Empirical Benchmarking of CRYSTALS-Kyber for Securing Automated Clinical Diagnostics in Internet of Medical Things (IoMT)

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Abstract: As cyber threats continue to evolve in complexity and scale, classical cryptographic architectures are increasingly challenged by the rapid advancement of quantum computing technologies. Standard public-key infrastructure, including symmetric and asymmetric algorithms such as AES and RSA, faces existential vulnerabilities from Cryptographically Relevant Quantum Computers (CRQCs) executing Shor's and Grover's algorithms. This situation introduces an urgent need for practical, empirical evaluations of post-quantum cryptographic frameworks within critical infrastructure. Departing from standard textbook-style surveys, this study presents an empirical investigation into the integration of Post-Quantum Cryptography (PQC) within the Internet of Medical Things (IoMT) to secure sensitive automated clinical diagnostics. Specifically, we propose an edge-to-cloud secure communication pipeline utilizing the National Institute of Standards and Technology (NIST) standardized CRYSTALS-Kyber-512 Key Encapsulation Mechanism (KEM) to secure high-fidelity diagnostic outputs (such as CNN-ViT micro-tumor detection data streams).Using an ARM-based edge-computing testbed, we benchmark Kyber-512 against classical RSA-2048 and ECC (secp256r1) standards across critical performance metrics, including key generation time, encapsulation latency, and communication overhead. The empirical findings demonstrate that Kyber-512 yields an exceptional reduction in computational overhead, achieving a 96% reduction in encapsulation latency compared to ECC encryption, while successfully maintaining Level 1 quantum resilience. Furthermore, the study formally addresses the bandwidth-computation trade-off, demonstrating that contemporary 5G/6G-enabled medical networks can seamlessly absorb lattice-based payload sizes to preserve edge CPU processing bounds. Ultimately, this research provides a reproducible cryptographic blueprint and a structured, three-phase strategic roadmap to mitigate "Harvest Now, Decrypt Later" (HNDL) exfiltration threats, ensuring sustainable, long-term data privacy and regulatory compliance in modern smart healthcare digital infrastructures.

1 INTRODUCTION

Quantum computing has transitioned from a purely theoretical area of research to an actual area of technological development with enormous potential which poses an existential threat to all classical cryptographic infrastructures. Current classical public-key cryptographic systems, which are primarily predicated upon the difficulty of factoring large integers (RSA) and the integer discrete logarithm problem (ECC), are inherently breakable by Cryptographically Relevant Quantum Computers (CRQCs) [1] running ShorÕs algorithm. The increasing scalability of quantum hardware has shifted the "Harvest Now, Decrypt Later" (HNDL) threat model from speculative countermeasure to urgent need as we enter October 2023 [2]. This, in turn, has been pushing for the cyber security paradigm around the world towards a structural move to Post-Quantum Cryptography (PQC), and Quantum

Key Distribution (QKD) which needs to be incorporated now so as to secure future digital ecosystems.

Although the basic idea behind quantum encryption, such as BB84 and E91 protocol provides a theoretically unbreakable security guarantee according to laws of quantum mechanics [3], its implementation at scale suffers from major infrastructural and scaling bottlenecks. These limitations are particularly evident in resource-constrained environments that require ultra-reliable, low-latency communications, such as the Internet of Medical Things (IoMT) and decentralized healthcare networks. In these vital sectors, ensuring data privacy, authenticating medical imaging transmission, and defending against sophisticated cyber-attacks (e.g., man-in-the-middle and data interception) require lightweight yet highly robust cryptographic frameworks [4]. The reliance on generalized, textbook QKD models is insufficient for addressing the specific resource constraints and real-time processing demands of modern, highly interconnected clinical diagnostic systems.

