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A Comprehensive Literature Review on Blockchain-Based Security and Privacy Models for IoT using Consortium Architecture

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Abstract

The convergence of Blockchain and the Internet of Things (IoT) introduces a promising paradigm for securing distributed, resource-constrained environments. This literature review provides a comprehensive analysis of blockchain-enabled architectures aimed at enhancing the security, privacy, and performance of IoT systems, with a particular focus on consortium blockchains. Traditional IoT frameworks are plagued by centralized control, lack of trust, metadata exposure, and limited scalability—issues that decentralized ledger technologies inherently address. The review systematically examines privacy-preserving technologies such as Zero-Knowledge Proofs, homomorphic encryption, and decentralized identity frameworks. It evaluates consensus algorithms across performance and adversary tolerance metrics, identifying layered and hybrid models as essential for real-time IoT scenarios. Smart contracts and decentralized storage technologies, including IPFS and PGP, are assessed for their roles in enforcing secure, transparent, and auditable data access. Moreover, the paper highlights research gaps in lightweight blockchain frameworks, metadata protection, and cross-chain interoperability. Future directions include integrating AI-driven contract automation, federated learning under privacy-preserving constraints, post-quantum cryptographic protocols, and regulatory-compliant architectures aligned with GDPR and ISO/IEC standards. Through this review, it becomes evident that the fusion of blockchain with IoT demands not only technical innovation but also legal and ethical foresight to ensure scalable, secure, and trustworthy next-generation cyber-physical systems.

Keywords: Blockchain, Internet of Things (IoT), Consortium Blockchain, Privacy Preservation, Smart Contracts, Metadata Security, Consensus Mechanisms, Federated Learning, Post-Quantum Cryptography, IPFS, GDPR, Decentralized Identity, Web3, Digital Twin, Zero-Knowledge Proof, Edge Computing, Interoperability, Layered Consensus, Smart Governance, Decentralized Storage

1. Introduction

The **Internet of Things (IoT)** represents a revolutionary paradigm that integrates physical objects with digital systems via embedded sensors, actuators, and communication modules, enabling real-time monitoring, analysis, and automation across domains such as healthcare, transportation, energy, and manufacturing [1][2]. According to recent projections, the global IoT device count is expected to surpass 29 billion by 2030, generating an estimated 79.4 zettabytes of data annually [3]. While this interconnected fabric enhances operational efficiency and data-driven decision-making, it simultaneously introduces a broad spectrum of security, privacy, and trust challenges.

1.1 Security and Privacy Challenges in IoT

IoT ecosystems are inherently vulnerable due to their heterogeneity, constrained computational resources, decentralized topologies, and exposure to open communication environments [4][5]. Attack vectors such as eavesdropping, man-in-the-middle (MITM) attacks, malicious firmware injection, and device spoofing are increasingly common, especially in critical infrastructure environments [6][7]. Moreover, traditional client-server security models are insufficient in ensuring end-to-end integrity, confidentiality, and availability in a distributed IoT landscape [8] (Figure 1.1).

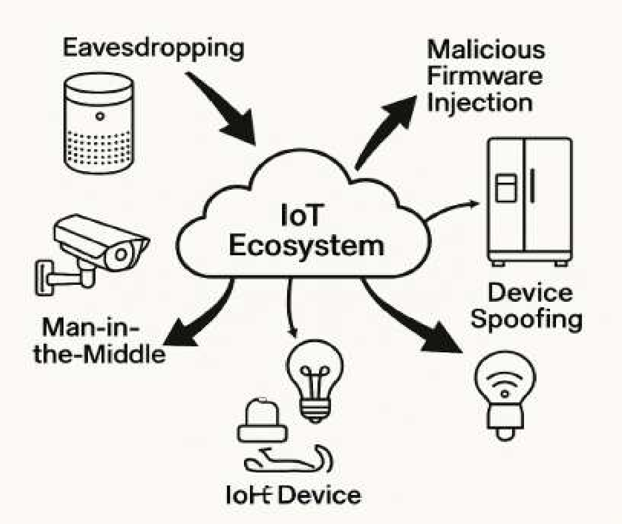


Figure 1.1: IoT Attack Surface and Threat Vectors

Compounding this issue is the lack of standardized security protocols across devices, resulting in fragmented security postures. Privacy becomes an even more complex issue in light of regulatory frameworks such as GDPR, CCPA, and HIPAA, which mandate data minimization, user consent, and the right to erasure—all difficult to implement in dynamic, sensor-rich environments [9][10].

1.2 Blockchain as a Transformative Solution

To mitigate the above issues, blockchain technology has emerged as a robust framework that provides decentralization, transparency, tamper-resistance, and cryptographic security [11]. Introduced by Nakamoto in 2008, blockchain operates as a distributed ledger where transactions are validated through consensus and stored immutably across network nodes [12]. These characteristics are ideal for resolving trust management, data integrity, access control, and device authentication in IoT networks [13] (Figure 1.2).

