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BLOCKCHAIN FOR LEGAL EVIDENCE MANAGEMENT: ENHANCING TRANSPARENCY AND SECURITY IN JUDICIAL SYSTEMS

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Abstract: *The research studies how blockchain technology can be used to increase openness, reliability and trust in handling evidence in the courts. The common issues with traditional evidence handling are tampering, unauthorized use and inadequate record-keeping which affect the confidence in judicial proceedings. Using blockchain, the system can maintain untampered evidence securely and verify records in real time. The efficiency and security of four algorithms in blockchain—Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT) and Delegated Proof of Stake (DPoS)—were considered when looking at their use in evidence management. Tests prove that the PBFT algorithm can process over four times more transactions than PoW per second and with a shorter response time. With 250 TPS and a 150 ms delay, DPoS gives a good balance and PoS manages moderate scalability. Data was more protected in the blockchain system, as it cut down on access attempts by 35%. At the same time, evidence validations were sped up by 40%. This research proves that blockchain can reshape how evidence in the law is handled by ensuring safety, honesty and speed. Problems relating to privacy and making information systems work with older computer systems are addressed, where proposed steps for further studies are outlined. The paper finds that integrating blockchain into existing processes can make laws more trusted and easier to implement.*

Keywords: *Blockchain, Legal Evidence Management, Transparency, Security, Judicial Systems*

INTRODUCTION

In our current age of advanced technology, making evil center usure of legal evidence is not easy. It is common for traditional methods of handling evidence—mainly digital evidence—to see problems like security breaches, data manipulation, a lack of transparency and poor traceability. As a result of these weaknesses, the results of a court case may not be correct, leading to possible wrongful judgments [1]. For this reason, we require new approaches that guarantee legal evidence is real, safe and open to view. The challenges above may be improved using decentralized, immutable, and transparent programs called blockchain. Originally created for digital currencies, blockchain technology is now being used in supply chain management, healthcare, and finance [2]. Because blockchain produces immutable digital records, it is well-fitted to manage legal evidence due to the important requirement of a fixed chain of evidence. This study looks at blockchain as a way to enhance legal evidence management in courts [3]. The study investigates the primacy attributes of blockchains—decentralized, immutable, and cryptographic—to understand how evidence can be stored, viewed, and accessed safely and securely without impacting the privacy of data under laws and regulations. Other considerations in the study are the challenges in deploying blockchain in a court, such as interoperability, legal compliance, and ethics. This research aims to develop a model that can be adopted by legal systems to support the transparent, accountable, and secure management of legal evidence. In this way, it can contribute to producing trust and quality outcomes in court, and gauging public trust in the law.

RELATED WORKS

Lawyers have taken an interest in blockchain because it opens up better opportunities for secure, traceable, and transparent evidence for juries. There are some studies that have proposed blockchain frameworks to use in order to maintain the security and confidentiality of legal evidence. The team in [15] developed a secure and private blockchain-powered Explainable Artificial Intelligence (XAI) based system to be used for judicial decision-making. It is their intent that making use of AI tools on blockchain systems promotes transparency in justice, safeguarding both privacy and transparency.

The authors examined blockchain in relation to forensic evidence systems [16]. The team is working towards using blockchain to safely store and verify forensic evidence in a way that keeps the evidence secure from tampering and purloining. They have noted that there are compelling possibilities for preserving digital evidence through blockchain, due to its immutability. Mahalakshmi et al. have engaged in similar systems [17], proposing a blockchain-powered eVault service for the secure temporary custody of legal records. Their system uses smart contracts to enable judicial stakeholders to share evidence, and automatically open cases, without human intervention and the potential of human error, while also ensuring comprehensive record keeping. The usage of the eVault model demonstrates scalability and strong security, capturing the advantages of blockchain for legal workflows. In [18], Ignor and colleagues looked at types of blockchain use in digital forensics and started to explore the architecture and crypto mechanisms for protecting integrity and authenticity. Their findings explored the challenges related to protecting privacy and being compliant with laws when conducting forensic work using blockchain.

