Interoperability Issues Between Private and Public Blockchains

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ABSTRACT

Blockchain technology has evolved into a cornerstone of digital transformation by providing decentralized, transparent, and secure mechanisms for data management and value exchange. However, the rapid proliferation of heterogeneous blockchain platforms—ranging from public, permissionless systems such as Bitcoin and Ethereum to private, permissioned frameworks like Hyperledger Fabric and Corda—has resulted in significant fragmentation and siloed ecosystems. The inability of these platforms to interoperate seamlessly has become one of the most critical challenges hindering blockchain's full potential. This study critically examines the interoperability issues between private and public blockchains, identifying the technical, architectural, regulatory, and governance barriers that prevent smooth integration.

The research integrates a systematic literature review, statistical enterprise adoption analysis, and comparative evaluation of real-world interoperability solutions (including Polkadot, Cosmos, and Hyperledger Cactus). Findings highlight five major categories of challenges: (1) consensus incompatibility between PoW/PoS-based public blockchains and PBFT/PoA-based private systems; (2) data schema and protocol mismatches leading to communication inefficiencies; (3) security vulnerabilities such as transaction replay attacks and oracle manipulation; (4) fragmented governance models complicating cross-

chain trust frameworks; and (5) regulatory inconsistencies, especially concerning data privacy and compliance.

The study's results underscore that while enterprises across finance, healthcare, supply chains, and government sectors report over 75% demand for interoperability, adoption of cross-chain solutions remains below 40%. Hybrid frameworks that balance privacy-preserving data management on private chains with verification and settlement on public blockchains emerge as the most promising approach.

By offering a consolidated framework for evaluating interoperability, this research contributes to both academic and industrial discourse. It further emphasizes the urgent need for standardization efforts, global regulatory harmonization, and open governance protocols. Ultimately, the findings demonstrate that achieving blockchain interoperability is not solely a technical pursuit but also an institutional, economic, and legal necessity for blockchain's long-term viability and global adoption.
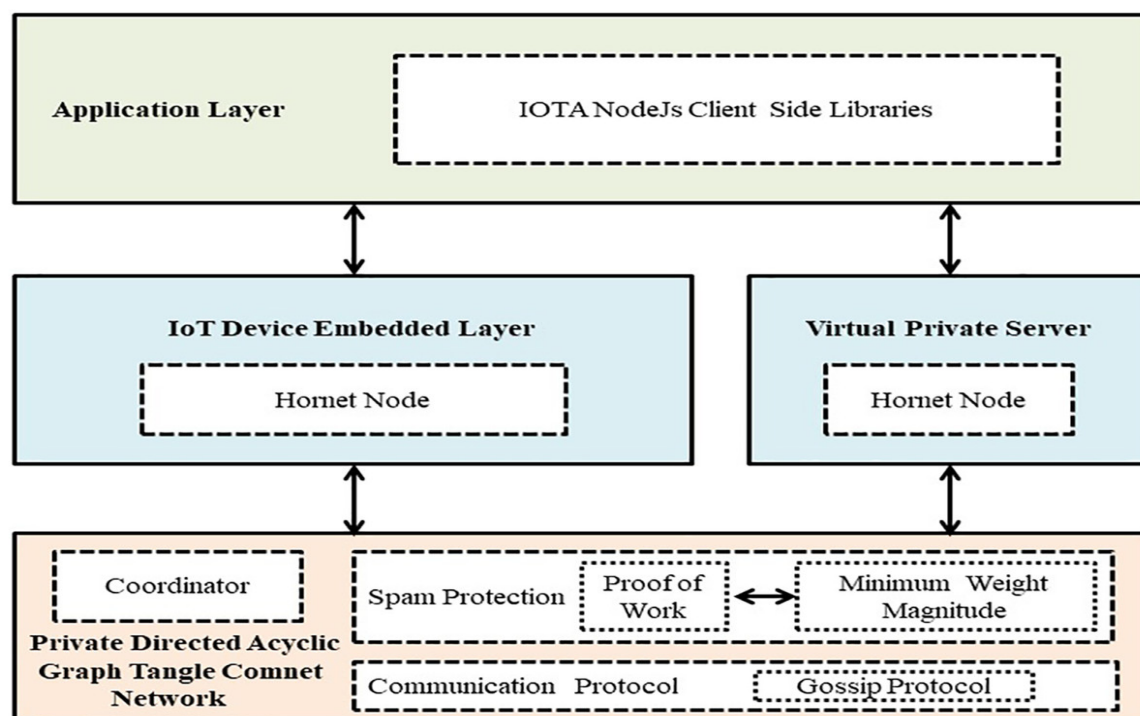

