Design of a Quantum-Resistant Communication Protocol Using Blockchain With Post-Quantum Security

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Problem Statement

Current blockchain-based communication platforms rely on cryptographic algorithms (e.g., RSA, ECDSA) that are susceptible to quantum attacks. With the rise of quantum computing, these platforms face the risk of message theft, forgeries, and loss of communication privacy. There is a lack of real-world, scalable, user-friendly, public blockchain protocols designed from the ground up to ensure secure, end-to-end encrypted messaging using natively post-quantum cryptographic primitives. This creates an urgent need for solutions that can preserve privacy and integrity of public communications in the quantum era.

Motivation

- Blockchain's promise of permanent security is on a collision course with the reality of quantum computing. The cryptographic signatures (ECDSA) that protect major cryptocurrencies are vulnerable to quantum attacks like Shor's algorithm, placing a significant portion of the digital economy at risk—including an estimated 25% of all Bitcoin in circulation. This threat is immediate, driven by "Harvest Now, Decrypt Later" strategies where adversaries store today's encrypted data for future decryption.
- In response, governments are issuing urgent mandates: the U.S. has set a 2035 deadline for federal agencies to migrate to Post-Quantum Cryptography (PQC), and the E.U. has set an even more aggressive 2030 target for its critical infrastructure. Despite this, enterprise adoption is dangerously low at just 5%.

Literature Survey

- The rise of quantum computing poses a direct threat to the security of modern blockchain systems, which rely on classical cryptography like the Elliptic Curve Digital Signature Algorithm (ECDSA) that will be breakable by quantum machines. This report summarizes the state of research on integrating Post-Quantum Cryptography (PQC) to secure these networks.
- The leading PQC solutions, particularly NIST-standardized lattice-based signatures like CRYSTALS-Dilithium and FALCON, offer a viable path forward. However, this transition involves significant trade-offs: PQC algorithms introduce larger keys and signatures, which drastically reduce transaction throughput, increase network latency, and demand more storage. The central challenge is not just technical but also one of governance, requiring a coordinated, network-wide migration—a process known as achieving crypto-agility—in a complex, decentralized ecosystem. [1]

Literature Survey

1. The Quantum Threat to Blockchain

Blockchain's core value is its permanent, immutable ledger, secured by cryptography that is assumed to be unbreakable for the long term. Quantum computing invalidates this assumption.

Vulnerability of Digital Signatures: Shor's quantum algorithm can efficiently solve the mathematical problems that underpin the security of ECDSA, the signature scheme used by Bitcoin and Ethereum. A quantum attacker could derive a user's private key from their public key, which is revealed during a transaction, and steal their funds.

Weakening of Hashing: Grover's algorithm offers a quadratic speed-up in breaking cryptographic hash functions like SHA-256, which are fundamental to Proof-of-Work (PoW) mining.[1] This would disrupt the security and economic balance of PoW-based networks.

Literature Survey

"Harvest Now, Decrypt Later": The threat is immediate. Adversaries can record today's encrypted blockchain data and decrypt it once a powerful quantum computer is available. Because blockchain data is public and permanent, it is a prime target for this attack strategy.

2. The Post-Quantum Cryptographic Arsenal

In response to the quantum threat, the cryptographic community, guided by the NIST standardization process, has developed several families of PQC algorithms. For blockchain, the most relevant are digital signature schemes.

Lattice-Based Cryptography (CRYSTALS-Dilithium, FALCON): This is the most promising family, offering a strong balance of security, speed, and relatively compact size. Their security is based on the hardness of problems in high-dimensional lattices. FALCON is particularly noteworthy for its exceptionally small signatures and fast verification, making it well-suited for the storage and computation constraints of blockchain.

Literature Survey

3. Performance Analysis and Trade-Offs

Quantitative benchmarking reveals the stark performance costs of migrating to PQC.

Size Overhead: PQC signatures are substantially larger than ECDSA's ~70 bytes. FALCON signatures are around 10 times larger, Dilithium signatures are ~35 times larger, and SPHINCS+ signatures can be over 100 times larger.

