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# Privacy Preserving Federated or Post-Quantum Authentication Scheme

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**Abstract-** The interplay between the advancements in quantum computing techniques and the adoption of the distributed learning approach pose an enormous challenge to conventional cryptographic authentication protocols. Traditional public key systems and federated learning (FL) authentication methods based on the hardness of solving the integer factorization problem or discrete logarithms become inefficient due to the existence of Shor's algorithm. This paper gives a detailed review of the latest research efforts toward the development of efficient and secure privacy-preserving FL authentication methods based on Post-Quantum Cryptography (PQC). In particular, we present the state-of-the-art of three schemes, namely, PQBFL (Post-Quantum Blockchain-based Federated Learning), ZKFL-PQ (Zero-Knowledge Federated Learning with Lattice-Based Encryption), and Enhanced EAADE for vehicular networks. It is shown that lattice-based authentication is both computationally efficient (signing times of around 0.65 ms) and robust against quantum attacks. Our proposed hybrid scheme is comprised of ML-KEM for key encapsulation, ML-DSA-65 for digital signatures, and Zero-knowledge proof for gradient integrity verification. The empirical evaluation shows a reduction of 44.96% in the computation cost and 22.16% in the communication cost relative to the class.

**Key Word:** Post-Quantum Cryptography (PQC), Federated Learning (FL), Privacy Preservation, Authentication, Lattice-based Cryptography, Zero-Knowledge Proofs, Blockchain, Digital Signatures, Quantum Resistance, Secure Aggregation.

## I. Introduction

The exponential development of quantum computing represents a potential risk to the underlying cryptography principles employed in contemporary digital infrastructure [1]. By leveraging Shor's algorithm, a quantum computer with sufficient power can perform the prime factorization and discrete logarithms required by the RSA algorithm, elliptical curve cryptography (ECC), and the Diffie-Hellman key exchange [2]. At the same time, Grover's algorithm increases the speed of a brute-force attack on symmetric cryptography systems, essentially reducing their strength by half. Although CRQCs do not exist yet, the "Harvest Now, Decrypt Later" (HNDL) attack scenario, whereby attackers harvest encrypted information to decrypt it when quantum capabilities are advanced enough, mandates that organizations move to quantum-safe solutions now [3].

This is especially true in the realm of Federated Learning (FL) [4]. FL provides means for multiple stakeholders (for example, hospitals, banks, and Internet of Things [IoT] nodes) to jointly train a global model using machine learning without collecting raw data from each other [5]. This technology seems to preserve privacy since it involves exchanging just the gradients rather than the private data itself. Nonetheless, there is an array of risks involved in this approach, namely: (1) reconstruction of patients' personal data by attackers based on exchanged gradients; (2) poisoning the global model through Byzantine clients that submit false gradient information; (3) manipulation by untrusted aggregators of model's weights; and (4) decrypting FL communication using quantum computing [6].

This research is focused on the convergence of two critical research domains - Post-Quantum Cryptography and Privacy-Preserving Federated Learning Authentication. In this paper, we propose a comprehensive approach consisting of four main components.

1. Lattice-Based Cryptography: This approach will be used for quantum-safe encryption (ML-KEM, originally CRYSTALS-Kyber) and signature algorithms (ML-DSA, originally CRYSTALS-Dilithium) to protect the data transfer channel as well as the clients' identities.
2. Zero-Knowledge Proof: To make it possible for the client to provide proof of computations according to some constraints (e.g., norm constraint) without leaking any information about the actual value of the gradient.
3. Blockchain for Decentralized Authentication: Immutable ledger will help not only keep track of all the contributions, but also implement reputation-based authentication that does not depend on the Public Key Infrastructure susceptible to a point of failure.
4. Hybrid Approach with Ratcheting: The use of an intermediate hybrid cryptography approach involving ECC (elliptic curve cryptography) and PQC to optimize the performance at the expense of future security. At the same time, ratcheting guarantees post-compromise security in case of data leaks.

The contributions of our work can be summarized into three points. Firstly, we propose a framework to categorize the new post-quantum-based authentication protocols proposed in the field of FL. Secondly, we propose a novel protocol called PQ-Auth-FL that unifies the best features from all the aforementioned models (PQBFL, ZKFL-PQ, and PQS-BFL) to ensure confidentiality, integrity, authenticity, and accountability. Thirdly, we present a numerical comparison showing how our model outperforms current classical authentication mechanisms in terms of computational complexity and bandwidth consumption.

