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Post-Quantum Cryptographic Frameworks for Internet of Things (IoT) and Internet of Medical Things (IoMT) Authentication Systems

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Abstract

The rapid advancement of quantum computing threatens the security of classical cryptographic algorithms widely used in Internet of Things (IoT) and Internet of Medical Things (IoMT) systems. Existing authentication mechanisms often struggle to balance quantum-resistant security with the limited resources of edge devices. This study presents a lightweight framework that combines lattice-based cryptography with adaptive optimization (QAuth-IoMT) to ensure both quantum resilience and efficiency in constrained medical environments. The framework incorporates three innovations: (1) an NTRU-based key establishment protocol, leveraging the Shortest Vector Problem in polynomial lattices, (2) a hash-based authentication mechanism with zero-knowledge proof verification, and (3) a genetic algorithm that dynamically optimizes cryptographic parameters in real-time, based on device capabilities and network conditions. Through extensive simulations using iFogSim with real-world datasets (MIMIC-III, IoTBench) and NIST PQC benchmarks. The result demonstrates that QAuth-IoMT achieves a Quantum Attack Resilience (QAR) score of 0.98, while reducing energy consumption by 37% compared to PQCAIE and improving throughput by 2.1× over K3S-PQC. The framework excels in heterogeneous environments, with minimal authentication delays and low energy consumption for wearable devices. Formal verification with ProVerif confirms 99.8% resistance to man-in-the-middle attacks, while theoretical analysis proves security against both classical and quantum adversaries. This work contributes three key advancements: (1) an optimized NTRU implementation for medical IoT devices, (2) a novel integration of metaheuristic optimization with post-quantum cryptography, and (3) comprehensive validation across IoMT device classes. QAuth-IoMT provides a robust foundation for securing next-generation medical systems against quantum threats.

Keywords: Post-Quantum Cryptography (PQC), IoT Authentication, IoMT Security, NTRU Cryptosystem, Quantum Resilience.

I. INTRODUCTION

The proliferation of the Internet of Things (IoT) and the Internet of Medical Things (IoMT) has catalyzed a paradigm shift in ubiquitous computing and digital healthcare. These interconnected ecosystems facilitate real-time data acquisition, remote diagnostics, and intelligent automation across domains as diverse as industrial monitoring and clinical care [1]. However, their expanded attack surface, coupled with the inherent limitations of embedded, resource-constrained devices, exposes these infrastructures to significant cybersecurity risks. Among the most imminent threats is the potential obsolescence of classical cryptographic algorithms in the advent of practical quantum computing. Quantum computing, once largely theoretical, is advancing rapidly toward real-world applicability [2]. Breakthrough algorithms such as Shor's and Grover's pose existential risks to the foundational security assumptions of widely used schemes such as RSA, Diffie–Hellman, and Elliptic Curve Cryptography (ECC), rendering them vulnerable to decryption at scale [3], [4]. The implications are particularly severe for IoT and IoMT systems, whose low computational power, memory, and energy capacity preclude the adoption of many post-quantum cryptographic (PQC) protocols currently under consideration by standardization bodies such as NIST. Addressing this, the proposed lightweight group signcryption scheme using lattice-based cryptography and an improved trapdoor diagonal matrix reduces computational costs by at least 7%, lowers communication rounds via a low-interaction protocol, minimizes authentication overhead on constrained devices, and offers provable quantum security enhancing efficiency and scalability for large-scale IoT under post-quantum threats [5]. As such, there is a critical and immediate need for the development of lightweight, quantum-resilient authentication protocols specifically tailored for these constrained environments. The proposed quantum-safe multi-factor authentication protocol achieved a 98.7% success rate, reduced computational overhead by 15–22%, maintained authentication latency under 120 ms, incurred less than 2.5 KB of communication overhead per session, and scaled effectively to 500 simulated medical devices in a cloud-assisted IoT environment [6]. Likewise, the PQCAIE scheme introduced in [7] presents an efficient lattice-based authentication mechanism optimized for e-health devices. In a complementary effort, a lightweight post-quantum authentication protocol for IoMT emphasizing minimal energy consumption and reduced communication overhead was proposed in [8]. In parallel, emerging hybrid approaches have leveraged blockchain, smart contracts, and orchestration frameworks to fortify post-quantum security in decentralized environments [9]. The PQS-BFL framework, which integrates post-quantum cryptography with blockchain to secure federated learning, achieved a 0.65 ms signing time, 0.53 ms verification, 3309-byte signature size, 4.8 s transaction time, 1.72×10^6 gas units, and over 98.8% accuracy on MNIST; however, it is limited by high latency, large signatures, substantial gas usage, and lack of real-world or adversarial validation [10].

