Blockchain for Secure Distributed Logging in Multi-Tenant Systems

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Abstract

As cloud computing services expand, multi-tenant systems face growing challenges in ensuring the integrity and auditability of distributed logs. Traditional logging mechanisms are susceptible to tampering, especially in shared environments where access is often decentralized. This paper investigates the feasibility of using blockchain technology to create tamper-proof, distributed logging systems. We design a lightweight logging framework based on Ethereum's private blockchain, where log entries are hashed and stored as transactions, preserving both order and immutability. Performance benchmarks are conducted on simulated multi-tenant cloud environments using Docker containers and virtual machines. Results indicate that while blockchain introduces latency overhead (averaging 200–300 ms per write), it significantly enhances log integrity and traceability. In cases of internal misconfigurations or external attacks, the system was able to accurately detect log alterations through hash verification and block comparison. Moreover, we examine the scalability of the solution using varying block sizes and consensus intervals. Though not ideal for high-frequency logging, the approach is suitable for sensitive applications such as financial systems, healthcare auditing, and critical infrastructure monitoring. This paper contributes to the emerging field of blockchain applications beyond cryptocurrency and offers a novel solution for secure, verifiable logging in multi-tenant architectures.

1. Introduction

Log data plays a crucial role in cloud infrastructure monitoring, auditing, compliance, and incident response. In multi-tenant environments—where multiple clients share computing resources—log integrity is critical for enforcing accountability and ensuring trustworthy post-event analysis. However, traditional logging mechanisms rely on centralized or semi-centralized servers, which are vulnerable to unauthorized modification by internal actors or attackers who gain privileged access. Even with techniques like syslog over TLS or hash-chaining, centralized control limits tamper detection in adversarial or misconfigured systems.

Blockchain, a distributed and cryptographically secure ledger, presents a promising approach to address these challenges. By storing log hashes as immutable transactions on a blockchain, organizations can establish a verifiable and auditable history of log events, resistant to tampering and unauthorized changes. Although most blockchain applications have focused on digital currencies and smart contracts, its core features—immutability, consensus, and transparency—make it an appealing foundation for secure log management.

This paper explores the use of a private Ethereum blockchain to implement a tamper-evident logging framework in multi-tenant systems. We present the design, implementation, and evaluation of a prototype system deployed across containerized and virtualized tenants. Our contributions include (1) a lightweight blockchain-based logging model, (2) performance and scalability benchmarks under realistic workloads, and (3) analysis of security trade-offs and use-case suitability. We demonstrate that blockchain logging is a viable solution for security-critical domains that require strong guarantees of data integrity and traceability.

2. Problem Definition

The core problem addressed in this study is the **lack of trustworthy, tamper-proof logging mechanisms** in multi-tenant cloud environments. Specifically:

1. **Centralized log storage** is a single point of failure and a target for tampering—either by attackers or insiders with elevated privileges.
2. **Traditional log file formats** can be overwritten or deleted without easy detection, especially in containers or VMs that reset or rotate logs frequently.
3. **Cross-tenant contamination risks** arise when multiple clients generate logs within the same infrastructure, increasing complexity in isolation and audit assurance.
4. **Existing integrity solutions** (e.g., hash chaining or remote syslog servers) depend on trusted intermediaries or assume infrastructure neutrality, which is not always guaranteed in shared environments.

Thus, there is a need for a decentralized, verifiable, and cryptographically sound logging mechanism that provides:

- **Tamper resistance**: Logs cannot be altered without detection.
- **Ordered record keeping**: Events are preserved in temporal sequence.
- **Cross-platform applicability**: Compatible with both containers and virtual machines.
- **Tenant isolation**: Each tenant's log stream must be independently verifiable.

This research proposes a blockchain-based architecture to meet these requirements.

3. Design Objectives

The design of our logging framework was guided by the following key objectives:

3.1 Tamper-Evidence and Integrity

The system must ensure that once a log entry is created, it cannot be modified or deleted without detection. This includes protection against retroactive alterations and insertion of falsified records.

3.2 Multi-Tenant Compatibility

The solution must support distributed tenants deployed in both containerized and VM-based environments, enabling isolated log streams while using a shared ledger for validation.

3.3 Lightweight Deployment

As blockchain operations can be resource-intensive, the framework should minimize computational and storage overhead, especially on tenant nodes with limited capacity.

3.4 Ordered Append-Only Storage

The logging mechanism must preserve event ordering and support append-only behavior to maintain chronological integrity of audit trails.

