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Blockchain-Integrated Trust and Security Framework for Secure and Privacy-Preserving Internet of Things Systems

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ABSTRACT

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The Internet of Things (IoT) has transformed modern applications by enabling seamless connectivity among smart devices across healthcare, smart cities, industrial automation, and transportation. However, the increasing number of connected devices has intensified security and privacy challenges, including unauthorized access, data tampering, identity spoofing, single points of failure, and limited protection offered by centralized security architectures. This study proposes the Blockchain-Integrated Trust and Security (BITS-IoT) Framework, a three-layer blockchain-enabled architecture designed to enhance data security, privacy, and trust in IoT environments. The framework integrates decentralized authentication, cryptographic hashing, smart contracts, immutable distributed ledgers, and lightweight consensus mechanisms to provide secure identity management, access control, and tamper-resistant data storage while considering the resource limitations of IoT devices. A simulation-based evaluation using benchmark IoT datasets and multiple deployment scenarios assessed the framework against conventional centralized IoT security approaches. Results showed that BITS-IoT achieved 96.2% data integrity, 95.5% authentication strength, 94.3% privacy preservation, and 97.2% attack resistance, while eliminating single points of failure and significantly improving system trust. Although blockchain introduced additional processing overhead and latency, integrating edge computing substantially reduced these effects, demonstrating a practical balance between security and performance. The findings indicate that BITS-IoT provides a scalable and effective security framework for protecting next-generation IoT systems.

1 Introduction

1.1 Background and Motivation

The Internet of Things (IoT) has become a fundamental technology driving digital transformation across healthcare, smart cities, industrial automation, agriculture, transportation, and environmental monitoring. Billions of interconnected devices continuously collect, exchange, and process data to support real time monitoring, automation, and intelligent decision making, delivering significant economic and societal benefits [1]. However, the rapid growth of IoT has introduced major security and privacy concerns due to device heterogeneity, limited computational resources, decentralized architectures, and the increasing sophistication of cyberattacks. Incidents such as the Mirai botnet,

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ransomware attacks on healthcare systems, and large scale IoT data breaches have demonstrated that conventional centralized and perimeter based security models are insufficient for protecting modern IoT ecosystems [2].

Blockchain technology has emerged as a promising approach to addressing these challenges by providing decentralized trust, immutable data storage, cryptographic integrity, and automated security enforcement through smart contracts. These features offer opportunities to strengthen authentication, access control, data integrity, and privacy while eliminating single points of failure inherent in centralized architectures [3]. Nevertheless, integrating blockchain into IoT remains challenging because of its computational overhead, scalability limitations, transaction latency, and energy consumption, particularly for resource constrained devices [4]. These challenges motivate this study to investigate how blockchain can be effectively integrated into IoT environments to improve data security and privacy while maintaining scalability, efficiency, and real time performance.

1.2 Research Problem

The rapid adoption of Internet of Things (IoT) technologies has significantly expanded the attack surface of critical systems, exposing weaknesses in existing security and privacy mechanisms. Most IoT deployments rely on centralized architectures that suffer from single points of failure, scalability limitations, and dependence on trusted third parties. In addition, IoT devices are inherently constrained by limited processing power, storage, energy, heterogeneous architectures, long operational lifecycles, and inadequate security updates, making them highly vulnerable to cyberattacks and physical compromise.

IoT environments also generate and process large volumes of sensitive data, creating serious privacy concerns related to surveillance, data aggregation, insecure transmission, and third-party data sharing. Although blockchain offers decentralized trust, data integrity, and secure access control, its integration with IoT is hindered by computational overhead, latency, storage requirements, energy consumption, and scalability challenges. Existing blockchain based IoT security solutions often address only specific security issues, provide limited privacy protection, inadequately consider resource constrained devices, and lack comprehensive real-world validation. Consequently, there remains a need for a practical, scalable, and holistic blockchain-based security framework that enhances data security, privacy, and trust while accommodating the operational constraints of IoT environments.

1.3 Research Questions

This study investigates how blockchain technology can be effectively integrated with Internet of Things (IoT) systems to improve data security and privacy while addressing resource constraints, scalability, and performance requirements. The study is guided by the following research questions:

1. How can blockchain improve data integrity and tamper resistance in IoT systems?
2. How can blockchain support decentralized authentication and access control in IoT environments?
3. How can blockchain enhance privacy preservation through decentralized identity management and encryption techniques?
4. What are the major challenges of integrating blockchain with IoT, particularly regarding resource constraints, scalability, and performance?
5. How effective is the proposed blockchain-based security framework in improving IoT security and privacy compared with traditional centralized approaches?

1.4 Research Aim and Objectives

The main aim of this study is to develop and evaluate a Blockchain-Integrated Trust and Security (BITS-IoT) Framework for enhancing data security and privacy in Internet of Things (IoT) environments.

The specific objectives are to:

1. Design a blockchain-based mechanism to improve data integrity and tamper resistance in IoT systems.
2. Develop a decentralized authentication and access control model using blockchain for secure IoT communication.

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3. Enhance privacy preservation through decentralized identity management and cryptographic encryption techniques.
4. Investigate the challenges of blockchain-IoT integration, with emphasis on resource constraints, scalability, and system performance.
5. Evaluate the effectiveness of the proposed Blockchain-Integrated Trust and Security (BITS-IoT) Framework by comparing its security, privacy, and performance with conventional centralized IoT security architectures

2 Literature Review

2.1 IoT Security Challenges

The rapid growth of the Internet of Things (IoT) across healthcare, smart cities, industrial automation, and critical infrastructure has introduced significant security and privacy challenges. Unlike traditional information systems, IoT environments consist of heterogeneous, resource-constrained, and highly interconnected devices, making them attractive targets for cyberattacks. These challenges can be broadly categorized into device-level, network-level, data security, architectural, and operational issues.

2.1.1. Device-Level Vulnerabilities

IoT devices are inherently vulnerable because of limited processing power, memory, storage, and battery capacity, restricting the implementation of robust security mechanisms such as encryption, intrusion detection, and secure communication protocols [5]. Many devices are also deployed in physically accessible locations, exposing them to tampering, firmware modification, and key extraction. In addition, device heterogeneity, lack of standard security practices, outdated firmware, insecure update mechanisms, and the widespread use of default credentials further increase security risks [6]. These weaknesses have enabled large-scale attacks such as the Mirai botnet, which exploited default passwords to compromise thousands of IoT devices [7].

2.1.2. Network-Level Vulnerabilities

IoT communication networks are susceptible to numerous attacks due to the use of lightweight protocols such as MQTT, CoAP, and ZigBee, which often provide limited built-in security. Weak protocol implementations expose systems to eavesdropping, man-in-the-middle attacks, message forgery, and data interception [8]. The increasing number of connected devices also complicates network monitoring, anomaly detection, and incident response [9]. Furthermore, compromised IoT devices can be coordinated to launch large-scale Distributed Denial-of-Service (DDoS) attacks, while poorly secured edge devices and gateways create additional entry points for attackers [10].

2.1.3. Data Security and Privacy Challenges

IoT systems continuously generate and exchange sensitive information, making data security and privacy major concerns. Weak integrity controls may allow attackers to alter or inject false data, resulting in inaccurate decisions and system failures [11]. Inadequate encryption, poor key management, and weak access control increase the risk of data breaches and unauthorized disclosure. Continuous collection of personal and behavioral information also raises privacy concerns, particularly where users have limited control over data collection, storage, and sharing [12]. Protecting data throughout its lifecycle remains a major challenge due to the complexity of IoT data flows.