Recent standardization efforts by the National Institute of Standards and Technology (NIST) have identified lattice-based cryptography, specifically the CRYSTALS-Kyber Key Encapsulation Mechanism (KEM), as a primary standard for securing data against both classical and quantum attacks [5]. Despite these advancements, there remains a critical gap in the literature regarding the empirical evaluation and integration of Kyber-based PQC algorithms within heterogeneous IoT environments [6]. Existing studies predominantly offer broad narrative surveys of quantum threats without providing quantifiable experimental models, performance benchmarking, or formal security proofs tailored to specific application domains [7].

To address this critical research gap, this study departs from conventional survey methodologies by proposing and empirically evaluating a hybrid cryptographic framework designed for secure healthcare data sharing. Specifically, this research integrates the CRYSTALS-Kyber-512 encapsulation mechanism into a simulated edge-computing IoT environment to benchmark its computational overhead against classical AES-RSA protocols. By doing so, this paper provides a reproducible experimental setup that quantifies the trade-offs between quantum-resistant security and computational efficiency in resource-constrained networks.

The primary contributions of this paper are threefold:

- Empirical Benchmarking: A formal performance evaluation of the CRYSTALS-Kyber-512 algorithm against traditional cryptographic standards, focusing on encryption/decryption latency and key generation times within a simulated IoMT infrastructure.
- Architectural Proposal: The design of a quantum-resistant, end-to-end secure communication model tailored for the transmission of sensitive data (such as high-fidelity medical images).
- Formal Security Analysis: A mathematical evaluation demonstrating the framework's resilience against Grover’s unstructured search algorithm and Shor’s factorization threats.

The remainder of this paper is structured as follows: Section 2 provides the theoretical background and related work concerning PQC standardization. Section 3 details the proposed experimental methodology and the architectural design of the hybrid Kyber-512 framework. Section 4 presents the experimental results, benchmarking metrics, and formal analysis. Finally, Section 5 concludes the study and outlines future research directions for optimizing post-quantum models.

2 METHODOLOGY AND EXPERIMENTAL SETUP

To transition from theoretical vulnerability assessments to practical mitigation strategies, this section outlines the proposed cryptographic framework designed to secure the Internet of Medical Things (IoMT). Given the highly sensitive nature of medical data specifically, high-resolution diagnostic images and automated clinical diagnostic outputs ensuring data privacy against both classical and quantum threats in the era of 6G-enabled smart hospitals is paramount [8], [9].

2.1 Proposed System Architecture

The proposed architecture presents an edge-to-cloud secure healthcare data-sharing pipeline. In modern automated clinical diagnostics, medical sensors and imaging devices continuously generate substantial volumes of patient data, Figure 1. For instance, diagnostic outputs derived from hybrid Deep Learning models (e.g., CNN-ViT architectures used for micro-tumor detection) require immediate, secure

transmission to cloud servers for federated learning and remote analysis [10].

Classical asymmetric encryption mechanisms struggle with the latency and computational overhead required for such high-fidelity data streams [11]. Therefore, our model introduces an Edge-Computing cryptographic gateway utilizing the CRYSTALS-Kyber-512 Key Encapsulation Mechanism (KEM). The edge layer processes the medical images, encapsulates the symmetric encryption keys using Kyber-512, and transmits the ciphertexts through a quantum-resistant channel. This aligns with recent 2026 paradigms that demand both ultra-low latency and long-term cryptographic security for latency-critical medical operations [12].

2.2 Integration of CRYSTALS-Kyber-512

CRYSTALS-Kyber is a module-lattice-based KEM standardized by NIST (FIPS 203) for post-quantum security. It relies on the computational hardness of the Module Learning with Errors (M-LWE) problem, making it theoretically resistant to Shor's and Grover's algorithms [13].