3.5 Decentralized Verification

The system should enable any authorized tenant or auditor to independently verify log integrity without relying on a central authority.

3.6 Configurable Consensus and Block Size

The framework must allow tuning of block size, consensus interval, and node participation to balance latency and throughput for different application needs.

These objectives formed the basis for the architectural and implementation decisions detailed in the following sections.

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4. System Architecture / Design Process

The logging system is built on a **private Ethereum blockchain** network comprising multiple nodes corresponding to cloud tenants. Each tenant runs a lightweight logging agent that forwards hashed log entries to a shared blockchain node. The architecture consists of the following components:

4.1 Logging Agent

- Installed within each tenant's container or VM
- Intercepts log messages from system daemons or application sources
- Generates a SHA-256 hash for each log entry with timestamp and tenant ID
- Submits the hash to the local Ethereum node via JSON-RPC API

4.2 Ethereum Blockchain Node

- Maintains a local copy of the blockchain
- Groups incoming log hashes into transactions and appends them to blocks
- Executes a simplified **Proof-of-Authority (PoA)** consensus mechanism to reduce overhead

4.3 Smart Contract (Optional)

- Can be deployed to record structured log metadata (e.g., event type, origin)
- Facilitates selective querying and tenant-specific auditing

4.4 Auditor Interface

- External verification tool that reconstructs and compares tenant logs with blockchain hashes
- Flags discrepancies, missing entries, or malformed data

The system operates under the assumption that tenants can be semi-trusted (e.g., each tenant trusts their own agent) but that no central authority can be implicitly trusted to preserve log integrity without independent verification.

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5. Implementation

The prototype system was implemented using the following technology stack:

- **Ethereum (geth v1.7.3)**: Deployed in a private network using Proof-of-Authority (PoA) consensus with three validator nodes.

- **Node.js Logging Agent**: A lightweight daemon that monitors log files or journald streams, computes SHA-256 hashes, and submits them via Ethereum's JSON-RPC.
- **Docker and VirtualBox**: Used to simulate tenant environments (12 Docker containers and 4 VMs, each with separate logging streams).
- **Smart Contract (Solidity)**: Deployed optionally to store metadata alongside log hashes, supporting structured queries and access control by tenant ID.
- **Monitoring Stack**: Prometheus and Grafana were used to track system metrics, including write latency, block confirmation time, and memory usage.

Log entries followed a standardized JSON format:

json

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```
{
  "timestamp": "2017-04-18T12:34:56Z",
  "tenant_id": "tenant_alpha",
  "log_type": "auth",
  "hash": "0x845f...a37b"
}
```

Each entry was hashed using SHA-256 locally before transmission. A batch of log hashes (up to 64 per block) was submitted every 5 seconds to reduce transaction overhead.

To ensure low-latency transaction processing, the gas limit per block was raised to accommodate log density, and block propagation was optimized using WebSocket communication between peer nodes.

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6. Testing and Evaluation

Testing was conducted in three phases:

6.1 Functional Validation

- Tenants generated synthetic logs with varying frequencies (10–500 logs/sec).
- Logging agents were stress-tested for hash collision handling, connection drops, and malformed log rejection.
- Blockchain nodes were tested for fork resolution and smart contract invocation.

6.2 Performance Benchmarking

Benchmarks were run on a hybrid cluster with:

- 4 vCPUs per node
- 8 GB RAM
- SSD-backed storage
- 1 Gbps LAN interconnect

Key metrics:

- **Write Latency**: Time from log generation to transaction confirmation on-chain.
- **Throughput**: Logs processed per second per tenant.
- **Block Confirmation Time**: Time from block creation to consensus finality.

Test scenarios included:

- Varying tenant loads (1 to 16)
- Block sizes (32, 64, 128 log hashes per block)
- Block intervals (2s, 5s, 10s)

6.3 Security Testing

Simulated attacks included:

- **Log tampering**: Manual modification of local log entries followed by hash mismatch detection.
- **Replay attack**: Resubmission of identical log entries—successfully flagged by timestamp-based duplication filters.
- **Key compromise**: Simulated Ethereum node corruption—resolved via key rotation and validator election.

Audit scripts independently verified log chains using the smart contract log index and compared them to tenant-exported logs.

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7. Results

7.1 Performance

Block Size	Avg Write Latency (ms)	Max Throughput (logs/sec)
32	187	285
64	241	325
128	297	352

- **Latency increased with block size**, but throughput improved due to reduced block propagation overhead.
- The sweet spot for most tenants was **64-log blocks at 5-second intervals**, balancing efficiency and responsiveness.

7.2 Security Outcomes

- **Tamper detection accuracy**: 100% for injected or modified logs.
- **Audit trace completeness**: 98.7%, with minor losses due to log agent restarts.
- **Consensus finality**: Consistently achieved within 3.4 seconds (PoA mode).

The system proved robust under normal and adversarial conditions. All unauthorized modifications were detected via hash mismatch or audit index inconsistency.

7.3 Resource Utilization

- Average blockchain node memory usage: ~300 MB
- Average CPU usage: 22% under peak log rates
- Logging agent CPU overhead: <5% per container

The system remained lightweight and feasible for deployment on standard cloud VMs.

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8. Conclusion

This study demonstrates the feasibility and effectiveness of using blockchain to enhance distributed logging integrity in multi-tenant cloud systems. By leveraging Ethereum's private blockchain, the proposed system enables tamper-evident, append-only log storage that supports independent auditing and resilient operation.

Despite a moderate latency overhead (averaging 200–300 ms), the framework is well-suited to environments where auditability and trust are paramount—such as financial transactions, healthcare systems, and regulated infrastructure. While it may not replace traditional high-throughput logging systems, it offers a complementary solution for **selective, security-critical logging**.

Key contributions include:

- A modular architecture compatible with containers and VMs
- A tunable PoA consensus model for performance-efficiency trade-offs
- Automated audit tooling for post-factum log validation

Future work could explore integration with **inter-tenant blockchain partitioning**, **Merkle tree compression**, and **zero-knowledge proof extensions** to protect log content confidentiality while preserving verifiability.

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9. References

1. Wood, G. (2014). Ethereum: A secure decentralized generalized transaction ledger. *Ethereum Project Yellow Paper*, 1–32.
2. Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. *https://bitcoin.org/bitcoin.pdf*
3. Cachin, C., & Vukolić, M. (2017). Blockchain consensus protocols in the wild. *arXiv preprint arXiv:1707.01873*.
4. Jena, J. (2015). Next-Gen Firewalls Enhancing: Protection against Modern Cyber Threats. International Journal of Multidisciplinary and Scientific Energing Research, 3(4), 2015-2019. https://ijmserh.com/admin/pdf/2015/10/46_Next.pdf
5. Szilagyi, P. (2017). Geth: Ethereum Go Client. *Ethereum Foundation*. https://geth.ethereum.org
6. Buterin, V. (2015). On public and private blockchains. *Ethereum Blog*. https://blog.ethereum.org

7. Goli, V. R. (2015). The impact of AngularJS and React on the evolution of frontend development. International Journal of Advanced Research in Engineering and Technology, 6(6), 44–53. https://doi.org/10.34218/IJARET_06_06_008
8. Christidis, K., & Devetsikiotis, M. (2016). Blockchains and smart contracts for the Internet of Things. *IEEE Access*, *4*, 2292–2303.
9. Xu, X., Weber, I., & Staples, M. (2017). *Architecture for Blockchain Applications*. Springer.
10. Zyskind, G., Nathan, O., & Pentland, A. (2015). Decentralizing privacy: Using blockchain to protect personal data. *2015 IEEE Security and Privacy Workshops*, 180–184.
11. Liu, Q., & Wang, C. (2016). A blockchain-based privacy-preserving data sharing system for cloud. *2016 International Conference on Big Data and Smart Computing (BigComp)*, 591–596.
12. Yue, X., Wang, H., Jin, D., Li, M., & Jiang, W. (2016). Healthcare data gateways: Found healthcare intelligence on blockchain with novel privacy risk control. *Journal of Medical Systems*, *40*(10), 218.
13. Deuber, D., Magri, B., & Thyagarajan, S. (2016). Redactable blockchain in the permissioned setting. *arXiv preprint arXiv:1610.09575*.
14. IBM. (2017). *IBM Blockchain: Enterprise-ready blockchain for business*. Retrieved from https://www.ibm.com/blockchain/
15. Docker Inc. (2017). Docker Engine Documentation. https://docs.docker.com
16. HashiCorp. (2017). Vault: Identity-Based Access and Key Management. https://www.vaultproject.io
17. Go Ethereum Team. (2017). Proof-of-Authority Consensus Model. https://github.com/ethereum/go-ethereum/wiki/Proof-of-Authority-(PoA)