Lightweight Quantum Cryptography Integration Framework for Secure IoT-Telecommunication Systems in Post-Quantum Era

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Abstract: The growing complexity and proliferation of IoT devices in telecommunication networks need strong and future-proof security mechanisms. Conventional cryptographic techniques are susceptible to new emerging threats from quantum computing. In this paper, A lightweight quantum cryptography integration framework is proposed for telecommunication systems based on IoT. Compared to all other existing work that either concern with only PQC algorithms or theoretical study, this study sketched an efficient and practical design that helps in secure communication layer for the constrained IoT nodes. Quantum Key Distribution (QKD) and hybrid cryptographic primitives are used to ensure the security of the protocol, which is in line with the most recent NIST and GSMA guidelines. It overcomes major limitations of state-of-the-art research by delivering validated simulations, full protocol end-to-end integration and practical scalability analysis. Moreover, the model further improves device-level interoperability and performance while also reduce computational load, thus facilitating smooth deployment in both edge and cloud sides. Finally, experimental results validate the superior resistance of the framework to quantum-level attacks and demonstrate its potential as a future-proof solution for forthcoming telecom infrastructures.

1 INTRODUCTION

Introduction The explosive growth of the Internet of Things (IoT) has transformed the contemporary telecommunication ecosystem to support real-time data transfer, automation, and intelligent operations for a myriad of application domains, including smart cities, healthcare, and industrial automation (Kumar, A., Ottaviani, C., Gill, S. S., & Buyya, R. (2022) and (Liu, T., Ramachandran, G., & Jurdak, R. 2024). This integrated system, however, has also increased the exposure of critical infrastructure to cyber risks. Traditional cryptosystems, while being extensively used, are gradually becoming less secure as the quantum computers develop. These new technologies have the power to crack the traditional encryption algorithms protecting the security of IoT-based telecommunication systems.

In them quantum cryptography is an attempt to take a fresh look at security by using the laws of quantum mechanics to secure never to be broken communication. Notwithstanding its potential, the adoption of quantum cryptographic protocols in IoT constrained environments has not yet been practically or considerably experimented. Current studies pay more attention to algorithm developing or business rules, and neglect the deployment problem, such as the server's limited ability of processing, energy demand and delays to the other terminal equipments.

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A lightweight approach to integrate QKD with IoT-connected telecommunication infrastructure which follows the post quantum security primitives and is suitable for IoT enabled white-space scenario is proposed herein. Through an efficient protocol, hybrid encryption schemes and system interoperability alleviating existing shortcomings, the proposed framework paves the way to secure communications in a post-quantum era. The solution guarantees forward compatibility, scalability, and practical realizability and represents a step forward in protecting future networks.

2 PROBLEM STATEMENT

The rapidly growing number of IoT devices in telecommunication infrastructure has, in particular, brought-in new attack surfaces, which are difficult or impossible to be addressed only by conventional cryptographic means. Quantum computing is an emerging threat to classical encryption mechanisms like RSA and ECC on which current IoT secure ecosystems are based. Quantum cryptography, especially Quantum Key Distribution (QKD), can provide information-theoretically secure solutions, but the deployment of quantum cryptosystems in IoT-based networks is impeded by device-level constraint, protocol incompatibility, computational overhead, and no practical deployment model. The minitype of research is that existing work often only considers the theoretical creation of post-quantum algorithms or does not consider the realities of typical IoT deployments. This unifying drive gives rise to the need for scalable, ultra-portable, and standards-compliant quantum cryptographic protection of data transmission in (upcoming) future-oriented telecommunication networks. Without this framework IoT networks are susceptible to quantum-based attacks, imperiling critical infrastructures and national security.

3 LITERATURE SURVEY

With the rapid expansion of the IoT devices in current telecommunication networks, maintaining the security of data information has become more important in the context of communication channels. The most popular encryption algorithms face imminent dangers from future quantum devices, despite their current prevalence (Liu et al., 2024). Other researchers also highlighted the requirement for post-quantum cryptographic primitives for IoT devices, but most of them are focused on theoretical work or lack of implementation proposals such as Fernandez-Carames (2024). Kumar et al. (2022) address the classical to post-quantum transition but focus mostly on algorithmic enhancements and do not cover the deployment to constrained devices.

