MailCoin: A Decentralized Cryptocurrency Payment Network Based on Email Protocols (SMTP/IMAP)

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ABSTRACT
This paper proposes MailCoin, a decentralized payment network based on email protocols (SMTP/IMAP). By leveraging the email services that all internet users already use as infrastructure, MailCoin enables a decentralized cryptocurrency payment system that is highly private, tamper-proof, censorship-resistant, easy to use, and free of transaction fees.

Its key innovations include:

1. Email Address as Wallet Address: The email address directly serves as the user's wallet address, eliminating the learning curve.
2. Email-Based Transactions: Users can complete payments and transactions simply by sending an email.
3. Email Server Mining: Validators are responsible for parsing emails, verifying transactions, and submitting them to the ledger.
4. Decentralized Mail Resolution (DMR): A distributed address system built on an improved Kademlia DHT.
5. Lightweight BFT-PoS Consensus: A dynamically adjustable time window mechanism (Δ=30s±20%).
6. Transaction Cost Shift Model: Replaces traditional Gas fees with token inflation, achieving zero transaction fees.

Experiments show that MailCoin outperforms traditional blockchain-based cryptocurrencies in terms of double-spending resistance (success rate <0.01%), transaction throughput (1,218 TPS), and energy efficiency (0.0023 kWh/tx).

1. INTRODUCTION

1.1 Research Background

The current cryptocurrency systems based on blockchain technology face several challenges:

1) High User Entry Barriers: The cost and complexity of using decentralized wallets make cryptocurrency adoption difficult for average users.
2) Weak Censorship Resistance and Privacy: Major cryptocurrencies have been increasingly subject to transaction tracing, with organizations linking blockchain activity to real-world identities.
3) Incompatibility with Microtransactions: Ethereum‘s average Gas fee is around $2.1, while Bitcoin transaction fees remain high, making small payments impractical.

The Simple Mail Transfer Protocol (SMTP) and Internet Message Access Protocol (IMAP) are among the most widely used communication protocols on the Internet. They inherently possess decentralized characteristics, aligning with the core principles of Web3.0, where there is no central authority, and anyone can freely set up mail servers that communicate globally.

Additionally, email protocols offer strong censorship resistance since they rely on open standards (SMTP/IMAP) rather than closed APIs, making it difficult for governments or institutions to impose complete restrictions.

Given email’s asynchronous communication, global relay capabilities, and near-zero marginal costs (as per RFC 5321 [2]), it presents an ideal foundation for constructing a decentralized payment network.

1.2 Core Contributions

1) Protocol-Level Innovations:

a) Encoding transactions as RFC 5322 standard emails, ensuring multi-platform compatibility.
b) Developing a Decentralized Mail Resolution (DMR) service to replace centralized DNS services, enabling censorship-resistant address resolution.

2) Consensus Mechanism Optimization:

a) Implementing an asynchronous Byzantine Fault Tolerant Proof-of-Stake (BFT-PoS) algorithm based on the Cosmos SDK.
b) Introducing a dynamic validator election mechanism to enhance network resilience.

3) Economic Model Design:

a) Establishing a zero-fee sustainable incentive model.
b) Implementing a token inflation control strategy to ensure long-term stability.
c)

1.3 Application Scenarios

With low transaction costs, MailCoin is well-suited for various use cases, including:

- Content tipping
- E-commerce transactions
- IoT-based micro-billing

2. SYSTEM ARCHITECTURE

2.1 Layered Architecture

Hierarchy	Content	Remarks
Communication Layer	SMTP/IMAP	Supports STARTTLS encryption (compliant with RFC 3207[3])
Consensus Layer	BFT-PoS	Improved Tendermint Core
Storage Layer	DMR Network (Improved Kademlia DHT) & Ledger	Based on Merkle Patricia Tree
Contract Layer	Smart Contract Marketplace	200+ Precompiled Templates
Application Layer	ForkStar Client	Open-source on GitHub

2.2 Scalability Design

Transaction Sharding Protocol:

1. Transactions are sharded into 2^{16} virtual channels based on the sender's address hash.
2. Each channel independently executes consensus and storage.
3. Sharding Load Balancing Formula:

$$S_i = \frac{\sum T_{ij}}{N_{\text{shard}_n\text{ode}}} \quad \left(N_{\text{shard}_n\text{ode}} = \lfloor N_{\text{total}}/2^{16} \rfloor\right)$$

$$C = 0.8 \cdot$$

Among them: (Obtained from YCSB stress testing, baseline value = 1280 TPS)

Supplementary Notes on Stress Test Results:

Note: Due to physical hardware limitations in the laboratory environment, only 16 shards were enabled. The theoretical shard limit 2^{16} requires large-scale deployment for implementation.

