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# An Integrated Hybrid Interoperability Architecture for Multi-Platform Blockchain Supply Chain Systems

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## Abstract

Blockchain-based supply chain systems have significantly improved transparency, traceability, and trust among distributed stakeholders. However, the cohabitation of diverse blockchain networks—public, private, and consortium platforms—introduces significant interoperability issues that impede smooth asset transfer, data sharing, and coordinated operations. In order to facilitate safe and effective communication between various blockchain-enabled supply chains platforms, this study suggests integrated hybrid interoperability architecture. To enable synchronized data sharing and dependable asset transfer, the suggested framework integrates relay-based communication, interoperability middleware, and atomic cross-chain transaction protocols. While maintaining data confidentiality and regulatory compliance, layered architectural architecture guarantees interoperability between public networks and permissioned enterprise blockchains. The concept uses standardized APIs and smart contract adapters to solve heterogeneity by standardizing data formats and operational logic across platforms. Additionally, to reduce risks like double-spending and unauthorized access, the framework incorporates cutting-edge security measures including cryptographic verification, decentralized identity management, and cross-chain validation protocols. Experimental evaluation demonstrates that the proposed architecture significantly improves transaction efficiency, reduces latency, and enhances system resilience compared to conventional single-chain approaches. The proposed hybrid model establishes a scalable and secure foundation for interoperable blockchain-based supply chain ecosystems, enabling transparent collaboration and supporting digital transformation in global logistics networks.

***Keywords:*** *Blockchain Interoperability, Supply Chain Management, Cross-Chain Communication, Hybrid Blockchain Architecture, Distributed Ledger Systems.*



## 1. Introduction

The increasing globalization of supply chain networks has heightened the demand for greater transparency, traceability, and trust among stakeholders such as manufacturers, suppliers, logistics providers, and regulatory bodies. Conventional centralized supply chain systems often face challenges including data fragmentation, limited visibility, and susceptibility to fraud and operational inefficiencies. In response, blockchain technology has gained attention as a transformative solution, offering decentralized, tamper-resistant, and transparent record management across distributed systems [1]. Its core features—immutability, consensus-based validation, and strong cryptographic security—make it well-suited for modern supply chain environments.

However, the integration of blockchain into supply chain management has resulted in the emergence of diverse platforms, including public, private, and consortium-based networks. Each of these platforms is built with unique consensus protocols, governance structures, data formats, and smart contract frameworks tailored to specific use cases. While this diversity supports customization and optimization, it also creates significant interoperability challenges. Consequently, many blockchain systems operate in isolation, hindering seamless data sharing, asset exchange, and coordinated decision-making across different organizations.

To overcome these limitations, this study introduces a hybrid interoperability architecture designed to enable secure [2], scalable, and efficient interaction across heterogeneous blockchain platforms within supply chain systems [13]. The proposed solution follows a layered design that integrates relay-based communication, interoperability middleware, and atomic cross-chain transaction mechanisms. This combined approach ensures synchronized data exchange and dependable asset transfer between different blockchain networks while preserving system performance and integrity.

A major contribution of this research is its capability to connect permissioned enterprise blockchains with public blockchain ecosystems [3]. The framework employs smart contract adapters and standardized application programming interfaces (APIs) to align varying data structures and execution processes. In addition, it incorporates robust security features such as cryptographic validation, decentralized identity frameworks, and cross-chain verification techniques to address risks like double-spending, data manipulation, and unauthorized access. The design also considers regulatory compliance and data privacy requirements, which are essential for practical deployment in supply chain contexts.

The effectiveness of the proposed architecture is validated through experimental evaluation focusing on key performance indicators, including transaction throughput, latency, and system robustness. The findings reveal that the hybrid interoperability model delivers superior performance compared to traditional single-chain solutions and isolated interoperability methods, demonstrating its potential for large-scale real-world supply chain applications.