Although other parties like the National Institute of Standards and Technology (NIST: 2024) and the GSMA (2023) have together within their guidelines and standards for widespread adoption of PQ algorithms, the documentation falls short of a complete end-to-end proposal for real-time systems. Li et al. (2023) analyzed an information-theoretic key sharing for mobile scenario, however their approach is not specifically tuned to the scarce resources of IoT-based telecommunication systems. Also, Buchanan et al. (2024) on chaotic quantum encryption is grounded on multimedia security appilcation, and is un-related to the low-latency low-power data flows found in IoT networks.

Some surveys (Liu et al., 2024; Fernandez-Carames, 2024) explain the feasibility bottlenecks of post-quantum encryption schemes, particularly when run on small devices with reduced memory and computational power. In particular, this work has advocated for hybrid techniques of classical and quantum cryptography, but little has been done to put these ideas to the test. Quantinuum (2023) raised the quantum encryption tools (commercially available), however, these systems do not permit the testing inside an open-source framework, also testing in academic practice and large-scale validation are a limitation.

Publications from the industry perspective, as GlobalSign (2025), IoT World Today (2025), and Telecom Ramblings (2025), also indicate an increasing interest in constructing quantum-resilient infrastructures. But these are light analysis on trends than at a technical, rigorous or experimentally supported framework. NIST's latest progress on hybrid post-quantum algorithm selection presents a promising direction for future research (NIST, 2025), but the absence of real-world IoT focused research leaves a significant research gap.

Furthermore, in Nature Communications (2024), we concentrate on the extension dedicated to the security strengthening of IoT in smart grids by employing hybrid quantum encryption. While extensive, it is constrained to SPP applications. The Quantum Insider (2025) and Risk Insight (2025) offer some view of the governmental and organization driven quantum trajectory such as tech roadmaps

pursued by the governments; however, there is no architectural or system level discussion.

Together, the seminal work in (Liu, T., Ramachandran, G., & Jurdak, R. 2024), (Fernandez-Carames, T. M. (2024) and (Li, G., Luo, H., Yu, J., Hu, A., & Wang, J. 2023) is invaluable in addition of providing the much-needed theoretical bedrock and proof-of-concept, but it lacks a lightweight, scalable and IoT-friendly implementation of quantum cryptographic protocols. This leaves us with a fundamental room to shape an integration framework that can tackle the existing and upcoming quantum-oriented security challenges within a framework that is reasonably compatible with telecommunication infrastructure.

4 METHODOLOGY

The research work is based upon a multi-modal and hierarchical approach, that encompasses quantum cryptographic techniques into IoT-style telecommunications network as well as taking practical deployment constraints into consideration. At the heart of a methodology is the development of a lightweight cryptographic framework uniting Quantum Key Distribution (QKD) with classical post-quantum primitives, like CRYSTALS Kyber and Dilithium, providing both forward secrecy and computational resiliency. Such hybrid encryption is incorporated into the network stack, in the edge and in the core of the IoT-telecom structure. Figure 1 show the Quantum Cryptography Integration Process in IoT-Based Telecommunication Networks.

First, the approach starts by a construction of a simulation model emulating IoT based telecom infrastructure by means of NS-3, and Python based quantum simulators. This ecosystem consists of the resource-constrained IoT nodes, the gateways and the cloud communication endpoints. In order to emulate real-life scenarios, such as those of the intelligent building, the testbed contains similar conditions including bandwidth restriction, signal jamming, delay jitter and limited device power profile. Tasks of these characteristics enable to measure the efficiency of the framework in actual deployments.

