Hybrid Blockchain Database Systems: Design and Performance (Detailed Explanation)

1. Introduction and Purpose

Hybrid blockchain database systems represent an effort to merge the high performance of distributed databases with the strong security and immutability of blockchain technology. Traditional databases are fast, scalable, and efficient but rely on central authorities, which introduces the risk of tampering. In contrast, blockchains are decentralized and tamper-resistant but suffer from high latency and low throughput due to the overhead of consensus mechanisms. The purpose of this study is to analyze and compare different hybrid systems that attempt to combine the advantages of both technologies.

The researchers implemented two systems, **Veritas** and **BlockchainDB**, from scratch and compared them with an open-source hybrid called **BigchainDB**. Their goal was to measure how design choices—such as consensus algorithms, database engines, and replication strategies—impact system performance.

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2. Overview of the Systems Studied

The paper examines three main systems:

2.1 Veritas

Veritas integrates blockchain verification mechanisms into a distributed database system. It is designed to provide verifiable, tamper-proof data while maintaining high throughput.

There are two versions:

- **Veritas (Kafka)** – Uses **Apache Kafka**, which is crash fault-tolerant (CFT). It assumes that nodes may fail but are not malicious. Kafka provides fast broadcast messaging for synchronization, making this version suitable for trusted environments.

- **Veritas (Tendermint)** – Uses **Tendermint**, a Byzantine fault-tolerant (BFT) consensus protocol that tolerates up to one-third malicious nodes. This model is slower but more secure, making it suitable for untrusted or public environments.

How it works:
Each node in Veritas has two key parts:

1. A **shared database** (implemented in Redis) that stores the actual data.

2. A **ledger** that records all transactions in the form of cryptographic logs using a **Sparse Merkle Tree** structure.

When a transaction (like an update) occurs:

- The node executes the transaction locally and sends the update log to other nodes through Kafka or Tendermint.

- Other nodes validate and acknowledge the update.

- Once confirmed, the transaction is committed to the shared ledger, ensuring verifiability.

Advantages: High performance, scalable for trusted networks.
Drawbacks: Performance depends on network communication; limited Byzantine protection in Kafka mode.

2.2 BlockchainDB

BlockchainDB takes the opposite approach: instead of adding blockchain features to a database, it builds a **database on top of an existing blockchain**. It uses **Ethereum** as the storage and consensus layer and implements a simple **key-value store API** for interaction.

Architecture:

- Data is stored in Ethereum blocks using a **Proof of Authority (PoA)** consensus.

- The database layer adds indexing, read/write logic, and verification capabilities.

- The system also supports **sharding**, splitting data across multiple nodes to improve scalability.

Operations supported:

- `Set(key, value)` – Adds data to the blockchain.

- `Get(key)` – Retrieves stored data.

- `Verify()` – Checks the status of a transaction or verifies integrity.

Advantages: Strong immutability and decentralized storage.
Drawbacks: Limited throughput (below 100 TPS), high latency, and heavy reliance on Ethereum's slow consensus and gas limits.

2.3 BigchainDB

BigchainDB starts from a database and adds blockchain characteristics such as consensus and immutability.

Components:

- **MongoDB** – Used for storage and querying.
- **Tendermint** – Used for consensus among nodes.
- **Server Layer** – Handles client transactions via HTTP APIs.

Optimizations:

1. **Blockchain Pipelining:** Allows new blocks to be proposed before the current one is finalized, reducing idle time and improving throughput.
2. **Parallel Validation:** Validates multiple transactions simultaneously on different CPU cores.

Advantages: Provides database-like query features while ensuring data integrity.
Drawbacks: Complex validation leads to redundant checks and slower performance.

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3. Experimental Design

3.1 Hardware Setup

- Machine: Ubuntu 18.04 with **256 CPU cores, 8 TB RAM, 3 TB HDD**.
- Each system was containerized using Docker.