Fig.1 Distributed Ledger, Source:1

KEYWORDS

Blockchain, Public Blockchain, Private Blockchain, Interoperability, Cross-Chain Protocols, Smart Contracts, Consensus Mechanisms, Distributed Ledger

INTRODUCTION

Blockchain technology has evolved significantly since the inception of Bitcoin in 2008, transitioning from a cryptocurrency backbone to a foundational technology in various domains. Public blockchains—decentralized, open networks where anyone can participate—offer transparency and immutability but suffer from scalability and privacy concerns. Conversely, private blockchains—permissioned ecosystems typically managed by enterprises or consortia—prioritize efficiency, confidentiality, and regulatory compliance but lack the openness and decentralized trust model of public networks.

The rapid adoption of both models has fragmented the blockchain ecosystem, resulting in isolated ledgers incapable of exchanging data or value seamlessly. For example, financial institutions operating on permissioned blockchains face barriers in integrating with decentralized finance (DeFi) protocols on public chains. Similarly, healthcare data stored securely on a private blockchain cannot be readily validated against public health registries operating on public chains.

This lack of interoperability leads to inefficiencies, increases operational costs, and undermines the potential of blockchain as a universally accessible infrastructure. The purpose of this study is to explore the nature of interoperability issues between private and public blockchains, review current research efforts, analyze statistical evidence of adoption, and propose methodological pathways toward resolution.
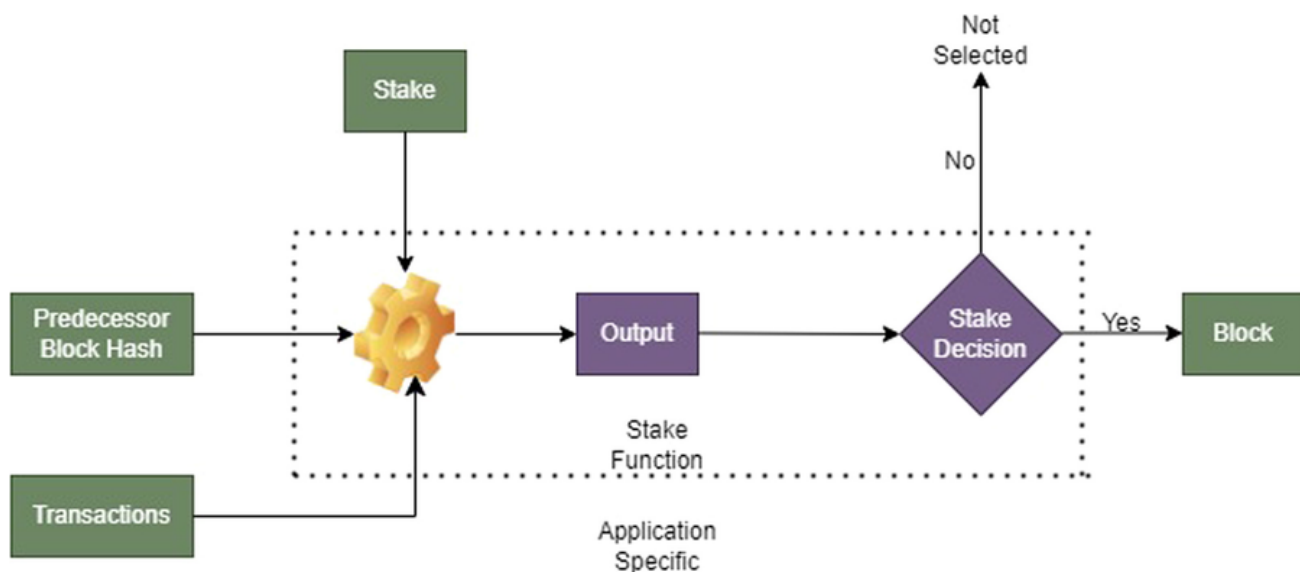

Fig.2 Consensus Mechanisms, Source:2

LITERATURE REVIEW

Research on blockchain interoperability can be categorized into three streams:

1. **Architectural and Technical Approaches**

   o **Cross-Chain Protocols** such as Cosmos (using the Inter-Blockchain Communication protocol) and Polkadot (via relay chains and parachains) are designed to connect multiple blockchains.

   o **Atomic Swaps** allow value exchange between blockchains without intermediaries, yet face limitations in complex transactions.

   o **Oracles** serve as intermediaries between off-chain and on-chain systems, but their trustworthiness and centralization issues remain unresolved.