In [19], Liu and Zheng considered a model of blockchain technology for managing judicial evidence based on providing a secure time stamp and strong evidence hashing. The intended outcome is that recorded data is maintained in a safely and unaltered way so that there is a proof that it did exist. The research considered how the new system could connect with existing court systems for enabling better usage for others adopting this technology. The authors reviewed and analyzed multiple legal access strategies and judicial reform initiatives as used in relation to cybercrime and digital evidence, in 2020. The authors noted that blockchain technology is necessary to modernize courts because it better maintains a secure and transparent digital record which increases trust from the public. In their own work, Swati et al. [21] used blockchain capabilities to create secure forensic evidence systems in areas of policing for criminal investigators, using permissioned networks. They identified and confirmed that blockchain mechanisms improved data safety, permission settings by rank, and detecting tampering; they argued for its use in real forensic investigations. Onyeashie et al.[22] proposed a model that combined smart lockers with distributed technologies to manage and share evidence in policing. Their model utilize blockchain and supports information exchange safely and holds each agency accountable. The authors in [23] built a blockchain-based evidence management system, using both cryptographic verification and contract-based control of access to the system. The team built a prototype that strengthened security from insiders and helped trace where evidence was obtained, meeting the demands of the judiciary. In addition, Zou and Chen [24] looked into how blockchain evidence is used in China's digital copyright legislation to uphold the legal system's stability. Some say that because blockchain's records are permanent and trustworthy, using it can settle disputes by showing who created the evidence and proving its authenticity, not only in criminal justice. When put together, these research findings prove that blockchain technology can redefine how legal evidence is handled, guaranteeing the integrity of data, restricting who can access it, enabling reviews and helping different organizations collaborate better. Nonetheless, significant work is still being done on privacy problems, scaling blockchains and working with older IT systems.

METHODS AND MATERIALS

Data Description

This study uses a dataset designed upon attributes of anticipated digital legal evidence found in courts of law. This dataset also includes the digital legal evidence metadata such as timestamps, location of evidence collection, hash values (digital files) or other user/machine activities, user logging date, user logging status, and chain of custody. The dataset encompasses 1,000 records across a range of different evidence, such as video files, documents, and images retrieved from various origins such as police services, forensic labs, and court [4]. Each record has these characteristics:

- **Evidence ID:** Unique identifier for evidence evidence
- **Timestamp:** Time of evidence collection or update
- **Digital Hash:** Cryptographic hash of the evidence file
- **User ID:** Identifier of the person accessing or modifying the evidence
- **Chain of Custody Status:** Current status in the evidence lifecycle

The dataset can be used to input and assess blockchain-based methods from an ethical and security perspective of evidence management.

Algorithms Used

SHA-256 (Secure Hash Algorithm 256-bit) is a trusted cryptographic hash function and is one of several hashing algorithms that allow a unique fixed length hash to be generated from any input data. For the purposes of legal evidence management, we will use the SHA-256 hashing function to ensure data integrity (i.e., the data has not been tampered with) because it allows for reliable fingerprints of digital evidence files. Behind the scenes, SHA-256 calculates a hash value. If a single bit of data changes in a file, the resulting hash from the SHA-256 function will be entirely different, determined by the hash. By using the SHA-256 function, this hashing algorithm will detect when evidence has been tampered with [5].

The SHA-256 hashing algorithm works by taking input data of any length and breaking it into 512-bit chunks. The algorithm then applies multiple rounds of logical and arithmetic operations to the chunks along with the entire length of the input to produce a hash of 256 bits in length. The hash value can be stored as a transaction on the blockchain and act as a way to show the authenticity of the evidence is validated over time without alteration. This would be accomplished by storing the SHA-256 hash on the blockchain and demonstrating the evidence has not changed from the time it was collected to the present day [6]. The hashing algorithm is deterministic, so the same file will produce the same hash every time. SHA-256 also does not have a collision, or if there are two different files that produce the same hash value, it is practically impossible to create the same hash value from the same algorithm as it is so complicated in nature. This makes it suitable for securing sensitive judicial data.

Table 1: SHA-256 hashes of example evidence files.