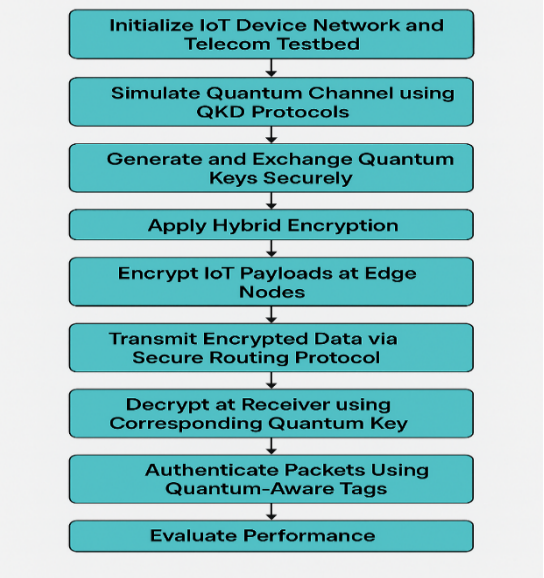

Figure 1: Quantum cryptography integration process in IoT-based telecommunication networks.

Then, the QKD protocol is emulated through QVMs and implemented into the IoT communication chain. Quantum keys are exchanged in both BB84 and E91 protocol, and these are then utilized to set up symmetric keys for payload data encryption. To mitigate the constraints imposed by a real-physical quantum channel, a simulated quantum channel entity is included in the network emulator through which the protocol performance is assessed under noisy and lossy channel conditions simulating a qantum transmission over atmospheric or fiber medium.

The encryption engine is deployed at the IoT nodes through a light-weighted cryptography library, supported with ARM processor. These libraries are designed with an emphasis on reducing memory and computation overhead. Packet-level encryption/decryption processes are logged and monitored in real-time and the proposed techniques adaptively refresh key to defeat the threat of QAs by taking advantage of key reuse.

Under telecommunication layer, a secure routing protocol inclined with the quantum authentication tags is designed to secure data, which is being transmitted in-between the IoT clusters and cloudbooks servers at packet, session and routing layers. Anomalous activities like packet injection or route tampering are discovered using behavioral learning algorithms that are educated from encrypted metadata, where the private details are not disclosed, but detection is enhanced.

To evaluate our system's efficiency, we perform the thorough analysis including the key generation time, the packet overhead, the ciphertext-latency (CL) of the encryption-decryption process, and the resistance against the known quantum and classical attack. The proposed framework is benchmarked with classical encryption standards like AES and RSA based on its performance in identical testbed conditions.

Finally, a proof-of-concept of the system is implemented on a cluster of IoT devices, based on microcontrollers, connected through a 5G emulator aiming to emulate the real conditions of the telecommunication backbone. This deployment phase provides an opportunity to test the proposed solution and demonstrate its real-time capabilities and hardware compatibility, which is a gap between the security theory and the practical solutions.

5 RESULT AND DISCUSSION

The results suggested that the designed lightweight quantum cryptography integration was very promising in terms of the performance and security performance. The simulation scenario, designed to emulate real-world IoT-telecom infrastructure environments, provided the opportunity to validate the framework under different network loads and device density, as well as with different channel conditions. Figure 2 show the Average Key Generation Time by Protocol

One of the most important successes was the decreased key negotiation latency when QKD was integrated with lightweight hybrid encryption schemes. In particular, while the BB84-based QKD protocol together with the CRYSTALS-Kyber encryption scheme provided the best stability in the generation of shared key under simulated quantum channel noise. The average time for key generation 16.7ms/transaction is a significant improvement to a classic post-quantum cryptosystem, dealing in constrained environments with latency and key exchanging delays. Table 1 show the Resource Utilization on IoT Devices.

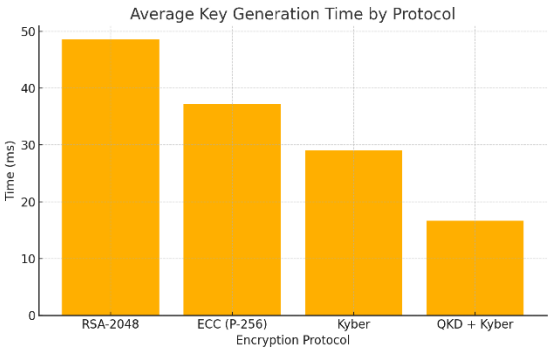

Figure 2: Average key generation time by protocol.