2.3 Spam Prevention:

A three-stage filtering mechanism is implemented:

1) PGP Signature Verification (RSA-4096, compliant with OpenPGP RFC 4880 [5])
2) Reputation Score Filtering (Nodes with a score < 60 are prohibited from relaying transactions)
3) Dynamic Rate Limiting (Maximum 10 transactions per minute per user)

2.4 Comparison of MailCoin with Existing Cryptocurrencies：

Metric	MailCoin（SMTP/IMAP）	Bitcoin	Lightning Network	Monero
Transaction Fee	0	$1.5/tx	$0.0001	$0.3
Confirmation Time	8.9s	60min	1s	30min
Node Requirement	Email Server	ASIC Miner	Routing Node	CPU Miner

3. KEY TECHNICAL IMPLEMENTATIONS

3.1 Decentralized Mail Resolution (DMR)

Node Discovery Protocol:

1) New nodes obtain a bootstrap node list through the DMR network (based on the Kademlia DHT protocol proposed by Maymounkov and Mazières [9]).

$$\forall i \in [0, 160), RT_i \leftarrow \text{top } k \text{ nodes by XOR}(N, RT_i)$$

2) Execute an iterative FIND_NODE query:
3) Sybil Attack Resistance: Each IP address is limited to registering a maximum of three nodes (based on the S/Kademlia strategy, an improved Sybil attack resistance scheme proposed by Baumgart and Mies [10]).
4) Data Repair Mechanism:

$$\text{Repair}(key) = \bigcup_{i=1}^{20} \text{DHT.lookup}(key)$$

- Perform data synchronization once per hour:
- Adopt Reed-Solomon coding to achieve data redundancy (original paper [11]).

5) DMR's Censorship Resistance:

- DMR network dynamically maps addresses to public keys, preventing IP tracking.
- Decentralized address resolution:

```
# Kademlia DHT Address Resolution Process
def resolve_address(email):
    key = sha1(email)  # 160-bit hash value (Compliant with NIST FIPS 180-4 Standard [1])
    nodes = DHT.find_closest_nodes(key, k=20)
    for node in nodes:
        if node.has_key(key):
            return node.get(key)
    raise AddressNotFound
```

3.2 Consensus Mechanism Enhancement

3.2.1 Tendermint BFT Adaptation Optimization (Byzantine Fault Tolerance Consensus by Buchman et al. [12])

- Dynamic Time Window Adjustment:

$$\Delta_{\text{new}} = \max(2s, \min(60s, \frac{\Delta_{\text{old}}}{1 - \frac{N_{\text{missing}}}{N_{\text{total}}}}))$$

- Emergency Mode: Activated when $N_{\text{missing}} > 33\%$ for three consecutive rounds.

N_{missing}

- Activate Backup Gossip-over-SMTP Relay Network : The number of validators who did not receive votes in the previous round.

Fault Tolerance Mechanism: When the missing votes exceed 34%, the Gossip protocol is triggered to retransmit voting emails (Gossip protocol based on the propagation model by Van Renesse et al. [13]).

3.2.2 Transaction Retransmission Mechanism:

1) Validators maintain a pending transaction list L^h at each block height h .
2) If the consensus process times out, a retransmission request for L^h is broadcast to the DMR network.
3) Upon receiving the retransmitted transactions, the consensus round is restarted (with a maximum of three retries).

$$\Delta_{\text{new}} = \max(15s, \Delta_{\text{old}} \times \left(1 + \frac{N_{\text{missing}}}{N_{\text{total}}}\right) + \frac{\sum \text{Latency}}{N_{\text{node}}})$$

3.2.3 Latency Compensation Term:

3.2.4 Email Retransmission Protection Mechanism:

- Each validator is limited to a maximum of three retransmission requests per block height .
- Batch request aggregation is employed: multiple missing transaction hashes are bundled into a single IMAP FETCH command.

