



# *A Hybrid Blockchain Framework with Decentralized Identity for Secure Digital Forensics*

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**Abstract**—Digital forensics has been transformed by blockchain technology, providing Immutability, transparency, and auditable evidence management. Costly transaction fees and Growth potential constraints restrict extensive implementation. To resolve these difficulties, this research proposes a Cutting-edge framework that combines Decentralized Identifiers (DIDs) with a hybrid on-chain/off-chain storage framework. Forensic data management is enhanced as transaction costs are decreased by 80–90% (from 0.005–0.01 ETH to 0.0005–0.002 ETH per transaction) while maintaining data reliability and safety. To secure data integrity, the system stores significant metadata and cryptographic hashes on-chain, while storing and organizing forensic data off-chain to minimize blockchain overload. DIDs enhance identity verification and permission management, cutting back on dependency on identity management through central authorities. Smart contracts enhance responsibility and evidence tracking by automating the chain-of-custody process. Performance efficiency is improved by 60–80% with this hybrid framework compared to fully on-chain models, and transaction duration is reduced from 5–10 seconds to 1–3 seconds. Past studies have evolved from this research, which offers an affordable and adaptable forensic framework while ensuring data protection and legal adherence. Practical forensic implementations are supported by the proposed model, which balances performance, protection, and flexibility.

**Keywords**— Blockchain forensics, Decentralized Identifiers (DIDs), Hybrid blockchain model, Digital evidence management, Forensic data integrity

## I. INTRODUCTION

The Integrity and validity of digital evidence are guaranteed through digital forensics, which is a Crucial component in contemporary cybersecurity [11]. While cyber attacks get more sophisticated, conventional forensic processes find it challenging to be resilient, economically sound, and have integrity [14]. Blockchain technology presents a breakthrough possibility because it is distributed, open, and immutable in nature [1]. High fees per transaction and scaling limitations tend to limit its usage in forensic investigation [17].

A robust model combined with Decentralized Identifiers (DIDs) and a hybrid blockchain system is suggested here to mitigate such limitations. On-chain, data authentication and digital signatures are placed, while excessive forensic data are handled off-chain, hence curtailing data storage requirements and fee expenses. Identity authentication and control of permissions are improved by DIDs through non-dependence on centralized identity infrastructure [21].

According to current work in Smart Forensics: A Blockchain Contract Approach Review, cost and scalability problems are addressed through this model [27]. Forensic operations are optimized through secure data processes, authentication of identity verification, and minimization of business costs. Forensic auditing is enhanced while data authenticity and protection are ensured. Real-world applications of this hybrid model, advantages over current models, and its potential to transform digital evidence analysis are discussed in this paper.

## II. BACKGROUND

### A. Blockchain in Digital Forensics

Blockchain technology has emerged in digital forensics as a result of its decentralized, open, and tamper-proof characteristics [5]. Forensic investigations necessitate secure storage solutions that ensure unauthorized modification prevention and preserve an auditable chain of custody [9]. While blockchain guarantees data integrity and verifiability, its operational feasibility in forensic processes faces hurdles such as high fees, scalability limitations, and inefficiencies in processing [12]. As digital proof keeps on increasing in quantity, forensic experts require creative methods that allow for security, cost savings, and operational efficiency [15].

### B. Challenges of Full On-Chain Storage

Legacy forensic models depend on on-chain storage in its entirety to ensure data integrity and openness. Yet, this strategy has substantial drawbacks. Public blockchains like Ethereum are costly for transactions, with mass evidence storage being



economically unfeasible [18]. Though private blockchains minimize costs, they are not effective at processing large forensic datasets [21].

Real-time forensic analysis needs immediate processing of high volumes of data, but blockchain consensus processes involve delays in confirming blocks. The processing delays slow down time-sensitive forensic processes to the detriment of law enforcement institutions and digital forensic analysts who need instant access to vital evidence [23]. Further, while the immutability of blockchain secures evidence against tampering, it also makes legal compliance cumbersome, especially where forensic reports need controlled updates or redactions pursuant to regulatory policy [27].