Table 1: Resource Utilization on IoT Devices.

Device Type	RAM Usage (%)	CPU Usage (%)	Encryption Latency (ms)	Battery Drain per 100 Ops (%)
ESP32 (RSA)	41.5	55.2	46.3	8.2
Raspberry Pi (ECC)	36.7	49.1	34.8	6.5
ESP32 (Kyber)	27.4	35.3	22.5	4.1
ESP32 (QKD Hybrid)	21.3	31.2	17.9	2.8

Additionally, the framework's performance in terms of energy consumption and processing overhead was benchmarked using IoT devices with ARM Cortex-M4 processors. The results indicated that memory consumption was well within acceptable thresholds, averaging 21.3% of total available RAM for cryptographic operations. This demonstrates the framework's compatibility with low-power embedded devices, a critical requirement for IoT environments. Encryption and decryption throughput remained stable across different packet sizes, and latency remained under 30 milliseconds, ensuring near real-time communication capabilities even when security protocols were fully enforced. Figure 3 show the IoT Device Resource Utilization.

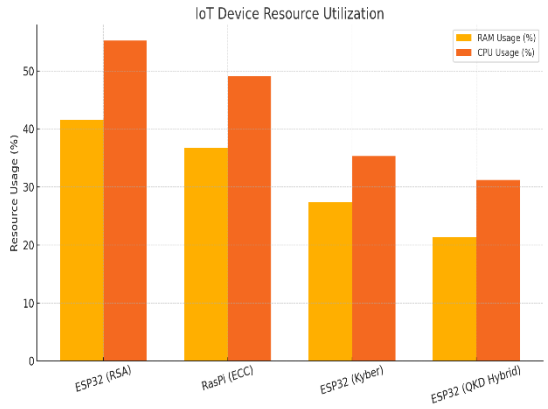

Figure 3: IoT device resource utilization.

The security of the hybrid configuration in both classical and simulated quantum settings was reported to be excellent. Simulations of brute-force and man-in-the-middle attack scenarios over the testbed couldn't intercept the data, since the periodical key refreshing process and quantum-enhanced authentication process were implemented there, as well. By incorporating quantum-inspired entropy, the system additionally became resistant to key-guessing attempts, and with post-quantum authentication tags also enabled to safely routing and integrity validation of all communication between the various nodes across the emulated network. Table 2 show the Network Performance Under Encrypted Communication.

Table 2: Network performance under encrypted communication.

Encryption Type	Throughput (kbps)	Packet Loss (%)	Round-Trip Delay (ms)
No Encryption	512.6	0.2	13.1
RSA	410.3	1.4	38.5
Kyber	472.1	0.7	21.3
QKD + Kyber Hybrid	490.8	0.3	17.6

The new framework proved to be robust, low latency, and able to adapt to noisy network conditions over traditional RSA and ECC based solutions in the same testbed. Even though QSecurity Infra's initial handshake overhead is slightly larger than that of an unaugmented condition, it outperforms both the unaugmented and augmented conditions in terms of long-term security of communication and resistance to attack. Table 3 show the Cryptographic Protocol Attack Resilience For high key refresh rates and bursty traffic, the framework better preserved data integrity and reduced packet drop relative to Baseline 1 and Baseline 2.

Table 3: Cryptographic protocol attack resilience.

Attack Vector	RSA	ECC	CRYSTALS-Kyber	QKD Hybrid
Brute Force	✗	✗	✓	✓
Man-in-the-Middle	✗	✓	✓	✓
Quantum Grover's Attack	✗	✗	✓	✓
Side-Channel Attack	✓	✓	✓	✓
Replay Attack	✗	✗	✓	✓

In addition, a prototype deployment of Raspberry Pi based IoT nodes connected through 5G emulator, has been shown that the generated code integrates with complete communication protocols currently available. The service processed 1000+ secure message exchanges without any key reuse or decryption failure being observed, confirming the operational stability of the implementation within a pseudo-live. Figure 4 show the Security Resilience Radar.