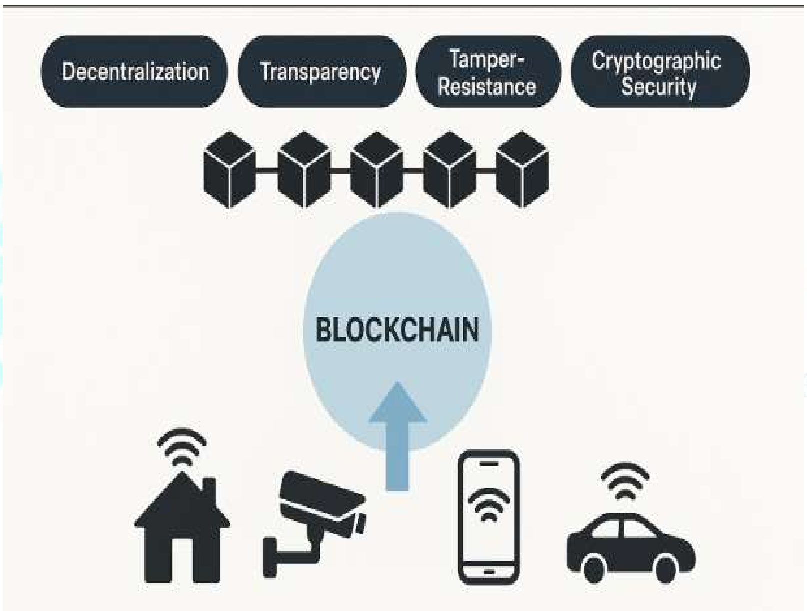


Figure 1.2: IoT + Blockchain Security Overlay

Smart contracts—self-executing code deployed on the blockchain—further enable automation and policy enforcement in data exchanges without relying on centralized intermediaries [14]. Platforms like Ethereum, Hyperledger Fabric, and Quorum have shown success in pilot projects across healthcare, supply chain, and industrial IoT [15].

1.3 Limitations of Public and Private Blockchain in IoT

Despite blockchain's potential, public blockchains (e.g., Bitcoin, Ethereum) suffer from high latency, low throughput, and energy inefficiency, primarily due to Proof of Work (PoW)-based consensus

[16][17]. These issues make them unsuitable for latency-sensitive and resource-constrained IoT applications.

On the other hand, private blockchains offer better performance but lack decentralization and resilience against single points of failure [18]. They are typically controlled by a single authority, undermining the trustless nature of blockchain and creating vulnerabilities to internal compromise (Figure 1.3).

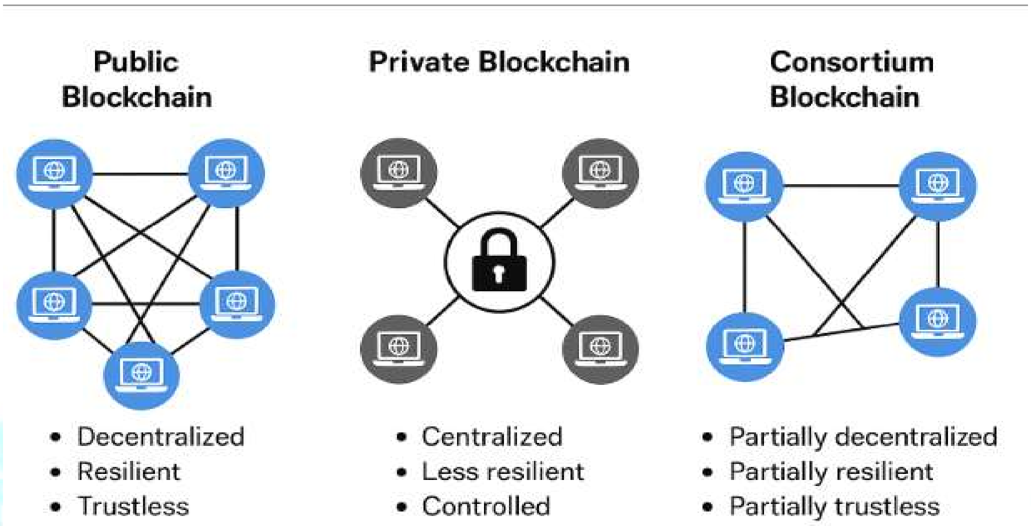


Figure 1.3: Comparison of Public, Private, and Consortium Blockchains

Table 1.1: Comparison of Public, Private, and Consortium Blockchains

Feature	**Public Blockchain**	**Private Blockchain**	**Consortium Blockchain**
Access Control	Open	Restricted	Semi-Restricted
Throughput	Low	High	Moderate to High
Decentralization	High	Low	Balanced
IoT Suitability	Poor	Medium	High

1.4 Consortium Blockchain: A Balanced Approach

Consortium blockchains provide a middle ground between public and private models. Operated by a preselected group of validators (e.g., businesses, institutions), consortium blockchains ensure controlled access, improved scalability, and customizable privacy levels, making them highly compatible with IoT systems [19][20].

For example, Hyperledger Fabric utilizes Practical Byzantine Fault Tolerance (PBFT) and pluggable consensus modules, enabling fine-grained permissioning and faster transaction finality [21]. Similarly, MultiChain and Quorum offer privacy-preserving smart contracts and rapid transaction processing, making them suitable for federated IoT applications [22] (Figure 1.4).

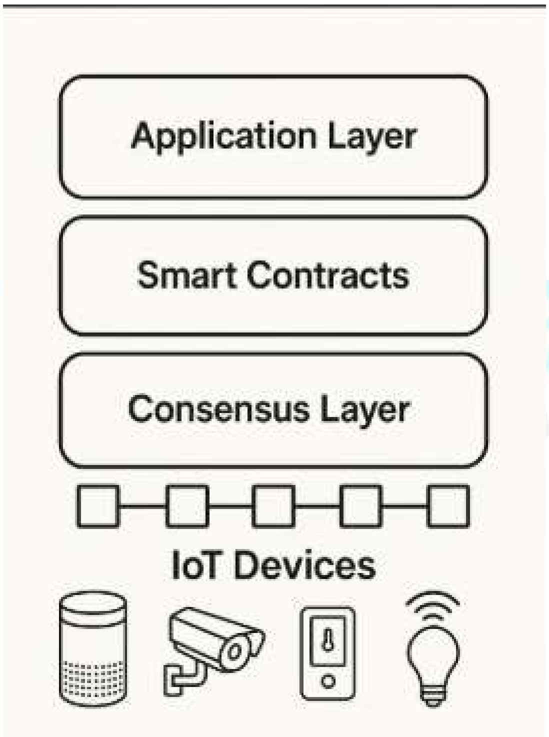


Figure 1.4: Layered Consortium Blockchain for IoT

Emerging designs even propose multi-tiered consensus combining local edge consensus with global chain finality, aiming to improve both energy efficiency and decentralization [23].

