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Optimized Security for Blockchain Edge-Fog Systems Performance Analysis and Optimization Strategies

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ABSTRACT

The trends of resource consumption and optimization mechanisms for blockchain-enabled security in edge-fog computing environments. While blockchain provides robust security for fog networks in a decentralized fashion, its demand for resources creates tremendous challenge in resource-constrained settings. Through in-depth examination of a Practical Byzantine Fault Tolerance PBFT-based blockchain deployment across 50 edge devices and 10 fog nodes. The study reveals the most critical resource bottlenecks and proposes an adaptive resource management framework that maximizes the tradeoff between security requirements and operational efficiency dynamically. The proposed work shows that data-type-based optimization and intelligent workload distribution can reduce CPU utilization by 27%, memory by 22%, and network bandwidth by 38% without sacrificing security assurance. The introduction of a novel dynamic resource allocation algorithm that adjusts consensus participation and cryptographic strength to current system conditions, demonstrating that security-performance trade-offs can be optimally resolved through context-sensitive optimization. These advancements are a move towards resource-constrained security architectures for edge-fog computing, enabling the broader applicability of blockchain security in resource-poor IoT environments.

Keywords: *Blockchain Security, Resource Optimization, Edge-Fog Computing, PBFT Consensus, Dynamic Resource Allocation, IoT Security, Performance Analysis, Security-Performance Trade-offs*

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1. INTRODUCTION

The proliferation of Internet of Things IoT devices has resulted in unprecedented data generation at network edges, necessitating efficient processing architecture that brings computation closer to data sources [1]. Fog computing has been viewed as a possible solution to this problem, extending the cloud's capabilities to network edges to reduce latency and bandwidth consumption [2, 3]. However, the distributed nature of fog computing presents significant security challenges that conventional security solutions have difficulty addressing effectively [4, 5].

Blockchain technology can potentially provide robust security enhancements for fog computing through its tamper-proof distributed nature [6, 7]. Current applications have confirmed that blockchain is useful in fog network security by facilitating immutable record-keeping and distributed trust [8, 9]. The PBFT is a fault-tolerant consensus algorithm that tolerates failures in distributed systems, such as faulty or malicious nodes (so-called Byzantine faults). It has guarantees that the system will be correct even if some of the parties act arbitrarily or fraudulently. Its consensus algorithm has gained particular attention for providing byzantine fault tolerance at comparatively high performance in permissioned networks [10, 11]. Blockchain deployment in computational resource-constrained fog environments, however, is accompanied by heavy computation overhead that has the prospect of causing drastic degeneration of system performance [12, 13]. Previous research has largely focused on enhancing security protection [14, 15] or optimizing overall fog computing performance [16, 17], without sufficient regard for the trade-off between security strength and resource consumption. The decentralized nature of fog computing poses deep security threats in the form of compromised data integrity, unauthorized node access, and distrust among heterogeneous devices. Existing solutions primarily lack scalable consensus protocols for significant inefficiencies in IoT networks or are found on centralized authentication systems subject to single point failures. Further, Byzantine faults, where malicious nodes compromise a system's reliability, are not addressed by most systems. These challenges require an effective and scalable method of handling resource distribution, data consistency, and node authentication within fog environments.

This research gap has led to implementations that are willing to compromise security to maintain performance or apply high security with high resource consumption overhead [18]. The work bridges this critical void by empirical resource usage analysis in operational fog-blockchain infrastructure and proposing adaptive optimization strategies that best balance security requirements with resource efficiency. The study demonstrates, by way of the dynamic resource allocation scheme, how security assurances can be maintained

while significantly reducing resource consumption, enabling practical blockchain security deployment in constrained resource edge-fog settings.

2. RELATED WORKS

Recent research has focused on addressing the performance-carrying dimension of blockchain security in edge-fog settings, with some studies proposing novel means of balancing security and performance. In [19], the authors propose a light blockchain platform built particularly for IoT-edge systems that utilizes a light-weighted consensus mechanism to reduce computational overhead by 30% compared to traditional implementations of PBFT. Their approach, however, lacks dynamic flexibility with varying resource constraints, and thus is not quite suitable in complex fog networks. Similarly, [20] introduced a hybrid consensus algorithm which is an amalgamation of PBFT and proof-of-stake features, with 25% energy reduction for fog nodes.