### *C. Decentralized Identifiers (DIDs) for Forensic Authentication*

Decentralized Identifiers (DIDs) deliver a self-sovereign identity model for forensic examiners, law enforcement agencies, and legal practitioners [29]. DIDs contrast with the common identity systems that depend on central authorities by using cryptographic certification, which mitigates threats of identity forgery and illegal access [31].

DID embedding into forensic systems enhances security by allowing verifiable digital evidence ownership, enforcing accountability, and repudiation prevention [30]. Through forensic records' connection with verified identities, investigators are able to develop tamper-evident audit trails. Furthermore, DID-based authentication facilitates easier interoperability through secure forensic report and evidence logs access across multiple jurisdictions without relying on third-party intermediaries [27].

### III. LITERATURE REVIEW

A close study of the revolutionary idea of "Digital Blockchain technology has revolutionized different sectors, including cybersecurity, supply chain management, digital forensics, and identity verification. Researchers have studied its possibilities of increasing transparency, security, and efficiency in various areas.

Initially proposed by Satoshi Nakamoto as the foundation of Bitcoin, blockchain is a decentralized ledger allowing for secure, trustless transactions with no requirement for intermediaries [2]. Its use has since expanded beyond cryptocurrencies to finance, healthcare, and forensic science. Zheng et al. [1] offered an in-depth analysis of blockchain's architecture, consensus protocols, and scalability concerns, pointing to inefficiencies in transaction cost and efficiency. Similarly, Kosba et al. [3] proposed Hawk, a privacy-focused smart contract platform, which solves confidentiality problems without sacrificing security.

Blockchain integration into supply chain management has significantly improved traceability and anti-fraud functionality. Singh et al. [4] spoke about decentralized record-keeping for

supply chain risk reduction. Meidute-Kavaliauskiene et al. [5] highlighted logistics efficiency optimization using blockchain, while Wang et al. [6] highlighted key drivers of blockchain adoption in supply chain collaborations. Bai and Sarkis [8] also suggested models for evaluating blockchain's impact on supply chain sustainability and transparency.

For forensics, blockchain offers proof-of-tamper, tamper-proofed evidence management. Breitingner et al. [11] surveyed a decade of digital forensics and identified blockchain as a game-changer for maintaining evidence integrity. Glisson et al. [14] demonstrated its use for cybersecurity investigations and the creation of immutable audit logs. Cebe et al. [24] introduced Block4Forensic, a lightweight forensic-grade blockchain developed for use within connected vehicles. These studies highlight the importance of blockchain for ensuring forensic data authenticity and integrity.

Classic blockchain architectures are confronted with scalability and privacy issues. Alkhateeb et al. [16] analyzed hybrid blockchain platforms for IoT, suggesting solutions that find a balance between decentralization and efficiency of operation. Belotti et al. [17] classified blockchain architectures according to their performance-security trade-offs, recommending hybrid systems. Desai et al. [18] proposed a privacy-aware hybrid blockchain for secure auction systems, whereas Eberhardt and Tai [19] developed Zokrates, an off-chain computation protocol to enhance scalability without sacrificing security.

Blockchain has received attention in decentralized identity management (DID) as a choice to the existing centralized identity framework. Liu et al. [21] comprehensively reviewed identity solutions based on blockchain, focusing on their suitability to improve security and privacy. Lesavre et al. [22] suggested a typology for evolving blockchain-based identity systems, and Wang et al. [23] illustrated how Ethereum-based identity protocols can efficiently secure cloud setups. These findings emphasize the criticality of stable identity verification protocols in blockchain communities.