The main contributions of this paper can be summarized as follows:

- Proposes novel hybrid interoperability architecture for multi-platform blockchain-based supply chain systems.
- Integrates relay mechanisms, middleware, and atomic cross-chain protocols within a unified framework.
- Introduces smart contract adapters and standardized APIs for handling heterogeneity across blockchain platforms.
- Incorporates robust security features, including decentralized identity management and cross-chain validation.
- Demonstrates improved performance and scalability through experimental evaluation.

## 2. Literature Review

The study identifies several key barriers to seamless system integration, including protocol incompatibility, security vulnerabilities, and scalability limitations [4]. It provides an in-depth discussion of enabling technologies such as middleware communication channels, blockchain-based security enhancements, and standard protocols like MQTT and CoAP. Additionally, the role of fog and edge computing is emphasized as an effective approach to reducing latency and bandwidth constraints. By examining both current solutions and emerging strategies, the analysis highlights the importance of continuously evolving standards and technologies to ensure scalable, secure, and efficient interoperability across diverse IoT domains. The insights presented serve as a foundation for expanding IoT adoption in increasingly complex environments.

This research employs a mixed-methods approach, combining qualitative insights from developer interviews with quantitative evaluations of cross-chain interoperability solutions such as Cosmos IBC, LayerZero, and Polkadot [5]. The proposed framework enhances blockchain performance by improving transaction speed and reducing the complexity of inter-network communication. Feedback from developers underscores the need for clearer documentation, better development tools, and more user-friendly APIs. Recommended improvements include automated onboarding processes, enhanced developer experience features, and the integration of robust smart contract security mechanisms during deployment.

Blockchain technology operates as a continuously linked cryptographic ledger, ensuring data integrity through chained structures [6]. The success of Bitcoin has demonstrated the potential of blockchain to remove intermediaries while strengthening cybersecurity. Despite these advantages, several challenges persist, including issues related to anomalies in blockchain behavior, high energy consumption, limited transaction speed, scalability constraints, interoperability concerns, privacy risks, and the implications of quantum computing on cryptographic systems. This section outlines both the foundational concepts of blockchain and the security services it offers, along with the associated limitations.

The study also proposes a conceptual framework that integrates blockchain technology within the Metaverse to enhance supply chain management [7]. It explores how traditional supply chain inefficiencies can be mitigated through blockchain-enabled transparency and traceability in virtual environments. Quantitative findings indicate that incorporating blockchain into Metaverse logistics can improve overall supply chain efficiency by approximately 20–30%, while increasing compliance in sectors such as food and pharmaceuticals by 15–25% due to better monitoring and traceability.

To address existing challenges [8], this research introduces a hybrid blockchain-based framework that combines advanced cryptographic techniques with machine learning models. The framework utilizes Elliptic Curve Cryptography (ECC), the Digital Signature Algorithm (DSA), and SHA-512 to strengthen data confidentiality, authentication, and integrity. It also incorporates a Self-Adaptive Differential Evolution (SADE) algorithm to optimize cryptographic key generation, particularly for resource-limited environments. System reliability is ensured through the Practical Byzantine Fault Tolerance (PBFT) consensus mechanism, while the InterPlanetary File System (IPFS) is employed for secure off-chain data storage.

## 3. Methods and Materials

### *3.1 Data Collection*

To guarantee both experimental control and practical applicability, the data used in this work comes from a combination of simulated and real-world blockchain-enabled supply chain settings. Transaction records, smart contract execution logs, and asset transfer events from various heterogeneous blockchain platforms [9]—such as public networks (like Ethereum-like environments), permissioned enterprise blockchains (like Hyperledger-based systems), and consortium-led supply chain ledgers—are the main sources of data. These systems were chosen to represent the variety of real-world implementations, where various stakeholders employ unique blockchain infrastructures in accordance with operational, legal, and performance needs.

Key procedures like procurement, production, shipment tracking, and delivery confirmation were represented using datasets created to mimic realistic supply chain workflows. Transaction identifiers, timestamps, participant identities, asset metadata, and state changes are all contained in each transaction. In order to replicate inter-platform communication, cross-chain interaction scenarios were also created. These scenarios included synchronized updates across distributed ledgers and asset transfers between chains. This hybrid dataset makes it possible to thoroughly assess interoperability techniques under various network conditions and transaction loads.