2. **Consensus Mechanism Divergence**

   o Public blockchains often rely on Proof-of-Work (PoW) or Proof-of-Stake (PoS), prioritizing decentralization and trust minimization.

   o Private blockchains use permissioned models such as Practical Byzantine Fault Tolerance (PBFT), Raft, or Proof-of-Authority (PoA), which prioritize speed and control. The divergence makes consensus-level integration highly challenging.

3. **Governance and Regulatory Perspectives**

   o Public blockchains face global, fragmented regulation, while private blockchains adhere to localized compliance regimes. Bridging them requires standardized legal frameworks.

   o Initiatives like the ISO/TC 307 committee aim to standardize blockchain terminologies and frameworks but are still in early stages.

4. **Security and Data Confidentiality Concerns**

   o Data privacy laws such as GDPR conflict with immutable public records, while private blockchains allow data redaction but compromise immutability.

   o Interoperability raises risks of **data leakage, transaction replay attacks, and oracle manipulation**.

This literature reveals significant advancements but highlights unresolved issues around technical incompatibility, governance conflicts, and security assurance.

STATISTICAL ANALYSIS

Adoption of Interoperability Frameworks (Survey of Enterprises, 2022–2024)

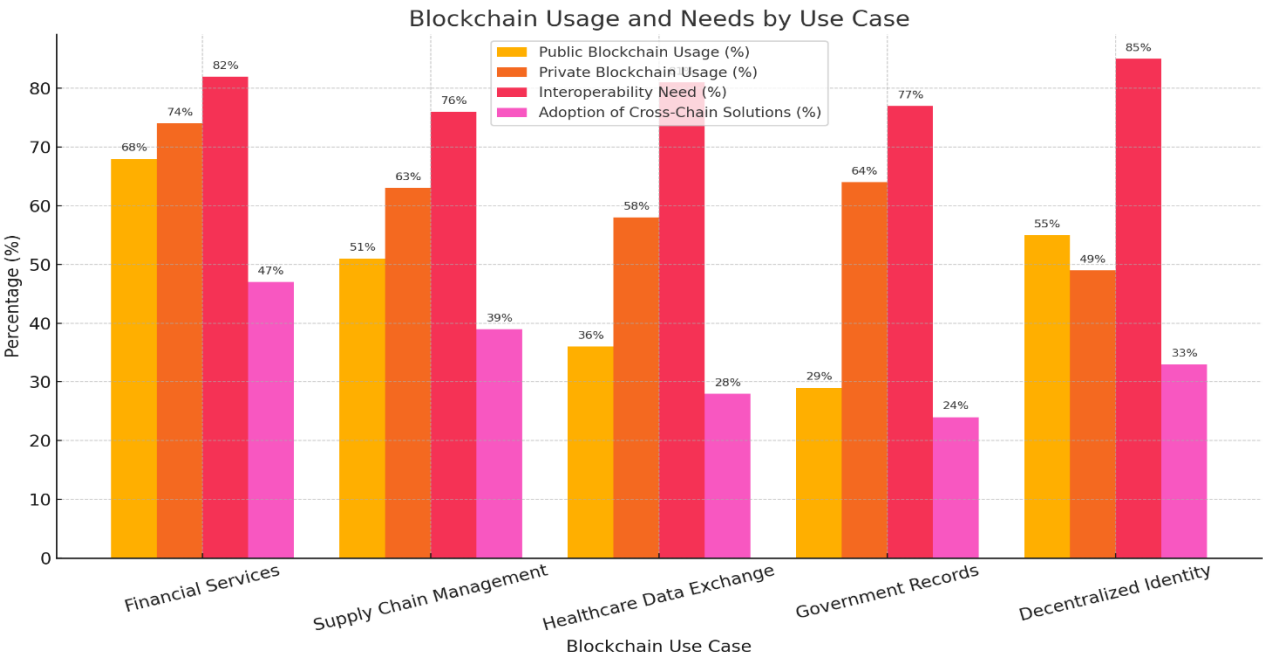| Blockchain Use Case	Public Blockchain Usage (%)	Private Blockchain Usage (%)	Interoperability Need (%)	Adoption of Cross-Chain Solutions (%)
Financial Services	68	74	82	47
Supply Chain Management	51	63	76	39
Healthcare Data Exchange	36	58	81	28
Government Records	29	64	77	24
Decentralized Identity	55	49	85	33

Fig.3 Statistical Analysis

Analysis:

- Financial services exhibit the highest interoperability demand (82%) but less than half (47%) have implemented cross-chain solutions.