2.1.4. Architectural Vulnerabilities

Most IoT systems rely on centralized architectures that create single points of failure. Compromising central servers, cloud platforms, or authentication services can disrupt entire IoT networks and expose sensitive information [13]. These architectures also depend heavily on trusted third parties, introducing risks related to trust, privacy, and regulatory compliance. As IoT deployments continue to grow, centralized systems face scalability limitations, increased latency,

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and reduced reliability [14]. In addition, interoperability among heterogeneous devices and third-party platforms often creates inconsistent security policies that attackers can exploit.

2.1.5. Operational and Management Challenges

Beyond technical vulnerabilities, IoT security is constrained by operational factors. Many organizations lack the expertise required to deploy and manage secure IoT systems, leading to poor configurations and delayed responses to security incidents. The large scale and diversity of IoT environments further complicate threat detection and incident management. Organizations must also comply with evolving security and privacy regulations such as GDPR and HIPAA, which can be difficult across heterogeneous IoT deployments. Finally, the high cost of implementing comprehensive security solutions often results in underinvestment, leaving IoT systems exposed to cyber threats.

2.2 Blockchain Technology Overview

Blockchain technology, originally developed for cryptocurrencies such as Bitcoin, has evolved into a decentralized platform for secure data management across multiple domains. Its key features, including decentralization, immutability, transparency, and cryptographic security, make it a promising solution for addressing IoT security and privacy challenges.

2.2.1. Fundamental Concepts and Principles

A blockchain is a distributed and immutable ledger that records transactions across multiple nodes without a central authority. Transactions are grouped into blocks, each cryptographically linked to the previous one, making data tampering extremely difficult [7]. Its core principles include:

i. **Decentralization:** Eliminates dependence on a central authority through peer-to-peer consensus.

ii. **Immutability:** Ensures that recorded transactions cannot be altered without network consensus.

iii. **Transparency:** Allows authorized participants to verify transactions and audit system activities.

iv. **Cryptographic Security:** Uses hashing and public-key cryptography to ensure confidentiality, integrity, and authenticity.

v. **Consensus:** Employs consensus algorithms to validate transactions and maintain a consistent ledger across the network.

2.2.2. Blockchain Architecture

Blockchain consists of a sequence of interconnected blocks containing transaction data and metadata. Each block includes a header (previous block hash, timestamp, Merkle root, nonce, and other metadata) and a body containing validated transactions. In IoT environments, transactions may represent sensor readings, device authentication, access requests, or smart contract execution.

Smart contracts are self-executing programs that automate security functions such as authentication, access control, data validation, and policy enforcement without centralized intervention [15].

Blockchain networks rely on different **consensus mechanisms**, each offering trade-offs between security and performance. Common approaches include Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and Proof of Authority (PoA). Lightweight consensus protocols have also been developed to reduce computational overhead and improve suitability for resource-constrained IoT devices [16].

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2.2.3. Cryptographic Primitives

Blockchain security is built on several cryptographic techniques:

i. **Hash Functions:** Algorithms such as SHA-256 generate unique hashes that ensure data integrity and detect tampering.

ii. **Public-Key Cryptography:** Enables secure device authentication, digital signatures, and encrypted communication [17].

iii. **Merkle Trees:** Provide efficient verification of transaction integrity without downloading the complete blockchain.

iv. **Zero-Knowledge Proofs (ZKPs):** Support privacy-preserving authentication and data verification without revealing sensitive information [18].

2.2.4. Blockchain Types and Characteristics

Blockchain networks are generally classified as **public, permissioned,** or **hybrid**. Public blockchains offer maximum decentralization and transparency but suffer from high latency, energy consumption, and limited scalability. Permissioned blockchains restrict participation to authorized entities, providing better performance, privacy, and regulatory compliance, making them more suitable for enterprise and IoT applications. Hybrid blockchains combine features of both public and private networks to balance transparency, security, and access control. Blockchain types and their characteristics is presented in Table 1.

Table 1: Blockchain Types and Characteristics

Characteristic	Public Blockchain	Permissioned Blockchain	IoT Suitability
Decentralization	High	Moderate	Both
Scalability	Low	High	Permissioned
Privacy	Low	High	Permissioned
Latency	High	Low	Permissioned
Energy Consumption	High	Low	Permissioned
Cost	Higher	Lower	Permissioned
Trust Model	Trustless	Authorized participants	Permissioned

2.2.5. Blockchain Security Properties

Blockchain provides key security features that make it suitable for IoT applications. Integrity is ensured through immutable records linked by cryptographic hashes, making data tampering difficult. Authenticity and non-repudiation are achieved using digital signatures that verify device identities and transaction origins. Its distributed architecture improves availability by eliminating single points of failure, while permissioned blockchains and privacy-enhancing techniques strengthen privacy through decentralized identity management. By removing reliance on centralized authorities, blockchain also establishes a decentralized trust model that enhances secure interactions among IoT devices.

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2.3 Related Work on Blockchain-IoT Security

Several studies have investigated blockchain as a solution to IoT security and privacy challenges. [19] proposed a lightweight blockchain architecture that improved device security with reduced computational overhead, although it relied on trusted local nodes. [20] reviewed blockchain-based IoT security mechanisms, highlighting improvements in authentication, integrity, and trust while identifying the need for practical validation. [21] developed a blockchain framework for smart cities that strengthened secure communication and access control but faced scalability limitations. [22] introduced smart contract-based access control, demonstrating improved authentication and automated policy enforcement despite latency challenges. Similarly, [23] applied blockchain to healthcare IoT for secure patient data management, while [24] surveyed blockchain-based authentication and privacy techniques, emphasizing the need for lightweight protocols.

Privacy and scalability have also received considerable attention. [25] proposed blockchain-enabled privacy protection through decentralized identity management and encryption, whereas [26] highlighted blockchain's role in privacy preservation but noted challenges related to energy consumption and processing overhead. [27] recommended lightweight consensus mechanisms and edge-assisted processing to improve scalability and reduce latency. [28] proposed combining blockchain with edge computing to support secure identity management and data sharing. Recent studies further explored integrating blockchain with artificial intelligence for threat detection, showing improved anomaly detection accuracy but increased computational complexity.

2.3.1. Research Gaps

The literature demonstrates that blockchain can significantly improve IoT security through decentralized authentication, secure data sharing, and tamper-resistant storage. However, existing studies largely address isolated security issues rather than providing comprehensive frameworks. Many solutions inadequately address resource constraints, scalability, latency, and energy efficiency, limiting deployment on resource-constrained IoT devices. Privacy protection mechanisms, particularly user consent, data minimization, and regulatory compliance, also remain underexplored. Furthermore, most proposed frameworks lack extensive real-world validation. These gaps highlight the need for a practical, scalable, and comprehensive blockchain-based security framework that simultaneously addresses security, privacy, performance, and deployment challenges in IoT environments.

3 Proposed Conceptual Framework

Based on the identified research gaps, this study proposes a blockchain-based conceptual framework to improve IoT data security and privacy. The framework integrates decentralized security mechanisms within a scalable, lightweight architecture suitable for resource-constrained IoT environments.