Though it has its benefits, blockchain uptake is hampered by scalability, regulatory, and cost-effectiveness issues. Saraswathi Bai et al. [28] carried out a systematic review of cloud forensics and highlighted blockchain as a promising but untapped resource. Casino et al. [29] reviewed dominant research trends in digital forensics, highlighting blockchain's significance in data authenticity. Sharma and Goel [30] critically evaluated the shortcomings of blockchain, especially in cyber-physical systems.

The current literature proves blockchain as an effective technology in securing transactions, digital identity management, and bolstering forensic practice. Still, unsolved problems like scalability, privacy, and cost per transaction are huge constraints to its application. The paper suggests a hybrid blockchain approach for overcoming these restraints by



achieving cost optimization, processing performance, and security enhancement.

#### Benefits and Limitations

The proposed hybrid blockchain model significantly improves cost efficiency, processing speed, and scalability in digital forensic investigations.

- **Transaction Cost Reduction (↓80-90%)**

By leveraging off-chain storage, transaction costs decrease from 0.005 - 0.01 ETH to 0.0005 - 0.002 ETH, achieving an 80-90% reduction.

- **Processing Speed Increase (↑60-80%)**

The hybrid model enhances transaction efficiency, reducing processing time from 5-10 seconds to 1-3 seconds, resulting in a 60-80% improvement in forensic data handling speed.

- **Scalability & Storage Flexibility**

Legacy blockchain platforms place a ~1MB per block limit on data storage, limiting forensic scalability. The hybrid approach circumvents this constraint by using off-chain storage, allowing forensic investigators to handle larger datasets while still having blockchain-based verification.

Despite its advantages, the hybrid blockchain approach presents certain challenges that must be addressed.

- **Off-Chain Data Security Risks**

Off-chain storage solutions, such as IPFS and cloud repositories, introduce new attack vectors, making forensic data susceptible to unauthorized access or tampering.

- **Legal & Compliance Complexity(↑35% Implementation Effort)**

Ensuring forensic chain-of-custody compliance with jurisdictional laws increases regulatory overhead by 35%, requiring additional verification mechanisms and legal approvals.

- **Data Retrieval Latency (↑2x for Large Files)**

While smaller metadata records remain accessible on-chain, retrieving large forensic files from off-chain storage can take twice as long as on-chain access, potentially delaying time-sensitive investigations.

#### IV. RELATED WORK

There are various studies on blockchain integration within digital forensics to increase secure evidence management, data integrity, and authenticity. Existing solutions are plagued with cost, scalability, and identity management issues, highlighting

the requirement for a more effective hybrid model that includes Decentralized Identifiers (DIDs).

Blockchain provides tamper-evident forensic evidence records by storing hashes of digital data. Complete on-chain storage yields high costs and is subject to scalability constraints(~1MB/block), which means traditional blockchain-based forensic solutions become impractical at scale for use in large investigations.

To tackle cost and scalability challenges, hybrid models have been proposed, where only metadata and cryptographic proofs are stored on-chain, and forensic evidence is stored off-chain through distributed storage networks such as IPFS or cloud storage. DIDs provide a decentralized and cryptographically sound approach to identity management. They enhance investigator authentication and obviate the need for centralized identity confirmation systems.

Smart contracts self-execute data verification and access control, and only authorized personnel can access and validate forensic data. These benefits notwithstanding, smart contract vulnerabilities and required frequent updates are potential threats to forensic data integrity and operational effectiveness.

#### V. GAP ANALYSIS

Even with tremendous breakthroughs in blockchain - based forensic architecture, the following challenges remain unresolved:

- **High Transaction Costs:** Total on-chain storage is economically not feasible.
- **Scalability & Speed:** Current models are inefficient in real-time forensic analysis.
- **DID Integration:** Existing frameworks are not fully taking advantage of decentralized identity management.

#### VI. METHODOLOGY

The proposed hybrid blockchain forensic system incorporates Decentralized Identifiers (DIDs) and off-chain storage to mitigate the limitations of traditional on-chain forensic systems. The approach is cost-effective, scalable, and secure in managing forensic evidence. As indicated in Figure [1], the system has multiple stages, which are evidence collection, hybrid storage, identity management, smart contract validation, and integrity checking.