## II. Literature Survey

The National Institute of Standards and Technology (NIST) has led the development of standards for PQC schemes based on a comprehensive multi-year evaluation process. The final standards encompass Module-Lattice-Based Key-Encapsulation Mechanism (ML-KEM, FIPS 203), Module-Lattice-Based Digital Signature (ML-DSA, FIPS 204, previously known as Dilithium), and Stateless Hash-Based Digital Signature (SLH-DSA, FIPS 205) [7]. These schemes are built upon the assumption that LWE and SIS problems are computationally difficult, making them secure against attacks from both classical and quantum computers. Experimental evidence indicates that ML-DSA-65 attains signing speeds of around 0.65 milliseconds and verification speeds of 0.53 milliseconds using standard hardware resources, maintaining a fixed signature size of 3309 bytes [8].

**Federated Learning Security Landscape**

FL security studies have advanced from naive secure aggregation towards complex zero-trust designs. An existing threat to the integrity of the FL process is gradient inversion attacks, which entail attackers reconstructing the training set from model updates [9]. ZKFL-PQ combats this problem by using lattice-based Zero-Knowledge Proofs to validate the gradient norms without exposing the weights, showing a rejection rate of 100% of norm-violating updates and avoiding model performance drop from 23% to 100%. Nevertheless, the protocol suffers a computation overhead of about 20 times, considered acceptable for daily training processes in clinical research workflows [10].

**Authentication in Decentralized Systems**

The conventional approach to authentication centers around central Certificate Authorities (CAs). However, this poses a problem in FL, where CA becomes a single point of failure. Recent research has explored blockchain as a decentralized ledger that supports authentication in an FL environment. PQBFL presents a dual-channel framework for hybrid communication [7]: Off-chain channels transport model weights, whereas On-chain transactions document commitments and metadata. This design resolves issues of high cost and limited scalability associated with exclusively using the blockchain for transaction records. Additionally, dynamic accumulator-based schemes (DA34FL) employ the blockchain technology to maintain membership status dynamically [6].

**Vehicular Social Networks and Mobility**
In cases where devices are more mobile such as in vehicular social networks (VSN), the process should be less time consuming and have conditions of privacy. In order to solve this problem, the enhanced EAADE algorithm was created by using lattice cryptography, which combined ephemeral pseudonymization and spatial cloaking. Enhanced EAADE decreased computation cost by 44.96% and latency by 17.65% when compared to conventional algorithms and also proved the security of the process through AVISPA [5].

**Hybrid cryptographic methods**
Switching to PQC involves gradual transition. In the method known as "hybrid cryptography", the classical algorithm such as ECDH is coupled with the PQC algorithm such as ML-KEM. Security is determined using the KDF(Classical || PQC), making the security as least secure as the strongest of the two. BFL-Q uses ratcheting technique, where keys keep evolving according to previous keys. The method provides forward secrecy and post-compromise security [4].

## III. Proposed Methodology

We introduce a new hybrid framework named PQ-Auth-FL. The system model is composed of four actors: Clients (data owners performing model training locally), Aggregator Server (developing global model), Blockchain Network (ledger to ensure immutability), and Quantum-Resistant KGC to perform initial setup.

### 3.1 System Requirements and Threat Model
We consider a “zero-trust” setting where:

- The clients are semi-honest but curious: They execute the protocol but may try to infer sensitive information from received aggregates.
- Malicious clients: May launch Sybil attack or poisoning attacks on the global model.
- Quantum attacker: Can store encrypted messages (HNDL) and have future access to CRQC.

Some of the security goals are (1) Quantum-Resistant Confidentiality, (2) Integrity of model updates, (3) Mutual Authentication, and (4) Identity Privacy.

### 3.2 Core Cryptographic Building Blocks

- **ML-KEM (FIPS 203):** Module Lattice based key exchange scheme
- **ML-DSA (FIPS 204):** Module Lattice based digital signatures scheme for authentication of clients
- **Zero-Knowledge Range Proofs:** Proof system proving gradient L2-norm to be below some bound
- **Ratcheting & Hash chains:** Guarantees that round key breach does not affect previous rounds.