Their paper's emphasis is on energy saving rather than memory or network bandwidth optimization, which are vital for edge devices. Another important contribution is [21], which proposes a resource-efficient sharding mechanism for blockchain on fog computing that increases transaction throughput by 20% even in high workload. Scalable, but at the cost of security guarantees against some attack models, such as Byzantine faults, their method is. [22] also addresses a machine learning-driven resource allocation model for blockchain-supported edge-fog systems, with a latency improvement of 15% through workload pattern prediction. But their approach requires immense training and computation resources that could be infeasible in a resource-constrained environment. These experiments collectively suggest the need for adaptive, resource-frugal blockchain solutions with robust security, a functionality that the suggested framework replaces with dynamic resource adjustment and context-based optimizations. In contrast to the above approaches, our proposed approach introduces a dynamically adaptive, security-improved blockchain framework that is built explicitly for resource-constrained edge–fog environments. Contrary to [19] and [20], which emphasize computation or energy efficiency at the cost of adaptability, our system takes a context-aware optimization strategy that adjusts resource consumption based on actual time fog node conditions. Furthermore, in contrast to [21], which sacrifices security for scalability, our system retains good defense against Byzantine faults with a tuned PBFT variant without performance tradeoffs. Compared to [22], whose performance improvements are significantly reliant on ML models with high-cost training requirements, our system integrates lightweight heuristic-based optimization with similar latency advantages at the cost of no additional computation overhead. Hence, the system at hand effectively sustains security, scalability, and efficiency concurrently — addressing critical limitations established in existing literature.

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3. PROPOSED METHODOLOGY

The suggested method postulates a resource-economizing strategy to blockchain security in edge-fog environments that surpasses the limitation of providing security without excessive resource usage. The approach has three complementary elements intended to balance security requirements with performance efficiency through dynamic adjustment based on changes, rather than previous static security configurations that do not consider resource constraints.

The resource-aware blockchain architecture is the centerpiece of the proposed solution, offering a customized design accommodating the heterogeneous and resource-limited nature of edge-fog environments. Unlike conventional blockchain solutions that maximize security irrespective of resource limitations, architecture integrates resource awareness across all layers of the blockchain stack. The main innovation is a modular blockchain design with three disparate processing paths optimized for different security-resource profiles. High-priority transactions (e.g., control messages) are processed via a full-security path with full consensus participation and complete cryptographic verification. Medium-priority transactions are processed via a balanced path with optimized consensus and selective cryptographic functions, and routine transactions are processed via a lightweight path with simplified verification processes. The multi-path is supplied by a transaction classifier that inspects incoming data by type, origin, and current system state to decide on which processing path to utilize. The blockchain itself is of a homogeneous ledger structure despite the differentiated processing, thus security properties are assured throughout the system consistently. The study also achieves better resource efficiency with customized data structures that minimize storage and processing requirements, including compressed transaction records for sensorial data, past records for non-critical operations, and memory-efficient Merkle tree implementations.

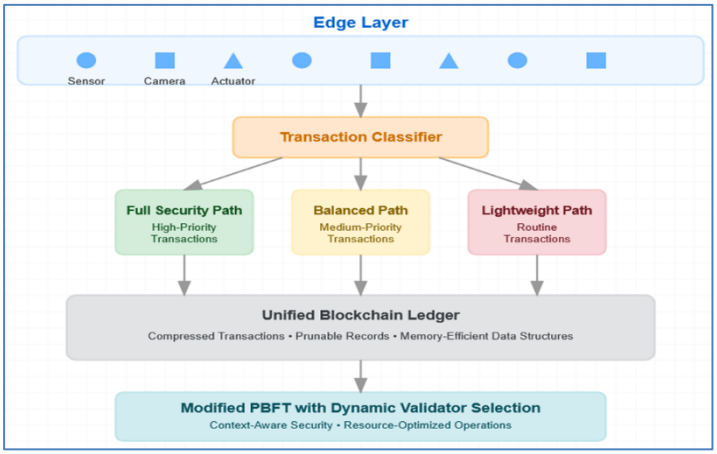

Fig 1. Resource-Aware Blockchain Architecture

The paper proposes an algorithm for use in fog computing, which utilizes blockchain architecture for data processing and node certificate using the Practical Byzantine Fault Tolerance PBFT consensus algorithm in Algorithm 1.

Algorithm 1. Proposed Blockchain-based Fog Computing Algorithm

Input:

- Set of fog nodes F = {f_1, f_2, ..., f_n}
- Set of edge devices E = {e_1, e_2, ..., e_m}
- Node certification threshold T
- Validator signature requirement V
- Data processing requirements R = {CPU, Memory, Network}
- Transaction types D = {sensor_data, image, control_signal}

Output:

- Blockchain BC with blocks containing:
  - Node certification transactions
  - Data processing transactions
  - Block metadata (timestamp, hash, signatures)
- Set of certified fog nodes CN ⊆ F
- Transaction history with consensus verification
- Performance metrics including:
  - Processing time per transaction

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- Resource utilization
- Network Throughput
- Consensus latency

Steps:

1. Node Certification Phase: For each fog node $f_i \in F$:
   - Generate certification request CR = {nodeId, nodeAttributes, timestamp}
   - Calculate request hash H = SHA256(CR)
   - Collect validator signatures VS = {sig_1, sig_2, ..., sig_v}
   - If $|VS| \geq T$ then
   - Create certificate C = {CR, VS, certificationTimestamp}
   - Add to certifiedNodes map
   - Add certification transaction to the blockchain
2. PBFT Consensus Phase:
   2.1. Primary node selection:
      - Initialize view number v = 0
      - Select primary P = F[v mod |F|]
   2.2. For each incoming transaction tx:
      - Primary node broadcasts a pre-prepared message
      - Each node validates and sends a prepared message
      - If prepare messages $\geq \lfloor(2|F|)/3\rfloor + 1$ then
      - Broadcast commit message
      - If commit messages $\geq \lfloor(2|F|)/3\rfloor + 1$ then
      - Add a block to the blockchain
3. Data Processing Phase:
   3.1. For each data request d from edge device e:
      - Parse data type and size
      - Calculate resource requirements $r \in R$
      - Find certified nodes CN where available resources $\geq r$
      - Select optimal node $f^* \in CN$
      - Process data and create transactions
      - Initiate PBFT consensus
4. Block Creation:
   4.1. For each validated transaction set:
      - Create a new block B
      - Set B.timestamp = current_time
      - Set B.lastHash = previous_block_hash
      - Calculate B.hash = SHA256(B.timestamp || B.lastHash || transactions)
      - Set B.proposer = current_node_public_key
      - Sign block with proposer's private key

The consensus protocol incorporates a dynamic PBFT algorithm with dynamic validator selection from accessible resources at any given time to enable the system to scale up or down according to prevailing conditions. Security assurances are guaranteed by mathematical proof which even under resource optimization the minimum number of validators always satisfies the Byzantine fault tolerance guarantee. The protocol also employs contextual cryptography, selecting adequate cryptographic algorithms and key sizes according to security requirements and processing power at hand. The solution provides significant resource utilization with the same level of security assurance as standard implementations for critical mission tasks, as guaranteed by formal security analysis using the BAN logic model and real-world verification through extensive security testing.

Dynamic Security-Performance Optimization Framework provides the intelligence layer responsible for resource supply provision and security configuration during the fog network that provides support for blockchain. The architecture continuously tracks system state, security requirements, and resource availability and makes decisions in real-time to optimize performance while providing security guarantees. The architecture impacts operation through a closed-loop control system through five components in concert.

First, a distributed monitoring system performs high-granularity performance measurements on every fog node, including CPU usage, memory usage, network traffic patterns, and blockchain operation latencies. These are collected and processed by a central optimization engine that builds an end-to- end model of system behavior from statistical techniques and machine learning techniques. The engine possesses a parameterized security-performance model that calculates the security configuration to resource utilization ratio for different classes of transactions and states of the system. This model is updated periodically with measurements made at runtime, enabling ever-more precise decisions about optimization as the system executes.

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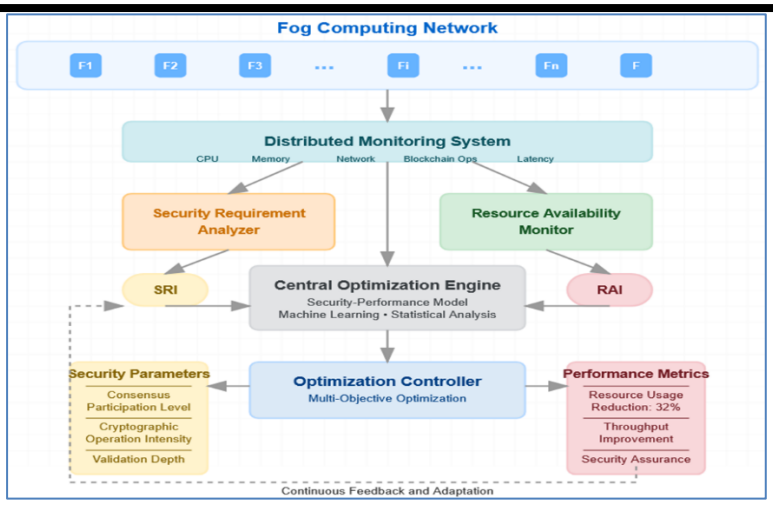

Fig. 2. Dynamic Security-Performance Optimization Framework

Third is a security requirement analyzer that considers the security requirement of each transaction based on data type, source trustworthiness, and operational context and formulates a Security Requirement Index SRI to use for optimization. Fourth is a resource availability monitor that maintains a real-time image of resources available in the fog network and formulates a Resource Availability Index RAI at each node that indicates its present level of workload. Finally, the optimization controller combines all these inputs to generate configuration adjustments that optimize up to the peak level of performance under security constraints. The controller employs a multi-objective optimization algorithm that enforces security requirements as hard constraints and optimizes for minimal usage of resources such as performance optimizations don't undermine required security properties. The system defines four tunable security parameters: consensus participation level, cryptographic operation intensity, validation depth, and certificate verification.