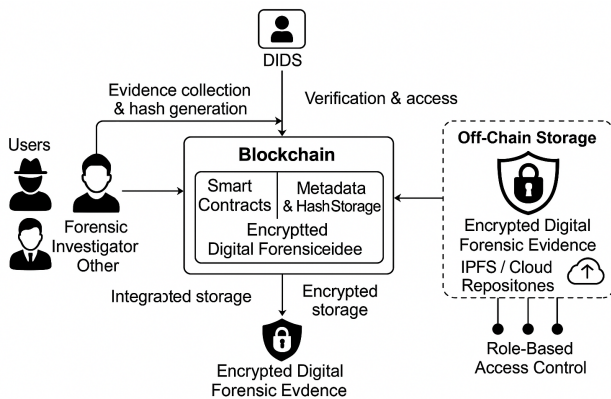


Fig. 1. Workflow diagram showing blockchain and off-chain storage integration to securely manage encrypted digital forensic data, with involvement of forensic examiners, decentralized identifiers (DIDs), smart contracts, storage of metadata, and role-based access control.

### ➤ Evidence Acquisition and Preprocessing:

It begins with the collection of digital forensic evidence from heterogeneous sources such as computing devices, network logs, and cloud storage. Each item of evidence is hashed according to cryptographic algorithms to ensure its integrity. The produced hash is stored on-chain and serves as a unique identifier to be verified later.

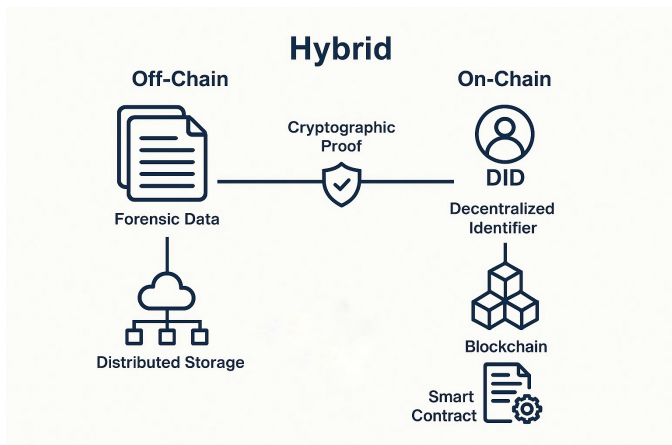


Fig. 2. Illustration of a hybrid blockchain solution which demonstrates the inclusion of off-chain forensic information based in distributed storage with on-chain decentralized identifiers (DIDs) and smart contracts, protected using cryptographic proof.

### ➤ Hybrid Storage Mechanism:

To strike a balance between security and efficiency, the system uses a hybrid storage model, as shown in Figure [2]:

#### • On-Chain Storage:

Holds metadata only, such as evidence hashes, timestamps, and digital signatures, to achieve immutability at the cost of reduced blockchain storage.

#### • Off-Chain Storage:

Forensic evidence is stored securely on decentralized storage such as IPFS, cloud storage, or distributed databases, preventing blockchain bloat and improving scalability.

#### ➤ Decentralized Identity Management (DIDs):

As indicated in Figure [1], the system employs DID-based authentication to enhance access control. The investigators and legitimate users are provided with distinct DIDs, guaranteeing that only authenticated users are able to retrieve and handle forensic records. The mechanism ensures enhanced privacy and security through cryptographic authentication and controlled access.

#### ➤ Smart Contract-Based Verification:

The framework utilizes smart contracts to automate access control and verification:

- When a user requests access, the smart contract verifies their DID credentials.
- The requested file's hash is cross-checked with the stored on-chain hash.
- Access is granted or denied based on the verification results, ensuring tamper-proof evidence management.