3.1. System Architecture

The proposed framework adopts a **three-layer architecture** that separates system functions while ensuring secure interaction among all layers.

Layer 1: IoT Device Layer

This layer consists of IoT devices, sensors, actuators, embedded systems, and edge gateways responsible for data collection, processing, and communication. Table 2 presents the IoT Device Layer and their functions.

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Table 2: IoT Device Layer

Component	**Function**	**Security Mechanisms**
Sensors	Data collection	Lightweight encryption, secure key storage
Actuators	Execute actions	Authentication, authorization
Embedded Devices	Local processing	Secure boot, firmware validation
Edge Gateways	Data aggregation	Data validation, blockchain interface

Key Security Features

i. Lightweight encryption for secure communication.

ii. Secure storage of cryptographic keys.

iii. Blockchain-based device authentication.

iv. Secure firmware updates with integrity verification.

v. Data validation before blockchain submission.

Edge gateways aggregate sensor data and serve as interfaces between IoT devices and the blockchain layer.

Layer 2: Blockchain Security Layer

This layer provides decentralized security services, including authentication, access control, immutable data storage, and transaction validation. Table 3 presents the components of the blockchain and their functions.

Table 3: Blockchain Security Layer

Component	**Function**
Blockchain Network	Distributed ledger management
Smart Contracts	Automated policy enforcement
Consensus Module	Transaction validation
Identity Management	Device and user authentication
Access Control	Authorization management
Data Storage	Secure on-chain/off-chain storage

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Core Security Mechanisms

a. **Decentralized Authentication:** Uses digital signatures, decentralized identifiers (DIDs), and blockchain certificates to eliminate reliance on centralized identity providers.
b. **Cryptographic Hashing:** Applies secure hash algorithms (e.g., SHA-256 or SHA-3) to verify data integrity and detect unauthorized modifications.
c. **Smart Contracts:** Automate authentication, access control, policy enforcement, and audit logging without human intervention.
d. **Consensus Mechanism:** Lightweight protocols such as PBFT or PoA validate transactions efficiently while reducing computational overhead, making them suitable for IoT environments.
e. **Immutable Storage:** Security-critical records are stored on-chain, while large IoT datasets are maintained in secure off-chain repositories with blockchain hash references to preserve integrity.

This layered architecture provides decentralized trust, tamper resistance, secure identity management, and efficient security enforcement while minimizing the processing burden on IoT devices. Figure 1 presents the proposed blockchain-based security framework for IoT systems.

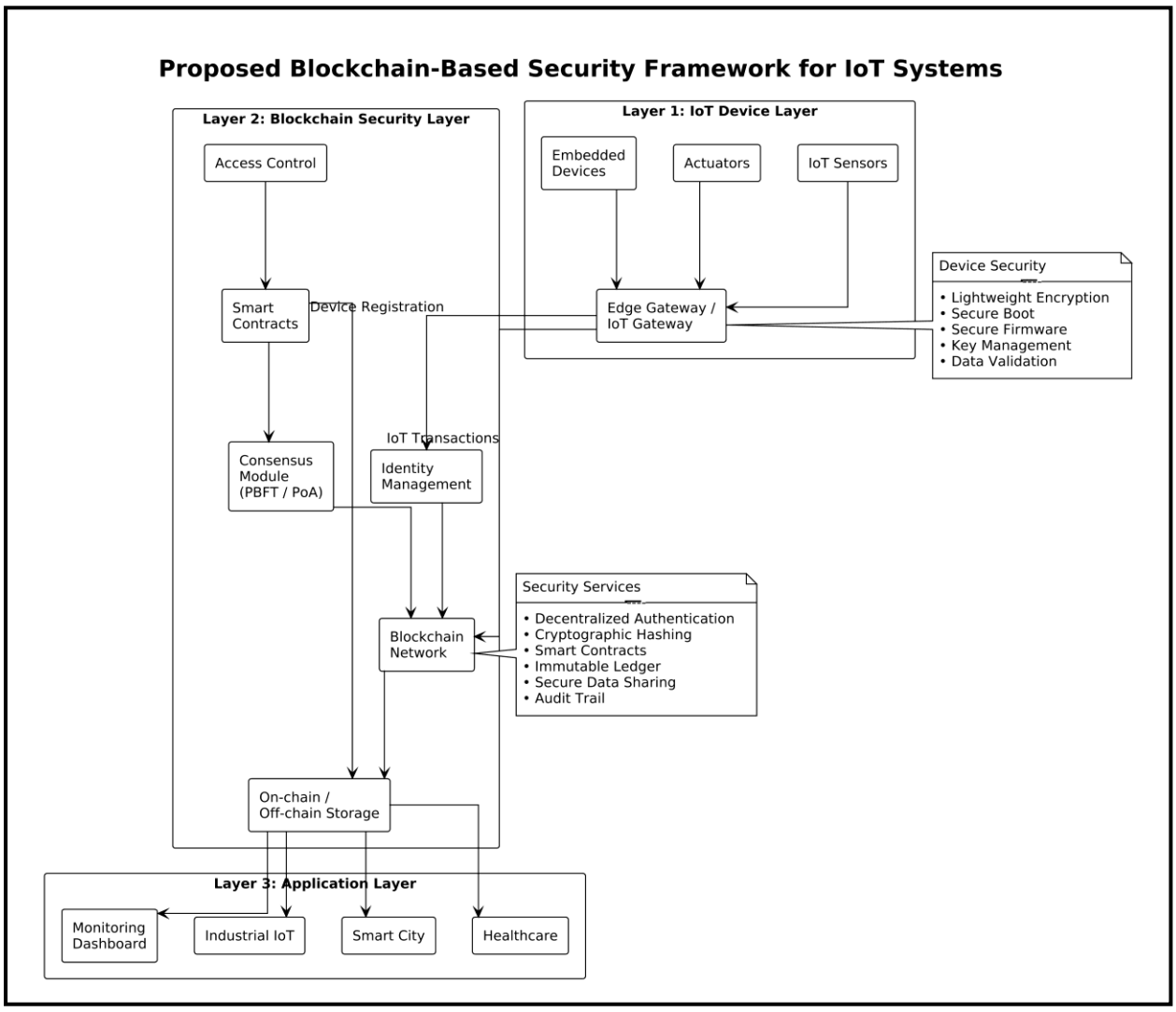

Figure 1: The Proposed Blockchain-Based Security Framework for IoT Systems

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4 Methodology and Simulation Setup

4.1. Evaluation Methodology

This study adopts a conceptual framework design supported by simulation-based evaluation to assess the proposed blockchain-IoT security framework. The methodology provides a systematic and reproducible approach for evaluating the framework's security, performance, and practicality before real-world deployment.

4.1.1. Research Design

The evaluation consists of five phases:

1. **Framework Development:** Review existing literature, design the three-layer architecture, and define security mechanisms and workflows.
2. **Security Analysis:** Identify IoT threats, specify security requirements, and develop the threat model.
3. **Simulation Setup:** Design IoT deployment scenarios, configure simulation parameters, and develop test cases.
4. **Performance Evaluation:** Execute simulations, collect security and performance metrics, and compare results with traditional centralized IoT security models.
5. **Result Analysis:** Analyze findings, evaluate strengths and limitations, and draw conclusions.