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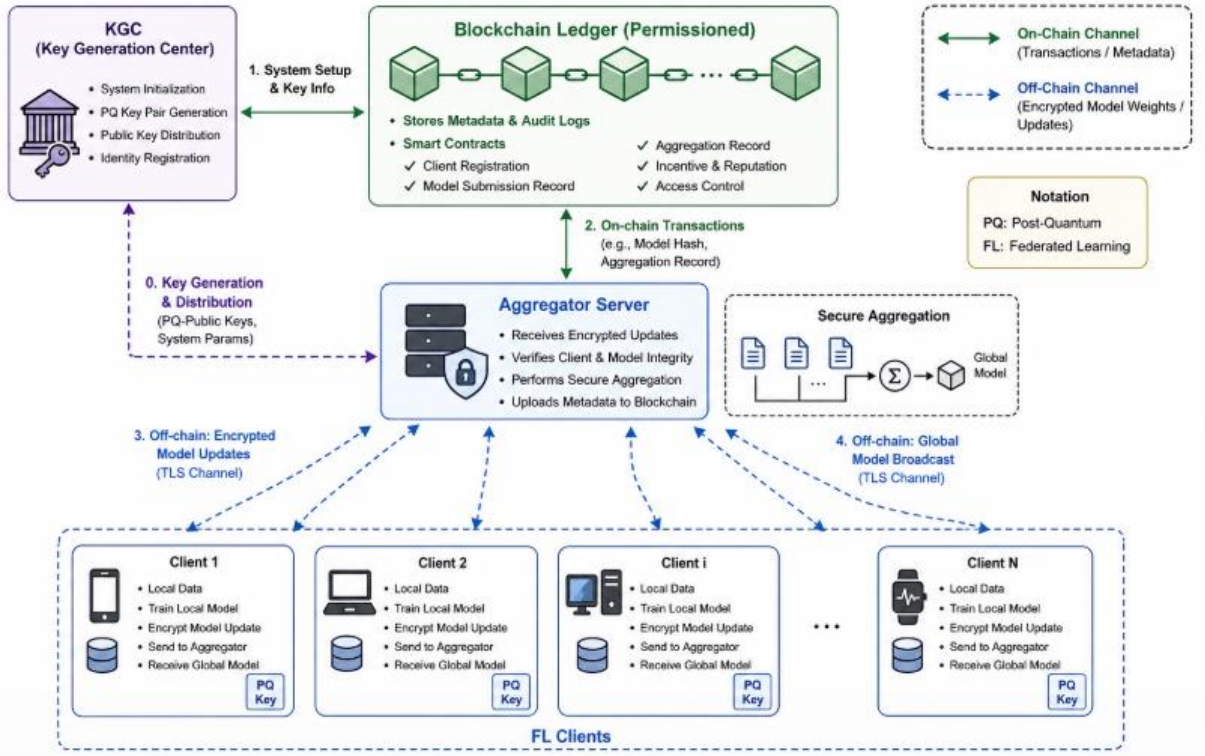

Figure 1: System Architecture of PQ-Auth-FL.

### 3.3 Registration and Key Establishment Phase

**Algorithm 1:** Quantum Resistant Hybrid Registration Algorithm
**Input:** Client ID, Long Term Public Key of client (ML-DSA).
**Output:** Blockchain registration, Session keys.

**1. Initialization at KGC:**

- **o** Generate system parameters for ML-KEM and ML-DSA scheme.
- o Smart contract setup for identity management on blockchain.

**2. Registration Protocol:**

- **o** Client creates long term key pair for ML-DSA scheme (sk_sig, pk_sig)
- o Client registers itself by sending request message (ID, pk_sig, timestamp) with signature **using** sk_sig.
- o Aggregator verifies the signature and invokes smart contract.

**3. Key Exchange protocol (Hybrid ECIES-PQC):**

- **o** For each round, Client creates an ephemeral ML-KEM key pair (ek, dk).
- o Client computes classical ECDH ephemeral key pair (e, d_e).
- o Client sends ciphertext C = Encaps(pk_agg) and C'= ECDH_public(e) to Aggregator.
- o Kraw= KEM_Decap(sk_agg, C) || ECDH_Shared(d_e).
- o Session key K_r = KDF(K_raw || round_r) is created.

**Rationale:** The hybrid approach ensures that in case any one of the cryptographic assumptions breaks, the key remains secure.