3.2 Dataset and Workloads

They used the **Yahoo Cloud Serving Benchmark (YCSB)**—a standard synthetic benchmark—to simulate realistic database operations:

- 100,000 key-value pairs, each 1 KB in size.
- Tested three workloads:
    - **Workload A:** 50% reads, 50% writes.
    - **Workload B:** 95% reads, 5% writes.
    - **Workload C:** 100% reads.
- Data access patterns: uniform, latest, and zipfian distributions.

3.3 Metrics Measured

- **Throughput (TPS):** Number of successful transactions per second.
- **Latency:** Average time taken to confirm a transaction.
- **Scalability:** Performance as the number of nodes increases.
- **Storage Overhead:** How much extra space is used by consensus metadata and cryptographic structures.

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4. Experimental Results

4.1 Throughput and Latency

System	Consensus	TPS	Latency
Veritas (Kafka)	CFT (Kafka)	~27,000–65,000	<1 sec
Veritas (Tendermint)	BFT (Tendermint)	~1,700	~1–2 sec
BigchainDB	BFT (Tendermint)	~175	~400 ms
BigchainDB (PV)	BFT (Tendermint)	~175	~400 ms
BlockchainDB	BFT (Ethereum PoA)	<100	~4 sec

Observations:

- Veritas (Kafka) far outperformed all others, achieving the highest throughput and lowest latency.
- BFT systems were 10–500× slower because of heavy message exchange during consensus.
- BlockchainDB's performance was limited by Ethereum's gas and transaction constraints.

4.2 Scalability

- **Veritas (Kafka)** scaled efficiently up to 32 nodes (≈41,000 TPS). Beyond that, network overhead in Kafka became a bottleneck.
- **Veritas (Tendermint)** throughput dropped drastically as node count increased because Tendermint's complexity grows cubically with node count ($O(N^3)$).
- **BigchainDB** and **BlockchainDB** did not scale well due to redundant validation and Ethereum's inherent limits.

4.3 Storage and Block Size Effects

- Larger block sizes increased throughput because more transactions were processed per consensus round but also increased latency.
- BlockchainDB consumed significantly more storage because every transaction was stored with complete metadata and hashes.
- Veritas' use of a Sparse Merkle Tree helped compress verification data efficiently while maintaining integrity.

4.4 Network Conditions

They simulated real-world network latency and bandwidth constraints:

- Reducing bandwidth (from 10 Gbps to 100 Mbps) and increasing latency (up to 60 ms) degraded performance significantly for BFT systems like Tendermint.

- Veritas (Kafka) remained stable even under weaker network conditions, proving more suitable for enterprise deployments.

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5. Discussion of Trade-offs

The authors identified several key trade-offs:

CFT vs BFT Consensus

- **CFT (Kafka):** Extremely fast but assumes trusted participants.
- **BFT (Tendermint/Ethereum):** Secure against malicious nodes but slower and resource-heavy.

SQL vs NoSQL Databases

- SQL (e.g., MySQL, PostgreSQL) ensures structured data integrity but adds parsing overhead.
- NoSQL (e.g., Redis, MongoDB) offers flexibility and faster performance but lacks strong schema enforcement.

Block Size vs Latency

- Bigger blocks improve throughput but delay confirmation for individual transactions.

Performance vs Security

- A trade-off exists between raw speed and fault tolerance. CFT designs like Veritas (Kafka) deliver higher performance for trusted environments, while BFT systems prioritize reliability for untrusted networks.

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6. Key Insights and Applications

1. **Consensus dominates performance:** Most delays come from how nodes agree, not from database storage or computation.

2. **Veritas (Kafka)** achieves performance comparable to traditional databases, making it ideal for enterprise or consortium setups (e.g., universities, banks).

3. **BFT systems** are necessary for public or adversarial environments but require optimization to scale effectively.

4. **Hybrid architectures**—with a fast database layer and verifiable ledger—can provide tamper-evidence without sacrificing speed.