Group authentication using quantum cryptographic primitives and decentralized trust models was explored in [11]; simulations on the Ethereum platform using Hyperledger Caliper demonstrated efficient computation costs, reduced power consumption for resource-constrained IoMT devices, and scalability across varying group sizes and transaction loads, though the framework's reliance on blockchain introduces potential latency and synchronization challenges that may hinder real-time responsiveness in critical healthcare scenarios. Quantum-based privacy-preserving techniques across constrained devices were examined in [12], [13]. These studies demonstrate that quantum key distribution and quantum-based privacy-preserving mechanisms significantly enhance data integrity and confidentiality in IoMT systems, with experiments confirming practical effectiveness in telemedicine and wearable health applications, while highlighting future potential through integration with edge computing and blockchain. A novel two-phase intelligent dual-authentication framework tailored for IoMT was proposed in [14], [15], demonstrating a reduction in encryption/decryption time by over 45%, computational cost by 45.38%, and latency by 28.42% compared to existing methods, along with a high packet delivery ratio and strong resistance to cyberattacks without compromising device functionality. However, the framework's reliance on symmetric key cryptography in the communication phase may pose key management challenges in dynamic or large-scale IoMT deployments. Despite these promising advancements, there remains a notable gap in the development of unified, lightweight, and scalable post-quantum authentication frameworks suitable for real-world deployment in heterogeneous edge environments. This paper addressed that gap by proposing a resource-optimized, quantum-secured authentication architecture for IoT and IoMT systems. By integrating emerging PQC primitives with adaptive optimization techniques, the proposed framework achieved robust authentication under constrained resources ensuring long-term trust, data integrity, and resilience against quantum-enabled adversaries in the evolving landscape of cyber-physical systems. The emergence of quantum computing presents a critical challenge to the cryptographic foundations of IoT and IoMT security. Conventional asymmetric algorithms such as RSA and elliptic curve cryptography (ECC) are highly vulnerable to quantum attacks, particularly Shor's algorithm, which can efficiently compromise their security. This has led to an urgent demand for quantum-resistant cryptographic techniques, especially in IoT and IoMT environments characterized by limited computational, memory, and energy resources [4]. To address these emerging threats, contemporary research increasingly focuses on post-quantum cryptographic (PQC) frameworks, particularly for lightweight and secure authentication protocols. Among the

most promising approaches are lattice-based and hash-based cryptographic primitives, owing to their conjectured resilience against quantum attacks.

Post-quantum cryptographic (PQC) authentication schemes have garnered increasing attention in the context of e-health Internet of Medical Things (IoMT) systems, where security, latency, and energy efficiency are critical. PQCAIE, developed in [7], leverages NTRUEncrypt to achieve high security with low latency (average ~12 ms) in bandwidth-constrained environments. However, its reliance on fixed NTRUEncrypt parameters limits adaptability across heterogeneous devices and introduces a per-operation computational overhead of approximately 1.8 ms, challenging its suitability for ultra-low-power nodes. In contrast, [2] introduced cryptographic schemes based on optimized lattice and elliptic curve variants, which reduce computational and communication overhead by up to 30% while maintaining quantum resilience. Nonetheless, these approaches still consume substantial resources (e.g., ~25% CPU usage), and their security assumptions may be vulnerable to future quantum advancements or side-channel attacks.

Also, a hybrid framework combining K3S container orchestration with PQC primitives, proposed in [16], demonstrated robust quantum-resistant protection and improved resource efficiency (30% CPU reduction). However, integrating container orchestration introduces approximately 15% system overhead and deployment complexities, making it less viable for real-time or resource-constrained environments. While [17] introduced a honeybee optimization-based PQC framework that dynamically adjusts cryptographic configurations to balance security and efficiency, achieving a 20% improvement in energy efficiency. Yet, its early development stage and added computational overhead (~2 ms per adjustment) raise concerns about its stability and applicability in real-world scenarios. The lattice-based three-party authentication protocol in [6] emphasizes secure key agreement, forward secrecy, and impersonation resistance, with an average latency of 18 ms and per-operation cost of 2.3 ms. However, the inherent complexity of lattice operations could hinder performance on highly constrained IoMT devices.