2. Background and Theoretical Foundations

2.1 Internet of Things (IoT): Architecture and Challenges

The Internet of Things (IoT) represents an interconnected network of smart physical devices embedded with sensors, software, and connectivity, capable of collecting, transmitting, and acting upon data in real-time. These devices operate in constrained environments where memory, bandwidth, energy, and processing power are inherently limited [24]. IoT ecosystems span multiple application domains such as smart healthcare, intelligent transport systems, smart agriculture, and industrial automation (IIoT) [25].

IoT architecture typically follows a three-layered model: Perception, Network, and Application layers. The Perception Layer includes physical sensors and actuators. The Network Layer transmits data, often via wireless protocols like Zigbee, LoRa, or NB-IoT. The Application Layer provides end-user services (Figure 2.1).

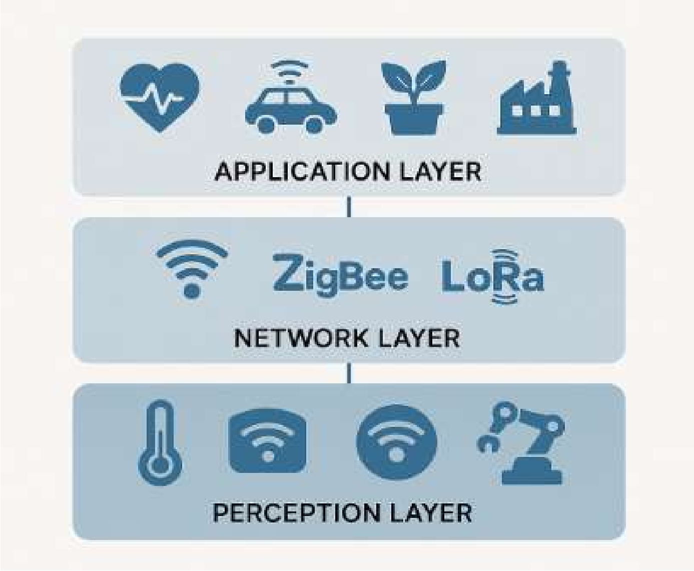


Figure 2.1: IoT Layered Architecture

However, this architecture suffers from significant vulnerabilities due to the centralized nature of data handling and storage, lack of end-to-end encryption, and reliance on third-party trust. Attack surfaces include man-in-the-middle attacks, eavesdropping, node spoofing, and DDoS [26][27].

2.2 Blockchain Technology: Fundamentals and Evolution

Blockchain, introduced through Bitcoin by Nakamoto in 2008, is a distributed ledger technology (DLT) enabling tamper-resistant and verifiable transactions without central intermediaries [28]. It comprises blocks of transactions linked cryptographically via hashes, validated through consensus algorithms like Proof-of-Work (PoW), Proof-of-Stake (PoS), and Byzantine Fault Tolerance (BFT) variants [29].

Over time, blockchain has evolved through three generations:

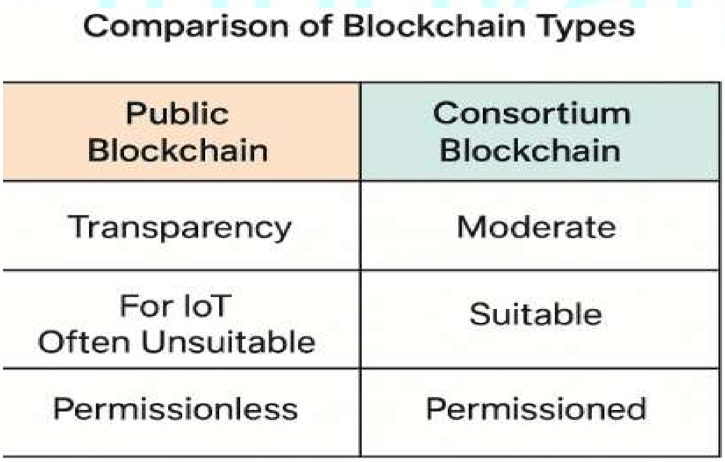
- **Blockchain 1.0**: Cryptocurrency focus (e.g., Bitcoin)
- **Blockchain 2.0**: Smart contract integration (e.g., Ethereum)
- **Blockchain 3.0**: Decentralized applications (DApps), interoperability, and IoT integration [30]

The core attributes of blockchain—immutability, transparency, decentralization, and pseudonymity—make it a viable candidate for strengthening IoT systems against internal and external threats [31].

2.3 Consortium Blockchain: A Permissioned Model for IoT

While public blockchains (e.g., Ethereum) offer high transparency, they are often unsuitable for IoT due to computational overhead and latency. Consortium blockchains—a form of permissioned blockchain governed by a group of predefined nodes—offer a balanced solution between decentralization and performance [32].

In consortium blockchains like Hyperledger Fabric and MultiChain, access is restricted to authenticated participants. This model significantly reduces consensus latency, enhances throughput, and supports customizable privacy controls—attributes well-aligned with IoT constraints [33][34] (Figure 2.2).



Comparison of Blockchain Types

Public Blockchain	Consortium Blockchain
Transparency	Moderate
For IoT Often Unsuitable	Suitable
Permissionless	Permissioned

Figure 2.2: Comparison of Blockchain Types

Table 2.1: Comparison of Blockchain Types

Feature	Public Blockchain	Private Blockchain	Consortium Blockchain
Access Control	Open	Restricted	Partially Restricted

Feature	**Public Blockchain**	**Private Blockchain**	**Consortium Blockchain**
Consensus Type	PoW, PoS	Central Authority	PBFT, RAFT
Throughput	Low	High	Moderate to High
Use in IoT	Poor fit	Moderate	Best fit

2.4 Consensus Algorithms: Suitability for IoT

Consensus mechanisms are critical in ensuring trust and agreement in distributed systems. Traditional algorithms like PoW are energy-intensive and not feasible for IoT. More lightweight alternatives like PBFT, dPBFT, and PoET are more compatible with constrained environments [35][36] (Figure 2.3).