Throughput Reduction: This size increase directly slashes transaction throughput. Studies modeling the impact on a Bitcoin-like chain estimate that switching to Dilithium could reduce the number of transactions per block by over 90%.

The "Sign-Once, Verify-Many" Paradigm: In blockchain, a transaction is signed once but verified by thousands of nodes. This makes verification speed and signature size the most critical metrics. This is why FALCON, despite slower signing, is a leading candidate due to its extremely fast verification and compact signatures, which reduce the overall burden on the network.

Methodology

1) **System Design and Implementation**

(A) Core Architecture and Cryptography

- The protocol's core function treats every message as an end-to-end encrypted and authenticated transaction. To achieve quantum resistance, the architecture exclusively utilizes NIST-standardized cryptographic primitives from the CRYSTALS (Cryptographic Suite for Algebraic Lattices) suite.
- Key Encapsulation: For secure message encryption and delivery, CRYSTALS-Kyber is employed.
- Digital Signatures: For transactional authenticity, integrity, and non-repudiation, CRYSTALS-Dilithium is used for all digital signatures. These lattice-based algorithms were selected due to their strong security guarantees and relatively compact public key sizes compared to alternative PQC schemes like SPHINCS+, making them more suitable for a blockchain environment where data efficiency is crucial.

Methodology

(B) Consensus Mechanism:

Delegated Proof of Luck (DPoL)

- The network achieves consensus using a novel Delegated Proof of Luck (DPoL) mechanism. This hybrid model was chosen to overcome the limitations of traditional algorithms; it avoids the high energy consumption of Proof of Work (PoW) and mitigates the "rich-get-richer" centralization risk of Proof of Stake (PoS). The DPoL model works in two stages:
- 1. Delegation: Token holders vote to elect a fixed, smaller set of trusted delegates who are responsible for running high-performance nodes and producing blocks. This governance layer is inspired by Delegated Proof of Stake (DPoS).

Methodology

- **Luck-Based Selection:** For each block, a block producer is chosen from this delegate pool through a cryptographically secure lottery. The selection is based on a Verifiable Random Function (VRF), which ensures the process is both unpredictable and universally verifiable. This "Proof of Luck" component ensures fairness and prevents resource-based centralization. This approach is designed to provide high speed, scalability, and energy efficiency while maintaining network security and decentralization

(C) Implementation

- The prototype for this blockchain protocol is being developed in Python, chosen for its extensive cryptographic libraries and rapid prototyping capabilities.

Methodology

2) Evaluation Plan

The performance and security of the proposed protocol will be rigorously evaluated. The methodology is designed to quantify the performance trade-offs inherent in using Post-Quantum Cryptography and to theoretically validate the protocol's security claims.

(A) Performance Evaluation: A prototype of the protocol will be deployed in a simulated network environment to measure its performance characteristics. The testing environment will consist of multiple nodes running on virtual machines to simulate a decentralized network. The following key metrics will be measured:

- **Transaction Throughput:** This metric will quantify the system's processing capacity. It will be measured in Transactions Per Second (TPS) by bombarding the network with a sustained load of transactions and calculating the rate at which they are successfully committed to the blockchain