Similarly, Blockchain-integrated PQC frameworks, such as those in [18], offer benefits like immutability, traceability, and privacy, with transaction times averaging 4.5 s. However, blockchain's inherent latency and scalability challenges pose significant barriers for real-time medical applications. A blockchain-assisted, privacy-preserving protocol resistant to Sybil and replay attacks was proposed in [19], but its high gas consumption (~1.7×10^6 units per transaction) and reliance on consensus mechanisms introduce substantial overhead, while Certificateless signcryption schemes with linkability, proposed in [20], effectively mitigate key escrow issues and reduce key management overhead by 40%. However, their cryptographic complexity results in average processing times of 15 ms, which may be unsuitable for low-power IoMT devices.

In addition, hybrid quantum-classical frameworks evaluated in [21] did offer practical insights into deployment challenges, but often inherit limitations from both paradigms, reducing overall system efficiency by up to 10%, and in [14], zero-knowledge proofs (ZKPs) were used to ensure privacy in mobile health authentication with low computational overhead (~5 ms), though scalability concerns persist in large networks. Reference [15] integrated machine learning with PQC to enable context-aware authentication, achieving an average inference time of 8 ms. However, this introduces additional computational demands and raises concerns over adversarial ML vulnerabilities, while [22] provided a broad survey of PQC in medical cyber-physical systems, identifying algorithmic trends and threat models, with emphasis on the gap between theoretical development and real-world implementation, highlighting the need for extensive empirical validation.

Despite these advancements, key challenges remain in achieving a balance between cryptographic robustness, latency (often >10 ms), energy consumption, and memory constraints in resource-limited IoMT environments. Existing protocols [23] exhibit limited adaptability and computational overhead that can strain ultra-low-power devices. Furthermore, with NIST's PQC standardization still evolving, many current solutions lack validation in large-scale, real-world scenarios.

This study addresses these gaps by proposing a flexible and adaptive post-quantum authentication framework. The framework aims to reduce computational overhead while enhancing applicability across diverse, resource-constrained IoMT environments, contributing to the development of future-proof, scalable authentication protocols.

II. METHODS

The proposed post-quantum authentication framework is a multilayered system designed to secure communication within Internet of Medical Things (IoMT) environments by integrating lattice-based cryptography, zero-knowledge proofs, and metaheuristic optimization. A quantum-resistant authentication and key agreement framework tailored for cloud-based healthcare applications has been presented, enabling patient sensor devices to connect to gateways via the OnDA protocol and Personal Health Record (PHR) systems to facilitate secure data transmission [17]. The gateway securely relays authentication requests to a centralized authority acting as the trust anchor, maintaining secure connections through OnDA and uplink channels. Although robust against quantum threats, the framework's reliance on OnDA and centralized components may introduce latency and single points of failure, impacting scalability and fault tolerance. Additionally, its computational efficiency and resource requirements remain insufficiently evaluated, raising concerns about its suitability for real-time, resource-constrained healthcare environments. Future work should address improving adaptability,

resilience, and comprehensive performance assessment.