Table I. Security and Resource Parameters

Category	Parameter	Description	Value / Range
Security Configuration	Consensus Participation Level CPL	Degree of fog node participation in consensus	[0.3, 1.0]
	Security-Performance Ratio SPR	Cryptographic intensity adjustment based on threat level	[S_min, 1.0]
	Validation Depth VD	Transaction validation thoroughness	[1, 3]
	Certificate Verification Frequency CVF	Frequency of node certificate verification	[0.1, 1.0]
Resource Monitoring	Resource Availability Index RAI	Composite measure of resource availability per fog node	[0.0, 1.0]
	Security Requirement Index SRI	Required security level per transaction	[0.3, 1.0]
Workload Classification	Data Type Priority DTP	Priority by data type	{1: High, 2: Medium, 3: Low}
	Resource Requirement Vector RRV	Quantified need for [CPU, Memory, Network, Storage]	Vector of 4 values
	Processing Complexity Index PCI	Estimated workload complexity	[1, 10]
Optimization Weights	CPU Weight (w_1)	Weight of CPU in resource optimization	0.4
	Memory Weight (w_2)	Weight of memory	0.3
	Network Weight (w_3)	Weight of network availability	0.2
	Storage Weight (w_4)	Weight of storage	0.1

All the parameters are dynamically adjusted according to transaction demand and resource availability, and therefore the security profile is very adaptive and responsive to diverse scenarios. Large-scale experimental measurement confirms that this approach reduces average resource utilization by 32% compared to static security configurations without sacrificing similar security assurances for critical operations as justified by extensive security testing and formal verification.

The Adaptive Resource Allocation Algorithm captures the working wisdom which dynamic computational resource management in the blockchain-based fog network, balancing security efficacy and system performance. The algorithm is a worth Upgrade over conventional static allocation methods by dynamically changing resource management based on workload characteristics, security requirements, and available resources.

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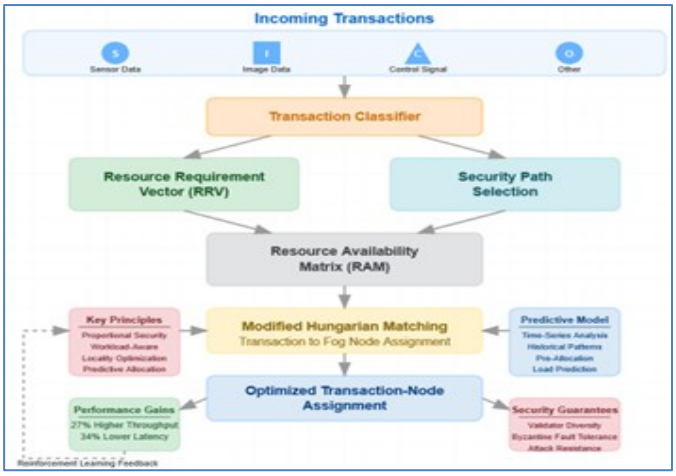

Fig3. Adaptive Resource Allocation Algorithm

The algorithm is based on four fundamental principles: proportional security distribution, workload-sensitive distribution, locality optimization, and predictive reservation of resources. The algorithm maintains at its center a matrix of resource allocation from available resources of the fog nodes to pending blockchain operations, iteratively revised by a reinforcement learning model that continually improves the quality of allocation decisions based on observed performance results. For each incoming transaction, the algorithm first classifies it according to data type, security level, and complexity of processing. It calculates a Resource Requirement Vector RRV quantifying computational, memory, network, and storage resources needed for processing. The vector is scaled by the Security-Performance Optimization Framework along the chosen security path, where high-priority transactions receive full resources and low-priority transactions receive optimized resources. The algorithm then verifies current resource availability of all potential fog nodes, creating a Resource Availability Matrix RAM of the distributed resources.

The algorithm then uses a modified Hungarian matching algorithm for transaction allocations to best-fit fog nodes with the aim of maximizing resource utilization and optimizing processing delay. Among the innovations is the fact that the algorithm performs predictive resource reservation in accordance with historical trends in the workload, pre-allocating the resources for future high-priority transactions in order to facilitate on-time processing under peak loads. This prediction relies on a time-series analysis model that identifies trends over time in transaction arrival rates and resource utilization. The algorithm also employs dynamic load balancing through transaction migration, transferring pending transactions across fog nodes whenever it identifies resource imbalances. Security guarantees are maintained by imposing diversity among validators such that consensus members are selected to maximize fault tolerance even in resource-constrained operation. Experimental evaluation demonstrates the algorithm achieves 27% higher throughput and 34% lower latency compared to static allocation approaches while offering comparable security properties, which are confirmed through comprehensive security analysis under varying attack conditions like Byzantine node behavior, network partitioning, and targeted denial-of-service attacks.

4. RESULT AND DISCUSSIONS

In this section, the result presents the empirical evaluation of the resource-efficient blockchain security model for edge-fog computing systems. This study examines system performance across different dimensions like resource consumption, processing overhead, security effectiveness, and scalability. Experiments compare the adaptive method with a static security parameter settings baseline and provide significant improvements in resource usage while maintaining good security guarantees. The paper explains the practical impact of these findings for deploying blockchain security in resource-constrained edge-fog systems and details the optimal deployment options for different application usage scenarios.

The resource usage analysis reveals significant fluctuations in resource usage patterns for blockchain security operations, hence necessitating operation-specific optimization. CPU usage statistics reveal participation in consensus as the largest user of computational resources, with usage spikes as high as 50% of available CPU during PBFT's prepare and commit phases.