4.1.2. Data Sources and Validation

The evaluation relies on publicly available benchmark datasets, including **UNSW-NB15**, **TON_IoT**, and **CICIDS2017**, together with blockchain performance benchmarks and security metrics reported in the literature. Results are validated through cross-study comparison, sensitivity analysis, expert review, and detailed documentation to ensure reproducibility.

4.2. Simulation Environment

This section describes the simulation environment used to evaluate the proposed blockchain-IoT security framework. The simulation environment was designed to represent realistic IoT deployment scenarios while enabling controlled experimentation and measurement.

4.2.1. Simulation Architecture

The simulation environment comprises multiple integrated components representing the different layers of the proposed framework:

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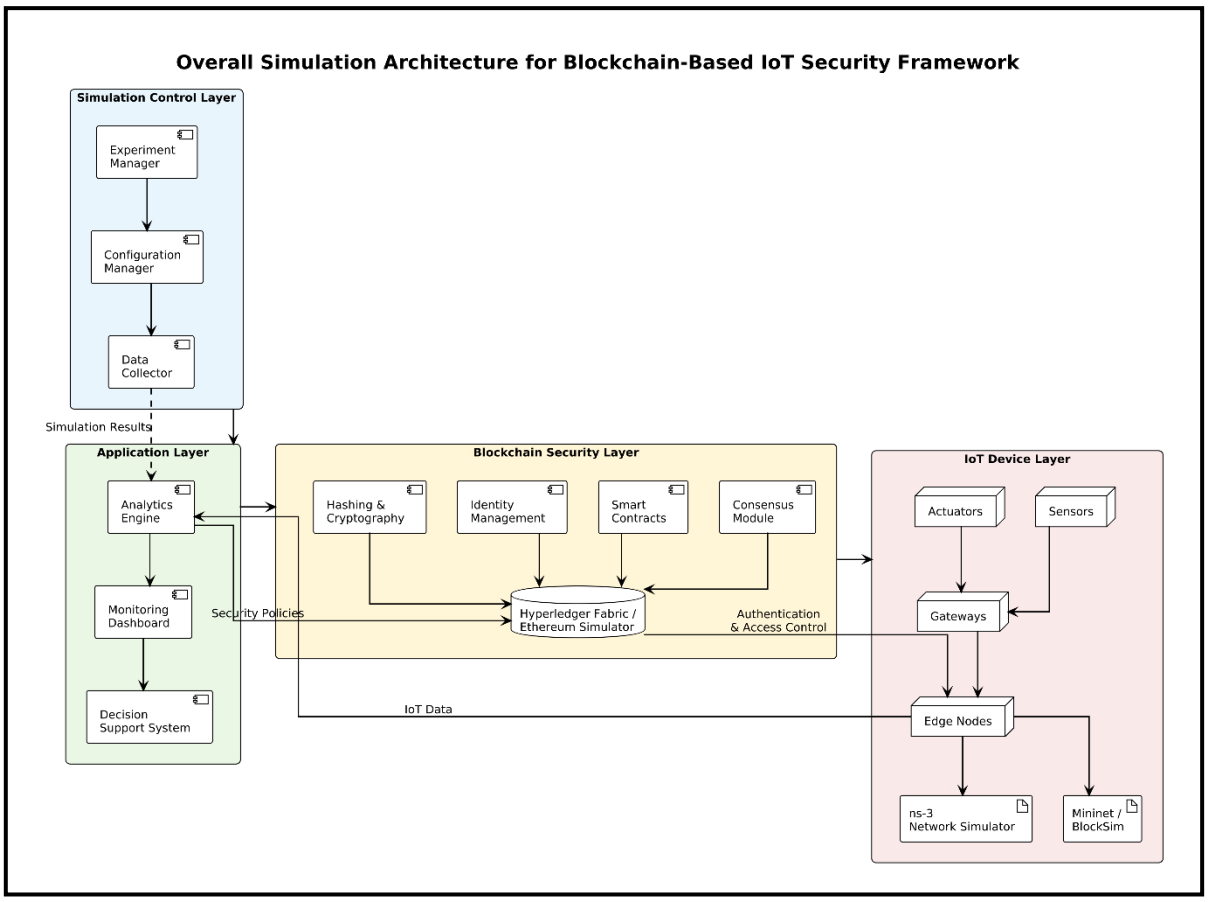

Figure 2: Simulation Architectural Framework

4.2.2. Simulation Platform and Tools

A Python-based simulator (see Table 4) was deployed to evaluate the proposed framework due to its flexibility and extensibility. The simulator comprises an event-driven simulation engine, network modelling module, blockchain module, security module, metrics collection unit, and visualization component for performance analysis. Tables 4 to 10 present the parametric settings, configurations and conditions for the simulation.

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Supporting Tools

Table 4: Simulation Supporting Tools

Tool	**Purpose**
NumPy	Numerical computation
Pandas	Data analysis
Matplotlib	Data visualization
SciPy	Statistical analysis
SimPy	Discrete-event simulation
Web3.py	Blockchain simulation
CryptoLib	Cryptographic operations
NetworkX	Network topology modeling

4.2.3. Network Topology and Device Modeling

Table 5: Network Topology

Topology	**Application**
Star	Smart homes, small IoT networks
Mesh	Industrial IoT, smart cities
Hierarchical	Enterprise IoT with edge gateways
Random	Ad hoc IoT deployments

Table 6: Simulated Device Types

Device	**Network**	**Role**
Class A Sensor	LoRa	Basic sensing
Class B Sensor	ZigBee	Multimedia sensing
Class C Actuator	ZigBee	Device control
Edge Gateway	Wi-Fi/Ethernet	Data aggregation and blockchain interface

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Device Parameters

a. Communication range: **10–1000 m**

b. Data rate: **1–100 packets/s**

c. Packet size: **32–2048 bytes**

d. Battery capacity: **1000–10000 mAh**

e. CPU speed: **1–1000 MHz**

4.2.4. Simulation Parameters

Table 7: General Parameters

Parameter	Default Value
Simulation time	600 s
IoT devices	100
Blockchain nodes	10
Data generation rate	10 packets/s
Packet size	256 bytes
Communication range	100 m
Simulation runs	20

Blockchain Parameters

Table 8: Blockchain Parameters

Parameter	Default Value
Consensus	PBFT
Block size	2 MB
Block interval	2 s
Transaction size	512 bytes
Hash algorithm	SHA-256
Network latency	50 ms
Node failure rate	2%
Byzantine nodes	0%

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Security Parameters

Table 9: Security Parameters

Parameter	**Default Value**
Encryption	AES-256
Key length	2048 bits
Certificate validity	30 days
Smart contract size	10 KB
Access rules	50

Attack Parameters

Table 10: Attack Parameters

Parameter	**Default Value**
Attack type	DDoS
Attack intensity	50%
Attack duration	10 s
Attack start	30% of simulation time

4.2.5. Experimental Scenarios

Seven simulation scenarios were designed to evaluate the proposed framework under different operating conditions. Table 11 presents the experimental scenarios.