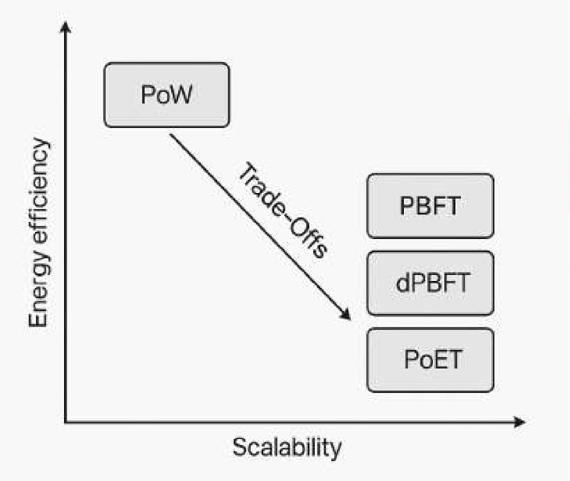


Figure 2.3: Consensus Mechanisms and Their Trade-Offs

Table 2.2: Consensus Algorithm Comparison for IoT

Consensus	**Latency**	**Throughput**	**Energy Efficiency**	**Fault Tolerance**	**IoT Suitability**
PoW	High	Low	Poor	<33% adversary	✗
PoS	Medium	Medium	Good	<51% stake	✗
PBFT	Low	High	Excellent	<33% replicas	✓

Consensus	Latency	Throughput	Energy Efficiency	Fault Tolerance	IoT Suitability
dPBFT	Low	High	Excellent	<35% replicas	✓✓
PoET	Low	High	Excellent	Trusted Enclave	✓✓✓

Recent innovations, like HotStuff (used in Diem) and Tendermint BFT (used in Cosmos), are being evaluated for their low-latency, high-throughput properties suitable for IoT systems [37][38].

2.5 Metadata and Privacy: The Hidden Risk in IoT Systems

While payload data is often encrypted in IoT systems, metadata—including device identity, location, and timestamps—remains exposed and vulnerable to inference attacks [39]. Studies show that compromised metadata can allow attackers to reconstruct device behavior, communication patterns, and even spoof device identities [40].

Blockchain's hash-based data integrity can be extended to metadata, but doing so raises challenges in balancing anonymity, traceability, and access control. Solutions such as hierarchical metadata models, attribute-based encryption, and zero-knowledge proofs (ZKP) are being researched for this purpose [41][42](Figure 2.4).

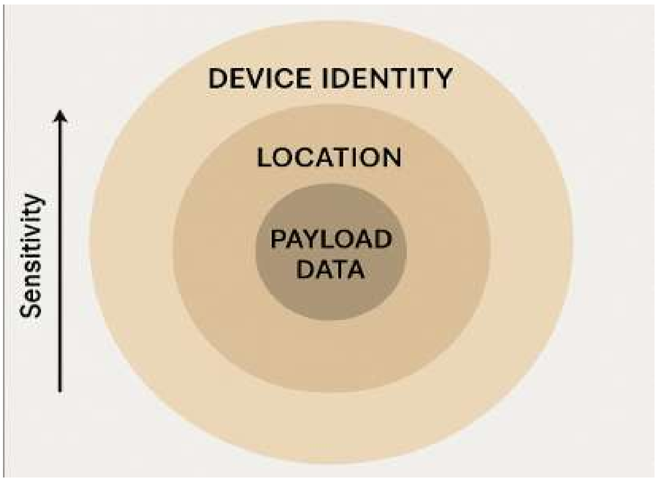


Figure 2.4: Metadata Sensitivity Levels in IoT

2.6 Smart Contracts and Edge-Based Off-Chain Computation

Smart contracts are self-executing programs deployed on the blockchain to automate rules and agreements. Languages such as Solidity, Chaincode, and Michelson are used across various platforms like Ethereum, Hyperledger, and Tezos [43]. In IoT, contracts automate data access control, payment for resource usage, or ownership transfer [44].

To address the scalability bottleneck, edge-based solutions like Ethereum Plasma or rollups process transactions off-chain and commit summaries on-chain. This hybrid model significantly reduces computational strain on IoT devices [45](Figure 2.5).

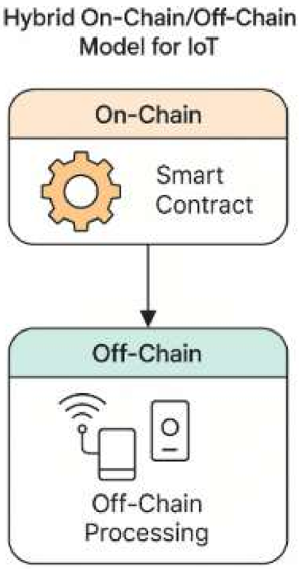


Figure 2.5: Hybrid On-Chain/Off-Chain Model for IoT

2.7 IPFS and Decentralized Storage Integration

Traditional cloud storage in IoT presents risks of data tampering and privacy breaches. InterPlanetary File System (IPFS) offers content-addressed, decentralized file storage where data integrity is ensured by cryptographic hashes [46].

Combining IPFS with blockchain (e.g., using hash pointers) decouples data from its hosting location, reducing central point of failure risks. When integrated with Pretty Good Privacy (PGP) encryption, this model ensures end-to-end confidentiality [47].

3. Internet of Things (IoT) systems using blockchain technologies

Securing Internet of Things (IoT) systems using blockchain technologies, with a focus on consortium blockchain architectures. The discussion is structured thematically to reflect the multidimensional challenges and technological approaches in recent literature.

3.1 Blockchain for IoT Privacy & Security

Ensuring privacy and data security is a foremost concern in IoT ecosystems. Traditional approaches rely heavily on centralized cloud-based infrastructure, which is vulnerable to single points of failure and targeted attacks [48]. Blockchain, particularly in permissioned or consortium configurations, offers a promising alternative through its decentralization, auditability, and cryptographic guarantees.

