IJARCCE ISSN (O) 2278-1021, ISSN (P) 2319-5940

International Journal of Advanced Research in Computer and Communication Engineering

Impact Factor 8.471 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 15, Issue 9, September 2026

Scalable and Quantum-Resistant Authentication for the Blockchain of Medical Things

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Abstract: The rapid proliferation of the Internet of Medical Things (IoMT) has revolutionized remote patient monitoring but introduces severe data privacy and security challenges. Integrating Blockchain technology (BIoMT) provides immutable auditing, yet classical cryptographic signatures (e.g., RSA, ECC) are highly vulnerable to the looming threat of quantum computing via Shor's algorithm. Furthermore, storing individual digital signatures on a distributed ledger incurs massive storage overhead, limiting scalability. This paper proposes a Post-Quantum Aggregate Blind Signature (PQ-ABS) framework tailored for BIoMT. Our architecture leverages Module Learning With Errors (Module-LWE) to guarantee quantum-resistant security. To ensure patient privacy, we employ blind signatures that allow medical authorities to authenticate health data without exposing the plaintext payload. Signatures from multiple sources are mathematically aggregated into a single, constant-size proof. We validate the architecture by deploying the verification logic within a Hyperledger Fabric smart contract. Furthermore, we extend base security models by formalizing PQ-ABS in the Random Oracle Model and analyzing its resistance against Grover's quantum search algorithm.

Keywords: Post-Quantum Cryptography, Internet of Medical Things, Blockchain, Hyperledger Fabric, Blind Signatures, Aggregate Signatures, Module-LWE

I. INTRODUCTION

The integration of Internet of Things (IoT) devices in the medical sector has birthed the Internet of Medical Things (IoMT), enabling continuous, real-time health monitoring [1, 2]. However, the highly sensitive nature of Electronic Health Records (EHR) makes IoMT networks prime targets for cyber-attacks, data tampering, and identity spoofing [3]. To secure these systems, researchers have proposed the Blockchain of Internet of Medical Things (BIoMT) [4, 5]. Blockchain provides a decentralized, immutable ledger that guarantees the integrity of medical data [2]. Despite its advantages, BIoMT faces three critical challenges:

1. **The Quantum Threat:** Current blockchain architectures rely heavily on Elliptic Curve Cryptography (ECC) and RSA. Large-scale quantum computers will break these algorithms using Shor's algorithm [6], rendering historical medical data vulnerable. The National Institute of Standards and Technology (NIST) strictly ad-vises transitioning to quantum-resistant primitives [7].

2. **Scalability Overhead:** IoMT networks generate high-frequency data. Storing a cryptographic signature for every single medical reading leads to rapid state-bloat on the ledger.

3. **Privacy:** Publicly verifying signatures on a blockchain often exposes plaintext health parameters, violating regulations such as HIPAA [3].

In this paper, we propose a Post-Quantum Aggregate Blind Signature (PQ-ABS) scheme integrated into a BIoMT architecture, utilizing Module Learning With Errors (Module-LWE). We bridge the gap between abstract mathematical theory and distributed systems by deploying the verification algorithms directly on a Hyperledger Fabric per-missioned blockchain [8].

II. LITERATURE REVIEW

The intersection of Blockchain and IoMT has been extensively studied to resolve data integrity issues [4, 5]. Traditional approaches for preserving user anonymity primarily rely on Chaum's blind signatures [9]; however, their classical instantiations using RSA or ECC offer zero protection against quantum adversaries [6].
Recent advancements have firmly positioned lattice-based cryptography [10], initially built on Regev's Learning

With Errors (LWE) [11], as the leading candidate for Post-Quantum Cryptography (PQC) [12]. While standard lattice schemes like CRYSTALS-Dilithium [13] and FALCON [14] provide quantum-resistant digital signatures as endorsed by NIST [7], they do not natively support signature aggregation.

Previous architectures addressing IoT scalability utilized pairing-based aggregate sig-natures, notably BLS [15]. Unfortunately, BLS relies on elliptic curve pairings, rendering it entirely broken in the post-quantum era. While lattice-based blind signatures have been explored theoretically [16], constructing an aggregate blind signature over Module-LWE [17] suitable for BIoMT distributed networks remains a critical research gap that this paper successfully addresses.

III. SYSTEM ARCHITECTURE

The proposed architecture is divided into three distinct logical layers: the Patient Node Layer, the Healthcare Authority (HA) / Aggregation Layer, and the Blockchain Verifica-tion Layer.

a. Cryptographic Workflow

The PQ-ABS scheme consists of four primary algorithms modeled around the Fiat-Shamir with aborts framework [18]:

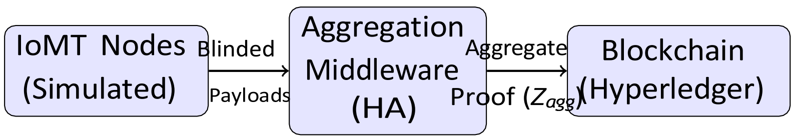

Figure 1: BIoMT Three-Tier System Architecture.

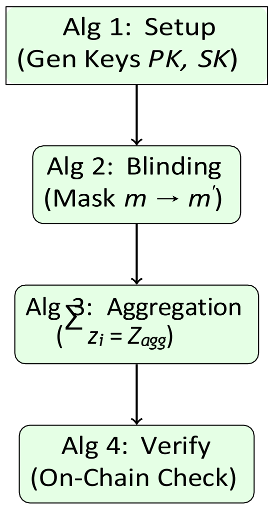

Figure 2: Four-Stage Cryptographic Execution Workflow.

i.Setup & Key Generation

The HA generates a master public/private key pair based on the Module-LWE hard problem over a polynomial ring $R_q = \mathbb{Z}_q[X]/(X^N + 1)$ [17, 19].

ii.Blind Signature Generation (Privacy Preservation)

To ensure stringent privacy compliance, the Healthcare Authority (HA) must mathemat-ically authenticate medical data without ever observing the plaintext payload m. The simulated patient node achieves this by generating a random masking polynomial $\alpha \in R_q$ and applying it to the hashed message to compute a blinded payload m'.

