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The Significance of Blockchain Technology in Preserving Digital Evidence Integrity in Forensic Investigations

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Abstract: Digital forensics is the application of technology to the investigation and accounting of digital crime and the extraction and analysis of digital evidence from systems and networks. As the number of IoT [Internet of Things] devices has proliferated, the complexity inherent in forensic investigations has skyrocketed. While IoT forensics addresses the challenges of a lack of standardized security protocol and ensuring the integrity as well as security of evidence data, it brings to bear all the difficulties existing in classic forensics. Unfortunately, traditional digital forensic tools are generally inadequate in shielding that evidence from tampering or unauthorized access. Digital evidence in IoT environments has been viewed as a potential solution that blockchain technology can offer with its tamper-proof and immune characteristics. This research explores how permissioned blockchain frameworks can enhance the integrity, confidentiality, and traceability of digital evidence in IoT forensic investigations. It hypothesizes that blockchain-based architectures outperform traditional evidence-handling mechanisms in preserving evidentiary reliability. While most encouraging, key findings show blockchain can do this establish data integrity, reliability, and confidentiality while featuring a very strong chain of custody for evidence. Furthermore, the study proposes how blockchain can be added to forensic practices to improve security and trust in forensic investigations. This study holds implications not only for digital forensic professionals but also for stakeholders in sectors such as healthcare, smart city governance, and critical infrastructure, where the reliability of digital evidence is paramount. By demonstrating blockchain's role in safeguarding forensic data, this research contributes to trust-building mechanisms essential for digital justice and regulatory compliance in cross-border investigations.

Keywords: Blockchain; Digital Evidence; Digital Forensics; IoT Forensics; Financial Inclusion; Health Data Management; Thematic Analysis

1. Introduction

Digital Forensics [DF] is a subspecialty of forensic science, the art and science of discovering, acquiring, analyzing, and reporting about evidence created in digital formats [1]. Due to the ever-developing sophistication of digital crimes such as malicious activity, data theft, and system compromise, DF has become essential to help law enforcement agencies around the world. What we uncover in digital evidence is often admissible in court, a reason why it matters for understanding events, tracking down malicious actors, and bringing people to account. Nevertheless, existing DF tools encounter obstacles; it is hard to guarantee the security, correctness, and admissibility of evidence in dynamic and heterogeneous environments, like the Internet of Things [IoT] [2].

IoT technology is how interconnected devices can exchange and process data and revolutionize industries. Such devices are sensors, actuators, and embedded systems that implement these devices distantly within architectures of layered architectures of perception, ubiquity, processing, and application layers. Tasks that these layers can perform are environmental sensing, data transfer, and real-time analytics [3-4]. While IoT is very flexible and scales well, it comes with its own special set of security challenges namely, the use of limited computational resources, the absence of unified standards, and poor and ad hoc security configuration. These IoT vulnerabilities expose IoT devices to many types of cyber threats, such as data breaches, unauthorized access, and deliberate manipulation [5-6].

IoTF, a subset of DF, seeks to address the challenge of IoT forensics in investigating crimes in an IoT environment. An investigative process starts with finding compromised devices, taking data and saving it, analyzing logs, and presenting the findings in legal and regulatory surroundings. Then, there are factors that make IoTF complicated: heterogeneous devices, diversity in data formats, and cross-border cloud environment complexities [7-8]. Currently, conventional DF methods fail to accommodate the dynamic with limited resources that IoT devices are experiencing, and these methods have to be designed such that the integrity and reliability of evidence are preserved [3].

As a solution, blockchain technology is emerging. A distributed ledger system with distributed timestamped data blocks linked with cryptographic hash functions in an immutable and decentralized fashion [9]. Furthermore, blockchain provides a tamper-resistant, traceable, data-integrity way to preserve digital evidence. It is furthermore transparent and accountable and creates secure collaboration among investigators without reliance on intermediaries, which is a characteristic of blockchain in its decentralized nature [10]. In the context of where a robust chain of custody [CoC] and evidence integrity are of the essence [11-12], these features fit well with the requirements of the IoTF.

The research in this paper aims to investigate how blockchain technology can be integrated into IoT forensic investigations by assessing the utility of blockchain technology in preserving digital evidence integrity, confidentiality, and reliability. Using qualitative methods, such as thematic analysis, this study investigates how blockchain may facilitate overcoming fundamental vulnerabilities of IoT devices and improve forensic processes. This research adds to the growing knowledge base on the confluence between blockchain and forensic science by addressing challenges like tampering risk, lack of evidentiary reliability, and lack of unauthorized access [13-14].

This study holds broad implications for law enforcement agencies, digital evidence custodians, and IoT manufacturers by advocating a blockchain-enabled evidentiary infrastructure capable of improving transparency, authenticity, and cross-border trust in digital forensics. Similarly, Almufarreh [59] highlight growing ethical concerns around large language model usage in academia particularly plagiarism, bias, and integrity issues and recommend strategies such as transparent usage policies and LLM literacy training to ensure responsible adoption, underscoring that technological integration must be accompanied by ethical safeguards.