Omar et al. [49] proposed a privacy-friendly platform for healthcare data management using a blockchain-based environment. The authors emphasized the pseudonymization of patient identities and encrypted storage, thereby safeguarding against privacy breaches in cloud repositories. Similarly, Mamun and Khan [50] presented a mutual exclusion protocol combining IoT and blockchain to ensure safety in industrial applications. Their work incorporated consensus resolution mechanisms suited for multi-user environments with minimal resource contention.

Recent advancements have integrated Zero-Knowledge Proofs (ZKPs) and homomorphic encryption to elevate privacy-preservation. ZKPs allow a party to prove possession of certain data without revealing it, making them ideal for IoT data validation in sensitive domains such as healthcare or smart surveillance [51][52]. Homomorphic encryption facilitates computations on encrypted data, enabling secure analytics without decrypting IoT payloads [53](Figure 3.1).

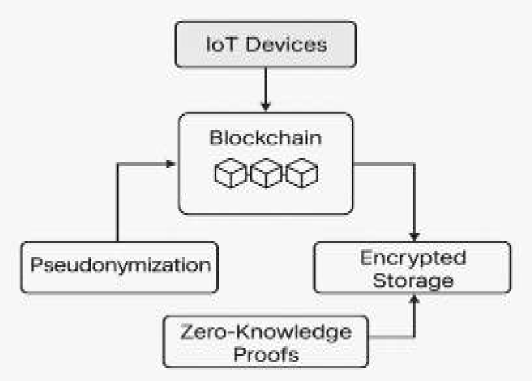


Figure 3.1: Blockchain-enabled Privacy Model for IoT

3.2 Smart Contracts and Secure Transactions

Smart contracts—self-executing codes deployed on the blockchain—serve as trustless agents for automating IoT services. Ethereum remains the dominant platform, using Solidity and Serpent for smart contract development [54]. Smart contracts help enforce data sharing agreements, automate billing, or validate ownership transfer without third-party intermediaries [55].

Xu et al. [56] classified blockchain systems by their support for programmable logic and categorized vulnerabilities that affect integrity, such as reentrancy bugs, timestamp dependencies, and denial-of-service loops. These flaws are particularly critical in IoT scenarios involving autonomous machine-to-machine (M2M) operations, where a faulty contract can cascade into systemic failures.

To mitigate risks, formal verification of smart contracts is gaining traction. Tools like Mythril, Oyente, and CertiK offer static analysis for vulnerability detection [57]. Moreover, domain-specific languages such as DAML and Pact are emerging, offering more concise syntax and built-in safeguards for contract correctness [58] (Figure 3.2).

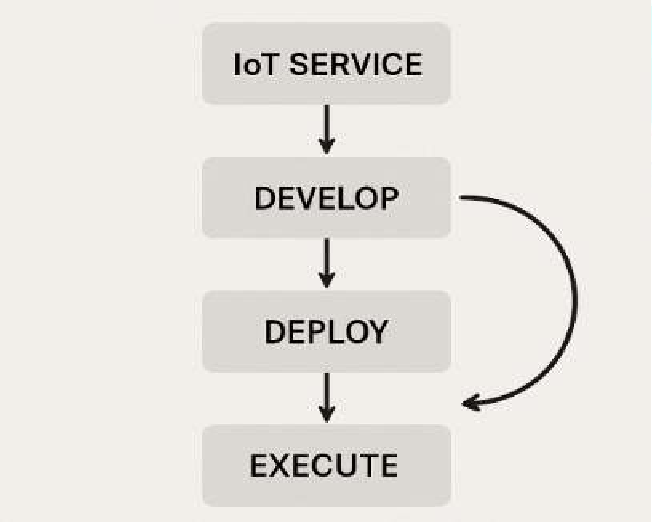


Figure 3.2: Smart Contract Lifecycle in IoT Ecosystem

3.3 Blockchain for Metadata Protection

IoT metadata—including timestamps, location coordinates, and device configuration—can be exploited to infer user behavior or spoof legitimate devices. Zhou et al. [59] demonstrated how unprotected metadata enables adversaries to reconstruct environmental context from raw sensor logs. Trivedi et al. [60] used relational clustering to classify metadata sensitivity in self-healing IoT environments.

Blockchain ensures metadata integrity through hash-based validation, but encryption and access control mechanisms must be layered for full protection. Hierarchical models segment metadata into basic, file-level, and contextual categories, each with distinct encryption and access requirements [61](Figure 3.3).

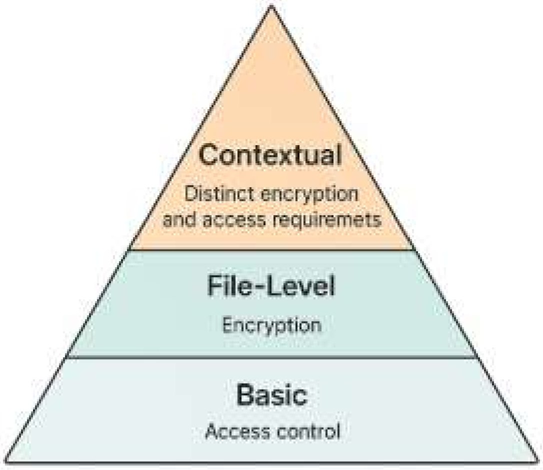


Figure 3.3: Hierarchical Metadata Security Architecture

3.4 Decentralized Storage and Data Sharing

Blockchain alone is insufficient for storing large IoT data volumes due to scalability and cost constraints. Instead, decentralized storage frameworks like the InterPlanetary File System (IPFS) are integrated, offering content-addressable storage and enhanced availability [62].