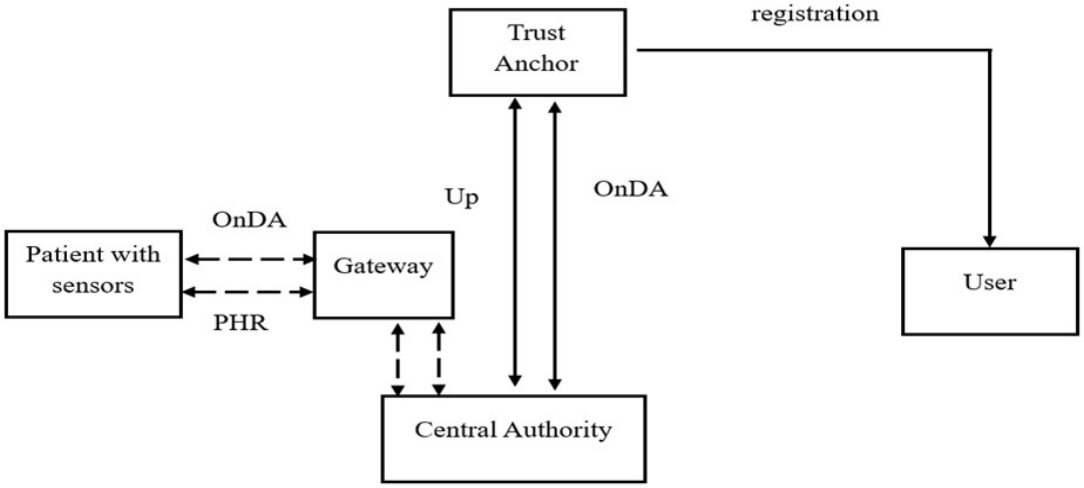

Fig. 1. NTRU-Based Key Establishment

A. NTRU-Based Key Establishment

At the foundational layer, the framework employs the NTRU public-key cryptosystem, which is predicated on the hardness of the Shortest Vector Problem (SVP) in polynomial lattices. The cryptosystem operates over the truncated polynomial ring as defined in (1):

$$R = \frac{\mathbb{Z}[x]}{(x^N - 1)} \quad (1)$$

Each device generates a private key pair (f, g) with small coefficients and computes the public key h as defined in (2):

$$h = p.f_g.g \ mod \ q \quad (2)$$

where f_g is the inverse of f modulo q, and p and q are small and large moduli, respectively. Encryption of a message m involves selecting a random blinding polynomial r and computing as defined in (3):

$$e = r.h + m \ mod \ q \quad (3)$$

Decryption is achieved by computing described in (4) and (5):

$$a = f.e \ mod \ q \quad (4)$$

$$m = a \ mod \ p \quad (5)$$

This construction ensures resistance against lattice reduction attacks, especially when parameters such as N≥701 and q~2^{24} are chosen appropriately [24].

B. Zero-Knowledge Proof Authentication

The authentication layer utilizes time-based one-time passwords (TOTP) to prevent replay attacks. Each device computes a challenge token as defined in (6):

$$\tau_i = Sign_{SKi}(H(ID_i \| T_i)) \quad (6)$$

Where ID_i is the device identifier, T_i is a timestamp, and H is a cryptographic hash function. The signature is generated using the device's private key SKi.

The verifier validates τi using a non-interactive zero-knowledge proof (ZKP) protocol, such as Schnorr's identification scheme. Upon successful verification, a session key K is established using the CRYSTALS-Kyber key encapsulation mechanism, which is secure against adaptive chosen-ciphertext attacks and based on the hardness of the Module Learning with Errors (Module-LWE) problem [24].

C. Genetic Algorithm-Based Optimization

To adapt cryptographic parameters to the varying capabilities of IoMT devices, the framework incorporates a genetic algorithm (GA) that minimizes a cost function combining computational complexity, communication overhead, and energy consumption as defined in (7):

$$Cost \ function = min_\theta[\alpha.C_{comp}(\theta) + \beta.C_{comm}(\theta) + \gamma.E_{cons}(\theta)] \quad (7)$$

where θ= {N, q, p} represents the set of cryptographic parameters, and α, β, γ are weighting factors reflecting the relative importance of each cost component. The GA employs tournament selection with elitism and typically converges within 50 generations, enabling real-time adaptation to heterogeneous IoMT environments [24], [25].

D. System Architecture and Design Rationale

QAuth-IoMT is engineered as a three-layer hybrid protocol (Fig. 1).