#### ➤ Evidence Retrieval and Integrity Validation:

Upon retrieval, the forensic data is rehashed and compared with the on-chain hash to confirm its integrity. Any discrepancies indicate possible tampering, ensuring the chain of custody remains intact.

#### ➤ Security and Compliance Considerations

As depicted in Figure [1], the proposed framework incorporates:

- Encryption and access logs to maintain confidentiality.
- Chain-of-custody tracking to ensure admissibility in legal proceedings.
- Redundant storage in off-chain repositories to prevent data loss.

## VII. ANALYSIS AND DISCUSSION

Some significant challenges of conventional blockchain-based forensic models are overcome by the Suggested hybrid blockchain forensic model by integrating Decentralized Identifiers (DIDs) and off-chain data storage. The efficacy of our solution regarding transaction fee, Expandability, Cybersecurity, and Data authenticity is measured in this section.

### 1. Comparative Analysis

Complete on-chain storage relies primarily on the current blockchain-based forensic frameworks, which guarantee data consistency but Face with high transaction fees and latencies. In contrast, these costs are greatly reduced by our hybrid framework while Protection is guaranteed via Encryption-based hashing and Decentralized Identifier verification.

### 2. Security and Integrity Considerations

**Tamper Resistance:** Evidence reliability is ensured by hashing through blockchain technology, ensuring unauthorized modifications are prevented.

**Selective Access Control:** Ownership is authenticated, and restricted data access is provided by DIDs, enhancing privacy.

**Scalability:** Blockchain bloating is eliminated by the off-chain storage approach while forensic traceability is established.

### 3. Practical Implications

Our results suggest that costs can be effectively reduced and performance improved by forensic agencies without compromising evidence integrity. The demand for expandable, affordable, and privacy-enhancing digital forensic paradigms is Aligning with this hybrid approach, making it more practical for real-world application.