Dagher et al. [63] proposed the Ancile framework that combines IPFS with blockchain for privacy-preserving Electronic Health Record (EHR) sharing. Files are stored off-chain in IPFS, while access policies and file hashes are anchored on-chain. Combining this with Pretty Good Privacy (PGP) adds asymmetric encryption, allowing granular control over data dissemination [64].

Web 3.0 initiatives such as Filecoin, Arweave, and Ocean Protocol build on these ideas by incentivizing decentralized storage and ensuring data provenance [65][66](Figure 3.4).

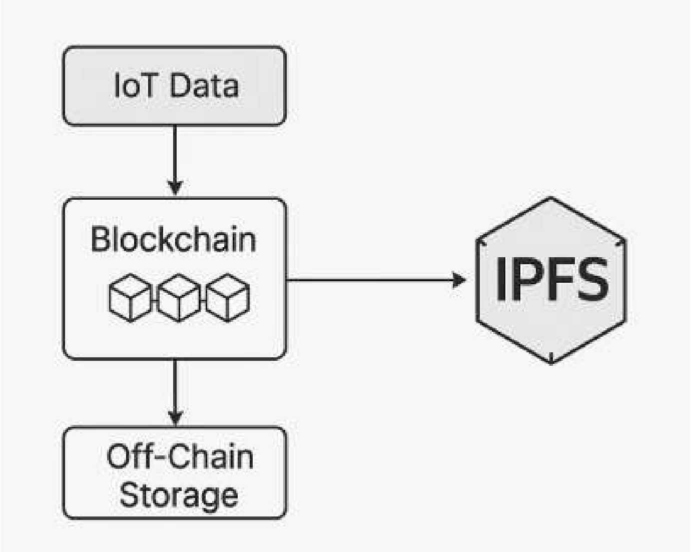


Figure 3.4: Blockchain + IPFS for Secure IoT Data Storage

3.5 Scalability and Performance Issues

IoT networks demand real-time responsiveness, which conventional blockchain protocols struggle to meet. The CAP theorem—which posits a tradeoff between consistency, availability, and partition tolerance—presents a structural challenge [67]. This leads to the infamous blockchain scalability trilemma [68].

Solutions include layered blockchain architectures such as Ethereum Plasma, zkRollups, and Optimistic Rollups, which offload transactions to child chains before settling on the main chain [69]. Gopalan et al. [70] presented empirical benchmarks showing 3–5x throughput improvement using such structures.

Modular blockchains like Celestia separate consensus from execution, allowing parallelization and easier integration with IoT gateways [71](Figure 3.5).

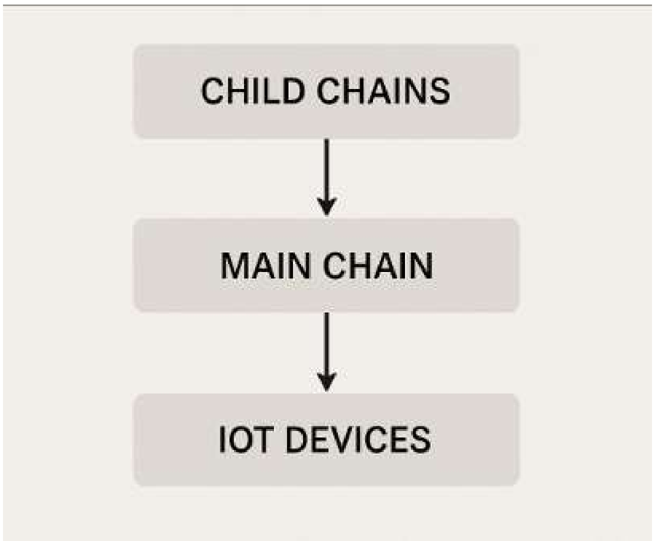


Figure 3.5: Layered Blockchain Architecture for IoT

3.6 Governance and Interoperability

Governance frameworks in consortium blockchains dictate participant behavior, onboarding processes, and consensus rights. Yue et al. [72] introduced a six-feature governance model focusing on decision transparency, operational flexibility, and stakeholder diversity. Their framework is suited for enterprise IoT where regulatory compliance and auditability are essential.

A major challenge is interoperability between different blockchain systems and legacy IoT protocols. Emerging standards like W3C DID, Verifiable Credentials (VCs), and Cross-Chain Messaging Protocols (XCMP) are promising solutions [73][74]. Projects like Polkadot, Cosmos, and Chainlink CCIP aim to unify disparate blockchain ecosystems(Figure 3.6).

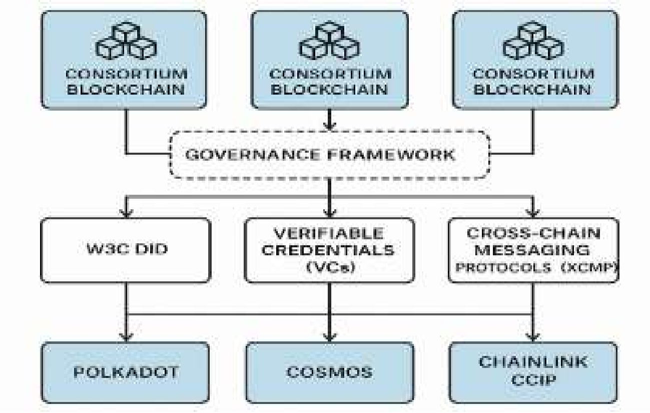


Figure 3.6: Interoperability Architecture for Consortium Blockchains

4. Research Gaps Identified

The integration of blockchain into the Internet of Things (IoT) has demonstrated notable potential in addressing data privacy, security, and integrity challenges. However, despite several advancements, critical research gaps persist that hinder real-world scalability and efficiency of such systems. These gaps span the areas of architecture design, metadata security, consensus performance, and interoperability in decentralized ecosystems.