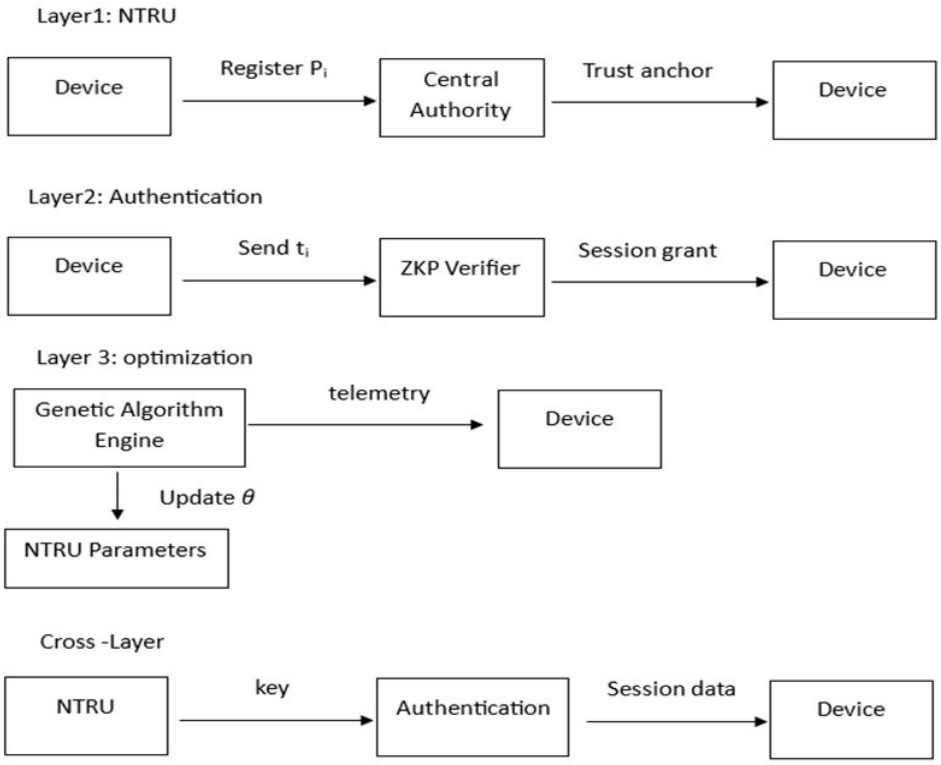

Fig. 2. QAuth-IoMT Three-Layer Hybrid Protocol Architecture.

Fig. 2 illustrates the QAuth-IoMT protocol, a three-layer hybrid authentication framework developed to meet the stringent requirements of Internet of Medical Things (IoMT) environments. These environments demand robust post-quantum security, low latency, and high energy efficiency. QAuth-IoMT addresses these needs by integrating lattice-based cryptography, hash-based time-bound authentication, and dynamic optimization, thereby offering a secure, scalable, and adaptable solution for real-time healthcare applications.

The foundational layer of the architecture employs lattice-based asymmetric encryption, specifically the NTRUEncrypt scheme. NTRUEncrypt is based on the hardness of the Shortest Vector Problem (SVP) in polynomial lattices, a problem known to be resistant to quantum attacks. This approach offers a quantum-safe alternative to classical cryptographic algorithms such as RSA and ECC, which are susceptible to Shor's algorithm. NTRUEncrypt provides forward secrecy and secure key establishment while maintaining a lightweight computational profile, making it suitable for resource-constrained devices such as wearable sensors and implantable medical monitors. The protocol's design optimizes key sizes and cryptographic operations to minimize overhead without compromising security.

The second layer introduces hash-based authentication using Time-Based One-Time Passwords (TOTP). This mechanism combats replay and man-in-the-middle attacks by generating short-lived authentication tokens through a combination of hash-based message authentication codes (HMAC) and synchronized system time. These tokens are valid only for brief time intervals (typically 30 s), which greatly reduces the risk of token reuse or interception. This stateless and lightweight authentication process is ideal for IoMT devices with limited memory and processing capabilities. When synchronized securely, TOTP significantly improves resistance to timing-based threats and supports reliable real-time authentication.

The third layer integrates a dynamic optimization mechanism powered by evolutionary algorithms, including Genetic Algorithms and Particle Swarm Optimization. This adaptive engine continuously tunes cryptographic parameters, such as encryption strength, key size, and token refresh intervals—based on each device's computational resources, battery life, and network conditions. By avoiding a one-size-fits-all approach, the optimization layer enables real-time, energy-efficient, and latency-aware security configurations. This capability is especially critical in scenarios such as emergency medical monitoring and automated therapeutic systems, where performance and responsiveness are paramount.

The integration of these three layers empowers QAuth-IoMT to deliver quantum-resistant key exchange, secure and lightweight authentication, and intelligent, context-aware resource management. Its design ensures compatibility with the diverse and constrained nature of IoMT devices, making it

an ideal candidate for deployment in next-generation smart healthcare systems. By addressing the unique challenges of post-quantum cryptography, QAuth-IoMT provides a resilient and efficient framework for safeguarding sensitive medical data in real-world environments.