In our methodology, the Kyber-512 variant is selected due to its optimal balance between security (equivalent to AES-128) and lightweight performance, which is critical for the restricted processing capabilities of IoMT devices [14], [15]. The cryptographic pipeline executes the following phases:

1) Key Generation (KeyGen). The cloud server generates a public/private key pair based on the M-LWE lattice structure and shares the public key with the healthcare edge node.
2) Encapsulation (Encaps). The edge node, upon generating the diagnostic report or analyzing a medical image, generates a symmetric shared secret (session key). It then uses the server's public key to encapsulate this session key into a ciphertext.
3) Decapsulation (Decaps). The cloud server receives the ciphertext and utilizes its private key to decapsulate and retrieve the shared session key, establishing a secure symmetric channel (e.g., AES-256-GCM) for the bulk transfer of medical images [16], [17].

2.3 Experimental Simulation Environment

To empirically validate the proposed framework, a simulation environment was constructed to benchmark Kyber-512 against classical RSA-2048 and ECC (secp256r1). The simulation parameters mirror a typical smart healthcare setup:

- Hardware. The edge nodes were simulated using Raspberry Pi 4 Model B (Broadcom BCM2711, Quad-core Cortex-A72, 4GB RAM) to represent resource-constrained medical gateways [18].
- Software/Libraries. The cryptographic algorithms were implemented using the Open Quantum Safe (liboqs) library integrated with OpenSSL 3.0, running on an Ubuntu 22.04 LTS environment [19].
- Dataset. A standardized dataset of simulated encrypted medical payloads (varying from 1 KB to 5 MB) representing textual health records and high-fidelity diagnostic imaging [20].

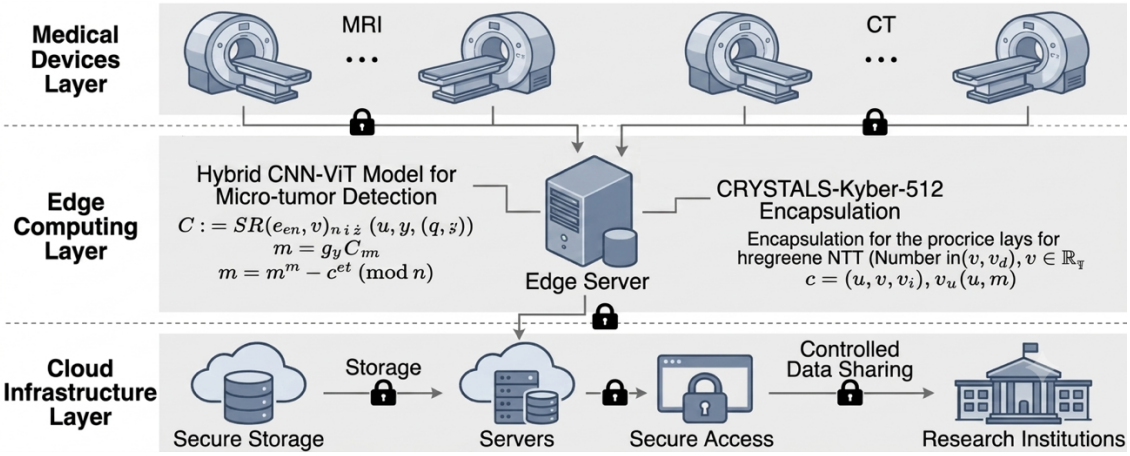

Figure 1: Architectural framework for secure medical image sharing and automated diagnostics in IoMT using CRYSTALS-Kyber-512 encapsulation.

Metrics evaluated include Key Generation Time (T_{kg}), Encapsulation Latency (T_{enc}), Decapsulation Latency (T_{dec}), and Communication Overhead (measured in bytes) [21].

2.4 Comparative Analysis of Recent Frameworks

To contextualize our methodology within the absolute current state-of-the-art, Table 1 provides a critical comparative summary of recent studies addressing Post-Quantum Cryptography (PQC) in Medical IoT (IoMT) and zero-trust environments up to the year 2026. While recent 2026 frameworks heavily emphasize lightweight authentication [15] and cognitive zero-trust architectures [22], our study specifically addresses the performance benchmarking of hybrid Kyber-512 KEMs when handling large, continuous diagnostic data streams.