2. Literature Review

With the advent of the Internet of Things [IoT], the digital forensics [DF] field is also going down a new path because of the expanding range of forensic investigations. IoT forensics deals with extracting and preserving evidence from different endeavored devices. Although DF provides a basic process for the identification, preservation, analysis, and presentation of evidence, IoT forensics presents new challenges as IoT devices are heterogeneous in nature, have no common standards, and device architectures are vulnerable.

2.1. IoT Security and Forensics

The IoT networks are populated by different kinds of devices like sensors, actuators, and smart appliances, which communicate with each other with protocols such as TCP/IP. IoT architecture is often divided into three or four layers [3], such as the layers of the perception [sensor], the network, the application, and the middleware. These architectures are shown in Figure 1. From the original thesis. However, IoT's flexibility and domain applicability have increased its adoption but also made IoT devices prime targets for cyberattacks [15-16].

In their study, [39] discuss enhancements in blockchain security, emphasizing its potential to address challenges in digital forensics, particularly in the IoT context. Their work aligns with the exploration of blockchain's role in forensic investigations, as highlighted in the research on integrating blockchain into IoT forensic practices. By focusing on blockchain's security improvements, Leong et al. contribute to understanding how blockchain's tamper-proof and integrity features can strengthen the chain of custody and reliability of digital evidence in forensic processes.

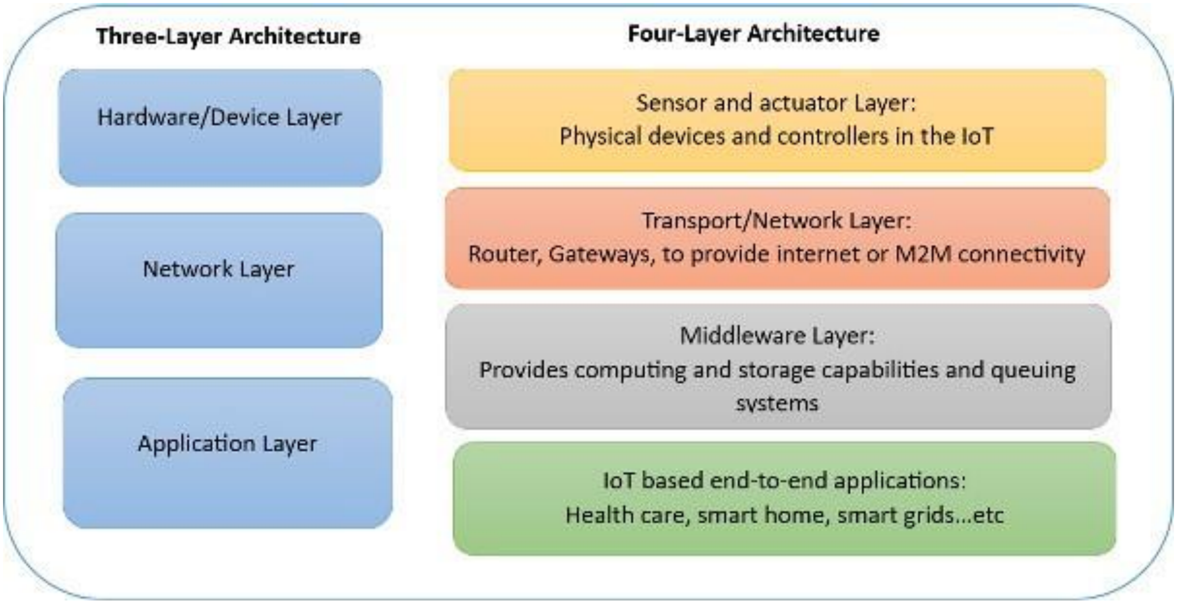
Three-Layer Architecture
Hardware/Device Layer
Network Layer
Application Layer
Four-Layer Architecture
Sensor and actuator Layer: Physical devices and controllers in the IoT
Transport/Network Layer: Router, Gateways, to provide internet or M2M connectivity
Middleware Layer: Provides computing and storage capabilities and queuing systems
IoT based end-to-end applications: Health care, smart home, smart grids...etc

Figure 1. IoT architecture with 3 and 4 layers [3]

IoT forensics must address several security and forensic challenges:

Heterogeneity: There are many manufacturers of devices that lack the same standards [17].

Vulnerabilities: Limited computing power, scarce security protocols, and vulnerability to hacks [6].

Evidence Collection and Preservation: IoT devices' evidence data must be protected from tampering, loss, or theft. Confidentiality, integrity, and availability [18] cybersecurity measures must be.

Arshad et al. [2025] [60] demonstrate how AI- and ML-driven forensic methods—such as text mining, network analysis, and metadata evaluation can effectively process large-scale social media evidence while preserving legal admissibility, providing a methodological precedent for scalable digital investigations.

IoT forensics can be divided into several levels, including device-level, network-level, and cloud-level forensic techniques of collecting and preserving data collected from different sources [3]. Figure 2 presents a forensic investigation model with identification, collection, analysis, and presentation phases.