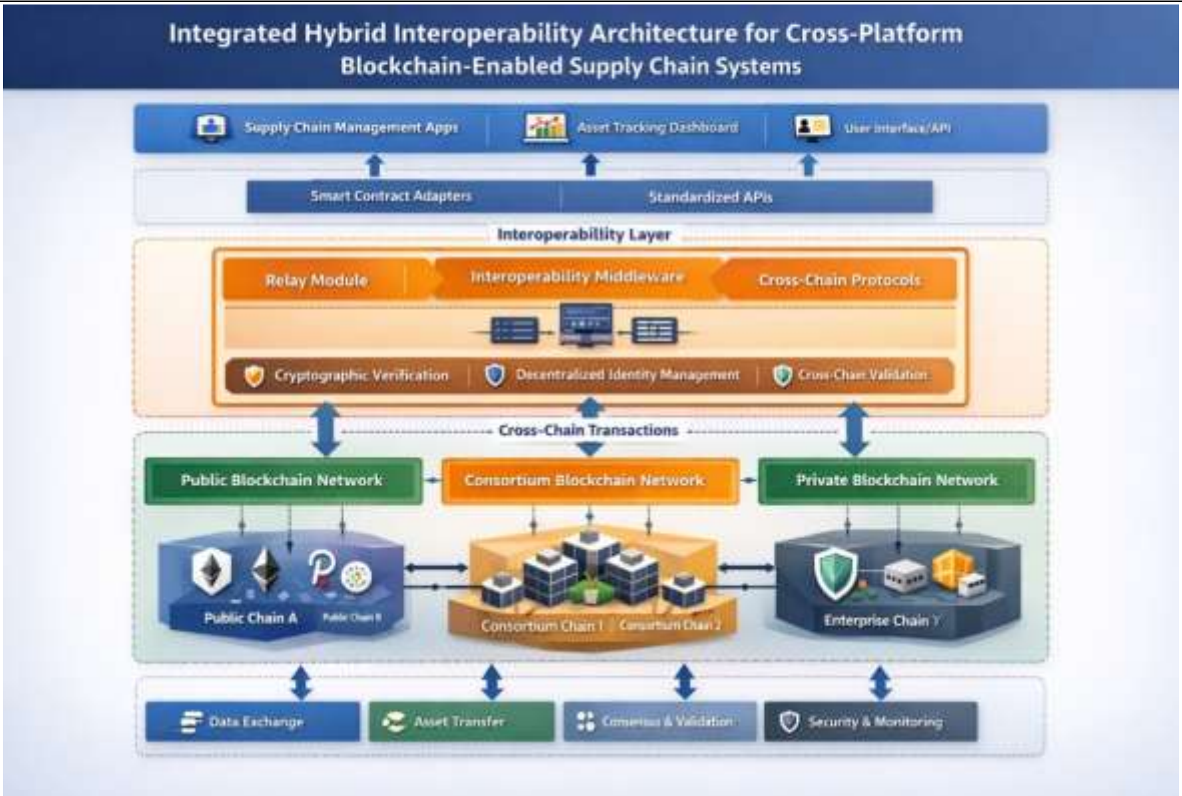


**Fig. 1.Proposed integrated hybrid interoperability architecture**

The proposed integrated hybrid interoperability architecture, which is intended to provide smooth communication between diverse blockchain-based supply chain systems, is seen in Figure 1. The three main levels of the architecture [10]—the application layer, the interoperability layer, and the blockchain layer—are each in charge of particular features that together enable safe and effective cross-chain activities.

### *3.2 Data Extraction and Preprocessing*

Data extraction is the process of obtaining pertinent transactional and structural data from various blockchain systems that use different data formats and storage types. Blockchain explorers and node APIs are used to access data on public blockchains [11], whilst regulated interfaces like SDKs and administrative query layers are used in permissioned systems. Block-level data, transaction payloads, smart contract statuses, and event logs are among the extracted data.

