# Frequency-Aware Skewed Merkle Trees for Blockchain Optimization: Performance Benefits and Fundamental Limitations

A Comprehensive Study

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**Abstract**

This study presents a comprehensive analysis of frequency-aware skewed Merkle tree structures as a potential optimization for blockchain systems. We investigate the application of skewed tree architectures that exploit transaction frequency patterns to improve performance in blockchain networks. Through systematic analysis of 21 research papers spanning dynamic integrity trees, traditional Merkle tree optimizations, sparse data structures, and blockchain implementations, we identify significant performance benefits (up to 30% improvement) alongside critical fundamental limitations. Our key finding demonstrates that while frequency-based skewed structures provide substantial performance gains, they violate core blockchain requirements including state reversibility, order independence (commutativity), and deterministic consensus properties. This study establishes the theoretical boundaries for frequency-based optimizations in distributed consensus systems.

**Keywords:** Blockchain, Merkle Trees, Performance Optimization, Distributed Systems, Consensus Protocols, Frequency Analysis

## 1 Introduction

Blockchain technology has revolutionized distributed computing by providing decentralized consensus mechanisms without requiring trusted intermediaries [1]. At the core of most blockchain implementations lie Merkle trees [2], which provide efficient cryptographic verification of large data structures while enabling lightweight client operations through compact proofs.

However, current Merkle tree implementations in blockchain systems face significant performance challenges. As documented in our research logs, the primary bottleneck stems from the database access pattern where "hash values are stored as keys in the database," resulting in O(log n $\times$ log n) time complexity instead of the theoretical O(log n) for tree traversal operations. This inefficiency becomes particularly problematic as blockchain networks scale to handle millions of transactions.

An intriguing observation in blockchain systems is the highly skewed nature of transaction patterns. Similar to other distributed systems, blockchain networks exhibit access patterns resembling a 1/x function, where a small percentage of accounts generate the majority of transactions [3]. This natural frequency distribution suggests potential for optimization through frequency-aware data structures.

This study investigates the feasibility of applying frequency-aware skewed Merkle tree structures to optimize blockchain performance. We systematically analyze existing research on dynamic skewed integrity trees [3], frequency-aware structures for embedded systems [4], memory-efficient adaptive algorithms [5], and traditional Merkle tree optimizations [7].

Our research reveals a fundamental trade-off between performance optimization and correctness requirements in distributed consensus systems. While skewed structures demonstrate significant performance improvements, they introduce critical limitations that render them unsuitable for blockchain applications requiring state reversibility, order independence, and deterministic consensus properties.

## 2 Related Work

### 2.1 Dynamic Skewed Integrity Trees

Vig et al. [3] proposed dynamic skewed integrity trees for memory authentication in embedded systems. Their approach dynamically restructures tree nodes based on runtime access patterns, positioning frequently accessed memory blocks closer to the root. The system achieved an average performance improvement of 30% compared to balanced trees through adaptive migration and rebalancing operations similar to adaptive Huffman coding.

The key innovation involves grouping data elements with identical access frequencies into single nodes, dramatically reducing the number of tree nodes from O(n) symbols to O(frequency_classes). This approach uses set migration operations to move symbols between frequency classes and rebalancing algorithms to maintain tree efficiency.

### 2.2 Frequency-Aware Skewed Merkle Trees

Zou and Lin [4] developed FAST (Frequency-Aware Skewed Merkle Tree) for embedded systems. Their approach profiles application memory access patterns during a simulation phase, then generates application-specific optimal skewed Merkle trees using Huffman encoding principles. While their work focused on embedded systems with hardware acceleration, the fundamental concepts are hardware-agnostic and relevant to blockchain systems where performance optimization is crucial.

FAST achieved up to 3× performance improvement over balanced Merkle trees by configuring the branching factor k to provide a tunable trade-off between computational complexity and bandwidth efficiency. The system weights read operations (weight=1) and write operations (weight=5) to optimize for the higher cost of chained update operations in Merkle trees.

### 2.3 Memory-Efficient Adaptive Huffman Coding

Pigeon and Bengio [5] introduced memory-efficient adaptive Huffman coding algorithms for large symbol alphabets. Their Algorithm M uses set-based nodes containing symbols with identical frequencies, reducing memory requirements from O(n) individual symbols to O(frequency_classes).

The algorithm maintains entropy bounds of [H(S), H(S)+2) and demonstrates particular effectiveness for large alphabets (millions vs. hundreds of symbols). Key operations include set migration when symbols change frequency classes and rebalancing using shift-up procedures adapted from AVL tree algorithms.

### 2.4 Traditional Merkle Tree Optimizations

Buchmann et al. [7] proposed improved algorithms for Merkle tree traversal in signature schemes. Their approach balances the number of leaves computed in each authentication path computation rather than balancing the total number of nodes, since leaf computation requires significantly more hash function evaluations than inner nodes.

Other optimization approaches include fractal Merkle tree traversal [8], which splits trees into smaller subtrees with stacked series for multiple authentication paths, and caching strategies that store frequently accessed nodes in memory [17].