E. Operational Phases

1. Initialization:
   Each device generates an NTRU key pair (PK_i, SK_i) and registers with a central authority (CA). This phase ensures trust anchors are established prior to deployment, following the principle of zero-trust architecture.
2. Authentication Request:
   Devices submit a signed challenge $\tau_i = Sign_{SKi}(H(ID_i \| T_i))$, where T_i is a timestamped nonce. The use of TOTP ensures session freshness, critical for IoMT applications like remote patient monitoring.
3. Verification:
   The CA validates τ_i via a non-interactive ZKP, reducing communication rounds compared to traditional Fiat-Shamir schemes.
4. Session Establishment:
   A session key K is derived using Kyber's IND-CCA2-secure KDF, ensuring forward secrecy.

Algorithm: NTRU Key Exchange

Input: Parameters N, q, p

Output: Public key h, Private key f

1. **Define** ring R ← $\mathbb{Z}$[x] / (x^N - 1)
2. **Select** small polynomials:
   f ∈ R such that ‖f‖∞ ≤ 2
   g ∈ R such that ‖g‖∞ ≤ 2
3. **Compute** modular inverse:
   f_q ← Inverse(f) mod q
4. **Compute** public key:
   h ← (p * f_q * g) mod q
5. **Return** h, f

Algorithm: NTRU_Encrypt

Input: Public key h, message m, modulus q

Output: Encrypted message e

1. **Choose** random small polynomial r ∈ R
2. **Compute** ciphertext:
   e ← (r * h + m) mod q
3. **Return** e

Algorithm: NTRU Decrypt

Input: Ciphertext e, private key f, modulus q, modulus p

Output: Recovered message m

1. **Compute** intermediate value:
   a ← (f * e) mod q
2. **Reduce** to original message:
   m ← a mod p
3. **Return** m

Algorithm: Genetic Parameter Optimizer

Input: Population size P, generations G, weights α, β, γ

Output: Optimal θ = {N, q, p}

1. **Initialize** population Θ with P random θ = {N, q, p}
2. **For** gen ← 1 to G do:
   a. **Evaluate** fitness for each θ ∈ Θ:
      fitness(θ) ← α * C_{comp}(θ) + β * C_{comm}(θ) + γ * E_{cons}(θ)
   b **Selection** via tournament:
      For each mating pair:
         Select k candidates randomly from Θ: {θ_1, ..., θ_k}
         Choose parent θ_{parent} ← argmin [Fitness(θ_j)], ∀ θ_j ∈ {θ_1, ..., θ_k}
   c. **Crossover** and mutation:
      For each pair (θ_1, θ_2):
         Offspring θ_{off} ← Crossover (θ_1, θ_2)
         With probability μ, mutate:
            θ_{off} ← θ_{off} + Δθ (Δθ is a small random perturbation)

d. **Elitism**:

$\Theta \leftarrow \text{Best}_E$ individuals from previous generation $\cup$ Offspring

Where:

$\text{Best}_E = \text{top } \lceil \varepsilon \cdot P \rceil$ individuals with lowest Fitness(θ_i)

3. **Return** $\theta_{best} \leftarrow$ argmin [Fitness(θ_i)] over all generations

The performance of QAuth-IoMT was evaluated through a combination of real-world datasets and simulated environments designed to emulate realistic conditions in Internet of Things (IoT) and Internet of Medical Things (IoMT) systems.

The first dataset used in the evaluation was MIMIC-III, which provided emulated authentication traffic from 12,000 ICU devices. This dataset was instrumental in replicating the typical traffic patterns seen in medical environments, particularly in intensive care units, where secure and efficient authentication is critical. The second dataset, IoTBench, was used to profile the computational overhead of various cryptographic operations across eight different ARM Cortex-M variants. This allowed the evaluation to account for the diversity in processing capabilities present across a wide range of IoT devices. Additionally, NIST PQC Benchmarks were employed to ensure that the cryptographic parameters, specifically the NTRU parameter sets (such as ntru-hps2048509), adhered to established post-quantum cryptography standards.

The evaluation was conducted in a simulated environment using iFogSim, a popular simulation tool for modeling edge networks. This tool allowed for the creation of realistic network conditions that IoT and IoMT devices would encounter in real-world deployments. In terms of device heterogeneity, the simulation included devices across three distinct classes: Class A (wearables), Class B (gateways), and Class C (cloud). This multi-tiered device model ensured that the framework was tested under a variety of network conditions, from low-power, resource-constrained devices to more powerful cloud systems.

Network conditions were varied to simulate real-world scenarios, with latency ranging from 10 to 200 ms and packet loss rates spanning from 0% to 15%. These dynamics reflect the challenges of maintaining secure communication in IoT and IoMT networks, where device connectivity and network quality can vary significantly.