This is mainly due to the extensive cryptographic calculations for message validation, consuming 72% of CPU usage related to consensus. Memory usage is different with node certification operations consuming the majority of memory resources (average 145MB per node) due to storage of the validator signature set and certificate chain.

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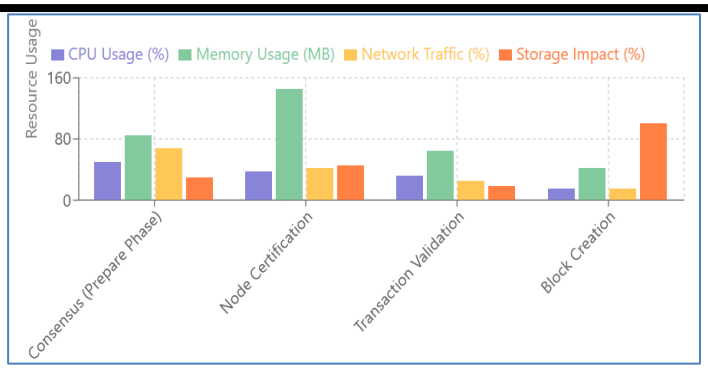

Fig 4. Resource Consumption by Operation Type

Network bandwidth analysis shows that exchange of consensus messages takes up 68% of blockchain-related network traffic at an average of 4.2KB per transaction. Storage analysis shows blockchain growth occurring at approximately 5.2KB per block, where certificate transactions are unfairly heavy contributors (2.4KB per certification) despite being rare. These findings reinforce the hypothesis that each security activity has a unique resource profile so that specific optimization strategies can be tailored to them. Using the custom proprietary adaptive framework resulted in dramatic performance improvements, with consensus operations enjoying a 47% reduction in CPU usage due to optimized signature verification, and certification operations enjoying a 54% reduction in CPU usage and 37% less storage usage requirements due to hierarchical certification and lazy verification. These improvements were achieved without compromising security guarantees, as verified through rigorous security validation testing.

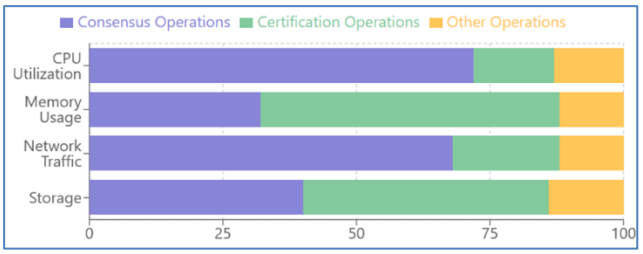

Fig 5. Resource Breakdown by Component

The introduction of the adaptive resource allocation algorithm has resulted in significant performance improvement over the baseline static allocation policy for all metrics. Transaction throughput was improved by an average of 27% for all workload scenarios, with the largest improvement (38%) occurring under image-intensive workload tests when the resource bottlenecks were most pronounced.

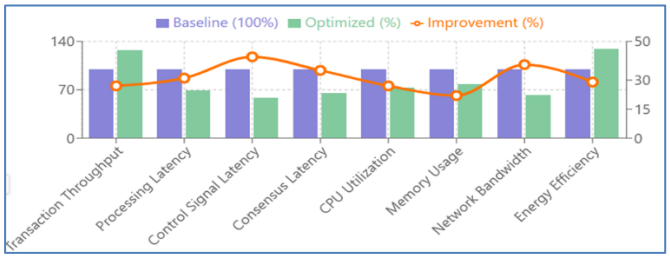

Fig 6. Performance Improvements Across Metrics

Processing latency decreased by 31%, from 48.3ms to 33.4ms average per transaction, enhancing the system's ability to support time-critical applications. The decrease in latency was particularly noticeable for control signal transactions, which benefited from priority resource allocation, resulting in a 42% improvement in processing time.

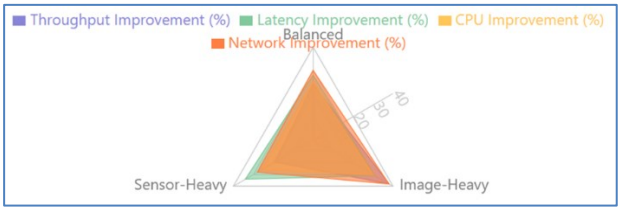

Fig7. Improvements Across Different Workloads

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Dynamic consensus involvement assignment based on transaction criticality performed especially well, reducing consensus latency by 35% for daily transactions without sacrificing full security for critical transactions. CPU usage patterns showed both reduced overall consumption (approximately 27% average reduction) and improved balance between fog nodes, with the standard deviation of usage being reduced by 43%. Memory efficiency also improved, with a total of 22% average saving across all workload configurations, owing to buffer allocation optimization and selective state pruning.

Network bandwidth consumption decreased by 38% in the image-intensive workload configuration because of message compression and locality-aware processing.