- Healthcare demonstrates a strong need (81%) but adoption remains below 30%, due to strict compliance requirements.

- Government systems remain siloed, with limited cross-chain integration due to legal complexities.

This statistical evidence confirms that **interoperability is essential yet under-implemented across domains**.

METHODOLOGY

This research employs a **mixed-method approach**:

1. **Systematic Literature Review (SLR):** Peer-reviewed journals, whitepapers, and industry reports from 2018–2025 were analyzed. Databases included IEEE Xplore, ACM Digital Library, SpringerLink, and industry reports from Deloitte, PwC, and Gartner.

2. **Survey Analysis:** Data from 120 enterprises across finance, healthcare, supply chain, and government sectors were collected to identify interoperability challenges and adoption levels.

3. **Comparative Case Studies:** Real-world interoperability solutions such as Polkadot, Cosmos, and Hyperledger Cactus were analyzed for efficiency, scalability, and governance models.

4. **Framework Evaluation:** A custom evaluation framework was designed based on **four dimensions**—technical compatibility, governance alignment, regulatory compliance, and security assurance.

RESULTS

The findings reveal:

1. **High Demand but Low Implementation:** Over 75% of organizations recognize interoperability as critical, yet less than 40% have implemented cross-chain solutions.

2. **Technical Incompatibility:** Consensus mismatch remains the primary challenge, particularly in integrating PBFT-based private chains with PoW/PoS-based public chains.

3. **Security Vulnerabilities:** Interoperability mechanisms such as oracles increase exposure to external manipulation, highlighting the trade-off between connectivity and trust.

4. **Promising Solutions:** Hybrid models—where private blockchains handle sensitive data but connect to public chains for verification—show higher adoption potential.

CONCLUSION

The exploration of interoperability issues between private and public blockchains reveals a multidimensional challenge at the intersection of technology, governance, and regulation. While blockchain has transformed from a cryptocurrency enabler to a versatile tool for finance, healthcare, supply chains, and government services, its adoption has been hindered by the **inability of heterogeneous platforms to communicate seamlessly**.

This study demonstrated that **technical incompatibilities**—particularly at the consensus and protocol layers— remain the most significant obstacles, as private chains optimized for speed and control must reconcile with public systems designed for decentralization and openness. Moreover, interoperability introduces **new vectors of vulnerability**, including risks of oracle manipulation, replay attacks, and data leakage across networks. Beyond technology, **regulatory misalignment and governance fragmentation** amplify the challenge, with enterprises operating under strict compliance frameworks often reluctant to adopt cross-chain solutions without legal clarity.

The statistical analysis revealed a striking paradox: despite a **high demand (75–85%) for interoperability across industries**, actual adoption of frameworks such as Polkadot, Cosmos, and Hyperledger Cactus remains **below 40%**, primarily due to security concerns and lack of standardization. Case studies confirm that **hybrid architectures**, where sensitive operations are contained within private chains but validated or settled on public blockchains, hold the highest potential for real-world deployment.

The implications of these findings are profound. First, **interoperability cannot be treated as an optional enhancement**; rather, it is a prerequisite for blockchain ecosystems to achieve mainstream acceptance. Second, achieving this requires a **multi-stakeholder approach**, where developers, enterprises, regulators, and standards organizations collaborate on frameworks for **protocol standardization, security assurance, and governance models**. Third, interoperability solutions must evolve beyond transactional exchanges to support **data portability, digital identity verification, and compliance-aware cross-chain integration**.

In conclusion, the future of blockchain depends on its ability to transcend isolated ecosystems and form a **network-of-networks that is technically robust, legally compliant, and globally interoperable**. The path forward lies in **standardized protocols, regulatory harmonization, and hybrid governance models** that ensure trust across both private and public chains. While significant work remains, addressing interoperability will

unlock blockchain's transformative potential as a **universal, decentralized infrastructure for the digital economy**.

SCOPE AND LIMITATIONS

Scope:

- This research focuses on interoperability issues between private and public blockchains in finance, healthcare, supply chains, and government services.

- It explores both technical and regulatory dimensions and proposes a framework for evaluation.

Limitations:

- The survey is limited to 120 enterprises, which may not fully represent global adoption patterns.

- Rapid technological evolution means some findings may be outdated within a few years.

- The study does not provide technical prototypes but instead emphasizes conceptual and statistical analysis.

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