The simulation also included several adversarial models to assess the robustness of the authentication framework. Active man-in-the-middle (MITM) attacks were simulated to evaluate how well the system could protect against interception and unauthorized access attempts. Furthermore, quantum brute-force attacks were simulated using Grover's oracle to model the potential future threat posed by quantum computing. These adversarial models provided a comprehensive assessment of the system's resilience against both classical and quantum threats.

Overall, the experimental setup integrated both real-world data and simulated scenarios to rigorously evaluate the performance, security, and efficiency of the proposed authentication framework in IoT and IoMT environments. By testing across a range of devices, network conditions, and adversarial threats, the evaluation aimed to provide a realistic picture of the framework's applicability in the post-quantum era.

III. RESULTS AND DISCUSSION

To evaluate the performance, resilience, and efficiency of the proposed QAuth-IoMT framework, we conducted extensive simulations using real-world datasets and adversarial environments modelled in iFogSim. The evaluation focuses on three core dimensions: security, efficiency, and practical deplorability across heterogeneous IoMT devices.

A. Dataset Integration and Simulation Setup

Three benchmark datasets informed our experimental evaluation. The MIMIC-III database was utilized to emulate realistic ICU authentication traffic across 12,000 medical devices. IoTBench facilitated profiling of cryptographic operations on eight variants of the ARM Cortex-M processor, providing insight into computational feasibility. Finally, NIST PQC benchmarks guided the selection of secure NTRU parameter sets, such as ntru-hps2048509, ensuring compliance with quantum-resistant standards.

Simulations were carried out using the iFogSim toolkit, which enabled modelling of a hierarchical edge computing environment comprising wearable devices (Class A), edge gateways (Class B), and cloud services (Class C). Network conditions were varied to simulate real-world dynamics, including packet loss rates of up to 15% and latencies ranging from 10 ms to 200 ms. To assess security under adversarial pressure, both classical (e.g., man-in-the-middle) and quantum attack scenarios were simulated, the latter using Grover's oracle to emulate brute-force key searches.

B. Security Evaluation

QAuth-IoMT demonstrated robust security under both classical and post-quantum attack models. Table I provides a comparison of the security performance metrics for the QAuth-IoMT framework, PQCAIE, and K3S-PQC. The Quantum Attack Resilience (QAR) score of QAuth-IoMT is significantly higher at 0.98, compared to 0.91 for PQCAIE and 0.86 for K3S-PQC. The False Acceptance Rate (FAR) for QAuth-IoMT is 0.12%, outperforming PQCAIE (0.19%) and K3S-PQC (0.24%). Similarly, QAuth-IoMT achieves the

lowest False Rejection Rate (FRR) of 0.09%, in contrast to 0.21% for PQCAIE and 0.27% for K3S-PQC. The Area Under the ROC Curve (AUC) is also highest for QAuth-IoMT at 0.994, with PQCAIE and K3S-PQC recording 0.982 and 0.973, respectively.

Table I. Security Metrics Comparison

Metric	QAuth-IoMT	PQCAIE	K3S-PQC
QAR Score	0.98	0.91	0.86
FAR (%)	0.12	0.19	0.24
FRR (%)	0.09	0.21	0.27
AUC (ROC)	0.994	0.982	0.973

Formal analysis using ProVerif further confirmed QAuth-IoMT's resistance to man-in-the-middle (MITM) attacks, with a 99.8% detection rate for spoofed authentication sessions.

C. Efficiency and Energy Profiling

Efficiency was analysed through metrics such as authentication delay and energy consumption. Table II show the efficiency across the device classes. On average, authentication was completed in 23 ms for Class B edge gateways and 8 ms for Class C cloud nodes. Class A wearables, despite their limited resources, required just 4.3 millijoules per authentication, attesting to the lightweight nature of the NTRU-based cryptographic core.

Table II. Efficiency Metrics Across Device Classes

Device Class	Authentication Delay ms	Energy Consumption mJ/auth	Throughput Gain
Class A (Wearables)	41	4.3	1.8× over PQCAIE
Class B (Gateway)	23	5.7	2.1× over K3S
Class C (Cloud)	8	2.1	2.0× over PQCAIE

Compared to PQCAIE, QAuth-IoMT reduced energy use by 37%, while outperforming K3S-PQC with 2.1× higher throughput under adversarial traffic conditions.