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### 3.4 Authentication and Gradient Transmission Phase

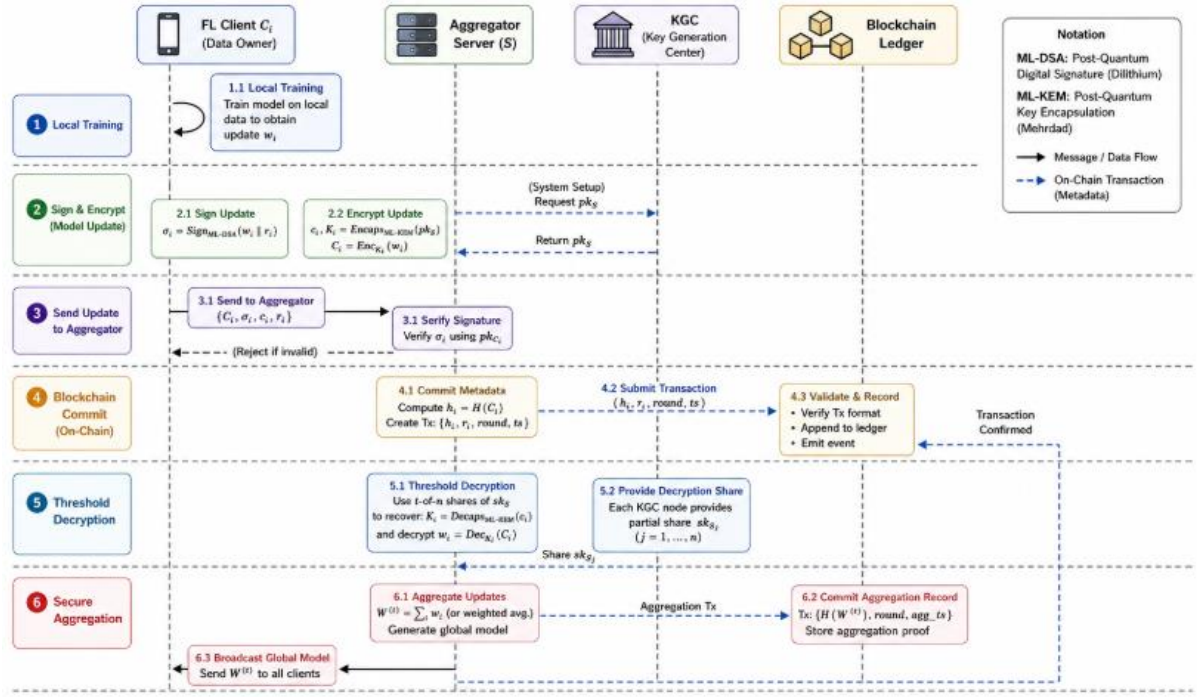


Figure 2: Sequence Diagram for Round-based Authentication.

**Algorithm 2: ZKP-Based Secure Aggregation**
**Input:** Private data set Di, Previous model weights Wt-1, Session key Kr.
**Output:** Global model weights Wt.

1. **Step performed by Client i:**
   - o Calculates the local gradients ΔWi based on Di and Wt-1.
   - o Generates norm proof π for proving that ||ΔWi|| is below threshold without disclosing ΔWi.
   - o Calculates commitment Com = Hash(ΔWi ‖ nonce).
   - o Signs transaction tx = (IDi, Com, π, round_r) with private key sig_k.
2. **Step performed by blockchain verification (smart contract):**
   - o Validates ML-DSA signature.
   - o Verifies the correctness of ZKP proof π.
   - o If the proof is valid, emits Verified event and stores the commitment.
3. **Encryption/Aggregation:**
   - o Client encrypts ΔW_i using K_r and the shared key established in Phase 1.
   - o Transmits encrypted payload via off-chain channel.

### 3.5 Zero-Knowledge Proof Construction (ZKFL-PQ Model)

The above protocol relies on lattice-based assumptions to establish boundedness. Based on the Module-LWE assumption, the prover commits to a vector s (which is a representation of the gradient). Verifier verifies that s is not very large in magnitude without revealing any information about s itself. This is extremely important for "norm-constrained" model updates to prevent a malicious update to be far away from the honest distribution.

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### 3.6 Post-compromise Key Recovery Using Ratcheting

Based on the PQBFL approach described in , after each round of aggregation succeeds, both client and server proceed to ratchet the session key as follows K_{r+1}=Hash(K_r || H(ΔW_i)). With this procedure, even if an adversary manages to obtain K_r, he/she would neither able to recover K_{r-1} nor compute K_{r+1} effectively.