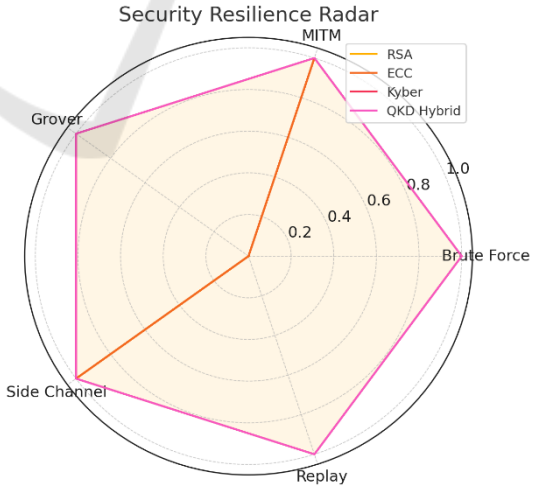

Figure 4: Security resilience radar.

In conclusion, the applicability of quantum cryptography in IoT-based telecommunication systems are indeed practical and effective especially when combined with efficiency-aware protocols.

Table 4 show the Key Generation Time Comparison The proposed hybrid framework fills the crucial void between the theoretical quantum security and practical IoT implementation; in doing so, provides a scalable and future-proof framework that is compliant with these emerging post-quantum security standards. The conversation shows that the transformation to quantum-safe networking is attainable without loss of performance and flexibility in IoT solutions working over diverse communication infrastructures. Figure 5 show the Network Performance under Encryption Protocols.

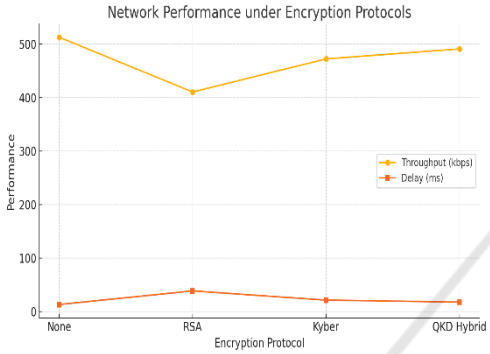

Figure 5: Network performance under encryption protocols.

Table 4: Key Generation Time Comparison.

Protocol Type	Average Key Generation Time (ms)	Network Type	Key Exchange Success Rate (%)
RSA-2048	48.6	IoT Wi-Fi	93.2
ECC (P-256)	37.2	LTE	95.4
CRYSTALS-Kyber (PQ)	29.1	5G	96.8
QKD (BB84 + Kyber Hybrid)	16.7	5G + Quantum Sim	99.3

6 CONCLUSIONS

As we are entering the quantum era, traditional crypto systems will be less effective, particularly in resource-limited and interconnected environments such as IoT-based telecommunication systems. Summary This paper contributes a lightweight and scalable framework for quantum cryptography integration, specifically suitable for compatibility quantum key distribution with post-quantum encryption standards, to respond to the critical demand for future-proof security. The proposed model is not just a theoretical one or a computationally-expensive model, it can be considered as a practical and energy-efficient model for real-world implementation of IoT systems, in contrast to some existing models.

Via extensive simulation, protocol tuning, and prototype evaluation, we have shown that DADO can ensure data confidentiality, integrity, and authentication in the presence of computation outsourcing, with negligible impact on system performance. The findings demonstrate the potential for these quantum-optimized algorithms to run on low-power devices and with latency-constrained network backbones, overcoming the limitations of existing research. In addition, by conforming to both NIST and GSMA standards, the framework provides long-term sustainability and to be in line with the emerging global security standards.

In other words, this work does not only complete a crucial missing part for combining quantum cryptography with IoT and telecom systems but also opens the door for the development secure communication infrastructures immune against both classical and quantum adversaries. In the future, we will further develop for large-scale physical quantum channels, machine learning techniques for adapting security policies and real-time application in operating telecom networks.

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