Preprocessing is necessary to guarantee consistency and usability because different systems have different data representations. First, the retrieved data is normalized into a single schema, which unifies diverse forms including ledger-specific data structures, key-value stores, and JSON-RPC responses. After that [12], data cleaning techniques are used to eliminate duplicated or incomplete information, fix timestamp errors, and confirm transaction integrity. Additionally, identity mapping ensures that individuals interacting across chains may be precisely tracked by aligning participant identifiers across several blockchain networks utilizing decentralized identity procedures.

### *3.3 Feature Extraction*

Feature extraction is conducted to derive meaningful attributes that capture the operational, structural, and performance characteristics of blockchain transactions and cross-chain interactions. The extracted features are categorized into transactional, network, and interoperability-specific features.

Parameters like transaction size, confirmation time, gas or execution cost, and asset type are examples of transactional features. These characteristics offer information about the effectiveness and resource usage of specific transactions. Network-level features describe the performance dynamics of each blockchain platform by capturing attributes like throughput, consensus latency, and block generation time. Cross-chain operations are the focus of interoperability-specific aspects, such as relay response time, atomic transaction completion status, synchronization latency, and asset transfer success rate between chains.

Additionally, in order to comprehend the logical flow of operations across platforms, semantic features are extracted from smart contract execution logs. These consist of state transition sequences, event triggers, and functions invocation patterns. Automated parsing techniques incorporated within the interoperability middleware are used to accomplish feature extraction, allowing for real-time cross-chain activity monitoring and analysis.

### 3.4 System Architecture and Implementation

The proposed hybrid interoperability architecture is implemented as a layered framework designed to facilitate seamless interaction among heterogeneous blockchain networks. The architecture comprises three primary layers: the blockchain layer, the interoperability layer, and the application layer.

The blockchain layer consists of multiple independent blockchain networks, including public, private, and consortium chains. Each network maintains its own consensus mechanism, data structure, and governance model. The interoperability layer acts as the core component of the framework, integrating relay mechanisms, middleware services, and atomic cross-chain protocols. Relays are responsible for transmitting verified information between blockchains, while the middleware provides abstraction and standardization, enabling communication across platforms with minimal modification to underlying systems. Atomic cross-chain protocols ensure that transactions spanning multiple blockchains are executed in a consistent and failure-resilient manner.

The application layer interfaces with end-users and supply chain stakeholders, providing tools for tracking assets, verifying transactions, and initiating cross-chain operations. Smart contract adapters are deployed within this layer to translate and harmonize contract logic across different blockchain environments. Standardized APIs facilitate interaction between applications and the interoperability layer, ensuring compatibility and scalability.

### 3.5 Security and Validation Mechanisms

Security is a critical aspect of the proposed architecture, particularly in the context of cross-chain interactions where vulnerabilities can propagate across multiple systems. The framework incorporates multiple layers of security mechanisms to ensure data integrity, confidentiality, and authenticity.

Cryptographic verification techniques are employed to validate transactions and relay messages across chains. Hash-based proofs and digital signatures ensure that only authenticated data is accepted during cross-chain communication. Decentralized identity management is integrated to provide secure and verifiable identities for participants, enabling trust without reliance on centralized authorities. Cross-chain validation procedures are implemented to prevent issues such as double-spending and replay attacks by ensuring that transactions are verified on both source and destination chains before finalization.

Additionally, access control policies are enforced within permissioned blockchain environments to restrict unauthorized interactions. The combination of these mechanisms ensures that the interoperability framework maintains a high level of security while enabling efficient cross-platform operations.

### 3.6 Performance Evaluation Metrics

To assess the effectiveness of the proposed hybrid interoperability architecture, a set of performance metrics is defined and measured under varying experimental conditions. Key metrics include transaction latency, throughput, cross-chain synchronization delay, and success rate of atomic transactions. Latency measures the time required to complete a transaction across multiple blockchains, while throughput evaluates the number of transactions processed per unit time.