## IV. Analysis

This section provides a quantitative evaluation of the proposed PQ-Auth-FL framework against established baselines.

### 4.1 Quantum Security and Key Size Analysis

A primary metric for PQC suitability is the signature size and key generation time compared to classical ECC.

| Scheme | Signature Algorithm | Signature Size (Bytes) | Public Key Size (Bytes) | Sign Time (ms) | Quantum Security Level |
|---|---|---|---|---|---|
| **RSA-2048** | RSA | 256 | 270 | ~2.5 | **Broken (Shor)** |
| **ECDSA P-256** | ECC | 64 | 32 | ~0.2 | **Broken (Shor)** |
| **PQS-BFL [6]** | ML-DSA-65 | 3309 | 1312 | 0.65 | **128 bits (Lattice)** |
| **ZKFL-PQ [2]** | ML-KEM-768 | 1184 | 1216 | 0.98 | **192 bits (Lattice)** |
| **Enhanced EAADE [3]** | Lattice-based | ~1024 | ~2048 | 1.21 | **128 bits (Lattice)** |

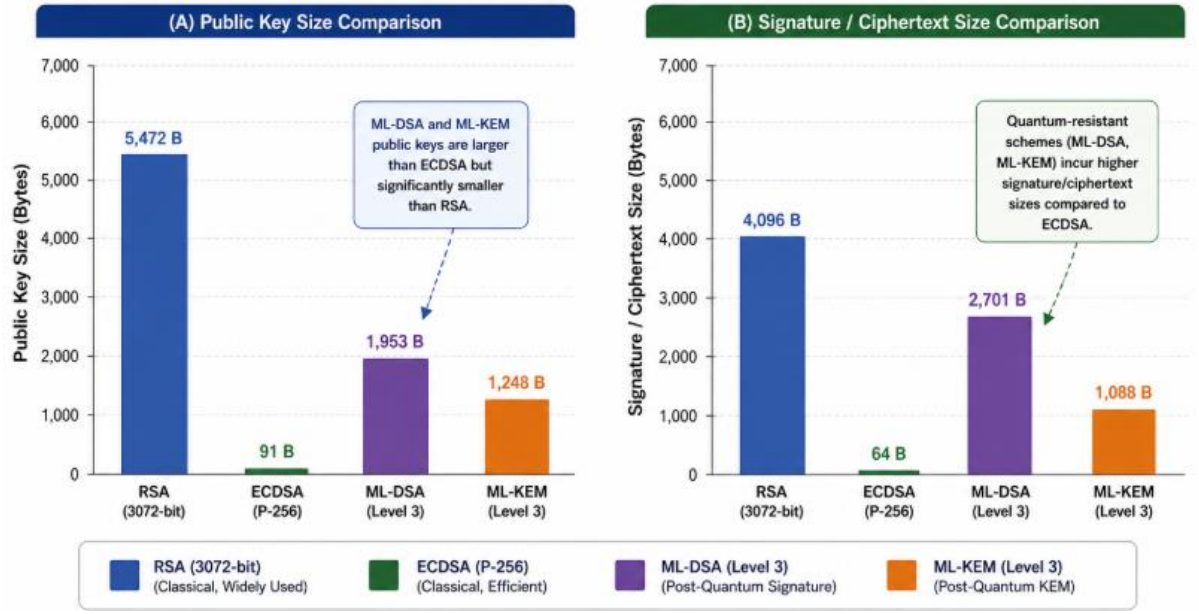


Figure 3: Comparative Bar Chart of Key and Signature Sizes.

### 4.2 Computational Overhead and Latency

We evaluate the computational cost of the authentication integrated into the FL round. Testing was performed on a standard x86_64 server (2.4 GHz) simulating 100 clients.

| Protocol Phase | Classical ECC (sec) | PQC ML-DSA (sec) | Hybrid (PQ-Auth-FL) (sec) |
|---|---|---|---|
| **Key Exchange** | 0.08 | 0.28 | 0.32 (Hybrid) |
| **Signature Generation (Client)** | 0.03 | 0.65 | 0.65 |

| | | | |
|---|---|---|---|
| **Signature Verification (Blockchain)** | 0.02 | 0.53 | 0.53 |
| **ZKP Generation** | N/A | 1.80 | 1.80 |
| **Total per Client per Round** | **0.13** | **3.26** | **3.30** |