### 2.5 Alternative Data Structures

**Sparse Merkle Trees**: Dahlberg et al. [10] develop efficient sparse Merkle trees supporting $2^N$ possible keys with constant-size proofs for membership and non-membership verification. With strategic caching and memory management, they report sub-4 ms proof generation.
**Verkle Trees**: Kuszmaul [11] introduces Verkle trees as bandwidth-efficient alternatives to Merkle trees. By replacing hash functions with vector commitments, Verkle trees achieve proof sizes of $\mathcal{O}(\log_k n)$ (versus $\mathcal{O}(\log n)$), providing up to 10× bandwidth reduction with manageable computational overhead.
$B^\varepsilon$ **Trees**: Bender et al. [12] present write-optimized $B^\varepsilon$-trees that buffer operations to amortize I/O costs. Through batched message flushing, these structures achieve orders-of-magnitude faster insert performance than traditional B-trees.

## 3 Methodology

Our research methodology involved systematic analysis of 21 research papers across four key areas:

1. **Core Skewed Tree Research**: Dynamic integrity trees [3], frequency-aware structures [4], and adaptive Huffman coding [5,6]
2. **Traditional Merkle Optimizations**: Traversal algorithms [7], fractal approaches [8], and optimal trade-offs [9]
3. **Alternative Data Structures**: Sparse Merkle trees [10], Verkle trees [11], $B^\varepsilon$ trees [12], and hash grids [13]
4. **Blockchain Context**: Bitcoin [1], Ethereum [14,15], and implementation analysis [16]

We also implemented and analyzed a Merkle Patricia Trie prototype to understand practical performance characteristics and identify implementation challenges in frequency tracking and tree restructuring operations.

## 4 Fundamental Limitations of Frequency-Based Structures

Our analysis reveals three critical limitations that render frequency-aware skewed structures unsuitable for blockchain applications:

### 4.1 State Reversibility Violation

Blockchain systems require the ability to "undo" transactions to reach previous states for fork resolution, smart contract failures, and network consensus. In balanced Merkle trees, each node position is deterministic based on data content, enabling efficient rollback operations.

However, in skewed trees, node positions depend on access history and frequency patterns. Rolling back requires reconstructing the exact frequency state at any historical point, which becomes prohibitively expensive as it necessitates maintaining complete frequency history for all time periods.

### 4.2 Order Independence (Commutativity) Violation

A fundamental blockchain requirement is that transaction processing order must not affect the final tree structure. For transactions T1 and T2, applying T1→T2 must produce identical tree structure as T2→T1, assuming equivalent final account states.

Frequency-based trees violate this property because:

**Scenario**: T1 accesses Account A, T2 accesses Account B

**Order 1** (T1 → T2):
Account A: frequency=1, positioned at level X
Account B: frequency=1, positioned at level Y
Result: Structure_AB

**Order 2** (T2 → T1):
Account B: frequency=1, positioned at level X
Account A: frequency=1, positioned at level Y
Result: Structure_BA

Structure_AB $\neq$ Structure_BA

This order dependency creates consensus failure scenarios where different nodes processing identical transactions in different orders reach different tree structures, breaking blockchain's deterministic consensus requirements.

### 4.3 Consensus Safety Violations

The combination of frequency dependency and order sensitivity creates multiple attack vectors:

- **Frequency Manipulation**: Attackers can artificially inflate access frequencies to manipulate tree structure
- **Timing Attacks**: Frequency patterns leak information about transaction patterns and account relationships
- **DoS via Rebalancing**: Triggering excessive tree restructuring operations can degrade network performance
- **State Confusion**: Different frequency states across nodes can create persistent consensus splits

## 5 Performance Analysis

Despite fundamental correctness issues, frequency-aware structures demonstrate significant performance benefits in appropriate contexts:

### 5.1 Empirical Performance Gains

Our analysis of existing implementations shows:

- **Dynamic Skewed Trees**: 30% average improvement over balanced trees [3]
- **FAST Architecture**: Up to 3× improvement with hardware optimization [4]
- **Memory Efficiency**: Reduction from O(n) to O(frequency_classes) memory usage [5]
- **Traversal Optimization**: Significant reduction in average tree levels accessed for hot accounts

### 5.2 Theoretical Complexity Analysis

For a blockchain with N accounts following a skewed access pattern:

- **Traditional Merkle Trees**: O(log N) per operation, O(log N × log N) with database overhead
- **Frequency-Aware Trees**: O(log k) per operation for k frequency classes where k ¡¡ N
- **Migration Overhead**: O(log k) per frequency update with rebalancing costs
- **Rollback Complexity**: O(N × history_depth) for maintaining frequency state history

The performance benefits become more pronounced as the skewness of the access pattern increases, but the rollback complexity makes this approach impractical for blockchain systems requiring frequent state transitions.

## 6 Conclusions

This study demonstrates that while frequency-aware skewed Merkle tree structures provide substantial performance improvements (30-50% in various implementations), they are fundamentally incompatible with blockchain system requirements. The core limitations include:

1. **State Reversibility Violation**: Cannot efficiently support transaction rollback operations essential for blockchain consensus and error recovery
2. **Order Independence Violation**: Transaction processing order affects tree structure, breaking deterministic consensus requirements
3. **Consensus Safety Risks**: Multiple attack vectors and consensus failure scenarios emerge from frequency-dependent behavior

These findings establish important theoretical boundaries for optimization approaches in distributed consensus systems. Performance improvements that compromise safety or determinism properties cannot be applied to blockchain systems regardless of their efficiency benefits.

This study contributes to the broader understanding of trade-offs between performance optimization and correctness guarantees in distributed systems, demonstrating that frequency-based optimizations, while effective in other domains, are fundamentally incompatible with the deterministic requirements of blockchain consensus protocols.

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