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7. Conclusion

This study demonstrates that hybrid blockchain database systems can achieve a balance between **security and performance** by carefully selecting consensus protocols and storage models. Systems like Veritas (Kafka) show that it is possible to reach tens of thousands of transactions per second while still providing cryptographic proof of integrity. The major bottleneck remains the consensus protocol, not the database engine itself.

For practical applications such as **academic transcript verification, digital identity systems, or inter-organizational data sharing**, hybrid systems like Veritas (Kafka) offer a realistic path forward—providing trust and verifiability at near-database speed.

Perspective: Relevance of Hybrid Blockchain Database Systems to the Academic Transcript Integrity Problem

1. Alignment with the Research Problem

Our problem statement focuses on ensuring the **integrity and verifiability of academic transcripts** using blockchain technology. The paper *Hybrid Blockchain Database Systems: Design and Performance* directly supports this objective by demonstrating how blockchain can be effectively combined with database systems to deliver both **security** and **performance**.

In academic record systems, universities already use distributed databases to manage student records. However, these systems depend on centralized administrators, creating vulnerabilities in data authenticity. Blockchain offers tamper-proof guarantees but struggles with scalability and transaction speed. The hybrid models presented in the paper bridge this gap by fusing blockchain's immutability with database-level performance, which is precisely what your system aims to achieve.

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2. Technical Perspective

From a technical standpoint, the paper demonstrates how hybrid systems can be optimized for your context.

a. Consensus Mechanism Relevance

- The research compares **Crash Fault-Tolerant (CFT)** and **Byzantine Fault-Tolerant (BFT)** designs.
- For a permissioned university consortium (where all nodes are trusted universities), a **CFT-based consensus (like Apache Kafka)** is ideal. It offers **10–500× higher throughput** than BFT while still providing data verification.
- This means our prototype can adopt a Kafka-like model for performance while retaining blockchain-level traceability.

b. Database Choice

- The paper shows that **NoSQL databases** such as MongoDB or Redis integrate efficiently with blockchain systems.
- Since we plan to use databases for student and transcript storage, this validates your choice — enabling **faster access, flexible data structures**, and easy linkage with blockchain logs.

c. Performance Expectations

- Veritas (Kafka) achieved **27,000–65,000 TPS** with sub-second latency, while BFT-based systems dropped below **2,000 TPS**.
- Academic transcript systems don't require massive throughput; what they need is **accuracy, reliability, and tamper detection**. This performance range confirms that a hybrid setup will easily handle real-world university workloads.

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3. Strategic and Research Implications

The findings guide how you should design and justify your system:

Aspect	Insight from Paper	Application to our Project
Architecture	Layered hybrid model (database + blockchain)	Store transcripts in DB; hash them on blockchain for verification.
Consensus Type	CFT for trusted networks; BFT for public ones	Use CFT (Kafka/Raft) for internal university systems.
Storage	NoSQL or SQL possible; consensus is the bottleneck	Focus optimization on consensus and synchronization.
Security vs. Performance	Higher performance in trusted setups	Universities are trusted parties; prioritize speed with sufficient auditability.
Scalability	Scales up to 32 nodes efficiently in Veritas	Multiple universities or departments can join without major redesign.

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4. Contribution to Your Problem Statement

This study enhances your project by:

1. **Providing a validated architectural model** for implementing blockchain-based verification without replacing existing databases.

2. **Clarifying the right consensus approach** (CFT) for a trusted academic environment, ensuring system practicality.

3. **Offering performance benchmarks** that show your hybrid transcript system can achieve both speed and integrity.

4. **Demonstrating real-world feasibility** — hybrid systems like Veritas and BigchainDB already implement what you propose in a more general context.

In essence, the paper transforms your problem from a conceptual idea into an **evidence-backed design direction**. It justifies that blockchain, when integrated with a distributed database, can protect transcript data from tampering while maintaining efficiency for day-to-day academic operations.