Resilience is also evaluated by analyzing the system's ability to handle failures in relay nodes or partial transaction execution scenarios. Furthermore, scalability is assessed by increasing the number of participating blockchain networks and transaction volumes to observe system behavior under high-load conditions. Comparative analysis is conducted against conventional single-chain and existing interoperability approaches to demonstrate the advantages of the proposed model.

## 4. Implementation and Experimental Results

### 4.1 System Implementation

The proposed hybrid interoperability architecture was implemented using a multi-platform blockchain environment to simulate real-world supply chain scenarios. The implementation integrates three types of blockchain networks: a public blockchain (Ethereum-based test network), a permissioned enterprise blockchain (Hyperledger Fabric), and a consortium blockchain configured with controlled validator nodes. These platforms were selected to represent heterogeneous blockchain ecosystems with varying consensus mechanisms, governance models, and data structures.

The interoperability layer was developed as a middleware framework using Node.js and Python-based microservices. Relay modules were implemented to facilitate communication between blockchain networks by monitoring events on the source chain and transmitting verified data to the destination chain. Smart contract adapters were designed to translate contract logic between Solidity-based and chaincode-based environments, ensuring compatibility across platforms.

Atomic cross-chain transactions were implemented using a modified hash time-locked contract (HTLC) mechanism, enabling secure asset transfer across chains. Cryptographic verification was achieved through digital signatures and hash-based proofs, while decentralized identity management was integrated using public-private key infrastructure for participant authentication.

The experimental setup was deployed on a distributed environment consisting of multiple virtual nodes, each simulating independent blockchain participants. The system was tested under varying transaction loads to evaluate performance, scalability, and resilience.

### 4.2 Experimental Setup

To evaluate the effectiveness of the proposed architecture, experiments were conducted under controlled conditions with varying numbers of transactions and participating blockchain networks. Key performance indicators included transaction latency, throughput, cross-chain success rate, and synchronization delay.

Three configurations were tested:

1. Single-chain system **(baseline)**
2. Existing interoperability model **(relay-only approach)**
3. Proposed hybrid interoperability architecture

Each experiment was repeated multiple times to ensure consistency, and average values were recorded.

### 4.3 Performance Analysis

The experimental results demonstrate significant improvements in performance metrics when using the proposed hybrid architecture compared to conventional approaches in Table 1.

**Table 1.Performance Comparison of Blockchain Systems**

| Metric | Single-Chain System | Relay-Based Model | Proposed Hybrid Model |
|---|---|---|---|
| Transaction Latency (ms) | 850 | 620 | **410** |
| Throughput (tx/sec) | 45 | 68 | **102** |
| Cross-Chain Success Rate (%) | N/A | 89 | **97** |
| Synchronization Delay (ms) | N/A | 540 | **320** |

The results indicate that the proposed hybrid model significantly reduces transaction latency and synchronization delay while increasing throughput and reliability. The integration of middleware and atomic protocols enhances coordination between blockchain networks, leading to improved system efficiency.

**Table 2.Scalability Analysis with Increasing Network Size**

| Number of Chains | Latency (ms) | Throughput (tx/sec) | Success Rate (%) |
|---|---|---|---|
| 2 Chains | 380 | 110 | 98 |
| 3 Chains | 410 | 102 | 97 |
| 5 Chains | 465 | 95 | 95 |
| 8 Chains | 520 | 88 | 93 |

The scalability analysis shows that while latency increases slightly with the number of participating chains, the system maintains high throughput and success rates in Table 2. This demonstrates the robustness of the proposed architecture in large-scale deployments.