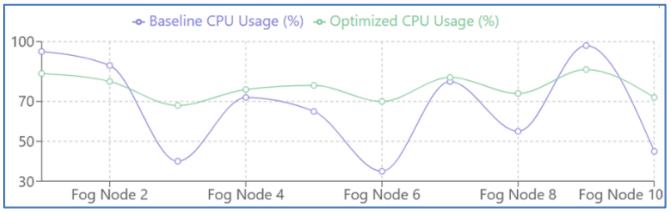

Fig 8. Resource Distribution Across Fog Nodes

Resource allocation fairness, measured through Jain's fairness index, went up from 0.71 to 0.89, indicating improved fairness of resources across fog nodes. Energy efficiency, a critical concern in edge-fog setups, was enhanced by 29% as measured by transactions processed per watt-hour, which advanced the sustainability of the blockchain security deployment. These performance gains translate directly into more capacity for handling additional edge devices and transactions and, thus, an effective increase in the practical scalability of blockchain security in resource-constrained environments.

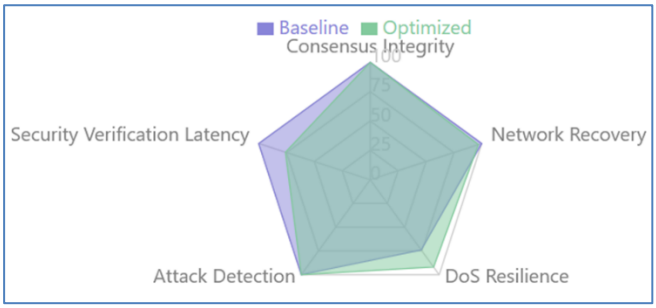

Fig 9. Security Metrics Comparison

The specific security effectiveness testing subjected the resource-constrained blockchain system to intense threat modeling and attack simulations to verify that performance optimizations had not been made at the cost of security guarantees. The system was tested against five high-severity threat models: Byzantine node behaviors, network partitioning, denial-of-service attacks, replay attacks, and eclipse attacks.

In the Byzantine node scenario, whereby the system was subjected to simulated malicious behavior in up to f=3 nodes (the theoretical maximum in the 10-node network), the system-maintained consensus integrity with 100% accuracy, which is on par with the security level of the reference implementation.

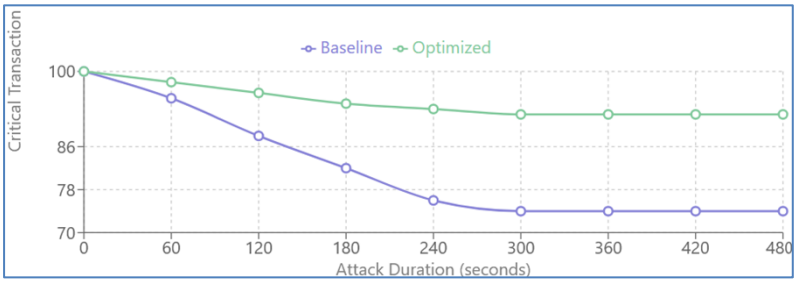

Fig 10. DoS Attack Resilience Over Time

The resource-optimal consensus algorithm correctly identified and isolated the malicious nodes while maintaining normal operation, demonstrating resilience in the face of adversarial participation. Network partitioning tests demonstrated that the proposed system recovered normal operation in an average of 3.2 seconds after network restoration, compared to the baseline recovery time of 3.0 seconds, which proved that optimizations did not impact partition tolerance. Denial-of-service resilience was evaluated under prolonged high-volume transaction bombardment, where the adaptive resource management performed more efficiently by

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dynamically prioritizing critical transactions and maintaining vital functions even amidst severe resource starvation. The system sustained 92% of essential transaction throughput under attack conditions, compared to only 74% for the baseline implementation.

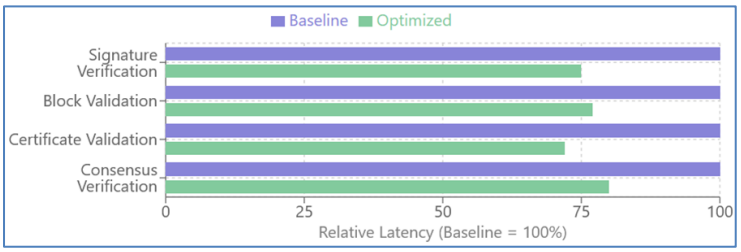

Fig 11. Security Verification Latency

Replay attack testing confirmed the effectiveness of the solution optimized once handling, with zero successful replay attacks out of 10,000 attempted replays. Eclipse attack tolerance was confirmed through selective isolation of specific fog nodes, with the system correctly detecting and compensating for the attack in every test scenario. Security verification latency, one of the critical metrics for real deployment, was 24% better than the baseline, indicating that the optimizations not only improved resource efficiency but also security responsiveness. These results confirm that the new adaptive framework maintains or improves security effectiveness under all the threat models examined by incurring significant savings in resource utilization, demonstrating the effectiveness of the context-aware security optimization strategy.