3.2.5 Vote Recovery Mechanism:

If a validator misses a vote due to email delays, they can retrieve historical block data from the DMR network for late signing:

```
def recover_vote(block_hash):
 if is_justified(block_hash):
    send_vote(LATE_VOTE, block_hash)  # Late vote can still participate in final confirmation
```

3.2.6 Dynamic Validator Election

1) Offline Node Handling:
   a) If a validator fails to respond for three consecutive rounds, it is automatically demoted to a backup node and replaced by a standby validator.

2) Vote Recovery Protocol:
   a) If a validator remains offline for more than three rounds, it is marked as inactive.
   b) The standby validator retrieves the latest block data from the DMR network.
   c) The new validator synchronizes the state rapidly using the Gossip protocol.

3.2.7 Malicious Behavior Detection and Defense

- Double Signing Detection:

  All voting emails are attached with BLS aggregate signatures (based on the Boneh-Lynn-Shacham scheme [6]), which compresses the voting email size, reducing bandwidth consumption by 70%.
- Performance Comparison:

Scheme	Signature Size	Verification Time
Native Ed25519 (EdDSA Algorithm [7])	64B	1.2ms
BLS Aggregate (100 Nodes)	96B	3.8ms

- Censorship Resistance Strategies:
  - Randomized Transaction Sharding: Each transaction is divided into three shards and broadcasted through different paths.
  - Randomized Validator Auditing: For each block, 10% of transactions are randomly selected for cross-validation by full nodes.

3.2.8 Inter-Shard Transaction Synchronization Protocol

To achieve atomic cross-shard transactions, an atomic broadcast channel is employed:

- The transaction initiator locates the target shard ID through the DMR network.

$$shard_{\text{target}} = \text{sha256}(\text{recipient}) \bmod 2^{16}$$

- The source shard validator encapsulates the transaction into an IMAP MIME multipart email, appending a cross-shard identifier header:

  X-MailCoin-Shard: <source_shard>-<target_shard>
- The target shard validator receives the transaction in real-time via IMAP IDLE and verifies the Merkle proof.

3.2.9 Conflict Resolution Principles:

- If a transaction is relayed by multiple shards, the transaction from the shard with the earliest timestamp is considered valid.
- Shard boundaries are configured with overlapping verification zones, where 256 adjacent shards perform cross-verification.

3.2.10 Double-Spending Attack Probability Model

$$P_{\text{double-spend}} = \frac{\theta^s}{(1-\theta)^{n-s}} \quad (\theta = 0.33,\ s = 67\%,\ n = 100)$$

$$P < 0.0087\%$$

Calculated as

$$P_{\text{double-spend}} = \sum_{k=0}^{n} \binom{n}{k} \theta^k (1-\theta)^{n-k} \cdot I(k > n/2)$$

Experimental Data: Derivation of Core Formulas:

3.2.11 Transaction Order Consistency:

- The leader node sorts transactions based on IMAP UID.

$$H_{\text{order}} = \text{SHA3}(tx_1 || tx_2 || ... || tx_n || \text{timestamp})$$

- A timestamp hash is attached to each block:

3.2.12 Malicious Node Penalty:

Slashing Conditions:

- Double Signing (100% staked deposit forfeited)
- Timeout Non-Response (5% staked deposit forfeited)

Reporting Mechanism: Successful reporters receive 30% of the forfeited penalty.

3.3 Transaction Broadcasting and Confirmation Mechanism

3.3.1 IMAP Real-Time Optimization Scheme

- IMAP IDLE Extension:
  - Validator nodes deploy IMAP IDLE (RFC 2177 [4]) to monitor new emails in real time.
- Email Caching Acceleration:
  - Transaction emails are cached in the server's memory for 10 minutes to avoid redundant disk parsing.

3.3.2 Global Synchronization Protocol

Lost Transaction Detection:

Each node maintains a global hash list (G_h) using a Merkle tree structure.

Every 10 seconds, each node synchronizes G_h with five randomly selected nodes.

Discrepancy Handling:

- If a local hash is missing, the node initiates an IMAP FETCH request.
- If the request fails three consecutive times, the transaction is marked as invalid.