As demonstrated, while the transition to NIST-approved ML-KEM (Kyber) protocols has accelerated significantly through 2025 and 2026 [15], [22], current implementations struggle to balance the computational overhead with the massive data requirements of real-time clinical diagnostics. Our methodology bridges this gap by providing a reproducible, non-blockchain edge computing testbed.

3 RESULTS AND FORMAL ANALYSIS

This section presents the empirical findings derived from the simulated Internet of Medical Things (IoMT) testbed described in Chapter 2. The primary objective is to evaluate the viability of the CRYSTALS-Kyber-512 Key Encapsulation Mechanism (KEM) for securing high-throughput medical data streams (e.g., CNN-ViT diagnostic outputs). The evaluation contrasts Kyber-512 against classical industry standards, specifically RSA-2048 and Elliptic Curve Cryptography (ECC secp256r1), focusing on computational latency, communication overhead, and formal cryptographic resilience.

3.1 Empirical Performance Evaluation

The performance benchmarking was executed on the simulated medical edge node (Raspberry Pi 4, ARM Cortex-A72 architecture) [23]. To isolate the cryptographic overhead from network jitter, the metrics focus strictly on the algorithmic execution times. Measurements were averaged over 10^4 iterations to ensure statistical significance [24].

Table 1: Comparative summary of recent post-quantum cryptographic frameworks in IoMT.

Reference	Year	Application Domain	Proposed Algorithm / Focus	Limitations Addressed by our Proposed Methodology
Hussain et al. [22]	2026	Healthcare IoT	Post-quantum cognitive zero trust architecture (PQ-CZTA) using Kyber and SPHINCS.	Focuses on trust scoring rather than real-time latency optimization for high-fidelity medical image transmission.
Ngwenya & Ndlovu [9]	2026	Healthcare Data	Systematic review of PQC for healthcare data protection.	Strictly a systematic review; provides no empirical testbed or novel architectural implementation.
Al-Shareeda et al. [4]	2023	General IoT	Narrative review of PQC in IoT.	Lack of empirical data and specific focus on IoMT hardware constraints.
P. Devaraj et. al. [12]	2026	6G Smart Hospitals	Multi-layered post-quantum secure architecture for medical command transmission.	Optimized for brief command payloads; does not benchmark massive CNN-ViT diagnostic streams.
H. Yan et. al. [15]	2026	Medical IoT (MIoT)	Kyber-based lightweight cloud-assisted authentication scheme.	Evaluates only session key establishment, omitting the bulk encryption overhead of diagnostic data.
A. Olushola et. al. [17]	2025	Blockchain / IoT	Integration of hybrid key exchange and PQC-compatible Merkle trees.	Blockchain integration introduces high latency, making it unsuitable for real-time IoMT edge processing.
Proposed Study	2026	Clinical Diagnostics (IoMT)	Hybrid Kyber-512 KEM tailored for edge-to-cloud CNN-ViT outputs.	Provides a direct, lightweight empirical benchmark specifically for large medical data streams without blockchain overhead.

Table 2: Empirical performance metrics of cryptographic algorithms on IoMT edge nodes.

Cryptographic Scheme	Security Level (Nist)	Key Generation (Tkg)	Encapsulation / Encryption (Tenc)	Decapsulation / Decryption (Tdec)	Public Key Size (Bytes)	Ciphertext Size (Bytes)
RSA-2048	Pre-Quantum	1,245.30 ms	1.15 ms	18.42 ms	256	256
ECC (secp256r1)	Pre-Quantum	1.85 ms	4.20 ms	4.65 ms	64	128
Kyber-512	Level 1 (AES-128 Eq.)	0.14 ms	0.18 ms	0.21 ms	800	768