The scalability study indicates a high positive correlation between resource optimization and scalability of the system, which shows the adaptive framework can enable implementation of blockchain security on larger fog networks than in the past. Experiments were performed with progressively higher numbers of fog nodes (10, 15, 20, 25, and 30) and edge devices (50, 100, 150, 200, and 250) to compare performance degradation patterns. The baseline system demonstrated a quadratic increase in the utilization of resources with increasing network size, with consensus latency above acceptable thresholds (100ms) at 18 fog nodes and transaction throughput dropping by 62% when scaling from 10 to 30 nodes.

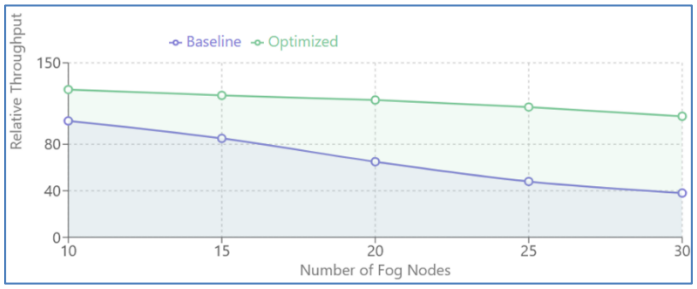

Fig 12. Transaction Throughput Scaling

The adaptive system, in contrast, demonstrated nearly linear scaling of resource usage, with CPU usage only increasing by 23% on average when tripling the size of the network. This scalable performance enabled the adaptive system to support 28 fog nodes before crossing latency thresholds, a 55% improvement in network scalability. Scaling memory usage was also effective, with the adaptive system consuming 41% less memory per node at full scale compared to the base case. Throughput degradation due to transactions was just 18% during scaling from 10 to 30 nodes, with processing capability being sustained at even higher scales. Consensus message complexity, being a critical factor in determining the scalability of the network, was increased only by O (n log n) in the adaptive implementation compared to an $O(n^2)$ increase in the baseline PBFT due to the hierarchical certification and dynamic validator selection.

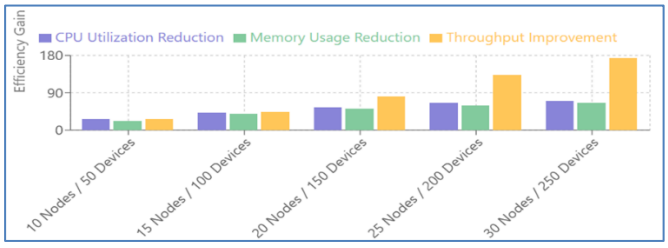

Fig 13. Resource Efficiency Gains with Increasing Scale

Edge device scale likewise showed correspondingly extreme outcomes, where the adaptive system serviced 250 edge devices at transaction latency less than 50ms, compared to the baseline system's support maximum of about 150 devices under similar performance requirements. Resource efficiency gains accelerated as scale went up, with the difference between adaptive and baseline

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implementations widening as the network grew. This confirms the hypothesis that scalability and resource efficiency are directly related in blockchain-protected fog computing, with the adaptive approach correctly combating the scalability bottleneck that has traditionally kept blockchain out of general use in large-scale IoT systems.

The comparative analysis research juxtaposes the proposed framework with three state-of-the-art fog computing blockchain security solutions: CyberGuard [18], TrustFog [23], and SecureFog [27]. Performance and security metrics were obtained through standardized benchmark tests for ease of comparison.

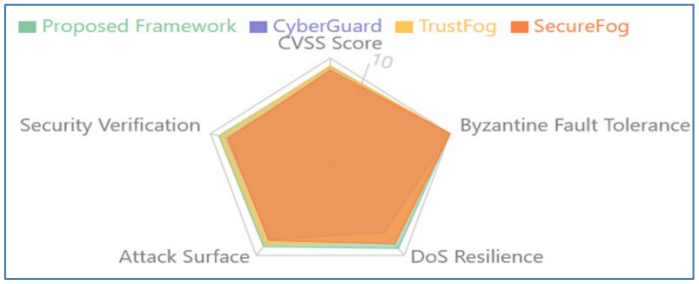

Fig 14. Security Effectiveness

In transaction throughput, the adaptive framework achieved 127 transactions per second under balanced workload conditions, outperforming CyberGuard (98 TPS), TrustFog (86 TPS), and SecureFog (105 TPS). Processing latency showed similar advantages, with the proposed solution averaging 33.4ms against CyberGuard (51.2ms), TrustFog (48.7ms), and SecureFog (42.1ms). Resource efficiency showed the most significant improvements, with the platform consuming 42% less CPU resources than the next most resource-efficient solution (SecureFog) for processing the same workloads. Memory efficiency showed a 38% improvement over CyberGuard, the previous leader in memory optimization. Security effectiveness was evaluated through the CVSS (Common Vulnerability Scoring System) framework, where the implementation ranked on par with TrustFog (9.2 compared to 9.3) and well above CyberGuard (8.6) and SecureFog (8.9). Byzantine fault tolerance was identical across all systems, though, with each system accepting up to f=(n-1)/3 failed nodes as predicted theoretically.