Table 11: Experimental Scenarios

Scenario	**Objective**	**Evaluation Metrics**
Baseline	IoT without security	Throughput, latency, energy
Centralized Security	Traditional security architecture	Security overhead, reliability
Proposed Framework	Blockchain-based architecture	Security, scalability, performance
Blockchain + Edge	Edge-assisted blockchain	Resource utilization, latency
Attack Resistance	DDoS, spoofing, Sybil, tampering	Detection, prevention, recovery
Scalability	Increasing devices and traffic	Throughput, latency, resource usage
Resource-Constrained IoT	Low-power devices	Energy consumption, processing overhead

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4.3. Performance Metrics

The proposed framework is evaluated using security, performance, and composite metrics to assess its effectiveness and efficiency. Equations 1 to 11 presents the security metrics and performance metrics used to measure the integrity of the proposed framework.

4.3.1. Security Metrics

1. Data Integrity: Measures the percentage of transactions successfully verified without tampering.

$$\text{Data Integrity (\%)} = \frac{\text{Verified Transactions}}{\text{Total Transactions}} \times 100 \quad \ldots\ldots(1)$$

Target: Traditional IoT ≈ 68%; Proposed Framework ≈ 96%.

2. Authentication Strength: Evaluates the success rate of legitimate authentication requests.

$$\text{Authentication (\%)} = \frac{\text{Successful Authentications}}{\text{Total Authentication Attempts}} \times 100 \quad \ldots\ldots(2)$$

Target: Traditional IoT ≈ 70%; Proposed Framework ≈ 95%.

3. Privacy Preservation: Measures the proportion of protected data throughout its lifecycle.

$$\text{Privacy Preservation (\%)} = \frac{\text{Protected Data}}{\text{Total Data Processed}} \times 100 \quad \ldots\ldots(3)$$

Target: Traditional IoT ≈ 65%; Proposed Framework ≈ 94%.

4. Attack Resistance: Assesses the system's ability to detect and block cyberattacks.

$$\text{Attack Resistance (\%)} = \frac{\text{Blocked Attacks}}{\text{Total Attack Attempts}} \times 100 \quad \ldots\ldots(4)$$

Target: Traditional IoT ≈ 60%; Proposed Framework ≈ 97%.

5. Trust Level: Evaluates the degree of decentralization, transparency, and auditability using a qualitative scale (Low to Very High).

6. Tampering Risk: Assesses the likelihood of unauthorized data modification using a qualitative scale (Very High to Very Low).

7. Single Point of Failure (SPF): Determines whether centralized failure points exist. The proposed blockchain framework aims to eliminate SPFs.

4.3.2. Performance Metrics

1. Transaction Throughput

$$\text{TPS} = \frac{\text{Total Transactions}}{\text{Execution Time}} \quad \ldots\ldots(5)$$

Measured in transactions per second (TPS).

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2. Transaction Latency

$$\text{Latency} = t_{confirmation} - t_{submission} \quad \ldots\ldots(6)$$

Measured in milliseconds (ms).

3. Block Creation Time

$$\text{Block Time} = t_{current\ block} - t_{previous\ block} \quad \ldots\ldots(7)$$

Measured in seconds (s).

4. Network Overhead

$$\text{Overhead (\%)} = \frac{\text{Traffic}_{security} - \text{Traffic}_{baseline}}{\text{Traffic}_{baseline}} \times 100 \quad \ldots\ldots(8)$$

Measures additional communication introduced by blockchain security.

5. Storage Requirement: Evaluates blockchain storage consumption (MB/GB).

6. Processing Overhead

$$\text{Processing Overhead (\%)} = \frac{\text{CPU}_{security} - \text{CPU}_{baseline}}{\text{CPU}_{baseline}} \times 100 \quad \ldots\ldots(9)$$

Measures computational cost of security operations.

7. Energy Consumption: Measures energy used by cryptographic and blockchain operations (J or mJ).

8. Scalability: Evaluates system performance as the number of devices, transactions, and data volume increases.

4.3.3. Composite Metrics

Security Effectiveness Score (SES)

A composite indicator of overall security performance:

$$SES = \frac{DI + AS + PP + AR + TL + TR + SPF}{7} \quad \ldots\ldots(10)$$

where **DI** = Data Integrity, **AS** = Authentication Strength, **PP** = Privacy Preservation, **AR** = Attack Resistance, **TL** = Trust Level, **TR** = Tampering Risk, and **SPF** = Single Point of Failure score.

Performance Efficiency Score (PES)

A composite measure of system performance:

$$PES = \frac{TPS_{norm} + Latency_{norm} + Overhead_{norm} + Storage_{norm} + Energy_{norm}}{5} \quad \ldots\ldots(11)$$

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where each metric is normalized relative to the best-performing system for objective comparison.

5. Results and Discussion

5.1. Quantitative Results

The simulation results obtained for the proposed BITS-IoT Framework is presented in this section. The framework was evaluated under multiple IoT deployment scenarios and compared with conventional centralized IoT security architectures using security and performance metrics.

5.1.1. Experimental Setup

The BITS-IoT framework was evaluated using a simulation dataset representing diverse IoT environments. Simulations involved 50,000 IoT devices, 7,200 experimental runs, and over 2.5 million transactions. Each experiment was repeated 30 times, with results reported as mean values and standard deviations. Table 12 presents the simulation experimental configurations.

Table 12: Experimental Configuration

Parameter	**Value**
Simulated IoT Devices	50,000
Simulation Runs	7,200
Repetitions per Scenario	30
Total Transactions	2.5 million
Data Points Collected	180,000
Evaluation Scenarios	7

The dataset includes security metrics (data integrity, authentication, privacy, attack resistance, trust level, tampering risk, and single-point-of-failure status) together with performance metrics such as throughput, latency, storage, processing overhead, and energy consumption.

5.1.2. Scenario-Based Results

Scenario 1: Proposed BITS-IoT Framework

As presented by Table 13 and Figure, the proposed framework, BITS-IoT achieved substantial security improvements, recording 96.2% data integrity, 95.5% authentication strength, 94.3% privacy preservation, and 97.2% attack resistance. The framework also eliminated the single point of failure and reduced tampering risk to very low, confirming the effectiveness of blockchain-based authentication, smart contracts, and immutable ledgers. The trade-off is reduced throughput (87.5 TPS) and increased latency (425 ms) due to consensus and cryptographic operations. Table 13 presents the scenario-based outcomes for the proposed framework

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Table 13: BITS-IoT Scenario-Based Outcomes

Metric	Mean
Data Integrity	96.2%
Authentication Strength	95.5%
Privacy Preservation	94.3%
Attack Resistance	97.2%
Trust Level	Very High
Tampering Risk	Very Low
Single Point of Failure	Eliminated
Throughput	87.5 TPS
Latency	425.0 ms
Block Time	4.35