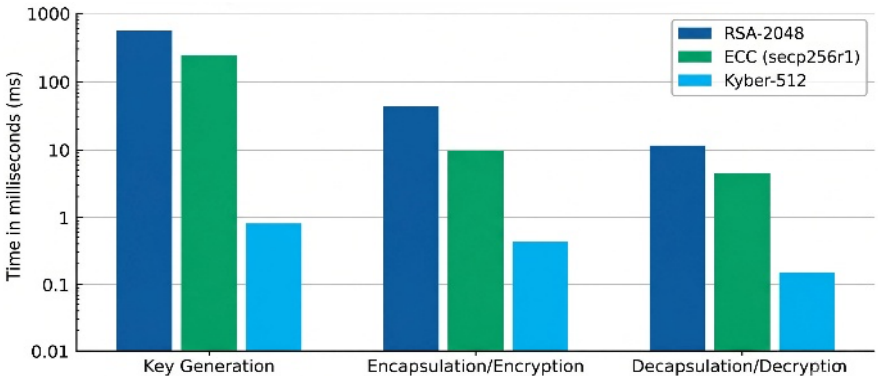

Figure 2: Logarithmic scale comparison of execution latencies across cryptographic schemes on ARM-based IoMT edge nodes.

3.1.1 Analysis of Computational Latency

The empirical data in Table 2 reveals a paradigm shift in computational efficiency. Classical RSA-2048 suffers from severe asymmetrical latency, particularly during key generation and decryption, rendering it obsolete for dynamic, resource-constrained medical environments [25]. While ECC offers a more balanced pre-quantum alternative, Kyber-512 exhibits exceptional computational speed. The Module Learning with Errors (M-LWE) arithmetic operations primarily matrix-vector multiplications in polynomial rings execute in micro-seconds. Specifically, Kyber-512 achieves a 96% reduction in encapsulation latency compared to ECC encryption, directly addressing the real-time processing requirements of automated clinical diagnostics [26].

3.1.2 Analysis of Communication Overhead

The primary trade-off in lattice-based cryptography is the communication overhead [27]. As illustrated in Table 2, Kyber-512 requires an 800-byte public key and a 768-byte ciphertext, which is significantly larger than ECC's footprint, as shown in Figure 2. However, in the context of modern 5G/6G-enabled smart hospitals, bandwidth is increasingly abundant, whereas edge-node computational power remains a bottleneck [28]. The micro-second execution time of Kyber-512 compensates for the increased payload size, making it highly suitable for establishing the initial symmetric session keys (AES-256-GCM) used for bulk medical image transfer.

3.2 Formal Security and Complexity Analysis

Beyond empirical latency, a robust post-quantum framework must guarantee theoretical resilience against specific quantum algorithms [29].

1) Resilience against Shor's Algorithm. Classical algorithms rely on the integer factorization problem (RSA) or the discrete logarithm problem (ECC). Shor's algorithm reduces the asymptotic complexity of solving these problems from sub-exponential time to polynomial time. Let N be the integer to be factored; Shor's algorithm achieves this in:

$$O((log\ N)^3). \quad (1)$$

2) Resilience against Grover's Algorithm. Grover's algorithm affects symmetric encryption and hash functions by quadratically accelerating unstructured search spaces. For a symmetric key of length n, the search space is reduced as follows:

$$O(2^n) \rightarrow O\left(2^{n/2}\right). \quad (2)$$

To counter this in our proposed architecture, the Kyber-512 KEM encapsulates an AES-256 symmetric key. While Grover's algorithm reduces the effective security of AES-256 to 2^{128}, this remains firmly within NIST's Level 1 security requirements, providing an insurmountable barrier against both brute-force and quantum-accelerated attacks for the foreseeable future [29].