4.1 Lack of Lightweight Blockchain Frameworks for IoT

One of the foremost challenges in deploying blockchain within IoT ecosystems is the absence of lightweight blockchain protocols optimized for resource-constrained environments. Traditional blockchain platforms like Ethereum and Bitcoin consume significant computational resources due to consensus mechanisms such as Proof of Work (PoW), which are unsuitable for devices with limited processing capabilities, memory, or battery life [75][76]. Even permissioned blockchain systems like Hyperledger Fabric, though efficient, introduce network and latency overhead unsuitable for edge IoT deployments [77](Figure 4.1).

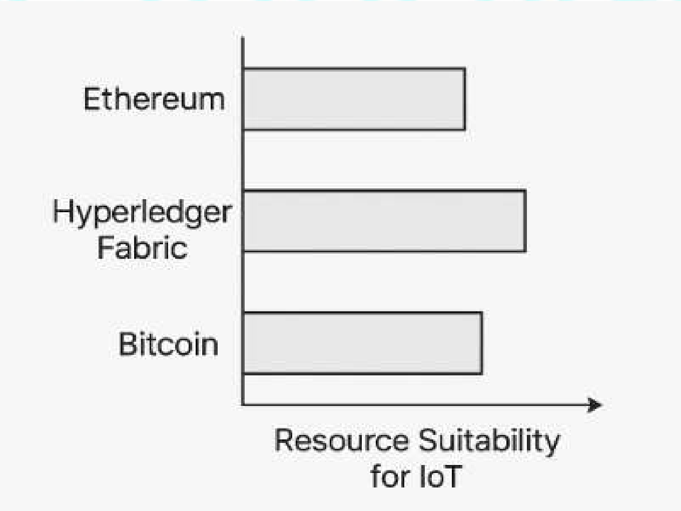


Figure 4.1: Comparison of Blockchain Frameworks Based on Resource Suitability for IoT

Emerging alternatives like IOTA’s Tangle, Nano, or LightChain are being explored [78][79], yet lack widespread adoption or mature tooling. These frameworks aim to eliminate mining overhead, but require further standardization and compatibility testing to ensure robustness across diverse IoT deployments [80].

4.2 Limited Research on Metadata Privacy and Inference Attacks

IoT systems generate massive volumes of metadata, including timestamps, device locations, and contextual event triggers. Despite the primary focus on payload data security, metadata remains largely unprotected and can be exploited for inference and linkage attacks [81][82]. As shown in Trivedi et al. [83], metadata sensitivity can even surpass raw data due to its utility in device impersonation and behavioral profiling(Figure 4.2).

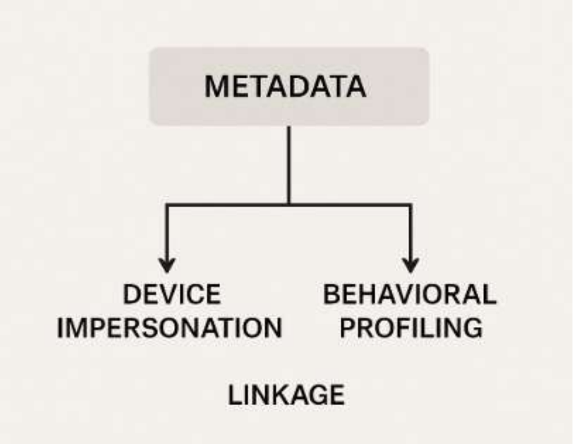


Figure 4.2: Metadata Inference Attack Vectors in IoT

Solutions like Attribute-Based Encryption (ABE) and Hierarchical Metadata Clustering have been proposed [84][85], yet their integration with blockchain systems is still immature. Very few blockchain platforms offer granular metadata access control, encryption, or obfuscation features. This lack of support leaves a vulnerability gap in security-by-design systems, particularly in healthcare and industrial IoT use cases [86][87].

4.3 Insufficient Use of Layered or Hybrid Consensus Protocols

Another critical gap is the underutilization of layered or hybrid consensus protocols, which are essential to balance trade-offs between security, decentralization, and throughput. The Nakamoto consensus (used in PoW) and Byzantine Fault Tolerant models (e.g., PBFT) represent opposite ends of the consensus spectrum—offering either strong decentralization with poor efficiency or centralized speed with weak scalability [88][89] (Figure 4.3).

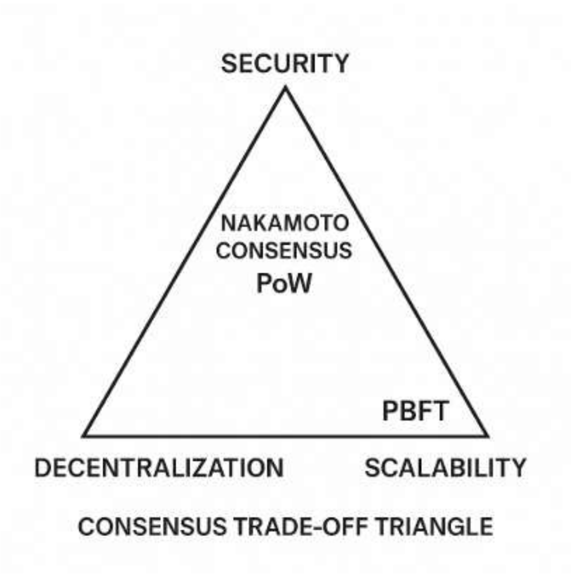


Figure 4.3: Consensus Trade-off Triangle (Security vs. Scalability vs. Decentralization)

Emerging hybrid designs such as Tendermint, HotStuff, Polkadot's GRANDPA, and Avalanche protocol offer improved latency and fault tolerance [90][91]. However, research into composite consensus tailored for IoT, especially multi-layered validation involving local edge consensus followed by global chain commitment, remains in early stages [92].

4.4 Scalability Bottlenecks in Monolithic Blockchain Architectures

Despite innovations in blockchain scaling, monolithic architectures still present significant barriers when applied to high-throughput IoT environments. Platforms like Ethereum face throughput ceilings (~30 TPS), making them impractical for environments like smart cities with thousands of simultaneous IoT transactions per second [93][94]. Furthermore, increased node counts degrade latency due to synchronization delays in global consensus protocols [95].