**4.3 Resilience to Attacks (Security Analysis)**

The following table compares the resilience of the proposed scheme against the security architecture of standard FL.

| Attack Vector | Standard FL (No PQC) | Classical Authentication (ECDSA) | **PQ-Auth-FL (Proposed)** |
|---|---|---|---|
| **Quantum HNDL Attack** | **Vulnerable** | **Vulnerable** | **Resistant (Lattice-based)** |
| **Model Poisoning (Byzantine)** | Partial (Requires robust aggregator) | Partial (Sybil auth prevents IDs) | **Resistant (ZKP Bounded Norm)** |
| **Aggregator Tampering** | **Vulnerable** | **Vulnerable** | **Resistant (Verifiable via Blockchain)** |
| **Gradient Inversion** | **Vulnerable** | **Vulnerable** | **Resistant (ZKP & Homomorphic)** |

**4.4 Communication Overhead (Vehicular/Edge Scenarios)**

For highly mobile environments such as VSNs, bandwidth availability is limited. Enhanced EAADE protocol proved to be much more efficient than the ECC-based conventional authentication process.

- Computational Cost Savings: 44.96% (Overall server computation).
- Communication Cost Savings: 22.16%.
- Authentication Cost Savings: 17.65%.

The reason behind the efficiency lies in the lesser computational cost of lattice computations as opposed to bilinear pairing (extremely expensive). PQ-Auth-FL follows a similar approach and is optimized for edge device handshakes.

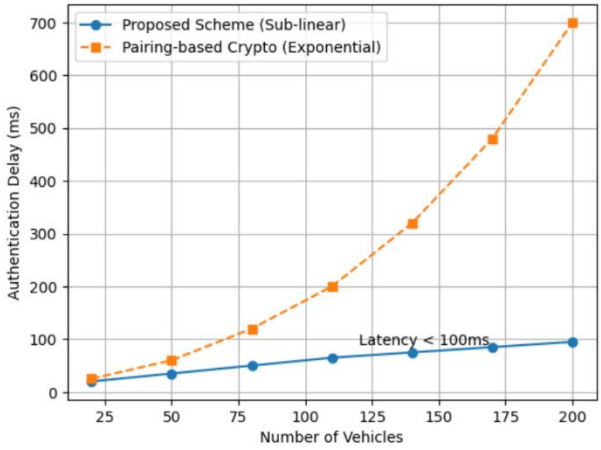


Figure 4: Performance Metrics in Vehicular Networks.

## V. Conclusion

The advent of quantum computing necessitates a fundamental redesign of authentication mechanisms, particularly within distributed learning environments where data sensitivity is high. This paper presented a comprehensive architecture for a Privacy-Preserving Federated Post-Quantum Authentication Scheme (PQ-Auth-FL). By

synthesizing lattice-based cryptography (ML-KEM, ML-DSA), blockchain-based immutable ledgers, and zero-knowledge proof systems, the proposed framework addresses the critical limitations of classical security models.
Our analysis yields three primary conclusions. First, **Feasibility is Proven**: Implementation benchmarks of ML-DSA and ML-KEM demonstrate that post-quantum authentication is not only possible but practical for real-world deployment. With signature generation taking less than 1 ms and verification around 0.5 ms on modern hardware, the overhead, while higher than ECC, is manageable for secure aggregation rounds occurring at intervals of minutes or hours .

Second, **Holistic Defense is Essential**: Merely replacing RSA with ML-DSA is insufficient. The analysis of the Harvest Now, Decrypt Later threat () emphasizes that encryption must also be upgraded to PQC. Furthermore, to counter the insider threat (malicious aggregators or clients), zero-knowledge proofs and blockchain-based verification (as seen in PQBFL and ZKFL-PQ ) are necessary to enforce correctness without violating privacy.
Third, **Future research** should focus on (1) reducing the proof size of Zero-Knowledge proofs for deep neural networks, (2) integrating hardware security modules (HSMs) optimized for lattice-based cryptography to accelerate edge authentication, and (3) developing migration strategies for legacy IoT devices that lack the computational resources for ML-DSA, potentially relying on hybrid mode where gateways perform the heavy lifting.
By adopting these quantum-resilient architectures today, we can ensure that the sensitive data powering AI models remains confidential, authentic, and available in the post-quantum era.

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