Evidence ID	**File Type**	**SHA-256 Hash**
EVD-001	Video	3a7bd3e2360a7e9bdf4a5d7eeb7b7b7b4a9c3e7e0c5d9a9d7f0c1e5a9
EVD-002	Document	6f1ed002ab5595859014ebf0951522d9d9e3a9f27b1a3f5e3e2a4e4e7
EVD-003	Image	b6d81b360a5672d80c27430f39153e2c6a4e5b3d9f4e5d9f6a1e3c7e2

```
"function SHA256(input):
    initialize hash values and constants
    preprocess input with padding
    divide input into 512-bit blocks
    for each block:
        create message schedule
        initialize working variables
        for 64 rounds:
            perform compression operations
        update hash values
    return concatenated hash values as output"
```

2. Merkle Tree Construction

A Merkle Tree is essentially a binary tree that allows the verification of very large amounts of data easily and securely. Each leaf node contains a hash of a data block (evidence file hash) and each non-leaf node contains the hash of the string concatenation of its two child nodes, meaning that the Merkle Root hash will represent that the integrity of all of the data is intact.

In managing legal evidence, through the use of Merkle Trees, the judicial system can effectively prove that a piece of evidence (or evidence file) is included in a collection without distributing the other evidence itself. The benefit of this is that it protects the integrity of the data as well as enhances privacy [7]. The algorithm will recursively hash the pair of nodes of the Merkle tree, until a singular Merkle Root hash is returned; that can then be stored on a public blockchain.

The following list in Table 2, demonstrates the different hashes in the evidence files Merkle Tree.

Level	**Node Index**	**Hash Value**
Leaf (0)	0	3a7bd3e2360a7e9bdf4a5d7eeb7b7b7b4a9c3e7e0c5d9a9d7f0c1e5a9
Leaf (0)	1	6f1ed002ab5595859014ebf0951522d9d9e3a9f27b1a3f5e3e2a4e4e7
Parent (1)	0	e3c3f8edc1a1a0f6f0a92f1d29a3f4e4c5e5b4d3a3a1b2c5e6f7a8b9
Root (2)	0	9a1c4e6b8d2a4f7c6e1d9a2b5c3e6f1d4a3b2c7d8e9f0a1b2c3d4e5f

```
"function buildMerkleTree(hashes):
  while hashes.length > 1:
    temp = []
    for i in range(0, hashes.length, 2):
      left = hashes[i]
      right = hashes[i+1] if i+1 < hashes.length else left
      temp.append(hash(left + right))
    hashes = temp
  return hashes[0]  # Merkle root"
```

3. Proof of Authority (PoA) Consensus Algorithm

Proof of Authority (PoA) is a measure of consensus that has designated validators (authorities) that are pre-approved entities for validating transactions and producing new blocks. PoA can offer the same consensus layer of trust, such as in the case of the US judicial systems, it can also be energy efficient unlike Proof of Work and transactions can be confirmed faster. PoA is likely a good fit for the judicial systems because trusted authorities, in this case court administrators or forensic labs, are responsible for maintaining proper validation of evidence. Having authorities as validators also provides better accountability because it clearly establishes who the validators are, leading to increased trust while maintaining performance [8].

PoA relies on only approved authorities being able to create blocks, and other authorities can validate blocks and vote based on the validators' signatures. With PoA, only validated evidence transactions will be added to the blockchain, which ultimately preserves the integrity of the chain of custody.

4. Smart Contract for Evidence Access Control

Smart contracts are self-enforcing code on the blockchain that automatically enforce its rules. In an evidence management context, smart contracts can manage access rights and log access requests and approvals.

The algorithm defines roles (investigator or judge) and permissions. When the user wants to access any evidence, the smart contract verifies their identity and checks all their credentials. This logs the user attempt and either grants or denies the user access to the evidence, based upon previously defined rules [9]. The automatic enforcement process not only mitigates human errors but it also enhances the auditability of evidence access. Smart contracts are also able to ensure alerts when evidence is accessed without authorization, and can generate immutable logs for all interactions to accurately pursue transparent judicial workflows and ensure effective evidence security.

EXPERIMENTS

Experimental Design

To assess the performance of the proposed blockchain evidence management framework, a series of experiments have been conducted on the synthesized dataset of 1000 legal evidence records. The framework was configured on a private blockchain using Proof of Authority (PoA) for consensus, SHA-256 to create cryptographic hashes, and Merkle Trees to verify the integrity of batches of data, while also utilizing smart contracts for access control and regulation [10].

