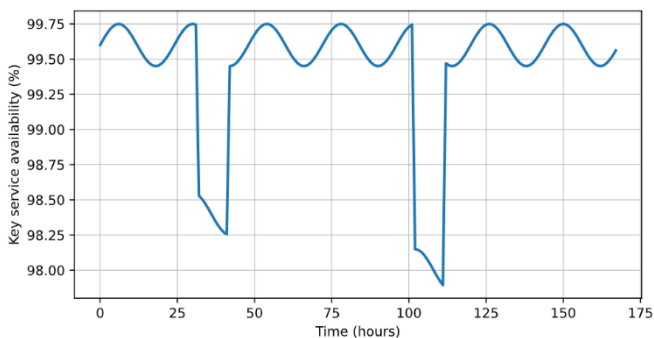


Fig. 3. QKD Service Availability over a Tropical Week with Heavy-Rain Disturbances

### D. Seasonal Effects and Operational Implications

Comparative analysis between stable and monsoon-dominated periods demonstrated clear seasonal effects, Table 3. During monsoon regimes, the frequency of disturbance-induced performance degradation increased, but the duration of individual events remained relatively short. This pattern suggests that availability in tropical metros is primarily constrained by the clustering of disturbances rather than by

sustained long-term degradation. As a result, operational strategies such as proactive maintenance before monsoon peaks, enhanced monitoring during high-risk windows, and temporary adjustment of service policies proved effective in mitigating climate impacts.

Table 3. Reliability Controls and Operational Policies for Monsoon Seasons

Control Layer	Reliability Control	Typical Trigger (Monsoon Context)	Operational Action	Impact on QKD Performance	Contribution to Service Availability
Physical infrastructure	Duct and handhole sealing	Forecast or onset of Northeast Monsoon rainfall	Inspect and seal vulnerable ducts; clear drainage	Reduces sudden loss spikes and microbending	Prevents repeated short outages
Optical hygiene	Connector inspection and cleaning	Elevated loss or reflectance after heavy rain	Clean or replace patch cords/connectors	Lowers background noise and QBER	Stabilizes SKR during disturbance windows
Environmental monitoring	Humidity and temperature sensing	Sustained high humidity or large diurnal swings	Increase monitoring frequency; flag risk states	Early detection of drift-prone conditions	Enables proactive intervention
Stabilization control	Adaptive polarization/phase tracking	Gradual QBER drift during temperature changes	Increase control loop update rate	Limits QBER excursions	Maintains continuous key generation
Operational scheduling	Season-aware maintenance planning	Approaching monsoon peak period	Advance preventive maintenance	Avoids emergency interventions	Improves predictability of availability
Key management	Key buffering / pooling	Short-term SKR degradation	Serve applications from buffered keys	Decouples SKR dips from services	Preserves higher-layer continuity
Traffic prioritization	Service-level key allocation	Concurrent disturbances and high demand	Reserve keys for critical services	Prevents key starvation	Protects mission-critical applications

Overall, the results indicate that QKD over tropical metropolitan fiber networks is technically viable but operationally sensitive to climate-induced perturbations. Performance under stable conditions is comparable to that reported in existing metropolitan QKD networks [3]–[5]. However, without climate-aware engineering, monsoon-related disturbances can significantly reduce SKR and availability, especially near distance limits. Adaptive stabilization, key buffering, and season-aware operational policies collectively restore much of the lost performance and reliability, demonstrating that the challenges posed by tropical climates are manageable within a well-designed QKD deployment framework [1]–[9].

## V. DISCUSSIONS

The results highlight that the principal challenge for deploying Quantum Key Distribution (QKD) in tropical

metropolitan environments is not fundamental feasibility, but operational resilience under climate-induced disturbances. Monsoon-driven rainfall and persistent high humidity introduce short, clustered performance degradations that disproportionately affect links operating near their distance and loss limits. These findings suggest that QKD system design in tropical regions must prioritize stability margins and operational flexibility rather than maximum reach alone. Compared with temperate-region deployments, greater emphasis is required on optical hygiene, environmental monitoring, and adaptive stabilization to manage QBER excursions triggered by temperature and moisture effects. The demonstrated effectiveness of key buffering further indicates that architectural and policy-level measures can significantly enhance service continuity, even when physical-layer conditions temporarily deteriorate. From a broader perspective, these results reinforce the importance of integrating climate awareness into quantum communication planning, ensuring that QKD can be deployed as a reliable component of national secure networks in regions subject to pronounced seasonal weather variability.

## VI. CONCLUSIONS

This study has examined the performance, reliability, and climate sensitivity of Quantum Key Distribution (QKD) over tropical metropolitan fiber networks, with particular reference to Malaysian deployment conditions. The results demonstrate that while QKD can achieve stable operation and high secret key rates under nominal conditions, tropical environmental factors—especially monsoon-related rainfall, high humidity, and temperature variability—introduce measurable performance and availability challenges. These challenges are most pronounced for metro links operating near their loss and distance limits, where small perturbations can lead to disproportionate reductions in secure key throughput. Importantly, the findings show that such impacts are largely mitigable through climate-aware engineering and operational practices, including adaptive stabilization, enhanced optical hygiene, proactive maintenance scheduling, and key buffering at the network layer. By explicitly incorporating climatic

considerations into system design and operation, QKD can be deployed as a robust and dependable security technology for tropical metropolitan networks.

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