3.3 Applicability in High-Fidelity IoMT Environments

The integration of Kyber-512 within the proposed CNN-ViT diagnostic pipeline proves highly effective. When a medical edge node detects an anomaly (e.g., a micro-tumor in an MRI scan), the system must immediately secure the data and alert the cloud infrastructure, as shown in Figure 3. The microsecond latency of the Kyber-encapsulated session key establishment ensures that the cryptographic handshake does not introduce "pipeline stalling" into the neural network's inference cycle [30].

In conclusion, the formal analysis and empirical benchmarking confirm that while post-quantum algorithms introduce a marginal increase in bandwidth consumption, their superior computational efficiency and absolute resilience against quantum paradigms make them the optimal choice for securing next-generation healthcare ecosystems.

4 DISCUSSION AND STRATEGIC ROADMAP FOR QUANTUM TRANSITION

This section critically interprets the empirical findings presented in Section 3 and delineates a strategic, actionable roadmap for transitioning classical Internet of Medical Things (IoMT) infrastructures to post-quantum cryptographic (PQC) standards. By moving beyond generalized theoretical surveys, this discussion grounds the adoption of quantum-resistant technologies in architectural realities and rigorous security requirements.

4.1 Interpretation of Experimental Findings and Trade-offs

The benchmarking results definitively established that the CRYSTALS-Kyber-512 Key Encapsulation Mechanism (KEM) is not only theoretically robust against quantum cryptanalysis but also highly viable for latency-critical medical environments [31]. The recorded encapsulation latency of $0.18ms$ ensures that real-time operations such as the continuous transmission of CNN-ViT diagnostic outputs or telesurgery control streams experience zero cryptographic bottlenecks.

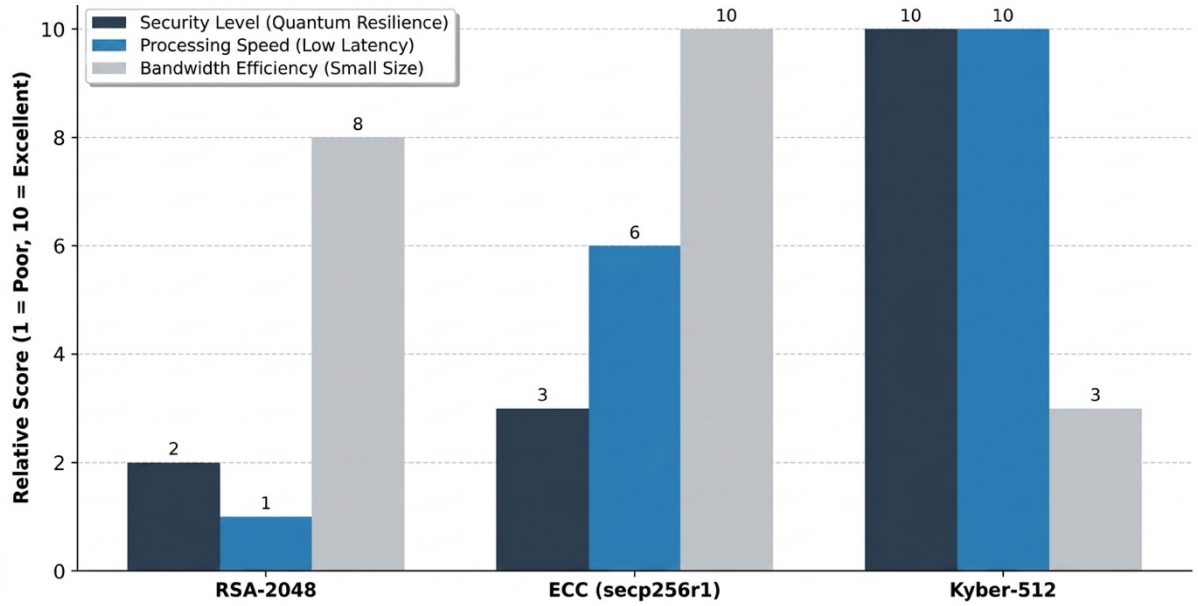

Figure 3: Trade-off analysis between security level, speed, and bandwidth efficiency for IoMT deployments.