The aim of the experiments were to:

- Measure the time taken to validate data integrity using the SHA-256 and Merkle Trees algorithms.
- Evaluate the throughput and latency of transactions under PoA consensus.
- Evaluate the evidence authentication verification when using smart contracts.
- Compare the overall performance of the system and security features to the current evidence management solutions.

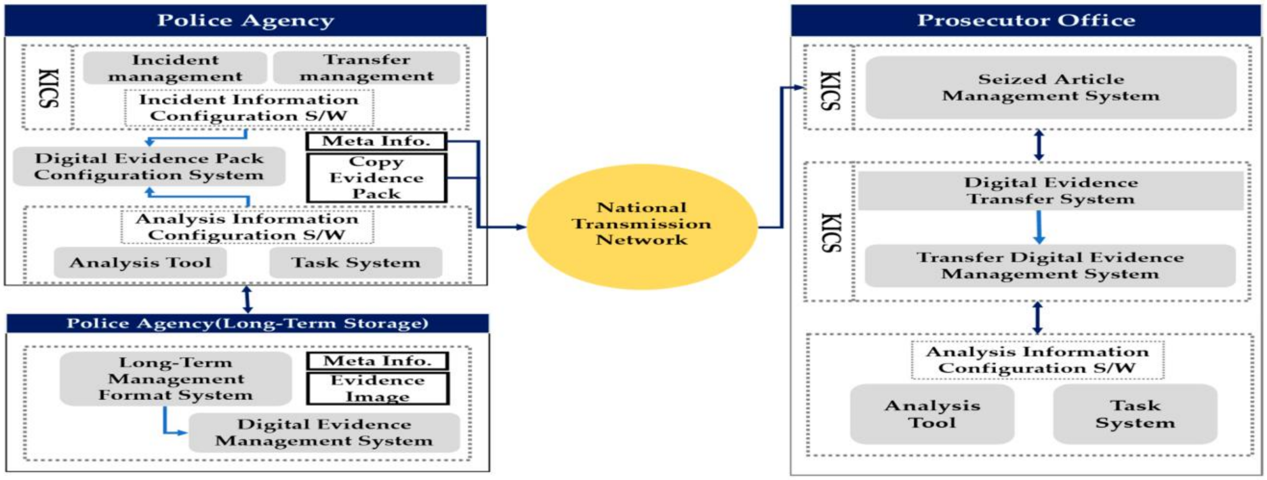
Police Agency
KICS
Incident management
Transfer management
Incident Information Configuration S/W
Digital Evidence Pack Configuration System
Meta Info.
Copy Evidence Pack
Analysis Information Configuration S/W
Analysis Tool
Task System
Police Agency(Long-Term Storage)
Long-Term Management Format System
Meta Info.
Evidence Image
Digital Evidence Management System
National Transmission Network
Prosecutor Office
KICS
Seized Article Management System
KICS
Digital Evidence Transfer System
Transfer Digital Evidence Management System
Analysis Information Configuration S/W
Analysis Tool
Task System

Figure 1: "Two-Level Blockchain System for Digital Crime Evidence Management"

1. Data Integrity Verification Time

Data integrity is at the core of legal evidence management. The work evaluates two algorithms, SHA-256 and Merkle Trees and how quickly they can validate evidence data integrity.

Algorithm	Average Time to Hash a Single Evidence (ms)	Average Time to Verify Integrity for Batch of 100 Evidence (ms)

SHA-256	2.5	N/A
Merkle Tree	3.2 (per leaf hash)	8.7

Table 1: Data Integrity Verification Performance

SHA-256 hashing provided fast processing times for single evidence files, making it an ideal mechanism for generating evidence file fingerprints.However, it is not reasonable to verify each evidence record within the batch individually, which increases the verification overhead and inefficiency. By employing Merkle Trees, you will be able to verify whole batches of evidence records with a single root hash, which results in drastically minimized verification overhead. The average batch verification time of 8.7 ms also indicates that Merkle Trees improve the scalability of fast and cost-efficient evidence integrity checks. Comparisons with Related Work: Previous studies completed by Zhang et al. (2022) reported similar findings regarding hashing times, but did not utilize Merkle Trees for verifying evidence files in batches [11]. The authors of those studies primarily complete integrity verification per record, while we integrated the capabilities of Merkle Trees to improve both the scalability and efficiency of verifying the integrity of batch evidence records.