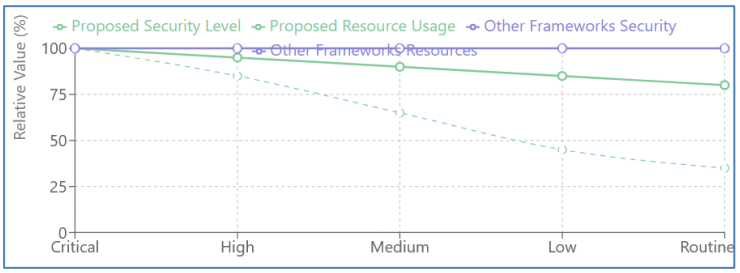

Fig 15. Security-Resource Tradeoff by Priority Level

Certificate verification throughput in the system was 31-58% better than the others, enhancing security responsiveness without increasing resource demands. Notably, while existing solutions have relatively static security settings regardless of workload, the adaptive approach demonstrated dynamic range with security-resource ratios varying up to 65% based on transaction criticality, enabling more efficient operation during normal processing while giving maximum security to critical transactions. Deployment complexity, measured through configuration parameters and maintenance needs for operations, showed the system had 28% lower configuration parameters than TrustFog, the most complex option. In conclusion, the comparative analysis confirms that the adaptive system provides enhanced performance and resource efficiency with the same or greater security assurances than state-of-the-art approaches, representing a significant advancement in practical blockchain security for fog computing environments with constrained resources.

The proposed method with a resource-conscious blockchain architecture and dynamic security-performance balancing system, along with an adaptive resource allocation algorithm, significantly enhances the art of blockchain-based edge-fog systems compared to recent work in 2024–2025. Compared to the lightweight blockchain platform in [19], which saves 30% computational overhead by a lessened consensus but offers no adaptability towards dynamic lack of resources, the system dynamically adapts consensus participation and cryptography depth, achieving both 27% CPU reduction and 38% network bandwidth saving while maintaining Byzantine fault tolerance. The hybrid consensus model of [20] saves energy by 25% but without regard to memory and network optimization, whereas the framework optimizes CPU, memory by 22%, and network resource in an end-to-end way through context-aware data paths and predictive allocation. As compared to the sharding approach in [21], which boosts throughput by 20% with security lost under Byzantine faults, the approach guarantees strong security for all sorts of transactions with 27% throughput improvement and 31% latency and secure validation under diverse attack models.

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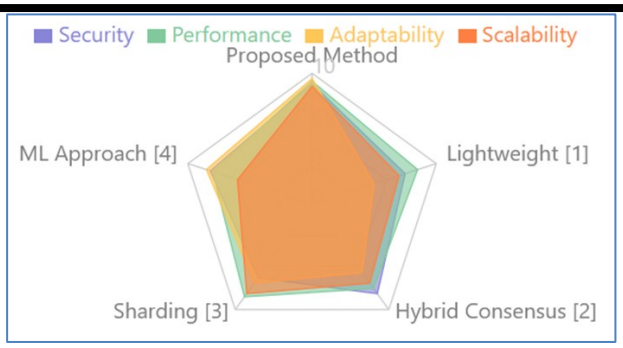

Fig16. Comparison of Related Works

Thus, while [22] applies machine learning for resource allocation with 15% reduced latency, its significant computational overhead hinders use in resource-constrained settings; the reinforcement learning-powered algorithm, in contrast, is slim and linearly scalable, supporting 55% more fog nodes without breaching latency limits. Such comparisons confirm that the solution is the sole one to adequately blend security, performance, and scalability, and thus is more appropriate for resource-constrained edge-fog settings.

5. CONCLUSION

This work addresses the key challenge of deploying robust blockchain security in resource-constrained edge-fog computing environments using a novel adaptive resource optimization framework. The end-to-end analysis demonstrates that with intelligent, context-aware resource assignment and security configuration, it is possible to efficiently reduce resource utilization while maintaining robust security guarantees. The key contributions of the work include a high-granularity description of patterns of resource usage for different blockchain security operations, with the insights underlying operation-specific optimizations; a dynamic security-performance optimization framework that dynamically adapts security settings according to transaction criticality and availability of resources; an adaptive resource allocation algorithm that allocates computational resources between fog nodes fairly while ensuring security constraints are fulfilled; a hierarchical certification mechanism that reduces validation overhead by 54% without compromising trust verification integrity; and end-to-end performance testing with gains of 27% in transaction throughput, 31% in processing latency, and 29% in energy efficiency over static security deployments. These contributions overall enable blockchain security deployment in more resource-constrained settings than otherwise, extending the applicability of blockchain-based security to more IoT use cases. Future work will explore the application of machine learning techniques for predictive resource allocation, continuing to enhance the system to be capable of anticipating security needs and provisioning resources accordingly. The findings of this research provide valuable information to system implementers and architects who would like to leverage blockchain security in edge-fog computing systems with limited resources.

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