Modular blockchain frameworks such as Celestia, Polygon Avail, and Layer-2 rollups offer promise through execution and data availability separation [96][97], but are not yet optimized for IoT-specific requirements like low-bandwidth environments or mobile device integration(Figure 4.4).

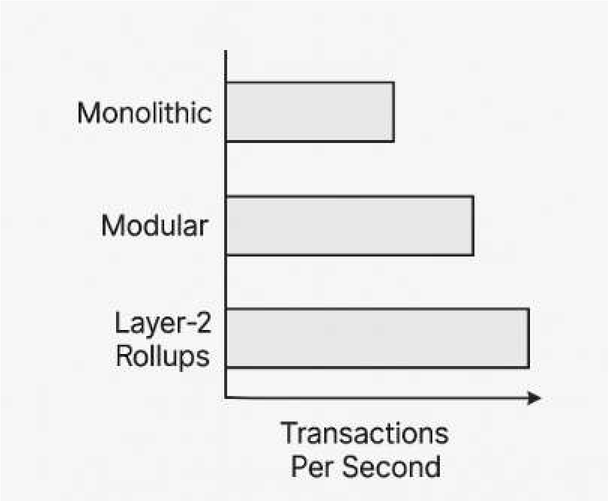


Figure 4.4: Transaction Per Second (TPS) Comparison Across Architectures

4.5 Governance and Interoperability Challenges in Consortium Blockchains

Finally, governance and interoperability represent major unresolved areas in consortium blockchain applications for IoT. Most platforms lack formalized governance models that define membership onboarding, node consensus rights, and dispute resolution procedures [98][99]. The absence of such structures can result in centralization drift, leading to loss of transparency and fairness.

Additionally, cross-chain interoperability between different IoT-ledger systems (e.g., Fabric ↔ Ethereum, or IPFS ↔ IOTA) remains technically complex and requires multi-protocol bridges, often introducing vulnerabilities [100][101]. Yue et al. [102] proposed a six-attribute governance model for consortium blockchain ecosystems, but it requires empirical validation across heterogeneous device networks(Figure 4.5).

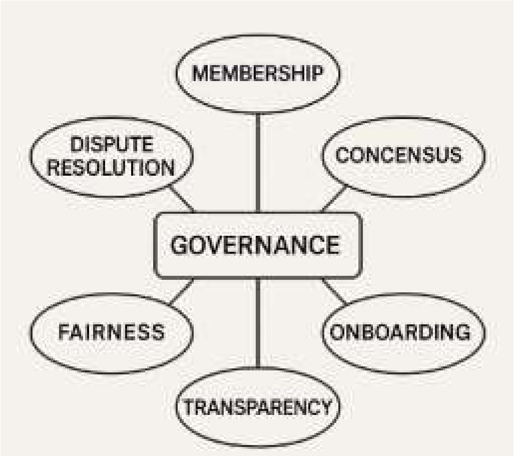


Figure 4.5: Governance Attributes of Consortium Chains (Yue et al.)

5. Conclusion

This literature review explored the intricate intersection of blockchain technologies and the Internet of Things (IoT), with a particular emphasis on enhancing data security, privacy, and system scalability through consortium blockchain architectures. The critical examination of existing frameworks, consensus mechanisms, metadata protection models, smart contract implementations, and decentralized storage approaches reveals a fragmented yet rapidly evolving research landscape.

The integration of blockchain into IoT promises a transformative paradigm, offering cryptographically secured, decentralized, and trustless systems capable of mitigating the systemic vulnerabilities inherent in centralized IoT infrastructures. Notably, consortium blockchains emerge as the most suitable architecture for constrained IoT environments, balancing transparency with performance by leveraging permissioned consensus protocols like PBFT and dPBFT. However, their deployment remains challenged by issues of governance, scalability, and cross-chain interoperability.

A recurring gap identified is the absence of lightweight blockchain frameworks tailored to low-power edge devices. Moreover, while payload encryption is well-studied, metadata remains a severely underprotected attack vector, requiring advanced models for obfuscation, access control, and hierarchical encryption. The analysis also revealed that hybrid and layered consensus models, although promising, remain underexplored in production-grade systems. Similarly, despite improvements in Layer-2 scaling solutions and decentralized storage (e.g., IPFS), monolithic blockchain systems still bottleneck high-throughput IoT scenarios.

Beyond the current landscape, the review illuminates emerging trends poised to redefine secure IoT ecosystems. These include AI-enhanced smart contracts for self-optimizing logic, federated learning systems backed by blockchain for privacy-aware decentralized intelligence, and quantum-resilient cryptographic primitives ensuring long-term security guarantees. Furthermore, Digital Twins, Web3 constructs, and Decentralized Identifiers (DIDs) exemplify how physical and digital systems are converging into trustless, composable frameworks.

Equally critical are the ethical and legal dimensions. Regulatory frameworks such as GDPR and NIST SP 800-213 underscore the urgency for privacy-preserving mechanisms that reconcile blockchain immutability with user rights like consent, redaction, and transparency. Technological solutions—Zero-Knowledge Proofs, off-chain data segregation, and privacy-by-design patterns—must be embedded into future system architectures to ensure compliance without compromising decentralization.

In conclusion, while blockchain offers a compelling foundation for securing IoT systems, its practical integration demands interdisciplinary innovation. Future research must focus on architecting modular, scalable, and interoperable blockchain frameworks capable of supporting heterogeneous IoT environments under stringent privacy, performance, and compliance constraints. As the digital world accelerates toward hyper-connectivity, the fusion of IoT and blockchain—augmented by AI, PQC, and ethical governance—will be essential for building next-generation cyber-physical infrastructures that are not only intelligent but inherently secure and resilient.

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