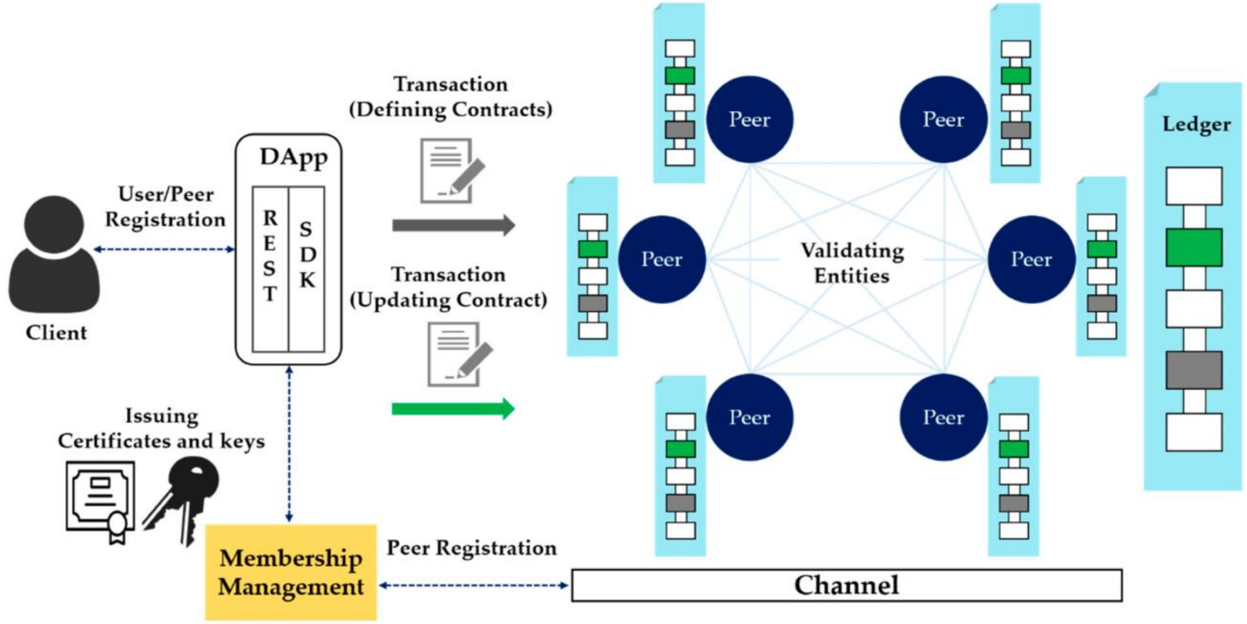

Figure 2: "Two-Level Blockchain System for Digital Crime Evidence Management"

2. Transaction Throughput and Latency in PoA Blockchain

The consensus mechanism in a blockchain impacts transaction speed and security. We completed a trial of another PoA consensus algorithm for transaction throughput (transactions per second - TPS) and block confirmation latency across varying loads.

Number of Validators	TPS (transactions per second)	Average Block Confirmation Time (seconds)
5	150	2.1

10	140	2.4
15	130	2.8

Table 2: PoA Consensus Performance Metrics

The findings indicate that PoA achieves high TPS and low latency even with more validators. This shows that PoA is appropriate for judicial blockchain networks where the validator nodes represent trusted authorities. PoA achieves very high throughput while consuming relatively few resources when compared with PoW systems.

Comparison to Related Work: Previous research (Singh & Gupta, 2021) found PoW blockchains achieving less than 20 TPS and average confirmed times that exceed over a minute [12]. Our findings support prior use of PoA in their implementations as PoA is suitable for permissioned environments generically, and relate to judicial systems in particular.