Methodology

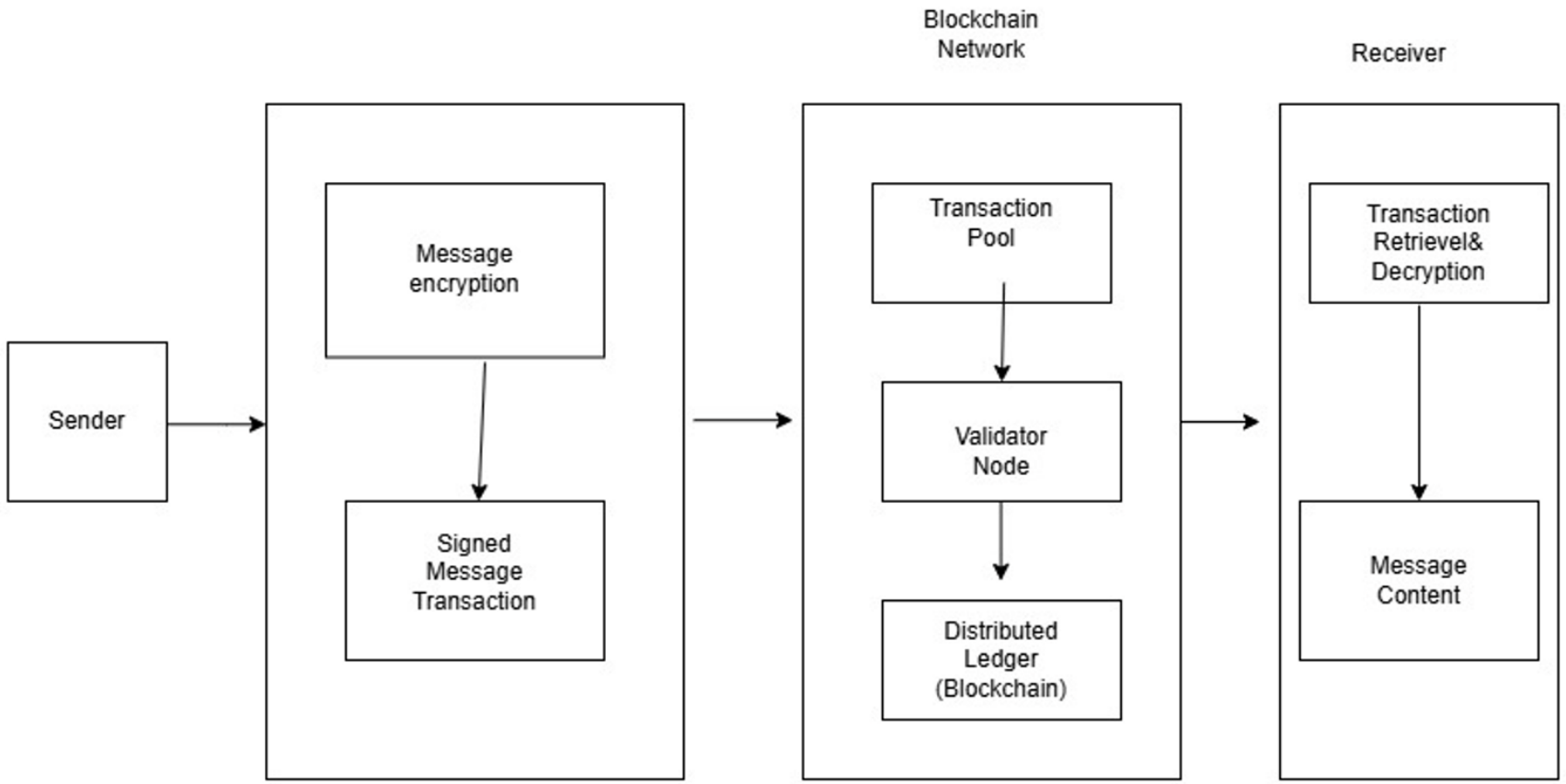
- **Transactional Latency:** This metric will measure the time required for a transaction to be finalized. It will be calculated as the time difference between the initial submission of a transaction by a client and its final confirmation in an immutable block, measured in milliseconds.
- **Space Overhead and Scalability:** This analysis will focus on the on-chain data footprint. We will measure and compare the average size of transactions and blocks against a theoretical baseline using traditional ECDSA signatures. This will quantify the "PQC tax"—the additional storage space required—and its impact on the long-term scalability of the ledger.

Methodology

(B) Security Analysis: Given that a physical large-scale quantum computer is not yet available for empirical testing, the security of the protocol will be validated through a theoretical analysis. This analysis will involve:

- **Cryptographic Primitive Review:** Verifying that the chosen PQC algorithms (CRYSTALS-Kyber and CRYSTALS-Dilithium) are implemented according to NIST's specifications and are secure against all known classical and quantum attack vectors.
- **Protocol-Level Threat Modeling:** Analyzing the entire protocol, including the DPoL consensus mechanism, to identify and address potential vulnerabilities. The protocol's resilience will be argued against established threats, such as those described by Shor's and Grover's algorithms, and against network-level attacks like Sybil attacks