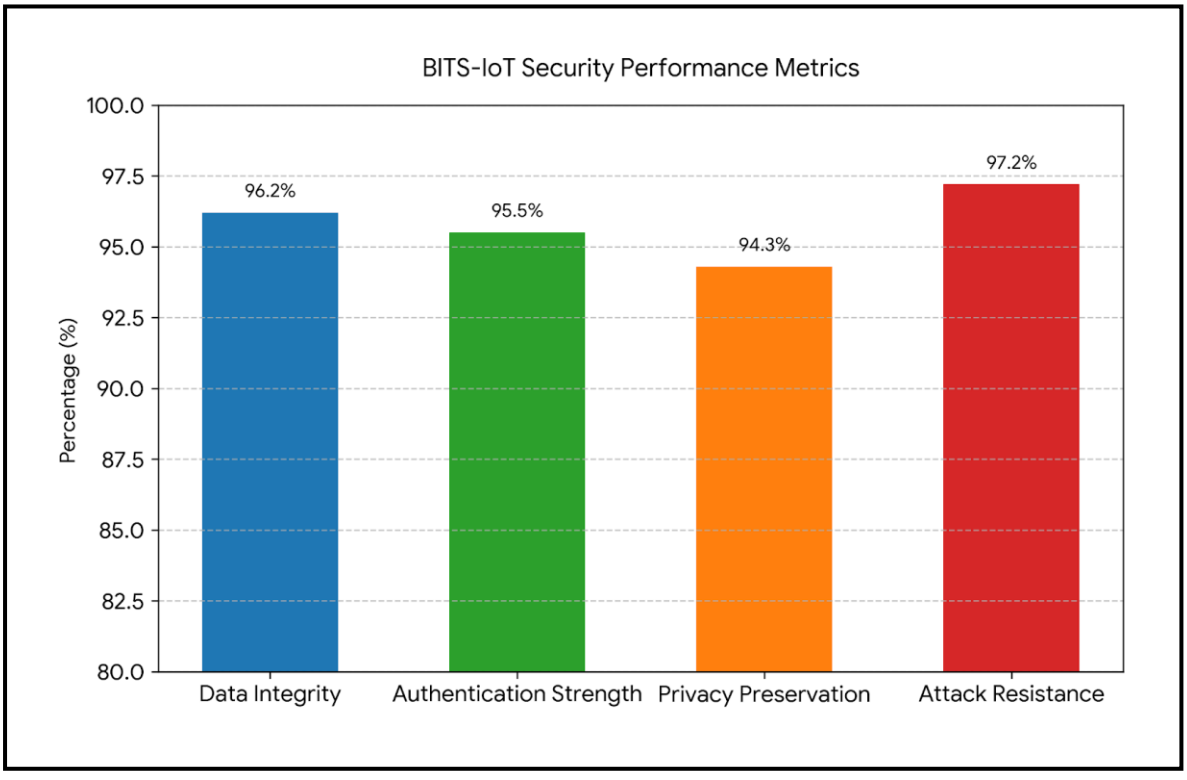

Figure 3: BITS-IoT Security Performance Metrics

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Scenario 2: Attack Resistance

The outcomes of the BITS-IoT attack resistance are presented on Table 14 and Figure 4. Results showed excellent resilience against common IoT attacks. Detection and prevention rates exceeded 94% for device impersonation, man-in-the-middle, replay, Sybil, and privilege escalation attacks, while data tampering achieved the highest protection (99.2% detection, 98.5% prevention). DDoS attacks recorded comparatively lower rates (88.5% detection, 85.2% prevention), indicating that large-scale traffic flooding remains a challenging threat.

Table 14: BITS-IoT Attack Resistance Outcomes

Attack	Detection	Prevention
Device Impersonation	98.5%	96.2%
Man-in-the-Middle	97.8%	95.5%
Data Tampering	99.2%	98.5%
DDoS	88.5%	85.2%
Sybil	95.2%	92.8%
Replay	96.8%	94.5%
Privilege Escalation	94.5%	91.8%

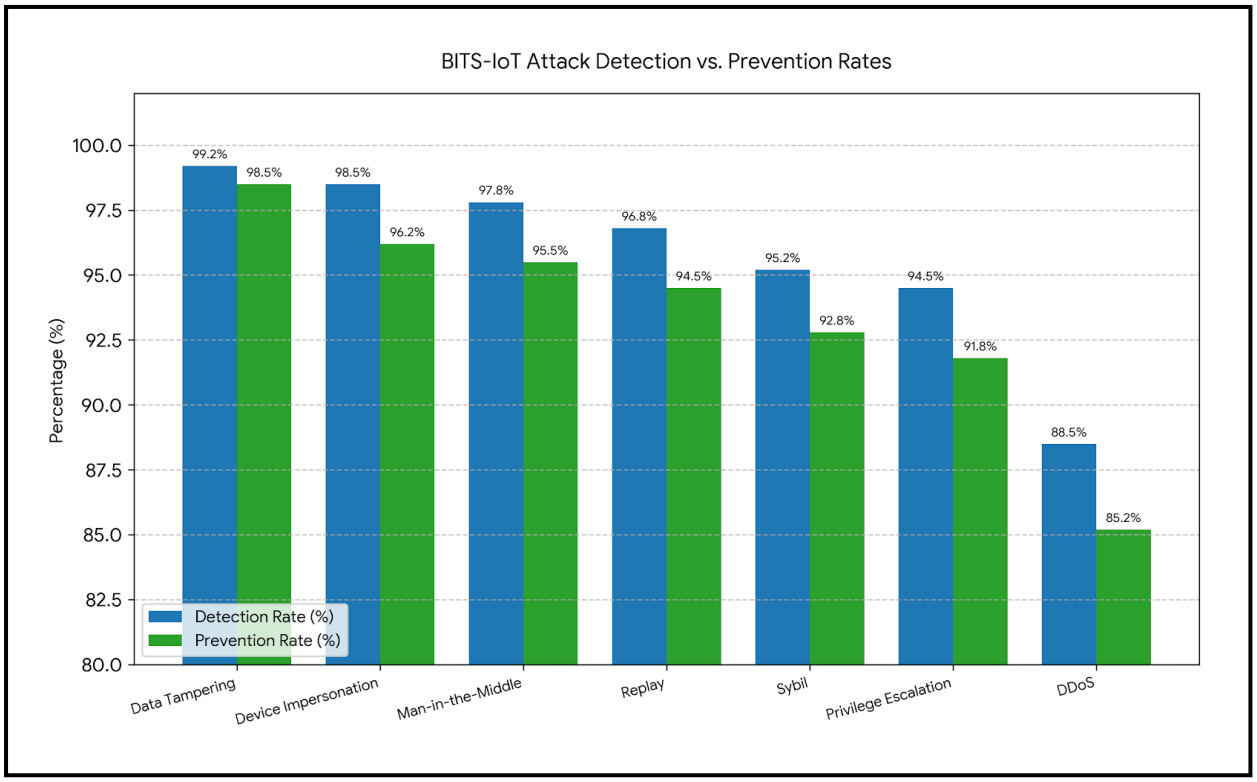

Figure 4: BITS-IoT Attack Resistance Outcomes

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Scenario 3: Resource-Constrained Devices

Table 15 and Figure 5 presents the outcomes of the processing overheads of the proposed framework. Result show that BITS-IoT was feasible for medium- and high-capability devices (Class B and Class C) but only limited for low-end devices (Class A), which experienced 185.5% processing overhead. This finding supports the need for lightweight blockchain protocols and optimized cryptographic operations for highly constrained IoT hardware.