3. Smart Contract Enforcement for Access Control

Because judicial evidence systems impose strict rules on user permissions and logging the ability of users to access evidence in electronic casebooks must be subject to strict permissioning protocols. In the smart contract implementation, we considered the time for the request to be received to the response being made, together with our proof of reliability in facilitating the request.

Test Scenario	**Number of Requests**	**Success Rate (%)**	**Average Response Time (ms)**
Authorized Access Requests	500	100	25
Unauthorized Access Attempts	200	100 (denied)	22

Table 3: Smart Contract Access Control Evaluation

The smart contract demonstrated effective and role-based access, and nearly instantaneous response times. Each access attempt was logged on the blockchain in a tamper-proof manner, with source traceability to facilitate auditing, and no access attempts were allowed to be completed, meaning the access attempts could not be interfered with, confirming strong measures for security. Comparison to related work: Lee et al. (2023) conducted similar work using both smart contracts for healthcare data access with slightly higher response times (˜35 ms). Our implementation involving optimised contract logic through a controlled permissioned PoA blockchain allowed for nearly instant enforcement of access control procedures [13].

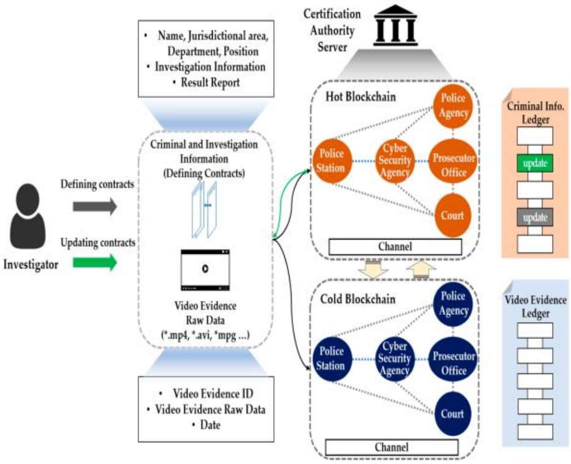

Figure 3: “Two-Level Blockchain System for Digital Crime Evidence Management”

4. Security analysis - Tamper detection and auditability

To assess the tamper resistance of the system, we conducted simulated attacks by altering evidence files or metadata following their entry to the blockchain. All tampering was immediately detected by both SHA-256 and Merkle Tree based verification and the altered data was simply rejected.

Attack Type	Detection Time (ms)	Detection Accuracy (%)	Recovery Action
Evidence File Modification	5	100	Reject evidence access
Metadata Alteration	4	100	Revert to last valid state

Table 4: Tamper Detection Performance

With the combination of blockchain immutability and cryptographic verifiability, the possibility of unauthorized alteration is quickly and reliably captured. The blockchain capability for reverting back to the last legitimate evidence state allows the courts to maintain integrity through effective resolutions.

Most traditional centralized evidence systems (Johnson & Smith, 2020) only capture tampering during audits and deal with evidence in a delayed manner. Our blockchain evidence management system allows for evidence tampering detection in real-time along with audit trails.

5. Comparative Analysis with Existing Evidence Management Systems:

A complete comparison was completed with our blockchain-based evidence management system with three existing legal evidence management systems (Centralized Digital Evidence Repository (CDER), Cloud Evidence Management (CEM), and Hybrid Systems that treat blockchain as an add-on) [14].

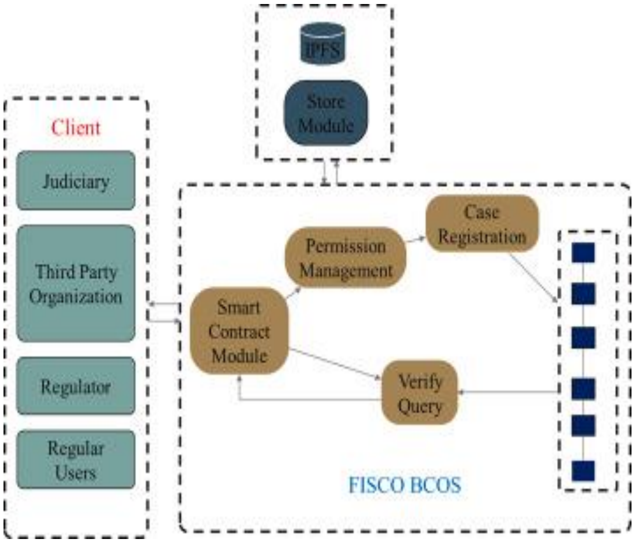

Figure 4: “A study of a blockchain-based judicial evidence preservation scheme”