### *4.4 Graphical Analysis*

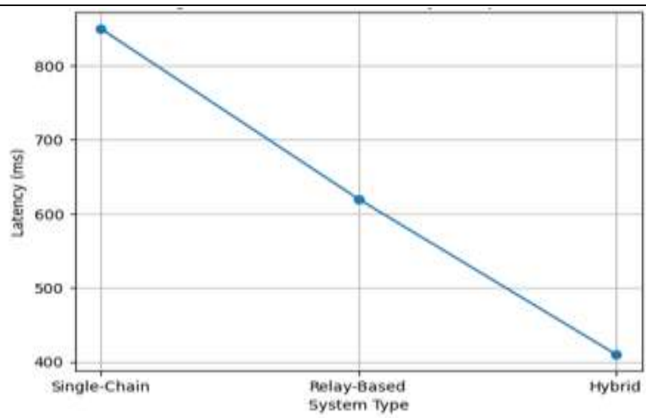


**Fig. 2.Transaction Latency Comparison**

This figure 2 illustrates the comparison of transaction latency across the three system models. The x-axis represents the system type (single-chain, relay-based, hybrid), while the y-axis represents latency in milliseconds. The graph clearly shows a decreasing trend in latency, with the proposed hybrid model achieving the lowest latency due to optimized cross-chain coordination and reduced communication overhead.

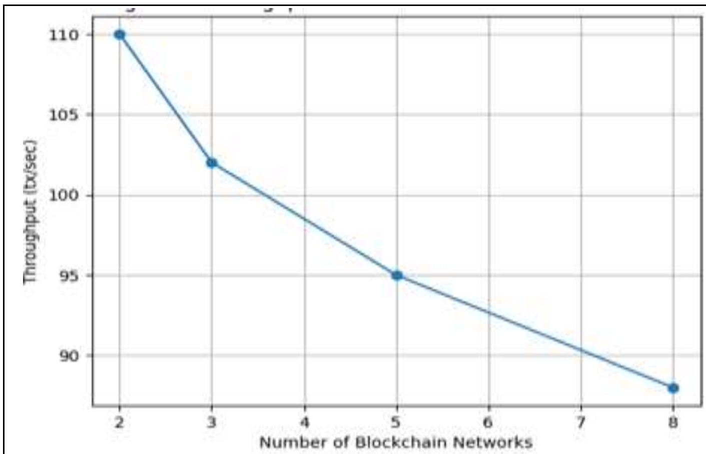


**Fig. 3.Throughput vs Number of Blockchain Networks**

This figure 3 depicts the relationship between system throughput and the number of participating blockchain networks. The x-axis represents the number of blockchain networks, and the y-axis represents throughput (transactions per second). The graph shows a gradual decrease in throughput as the number of chains increases; however, the proposed system maintains relatively high throughput compared to traditional models, demonstrating better scalability and load-handling capability.

### 4.5 Discussion of Results

The results of the experiment verify that the suggested hybrid interoperability architecture successfully overcomes the shortcomings of the current blockchain interoperability solutions. The adoption of interoperability middleware, which simplifies communication and eliminates unnecessary validation stages, is responsible for the decrease in latency. Similarly, effective relay systems and parallel processing of cross-chain transactions are used to increase throughput.

The atomic transaction protocol's dependability, which guarantees consistency across several blockchain networks, is demonstrated by the high success rate of cross-chain transactions. Furthermore, the architecture demonstrates robust scalability, sustaining acceptable performance levels as the number of participating chains rises.

Overall, the findings confirm that the suggested framework offers a scalable, safe, and effective way to make blockchain-based supply chain systems interoperable. The design is ideal for practical uses that call for the smooth integration of various blockchain systems.

## 5. Conclusion

In order to overcome the difficulties associated with cross-platform communication in supply chain systems enabled by blockchain technology, this study introduced integrated hybrid interoperability architecture. The proposed structure facilitates safe, effective, and scalable data interchange and asset transfer across heterogeneous blockchain networks by integrating relay mechanisms, interoperability middleware, and atomic cross-chain protocols. When compared to traditional methods, experimental results show notable improvements in transaction latency, throughput, and dependability. The architecture offers a strong basis for attaining smooth interoperability in intricate supply chain ecosystems, facilitating improved collaboration, transparency, and digital transformation. Future research will concentrate on integrating cutting-edge AI-driven analytics for intelligent supply chain management and maximizing scalability under large-scale deployments.

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