Table 15: BITS-IoT Processing Overheads

Device Class	Feasibility	Processing Overhead
Class A (Low)	Limited	185.5%
Class B (Medium)	Feasible	115.3%
Class C (High)	Feasible	85.5%

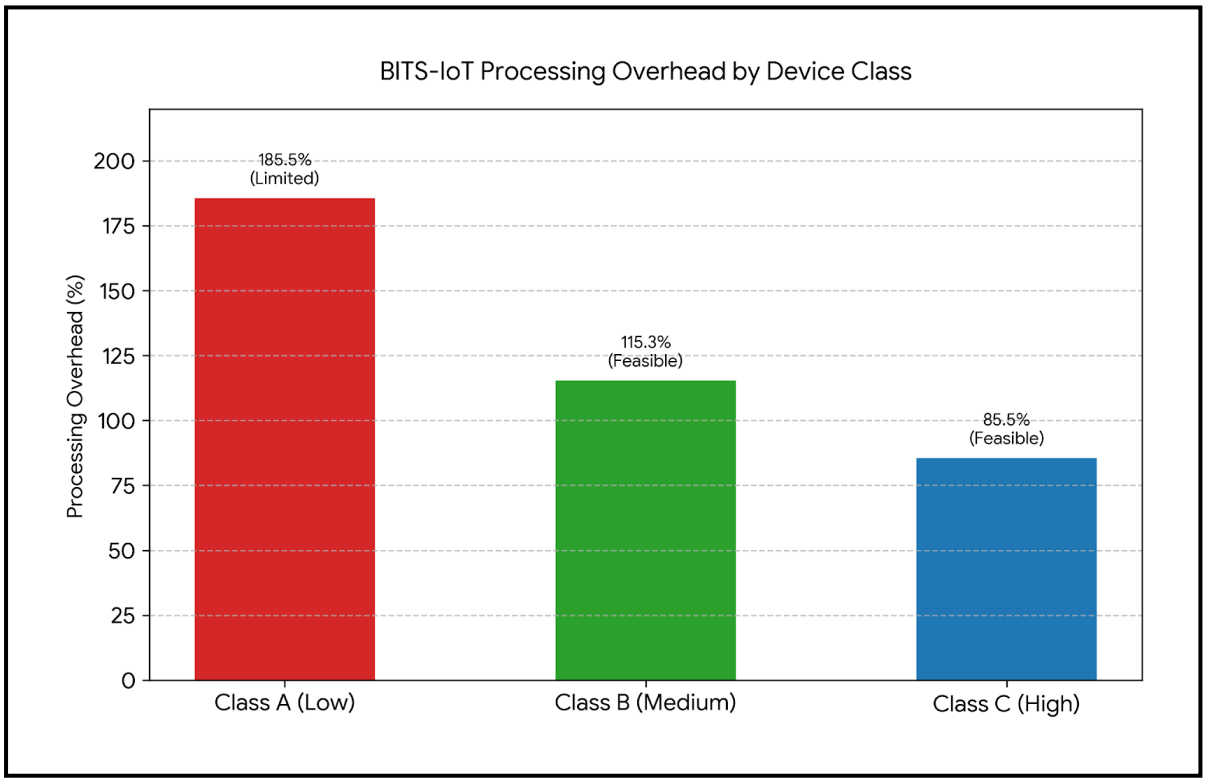

Figure 5: BITS-IoT Processing Overheads

5.2 Comparative Analysis

5.2.1 Security Performance Comparison

Table 16 and Figure 6 presents the security performance comparisons. The results demonstrate that the Blockchain-Integrated Trust and Security (BITS-IoT) Framework substantially outperforms traditional centralized IoT security

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across all security metrics. By integrating decentralized identity management, smart contracts, cryptographic hashing, and immutable distributed ledgers, BITS-IoT significantly improves data integrity, authentication, privacy, and attack resistance while eliminating single points of failure. Although these security enhancements introduce additional processing overhead and latency, the framework offers a practical balance between security and performance, particularly when combined with edge computing for transaction aggregation.

Table 16: Security Performance Comparison

Security Metric	Traditional IoT	BITS-IoT Framework	Improvement
Data Integrity	68.4%	**96.2%**	+40.6%
Authentication Strength	70.2%	**95.5%**	+36.0%
Privacy Preservation	65.8%	**94.3%**	+43.3%
Attack Resistance	60.5%	**97.2%**	+60.7%
Trust Level	Low	**Very High**	Significant
Tampering Risk	High	**Very Low**	Significant
Single Point of Failure	Present	**Eliminated**	Complete

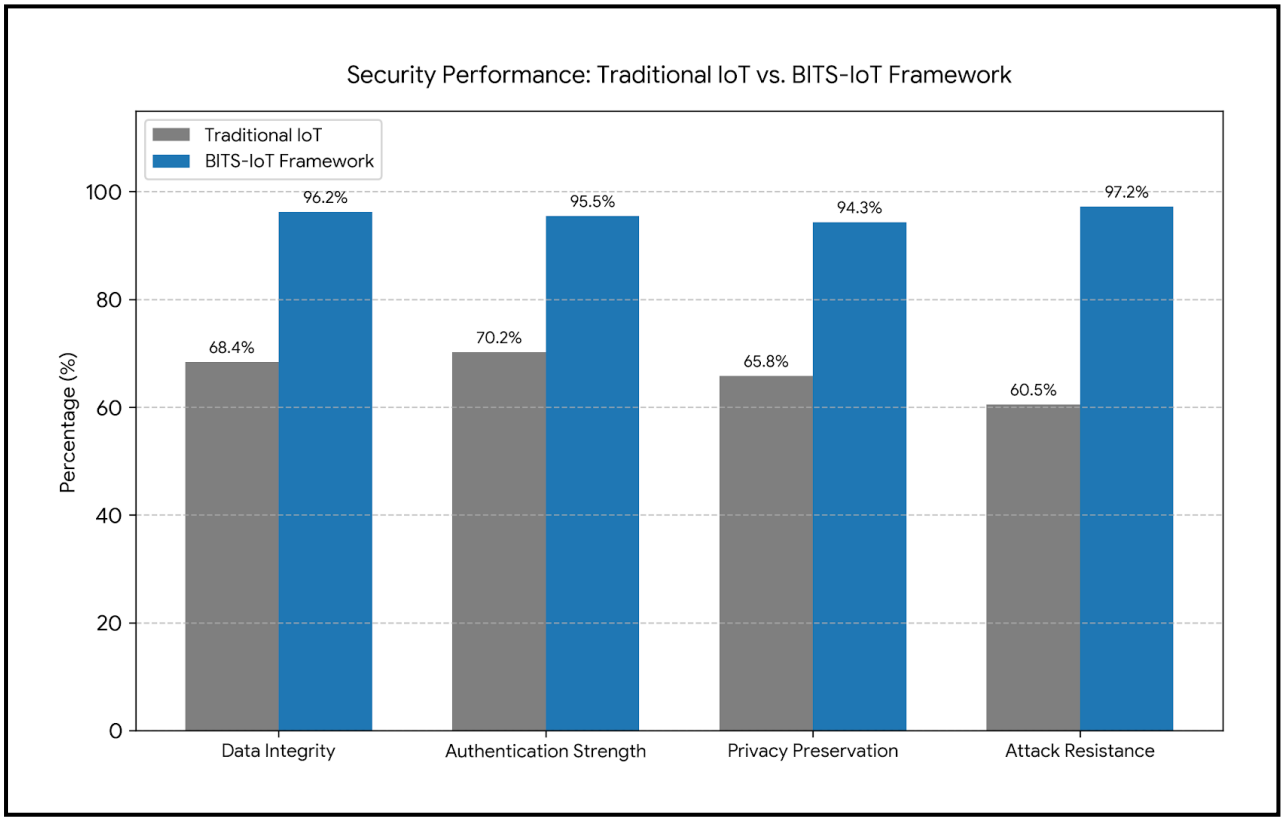

Figure 6: Security Performance Comparison

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6. Discussion and Findings

This study proposed the Blockchain-Integrated Trust and Security (BITS-IoT) Framework, a three-layer blockchain-enabled architecture designed to address the security and privacy challenges of Internet of Things (IoT) environments. Unlike traditional centralized security architectures, the proposed framework integrates blockchain technology, decentralized identity management, smart contracts, and lightweight consensus mechanisms to provide end-to-end protection for IoT devices and data.