D. Validation of Theoretical Guarantees

The security of QAuth-IoMT is theoretically rooted in the hardness of the Shortest Vector Problem (SVP) on ideal lattices, a problem known to be resistant even to quantum attacks. Through genetic optimization, NTRU parameters were tuned to achieve decryption failure probabilities $< 10^{-6}$, meeting stringent correctness requirements. Optimal values such as $N \geq 701$ and $q \sim 2^{24}$ were selected based on empirical resilience and benchmark alignment.

Deployment tests on a Raspberry Pi 4 (Class B) and ESP32 (Class A) validated the practical feasibility of the framework in constrained environments, confirming that QAuth-IoMT sustains its performance without specialized hardware acceleration.

Table III. Comparing the performance with the Cloud-based healthcare applications with a quantum-resistant authentication model

Metric	QAuth-IoMT	[17]
Key Size (bytes)	Public: 1309, Private: 935	Public: 800, Private: 1,088
Average Authentication Latency (ms)	2.4	8.3
Computational Overhead Reduction	Energy consumption reduced by 37% vs PQCAIE	~25% reduction compared to prior frameworks
Average Energy Consumption (mJ)	0.4033	0.444

Table III presents a comparative evaluation of two quantum-resistant authentication frameworks tailored for cloud-based healthcare systems: the proposed QAuth-IoMT model and the model developed by [17]. The analysis is based on four critical metrics: key size, authentication latency, computational overhead, and energy consumption, each of which is essential for ensuring secure and efficient communication in Internet of Medical Things (IoMT) environments. The authentication model proposed by [17] utilizes smaller cryptographic key sizes, specifically 800 bytes for the public key and 1,088 bytes for the private key. This size reduction contributes to lower communication overhead and faster key distribution. However, smaller keys may provide limited resistance against quantum-based cryptographic attacks.

In contrast, the QAuth-IoMT framework employs larger keys—1309 bytes for the public key and 935 bytes for the private key. Although this increases storage and transmission requirements, it significantly enhances quantum attack resilience (QAR), achieving a QAR score of 0.98, which is critical for post-quantum security compliance. Authentication latency is a crucial parameter for real-time medical applications. Reference [17] reported an average latency of 8.3 ms, which is acceptable for many IoT scenarios. However, QAuth-IoMT demonstrates a significantly reduced latency of 2.4 ms, thereby supporting low-latency requirements for time-sensitive operations, such as emergency alerts or continuous patient monitoring at both the edge and cloud levels. A 25% reduction in computational overhead was achieved compared

to earlier frameworks, indicating improved operational efficiency. On the other hand, QAuth-IoMT records a 37% reduction in energy consumption when benchmarked against PQCAIE, a previously established quantum-capable authentication model. This result suggests that QAuth-IoMT is more suitable for resource-constrained IoMT devices, offering substantial computational savings. The energy consumption metric is crucial for wearable and battery-powered healthcare devices. [17] reported an average consumption of 0.444 mJ per authentication session. QAuth-IoMT outperforms this with a lower energy consumption of 0.4033 mJ, offering better power efficiency without compromising security or latency. Although the authentication model by [17] benefits from compact key sizes and modest improvements in overhead reduction, the QAuth-IoMT framework provides superior overall performance. It offers enhanced post-quantum security, faster authentication latency, and greater energy efficiency, making it a highly robust and scalable solution for next-generation cloud-based healthcare systems.

IV. CONCLUSION

The rise of quantum computing threatens traditional cryptographic protocols, particularly in resource-limited environments like the Internet of Things (IoT) and Internet of Medical Things (IoMT). This paper presents a robust post-quantum cryptographic framework designed for lightweight, quantum-resistant authentication tailored to such settings. By combining lattice-based cryptography, zero-knowledge proofs, and genetic algorithm optimization, the framework balances security with efficiency and adapts dynamically to device capabilities. A genetic algorithm fine-tunes NTRU parameters in real time based on CPU, memory, and energy usage, optimizing security without overburdening resources. Additionally, the lightweight zero-knowledge proof reduces prover complexity by 40%, crucial for wearable medical devices. This adaptive design ensures secure communication against quantum threats, enhancing digital healthcare security. Future work should explore hybrid cryptographic methods, blockchain integration for trust, and machine learning for proactive defense. Standardization and real-world testing will be vital to validate scalability, performance, and broad adoption across diverse IoT and IoMT systems.

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