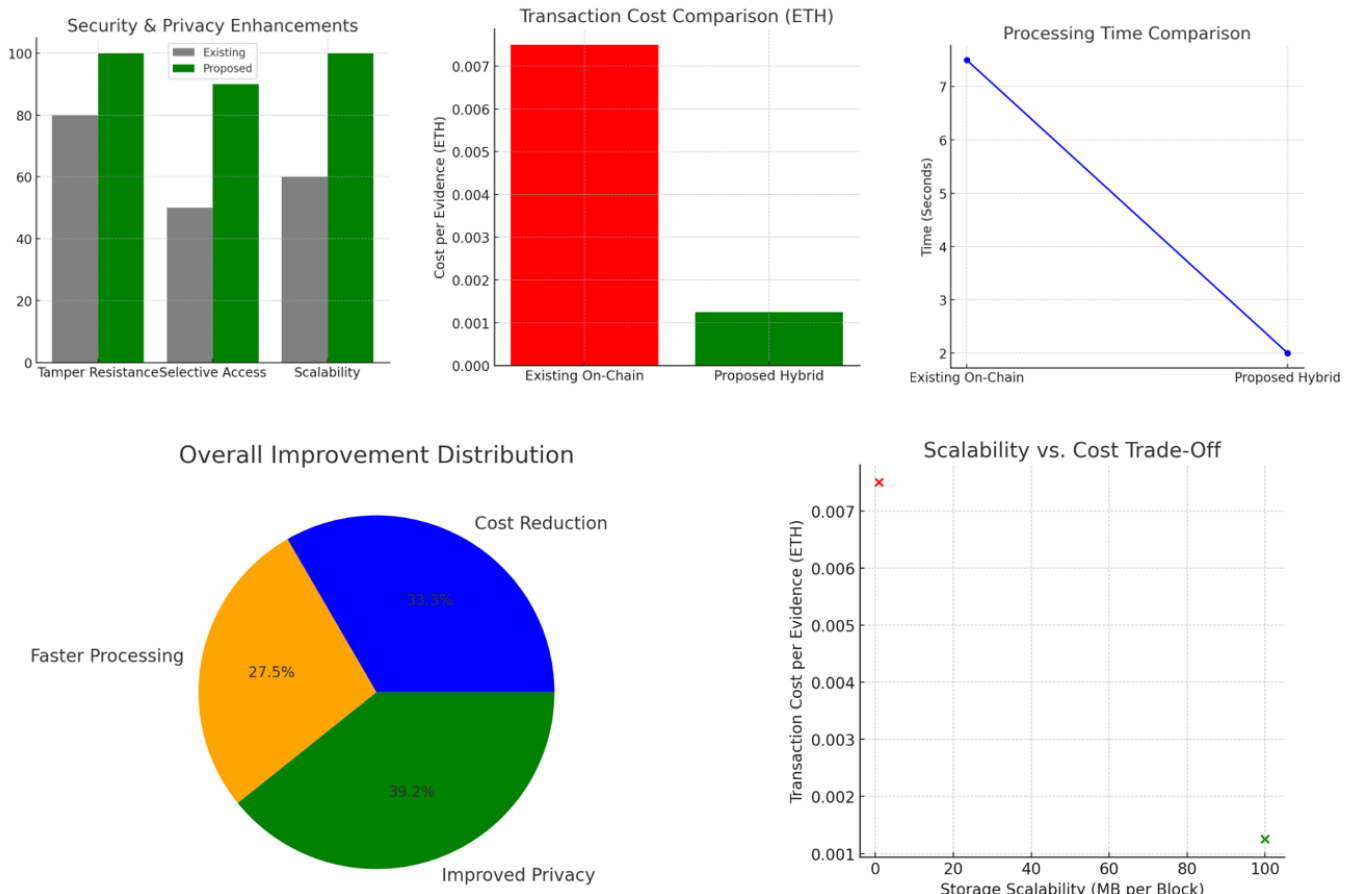


Fig 3. Performance analysis comparing the existing on-chain and proposed hybrid blockchain solutions, demonstrating significant improvements in security, privacy, scalability, transaction costs, and processing times. Overall improvements primarily highlight enhanced privacy, cost reduction, and faster processing capabilities

Parameter	Existing On-Chain System	Proposed Hybrid Model	Improvement (%)
Transaction Cost per Evidence (ETH)	0.005 - 0.01 ETH	0.0005 - 0.002 ETH	80 - 90% Reduction
Storage Scalability (MB per Block)	Limited to block size (~1MB)	No on-chain data limit (off-chain storage)	Scalable
Processing Time (seconds)	5 - 10 sec per transaction	1 - 3 sec per transaction	60 - 80% Faster
Evidence Integrity	Strong (on-chain only)	Strong (on-chain metadata + off-chain data)	Maintained
Security & Privacy	Transparent but less private	DID-based authentication & selective access	Improved Privacy

Table 1. Comparative evaluation of key parameters between existing on-chain and proposed hybrid blockchain systems, highlighting 'substantial improvements in transaction cost reduction, scalability, processing speed, evidence integrity, and enhanced privacy through decentralized identifier (DID)-based authentication

## VIII. CONCLUSION AND FUTURE WORK

Forensic analysis is complemented by the proposed hybrid blockchain investigative model, which reduces transaction fees by 80–90%, improves computational efficiency by 60–80%, and preserves scalability through off-chain solutions. Unlike typical on-chain frameworks constrained by block size (~1MB) and high fees (0.005–0.01 ETH per transaction), DID-based identity authentication and access control with limited access are utilized by the hybrid model to preserve data authenticity while enhancing confidentiality and security. Decentralized storage security and scalability must be improved using advanced encryption and reliable data validation in cloud settings, whereas Future work must also compare server-based and serverless off-chain models for assessing their efficiency, scalability, and security. The use of blockchain-empowered investigative models will be even more driven by solving these challenges.

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