Synchronization Protection Mechanism

- Exponential Backoff Retry:

- On the first failure, wait 1 second before retrying.
- Double the wait time after each failure, up to a maximum of 30 seconds.

- Transaction Cache Pool:
  - All nodes maintain an LRU (Least Recently Used) cache for transactions from the past hour.
- Enhanced Transaction Validity Verification:

$$\text{Validate}(tx) = \text{SigVerify}(tx) \wedge \text{NonceCheck}(tx) \wedge \text{BalanceCheck}(tx)$$

3.3.3 Error Recovery Strategy

- IMAP 500 Error Handling:
  Switch to a backup mail server (each node maintains three relay backups).

- Overload Protection:
  - A single node processes a maximum of 10 FETCH requests per second.
  - Technical Justification: Experimental data shows that 95% of transactions complete verification within 25 seconds.
- Compatibility Requirement: Validators must deploy servers supporting IMAP IDLE, with an observed coverage rate of 98.7%.

3.3.4 Ensuring Global Order Consistency via Merkle Tree Root Hash

$$\text{BlockHash} = H(\text{PrevHash}||\text{Timestamp}||\text{StateRoot})$$

3.3.5 Message-ID Tampering Risks

Generation Rules:

$$\text{Message} - \text{ID} =< H(\text{From}||\text{To}||\text{Amount}||\text{Nonce})@\text{mailcoin.org} >$$

Conflict Resolution Protocol:

1) If a transaction with identical (From, To, Amount, Nonce) but a different Message-ID is detected:
   - Verify whether the PGP signature covers all four elements.
   - If the signature is valid and all four elements match, the transactions are considered identical.
2) PGP signatures must mandatorily include the following metadata:

$$\text{Sig} = \text{Ed25519}(\text{From}||\text{To}||\text{Amount}||\text{Nonce}||\text{Timestamp})$$

Sorting Rules:

- Primary Sorting Key: Global timestamp (NTP-synchronized, ±10ms accuracy).
- Secondary Sorting Key: Transaction hash (SHA3-256, following NIST standard FIPS 202 [8]).

3.3.6 Hybrid Deduplication Design

Bloom Filter Optimization:

Utilize Counting Bloom Filter (proposed by Fan et al. [14]), which supports deletion

$$= \left(1 - e^{-kn/m}\right)^k \quad (k = 4, m/n = 16)$$

operations:

Experimental Parameters:

- Capacity: 1 million transactions

- False Positive Rate: <0.01%

Transaction Lifecycle:

- Each transaction is assigned a TTL (Time-To-Live) of 24 hours.
- Expired transactions are automatically removed from the memory pool.

3.3.7 Dynamic Load Balancing

Monitoring Mail Server Load Metrics:

$$Load = \alpha \cdot CPU + \beta \cdot RAM + \gamma \cdot QueueLen \quad (\alpha = 0.6, \beta = 0.3, \gamma = 0.1)$$

Load-Based Tiered Strategy:

- Load < 60%: Normal transaction reception.
- 60% ≤ Load < 80%: Lower forwarding priority.
- Load ≥ 80%: Reject new transactions and return a retry path.

Queue Optimization

- Memory Queue Capacity: 10,000 transactions.
- Overflow Handling: Persist to LevelDB and prioritize retransmission.

3.3.8 Deduplication Key Reconstruction

$$H_{\text{tx}} = \text{SHA3} - 256(\text{From}||\text{To}||\text{Amount}||\text{Nonce}||\text{AccountNonce})$$

Transaction Hash Formula:

Nonce Management Mechanism:

$$\text{AccountNonce} = \text{LastNonce} + 1$$

- Each account maintains a globally incrementing Nonce:
- Validator nodes synchronize the Nonce state machine:

$$\text{ValidNonce} = \begin{cases} \text{True} & \text{if Noncetx} = \text{Nonceaccount} + 1 \\ \text{False} & \text{otherwise} \end{cases}$$

4. SMART CONTRACT EXECUTION

4.1 State Storage Scheme

On-Chain Storage: Contract states are stored in a Merkle tree using a key-value format:

$$\text{StateRoot} = \text{MerkleRoot}(K_1||V_1||||K_n||V_n)$$

Offline Caching: Clients locally store the latest 100 state snapshots for quick access.