Block Diagram



Implementation

```
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ python node.py config_node1.json
/home/ubuntu/Downloads/pq-block(1)/pq-block/node.py:136: DeprecationWarning: There is no current event loop
  loop = asyncio.get_event_loop()
 * Serving Flask app 'node'
 * Debug mode: off
INFO:werkzeug:WARNING: This is a development server. Do not use it in a production deployment. Use a production WSGI server instead.
 * Running on http://127.0.0.1:5001
INFO:werkzeug:Press CTRL+C to quit
WARNING:root:Failed to connect to peer ws://127.0.0.1:6002: [Errno 111] Connect call failed ('127.0.0.1', 6002)
INFO:websockets.server:server listening on 127.0.0.1:6001
INFO:root:P2P server running on ws://127.0.0.1:6001
WARNING:root:Failed to connect to peer ws://127.0.0.1:6003: [Errno 111] Connect call failed ('127.0.0.1', 6003)
INFO:websockets.server:connection open
INFO:websockets.server:connection open
INFO:werkzeug:127.0.0.1 - - [29/Aug/2025 12:58:52] "POST /tx HTTP/1.1" 202 -
INFO:root:Added new transaction to mempool. Nonce: 1
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Implementation

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/home/ubuntu/Downloads/pq-block(1)/pq-block/node.py:136: DeprecationWarning: There is no current event loop
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INFO:websockets.server:server listening on 127.0.0.1:6002
INFO:root:P2P server running on ws://127.0.0.1:6002
INFO:root:Connected to peer: ws://127.0.0.1:6001
WARNING:root:Failed to connect to peer ws://127.0.0.1:6003: [Errno 111] Connect call failed ('127.0.0.1', 6003)
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Implementation

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ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ source venv/bin/activate
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ pip install requests
Collecting requests
  Downloading requests-2.32.5-py3-none-any.whl.metadata (4.9 kB)
Collecting charset_normalizer<4,>=2 (from requests)
  Downloading charset_normalizer-3.4.3-cp312-cp312-manylinux2014_x86_64.manylinux_2_17_x86_64.manylinux_2_28_x86_64.whl.metadata (36 kB)
Collecting idna<4,>=2.5 (from requests)
  Using cached idna-3.10-py3-none-any.whl.metadata (10 kB)
Collecting urllib3<3,>=1.21.1 (from requests)
  Downloading urllib3-2.5.0-py3-none-any.whl.metadata (6.5 kB)
Collecting certifi>=2017.4.17 (from requests)
  Downloading certifi-2025.8.3-py3-none-any.whl.metadata (2.4 kB)
Downloading requests-2.32.5-py3-none-any.whl (64 kB)
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Downloading charset_normalizer-3.4.3-cp312-cp312-manylinux2014_x86_64.manylinux_2_17_x86_64.manylinux_2_28_x86_64.whl (151 kB)
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Using cached idna-3.10-py3-none-any.whl (70 kB)
Downloading urllib3-2.5.0-py3-none-any.whl (129 kB)
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Installing collected packages: urllib3, idna, charset_normalizer, certifi, requests
Successfully installed certifi-2025.8.3 charset_normalizer-3.4.3 idna-3.10 requests-2.32.5 urllib3-2.5.0
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ python send_tx.py Alice Bob "This is much easier than using curl!"
✅ Transaction submitted successfully!
{'message': 'Transaction submitted', 'tx_hash': '6235747aeaf391c0d7fc3990dd5592b3be01c07cef5b000f12ea54ad62fb81c9'}
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ python send_tx.py Alice Bob "This is much easier than using curl!"
✅ Transaction submitted successfully!
{'message': 'Transaction submitted', 'tx_hash': '474c3513b478db0feb10f7fa6fe8da2788460c72334d8d9dee51925233945199'}
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$ ^C
(venv) ubuntu@ubuntu:~/Downloads/pq-block(1)/pq-block$
```

Implementation

```
WARNING:root:Invalid nonce for 914d710ff828e99343d05f1f76abed686fb24ab95aa6a48fbae9a65dcd7d941325141b09bca4b053f55c33150b3001332bb16b2b889cb41183f60b7cef6cf4dad508d1cc9bacea525fae9921a
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