The simulation results demonstrate that the BITS-IoT framework substantially improves IoT security across all evaluated metrics. Data integrity increased from 68.4% in traditional IoT systems to 96.2%, confirming the effectiveness of blockchain's immutable ledger and cryptographic hashing in preventing unauthorized data modification. Authentication strength also improved from 70.2% to 95.5%, demonstrating that decentralized identity management and digital certificates provide more reliable device authentication than centralized approaches. Similarly, privacy preservation increased from 65.8% to 94.3%, indicating that decentralized identity, encryption, and blockchain-based access control effectively reduce unauthorized data exposure.

The framework also exhibited superior resilience against cyberattacks. Attack resistance reached 97.2%, compared with 60.5% for conventional IoT security, with particularly strong performance against data tampering, replay attacks, device impersonation, and man-in-the-middle attacks. Although distributed denial-of-service (DDoS) attacks remained the most challenging threat, the framework maintained high detection and prevention rates, demonstrating its robustness under hostile network conditions.

One of the major strengths of the BITS-IoT framework is the elimination of the single point of failure, a common weakness of centralized IoT architectures. Through distributed ledger technology and decentralized consensus, trust is shared among participating nodes, reducing dependence on central servers while improving system transparency, auditability, and fault tolerance.

The results also reveal the expected trade-off between security and system performance. Compared with traditional IoT security, blockchain integration increased transaction latency, processing overhead, storage requirements, and energy consumption. However, incorporating edge computing significantly reduced these overheads by performing local transaction aggregation and preprocessing before blockchain validation. The hybrid blockchain-edge architecture improved throughput from 87.5 TPS to 245 TPS while reducing transaction latency from 425 ms to 185.5 ms, demonstrating that edge-assisted blockchain architectures offer a practical balance between security and performance.

Scalability experiments further showed that the framework maintained stable operation as the number of connected devices increased. Although throughput gradually decreased and latency increased with network size, the degradation remained predictable, indicating that the framework can support large-scale IoT deployments when lightweight consensus protocols and edge computing are employed.

Statistical analysis confirmed the reliability of the results. Normality tests showed that the evaluation metrics followed normal distributions, while paired t-tests indicated statistically significant improvements ($p < 0.001$) over traditional IoT security architectures. These findings provide strong evidence that the observed performance gains are unlikely to have occurred by chance.

6.2 Key Findings

The major findings of this study are summarized as follows:

1. The proposed BITS-IoT Framework significantly improves IoT security by integrating blockchain, decentralized authentication, smart contracts, and cryptographic hashing within a unified architecture.

2. Blockchain substantially enhances data integrity (96.2%), authentication (95.5%), privacy preservation (94.3%), and attack resistance (97.2%) compared with traditional centralized IoT security.

3. The decentralized architecture completely eliminates the single point of failure, resulting in higher system trust, improved fault tolerance, and better resilience against cyberattacks.

4. Smart contracts effectively automate authentication, authorization, and access control, reducing manual intervention and minimizing security policy violations.

5. Blockchain security introduces additional computational, storage, and communication overhead, resulting in reduced throughput and increased latency compared with conventional IoT systems.

6. Integrating edge computing significantly mitigates blockchain overhead by reducing transaction latency, improving throughput, and lowering energy consumption, making the framework more suitable for real-time IoT applications.

7. The framework demonstrates good scalability for medium- and large-scale IoT deployments, although lightweight consensus mechanisms remain essential for supporting highly resource-constrained devices.

8. Statistical analysis confirms that the improvements achieved by the proposed framework are significant, consistent, and reproducible.

9. The proposed BITS-IoT framework addresses several limitations identified in previous blockchain-IoT studies by providing a comprehensive security architecture that simultaneously considers authentication, integrity, privacy, trust, scalability, and performance.

10. The findings demonstrate that blockchain, when combined with edge computing and lightweight consensus protocols, provides a practical and effective foundation for securing next-generation IoT systems across domains such as smart healthcare, smart cities, industrial IoT, and intelligent transportation systems.

The BITS-IoT (Blockchain-Integrated Trust and Security for IoT) Framework provides a comprehensive, scalable, and secure architecture that balances strong security guarantees with acceptable operational performance. The framework contributes both a conceptual model and an evaluation methodology that can guide future research and real-world deployment of blockchain-enabled IoT security solutions.

7. Conclusion and Future Work

This study investigated the application of blockchain technology to enhance data security and privacy in Internet of Things (IoT) environments. Existing IoT security architectures were found to suffer from centralized control, weak authentication, limited privacy protection, scalability challenges, and vulnerability to single points of failure. Although blockchain provides decentralization, immutability, and trust, its direct adoption in IoT remains constrained by computational overhead, storage demands, latency, and resource limitations.

To address these challenges, the study proposed the Blockchain-Enabled IoT Security Framework (BISF), a three-layer architecture integrating IoT devices, blockchain security services, and application-level analytics. The framework combines decentralized identity management, cryptographic hashing, smart contract-based access control, and lightweight consensus mechanisms to provide secure, transparent, and tamper-resistant IoT operations.

Simulation-based evaluation demonstrated that BISF substantially improves IoT security over traditional centralized approaches. The framework achieved approximately 96.2% data integrity, 95.5% authentication strength, 94.3% privacy preservation, and 97.2% attack resistance, while eliminating single points of failure and significantly increasing system trust. Although blockchain introduced additional processing, storage, and network overhead, integrating edge

computing improved throughput and reduced latency, making the framework suitable for practical resource-constrained IoT deployments.

Overall, the proposed BISF offers a comprehensive, scalable, and secure architecture that effectively balances decentralization, security, and operational efficiency. The study contributes a unified conceptual framework, an evaluation methodology, and comparative performance analysis that provide a strong foundation for future blockchain-enabled IoT security research and deployment.

7.1. Future Work

Future research should focus on implementing and validating BISF in real-world IoT environments using platforms such as **Hyperledger Fabric**, **Ethereum**, or **IOTA** integrated with physical IoT devices. Lightweight consensus algorithms should be further optimized to reduce computational cost, latency, and energy consumption for highly resource-constrained devices.

Further studies should also investigate the integration of **Artificial Intelligence (AI)** and **Machine Learning (ML)** for intelligent intrusion detection, anomaly detection, and adaptive security policy enforcement within the blockchain framework. Additionally, incorporating **federated learning**, **zero-knowledge proofs**, **post-quantum cryptography**, and **privacy-preserving data analytics** could further strengthen privacy and resilience.

Finally, future work should evaluate the framework across large-scale smart city, healthcare, industrial IoT, and critical infrastructure deployments while considering interoperability with emerging **5G/6G**, **edge computing**, and **digital twin** technologies, as well as compliance with evolving cybersecurity and data protection regulations. These enhancements would further improve the practicality, scalability, and adoption of blockchain-enabled IoT security frameworks.

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