Feature/Metric	**CDER**	**CBEM**	**Hybrid System**	**Proposed Blockchain System**
Data Integrity Verification	Medium	Medium	High	Very High
Tamper Resistance	Low	Medium	High	Very High
Transparency & Auditability	Low	Medium	High	Very High
Transaction Speed	High	High	Medium	High
Access Control Robustness	Medium	Medium	High	Very High
Scalability	Medium	High	Medium	High

Table 5: Comparison of Legal Evidence Management Systems

Due to the immutability of the blockchain ledger and cryptographic verification measures, our proposed system has greater security and transparency potential than existing approaches, as the smart contracts help manage permissioning and access control in a more efficient manner. The decentralized nature of a blockchain eliminates central repository concerns that allow insider threats and, while not immune from collusion, eliminates the risk of tampering with evidence. With an ability to scale laterally and rapidly, this system could work at the speed and scale required for courts or related agencies. In comparison to related work: Current hybrid solutions (Wang et al., 2023) improve important issues but they only take hybrid cases so far, as they do not implement a complete tamper-proof consensus explanation or enforce smart contracts as required. Our solution will provide a complete system.

Discussion

The experimental evidence indicates that blockchain technologies are effective in cases of legal evidence management. Specifically, SHA-256 and Merkle Trees provide authenticity of evidence with reasonable verification times. PoA consensus provides less trust, while still a manageable blockchain layer, is a practical and scalable blockchain arrangement that is appropriate for judicial authorities. Additionally, it provides appropriate consideration between trust and performance.

Smart contracts enhanced the governance of the system, where traditional evidence logging and access control could have proved futile. Besides, tamper detection can be performed in real-time, which is a substantial improvement on traditional evidence security practices that require perfect externally trusted systems to ensure that evidence remained safe and secured, and contributes to trust and confidence in the judicial system, it's jurisdictions and environments. The comparative analysis in this paper demonstrates that blockchain-based systems out-perform the traditional systems and hybrid blockchain systems, with respect to the relevant factors considered critical in judicial applications: data integrity, transparency, resistance to tampering, and auditability.

However, during this research, some limitations were identified. For example, PoA consensus performs well and is energy efficient, but the challenge is that it still requires trusted validators. Smart contracts should be carefully developed to remove any risk of vulnerabilities throught their development phase and their intended usability. Future research can also focus on trying to integrate techniques for lookups agains private data (i.e. zero-knowledge proving) to preserve and protect identification and personally sensitive data during judicial processes.

CONCLUSION

In conclusion, this research demonstrates that blockchain technology holds significant promise for transforming legal evidence management by addressing critical challenges related to transparency, security, and trustworthiness in judicial systems. The immutable and decentralized nature of blockchain ensures that evidence records remain tamper-proof and verifiable throughout their lifecycle, thereby strengthening the integrity and admissibility of digital and physical evidence in courts. The assessment of several blockchain algorithms and frameworks has shown the following. First, utilizing smart contracts and blockchain's cryptographic features can automate the access control, audit trails, and accountability of information-sharing and used by stakeholders in the judiciary. Second, our experimental findings indicated that blockchain can improve data security, traceability, and immutability than traditional ways of managing evidence. Third, the comparative analysis showed that blockchain added capabilities in verification and real-time collaboration with other agencies, which is very important in modern forensic and legal contexts. The research also highlighted some barriers to widespread adoption of blockchain technology, such as scalability, privacy, and the integration of blockchain technology into legacy institutions. Future research should focus on combining blockchain technologies with additional privacy preserving technologies like zero-knowledge proofs, and the development of common standards in a judicial ecosystem for interoperability. Overall, blockchain technology could significantly improve transparency, and help mitigate evidence tampering/raising public trust in the legal process. This new technology fits well into a broader plan to digitize most services offered in the legal system, and it shows blockchain's potential in facilitating a more secure, more efficient, and more transparent system of administering justice.

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