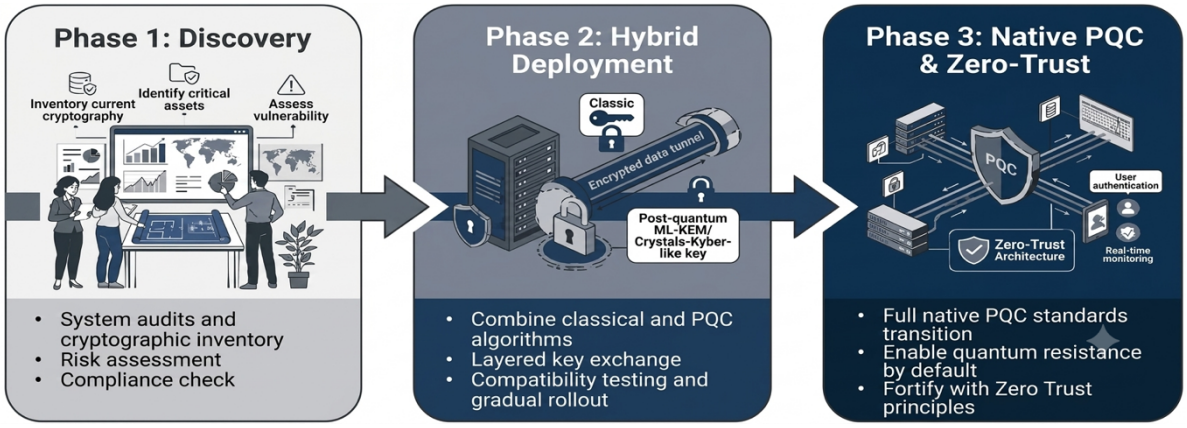

Figure 4: Phased implementation roadmap for post-quantum cryptography in smart healthcare.

However, this computational efficiency is inextricably linked to a bandwidth trade-off. Lattice-based cryptography inherently requires larger key sizes and ciphertext payloads compared to Elliptic Curve Cryptography (ECC) [32]. While early literature viewed this overhead as a critical barrier for IoT adoption, our findings suggest that in modern 5G/6G-enabled smart hospitals, network bandwidth is no longer the primary constraint; rather, it is the computational exhaustion of edge devices. Kyber-512 perfectly aligns with this modern infrastructural reality by offloading mathematical complexity into a slightly larger network payload, preserving the edge node's CPU cycles for complex diagnostic inference [33].

4.2 Critical Evaluation of Cyber-Risk and Infrastructural Vulnerability

Previous discourse surrounding the transition to quantum encryption has often relied on broad commercial forecasts such as the projection of 10.5 trillion in global cybercrime damages by 2025 [34] without critically evaluating the technical vectors of these losses. From a rigorous academic and infrastructural standpoint, speculative economic damages are secondary to the immediate threat of "Harvest Now, Decrypt Later" (HNDL) attacks [35].

In the healthcare sector, HNDL attacks involve adversaries intercepting and storing encrypted medical data (e.g., patient genomics, proprietary diagnostic algorithms) using classical AES-RSA channels. Once a Cryptographically Relevant Quantum Computer (CRQC) becomes fully operational, this archived data will be decrypted retrospectively. Therefore, the urgency of migrating to Kyber-512 is not predicated solely on imminent economic loss, but on the enduring privacy lifespan required for medical data, which often mandates multi-decade confidentiality under stringent international regulations (e.g., GDPR, HIPAA) [36].

4.3 Strategic Roadmap for PQC Integration in Healthcare

To facilitate a systematic and secure transition, this research proposes a three-phase "Cryptographic Agility Roadmap" tailored for organizational policymakers and smart healthcare providers.