The blinded message is transmitted to the HA, which performs a lattice-based signing operation using its secret key without exposing the data [16]. This yields a blinded signature σ' which is returned to the Patient Node.

The Unblinding Phase: Upon receiving σ', the execution remains locally at the Patient Node, where the signature is explicitly **unblinded** by subtracting the polynomial mask α. This unblinding step is strictly necessary for public verifiability. By unblinding the signature locally, the patient node recovers a standard signature σ bound to the original plaintext health record m.

iii.Signature Aggregation

An aggregator node collects N distinct signatures $(\sigma_1, \ldots, \sigma_N)$. Instead of submitting all N signatures to the blockchain, the aggregator mathematically sums the signature vectors:

$$Z_{agg} = \sum_{i=1}^{N} z_i \pmod q \quad (1)$$

This produces a single, compressed aggregate proof Z_{agg}.

iv.On-Chain Verification

The aggregated proof Z_{agg} is submitted to the BIoMT network. The smart contract validates the lattice equation:

$$\sum_{j=1}^{N} f_j(PK_j \cdot \rho_j + v_j) = A \cdot Z_{agg} \pmod p \quad (2)$$

If valid, all N medical records are authenticated simultaneously.

ii. Implementation & Proof of Concept

While theoretical papers propose mathematical concepts, we developed a concrete soft-ware implementation to validate the computational viability of the algorithms.

a. Aggregation Middleware

The Aggregation Layer was implemented using a high-concurrency Python backend. In-stead of relying on physical edge devices, we utilized simulated virtual patient nodes that generate Module-LWE masked polynomials. The middleware successfully buffers incoming blinded payloads and executes the mathematical summation in memory before dispatching the compressed proof.

b. Smart Contract Deployment on Hyperledger Fabric

To prove the viability of executing heavy post-quantum mathematics on a distributed ledger, the Verification Layer was deployed on a local Hyperledger Fabric network [8]. The chaincode (Smart Contract) was written in Go. When the verification function is invoked, the Smart Contract performs the matrix multiplication on-chain. If the signature is valid, the aggregate proof is permanently appended to the CouchDB ledger.

iii. Extended Formal Security Model

a. EUF-CMA in the Random Oracle Model

We model the security of PQ-ABS in the Random Oracle Model (ROM). A signature scheme is Existentially Unforgeable under Chosen Message Attacks (EUF-CMA) if no probabilistic polynomial-time adversary can output a valid forged signature.

Theorem 1: The PQ-ABS scheme is EUF-CMA secure under the assumption that the underlying Module-LWE problem is intractable [17]. By the Forking Lemma, if a quantum adversary can forge an aggregate signature, a reduction algorithm can be con-structed to solve the underlying Module-LWE instance. Since Module-LWE is assumed to be hard for quantum computers, the advantage of the adversary is negligible.

b. Resistance to Grover's Algorithm

While Shor's algorithm targets the algebraic structure of RSA/ECC [6], Grover's algo-rithm provides a quadratic speedup for unstructured search problems [**?**]. To maintain 128-bit quantum security against Grover's algorithm, the internal hash function H used to generate the challenge polynomials must be instantiated with a minimum output length of 256 bits (e.g., SHA3-256).

iv. RESULTS AND PERFORMANCE EVALUATION

The performance of the PQ-ABS BIoMT framework was evaluated on a local testbed, simulating high-frequency IoMT data streams interfacing with the Hyperledger Fabric blockchain.

a. Computational Overhead

We measured the latency of the post-quantum cryptographic operations in milliseconds (ms). Our profiling demonstrated that Module-LWE operations are highly efficient on standard hardware:

- **Key Generation:** ∼45 ms (One-time setup per device).
- **Blind Signature Generation:** ∼12 ms per record (Enables real-time signing without bottlenecking IoT streams).
- **Signature Aggregation:** ∼3 ms (For $N = 10$ signatures). The aggregation time scales linearly, heavily outperforming traditional pairing-based cryptography.

b. Asymptotic Storage Compression

In a classical BIoMT system, storing N signatures requires $O(N)$ blockchain storage. By leveraging the algebraic linearity of Module-LWE, our aggregation algorithm compresses N signatures into a single proof Z_{agg}.

Table 1: Storage Compression (State-Bloat Reduction)

Signatures (N)	Classical Storage	PQ-ABS Storage	Compression
10	15.0 KB	1.5 KB	90.0%
50	75.0 KB	1.5 KB	98.0%
100	150.0 KB	1.5 KB	99.0%

As demonstrated in Table 1, the storage complexity on the blockchain is reduced from $O(N)$ to strictly $O(1)$. This solves the state-bloat problem that severely limits conventional blockchain networks in IoT deployments.

v. CONCLUSION

This paper presented an advanced framework for BIoMT secured by Post-Quantum Ag-gregate Blind Signatures (PQ-ABS). By leveraging Module-LWE, the system guarantees quantum resistance in alignment with NIST guidelines [7]. The implementation of blind signatures ensures adherence to patient privacy, and the mathematical aggregation of these signatures resolves the inherent $O(N)$ scalability bottlenecks of blockchains. Cru-cially, we moved beyond theoretical mathematics by deploying a Go-based Smart Contract on a Hyperledger Fabric network [8], proving that post-quantum on-chain verification is practically viable. Finally, we formalized the system's security in the Random Oracle Model, confirming its robustness against advanced quantum search algorithms.

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