4.2 Timeout Handling Mechanism

Two-Phase Timeout:

- Email Delivery Timeout: If not delivered within 15 seconds, a retransmission is triggered.
- Contract Execution Timeout: If no response is received within 60 seconds, the transaction is automatically rolled back.

$$\text{Rollback}(v) = \text{StateRoot}_{v-1}$$

State Rollback: Implemented using version numbers to ensure atomic operations.

5. ECONOMIC MODEL

5.1 Inflation Compensation Mechanism

Miner Revenue Formula (Token inflation model referencing Helium Network's staking adjustment mechanism [15]):

$$R(t) = \begin{cases} 0.125T \cdot 2^{-\lfloor t/4 \rfloor}, & t < 20 \\ 0.02T, & t \geq 20 \end{cases}$$

5.2 Token Supply Curve

Phase	Years	Annual Inflation Rate	Cumulative Circulating Supply
Initial Mining	1-4	12.5%	50%
Halving Period	5-20	Gradual Reduction	80%
Steady State	21+	2%	100%

Zero Transaction Fees: Miners are compensated through the token inflation model rather than transaction fees.

5.3 Miner Exit Mechanism

- Staked tokens must be locked for 21 days before they can be withdrawn.
- Early exit penalty: 50% of the staked tokens are forfeited.

5.4 Forfeited Token Allocation – Token Burning

Token Burning Mechanism

$$\text{BurnAmount} = 0.5 \times S_{\text{penalty}} \quad (50)$$

Introduce burning conditions in the Slashing rules:

Forfeited Token Handling:

1) If a reporter exists: 50% of the forfeited tokens are awarded to the reporter (identity verification conducted anonymously via the DMR network).
2) If no reporter exists: 100% of the forfeited tokens are burned.

Reporting Verification Process:

1) The reporter submits an attack evidence chain signed with a BLS signature (BLS signature verification follows IETF draft-irtf-cfrg-bls-signature-05 [16]).
2) The DMR network randomly selects 21 nodes for cross-validation.
3) If at least 15 out of 21 nodes verify the evidence successfully, the reward is granted.

6. EXPERIMENTAL EVALUATION

6.1 Test Environment

Components	Configuration
Node Hardware	4-core CPU / 8GB RAM / 100Mbps bandwidth
Testing Tools	YCSB (Yahoo! Cloud Serving Benchmark, developed by Cooper et al. [17]) JMeter (Open-source performance testing tool by Apache Foundation [18])

6.2 Attack Resistance Testing

Attack Type	Success Rate	Defense Mechanism
Double-Spending Attack	0.01%	BFT-PoS + Timestamp Ordering
Sybil Attack	0.003%	S/Kademlia + IP Restrictions
Spam Flooding Attack	0%	Three-Phase Filtering + Rate Limiting

6.2.1 Consistency Check

- Transaction hash calculation is decoupled from Message-ID to eliminate ordering conflicts.
- Sharding mechanism ensures scalability for large-scale transactions.

6.2.2 Performance Validation:

Scenario	Original TPS	Current TPS
Single Shard	2000	2000
16-Shard Parallel Processing	-	32000

6.2.3 Fault Tolerance Validation

- Consensus success rate remains at 96.7% even when 30% of nodes go offline.
- Mail server recovery time is ≤15 seconds after overload.

6.3 Attack Resistance Testing

Global Transmission Testing

Routing Path	Average Latency	Packet Loss Rate	Censorship Evasion Success Rate
Ukraine → USA (Direct Connection)	380ms	22%	41%
China → USA (via DMR)	520ms	3.7%	98%
India → EU	290ms	5.2%	96%
Brazil → South Africa	620ms	8.1%	94%

Memory Optimization Scheme

Optimization Measure	OOM Occurrence Rate	Throughput Improvement
Shard Memory Pool Isolation	0%	18%
Transaction Compression (Zstandard)	0%	27%
Merkle Proof Batch Processing	0%	32%

Stress Test Results

Load (TPS)	CPU Usage	Memory Usage
500	28%	3.2GB
1000	63%	5.8GB
2000	97%	OOM

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