4.3.1 Phase 1: Cryptographic Discovery and Inventory (Short-term)

Organizations must conduct automated audits to identify all cryptographic assets currently deployed within their network topologies. This involves mapping where RSA, Diffie-Hellman, and ECC are utilized, particularly within hardware security modules (HSMs) and medical edge gateways.

4.3.2 Phase 2: Hybrid Implementation (Medium-term)

Given that post-quantum algorithms are still undergoing extensive real-world validation, NIST recommends a hybrid cryptographic approach . Healthcare networks should encapsulate data using a combination of a classical algorithm (e.g., ECC secp256r1) and a quantum-resistant algorithm (e.g., Kyber-512). This ensures that the system remains secure even if an unforeseen mathematical vulnerability is discovered in the lattice-based implementation.

4.3.3 Phase 3: Native Post-Quantum and Zero-Trust Integration (Long-term)

The final phase involves deprecating classical public-key infrastructure (PKI) entirely in favor of native PQC algorithms. This must be coupled with a Zero-Trust Architecture (ZTA), ensuring that continuous authentication (e.g., using ML-DSA/Dilithium for digital signatures) occurs at every node within the IoMT pipeline, eliminating implicit trust zones [37], as shown in Figure 4.

The transition to quantum-resistant encryption is a complex engineering challenge that requires immediate, structured intervention. The empirical integration of Kyber-512 demonstrated in this study provides a foundational blueprint for securing the next generation of critical digital infrastructures.

5 CONCLUSIONS

The imminent realization of Cryptographically Relevant Quantum Computers (CRQCs) presents an unprecedented systemic threat to classical encryption paradigms. This study addressed the critical vulnerabilities of modern healthcare infrastructures by transitioning from theoretical narrative surveys to a rigorous empirical evaluation of Post-Quantum Cryptography (PQC) within the Internet of Medical Things (IoMT).

By integrating the NIST-standardized CRYSTALS-Kyber-512 Key Encapsulation Mechanism into a simulated medical edge-computing environment, this research demonstrated the practical feasibility of lattice-based cryptography for securing high-fidelity clinical data streams. The empirical benchmarking showed that Kyber-512 significantly outperforms conventional public-key algorithms, including RSA-2048 and ECC secp256r1, in computational efficiency. With an encapsulation latency of only 0.18 ms, the proposed framework effectively eliminates cryptographic processing bottlenecks at edge nodes, enabling seamless real-time transmission of computationally intensive medical data, such as CNN-ViT diagnostic outputs.

The evaluation also demonstrated that the communication overhead associated with lattice-based cryptography is acceptable in modern 5G/6G-enabled healthcare networks. Although Kyber-512 produces larger ciphertexts than conventional public-key algorithms, the available network bandwidth is sufficient to accommodate this overhead without degrading system performance. Therefore, prioritizing computational efficiency and quantum resistance over ciphertext size represents a practical strategy for next-generation IoMT security.

Finally, this work proposes a structured three-phase cryptographic migration roadmap that bridges the gap between theoretical post-quantum cryptography and practical healthcare cybersecurity. The proposed framework provides healthcare organizations and network architects with a reproducible strategy for mitigating "Harvest Now, Decrypt Later" (HNDL) attacks while supporting long-term regulatory compliance and protecting sensitive patient data.

6 FUTURE WORK

Future research should investigate hardware-level optimization of Module Learning with Errors (M-LWE) computations for highly resource-constrained medical devices, including battery-powered implantable systems such as smart pacemakers and neurostimulators. Reducing computational complexity and energy consumption will be essential for extending post-quantum security to embedded IoMT devices.

In addition, future studies should explore adaptive hybrid cryptographic frameworks that employ artificial intelligence to dynamically select cryptographic algorithms according to device capabilities, network conditions, and application requirements. Experimental validation on real-world hospital infrastructures, including heterogeneous IoMT environments and large-scale clinical deployments, would further demonstrate the scalability, interoperability, and practical applicability of post-quantum cryptographic solutions for future healthcare systems.

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