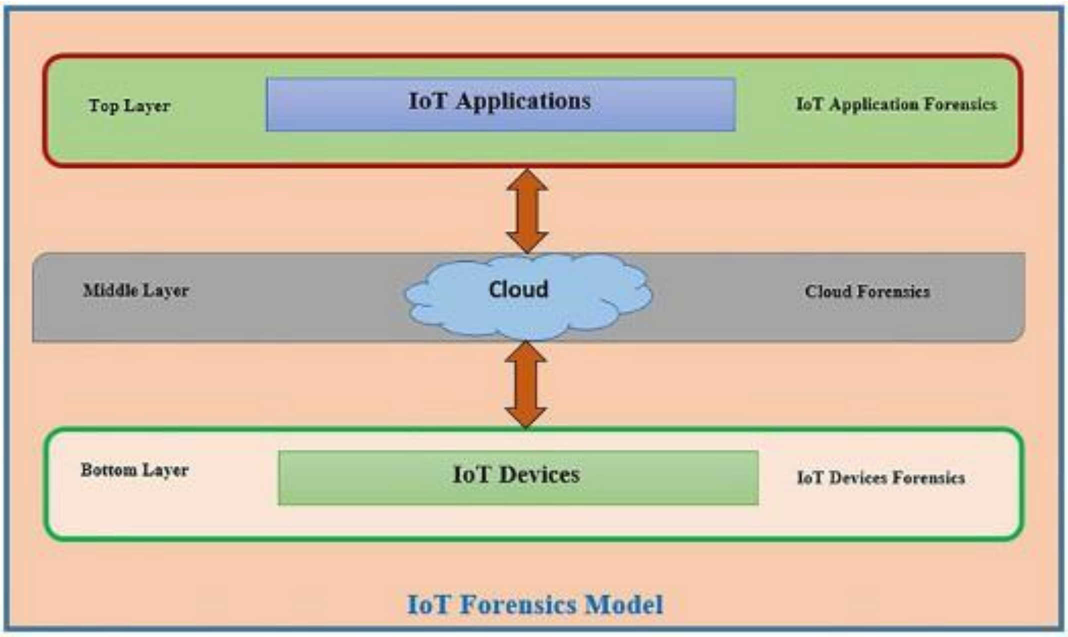

Figure 2. IoT Forensic investigation model [3]

2.2. Challenges in IoT Forensics

IoT forensics faces unique challenges compared to traditional DF:

1. **Data Heterogeneity**: Data produced by IoT devices can come in numerous formats, making analysis possible [19].
2. **Security Risks**: Because IoT devices are typically vulnerable to weak encryption, insecure protocols, and unregulated design [20], all of these devices need to be secured as soon as they connect to the internet.
3. **Lack of Standards**: The lack of standards [2] makes it difficult for investigators to retrieve and keep evidence.
4. **Chain of Custody [CoC]**: However, it is crucial and also challenging to maintain the integrity and traceability of evidence in the distributed IoT environment [13].

2.3. Blockchain in IoT Forensics

The reason blockchain technology has emerged as a potential solution to address these challenges is because of its own intrinsic properties, like immutability, transparency, and decentralized operation [21]. A distributed ledger technology, blockchain records data in tamper-proof blocks that are cryptographically linked. It supports three primary configurations: consortium, permissioned, and permissionless blockchains. These include permissioned and consortium blockchains, which are especially appropriate for forensic investigation because of their restricted access to authorized users and accountability and confidentiality [22].

Advantages of using blockchain in forensic investigation:

1. **Integrity and Tamper-Proof Storage**: Data integrity is guaranteed in blockchain through its requirement that all data be stored in immutable blocks [9].
2. **Traceability**: Timestamps of all transactions make it easy to track the chain of custody [12].
3. **Decentralization**: The data evidence is stored across several nodes, which means the chance of single points of failure [23].
4. **Transparency:** Transactions can be verified by authorized users without losing evidence confidentiality [10].

Studies also point to how blockchain can be used as a mechanism for CoC. For example, metadata and evidence records could be stored on permissioned blockchains as smart contracts and would be accessible by and be able to be modified by only authorized entities [24].

Unlike prior studies that propose general blockchain-ledger models for IoT evidence management, this research contributes a domain-specific framework emphasizing smart contract enforcement of the chain of custody, evidence access policies, and regulatory admissibility under global standards [e.g., ISO/IEC 27043, FRE 902[14]]. This positions the study as an advancement from descriptive blockchain applications to procedural forensic integration.

2.4. Blockchain Applications in IoT Forensics

Blockchain has been utilized in various experimental frameworks to enhance forensic processes.

- **Distributed Ledger Models**: [24] presented a permissioned blockchain with a smart contract for managing evidence metadata, but guarantees integrity and restricted access.
- **Proof-of-Concept Solutions**: [25] then evaluated how public blockchains like Ethereum and EOS could seamlessly store forensic data as being both cost-effective and secure.
- **Hybrid Frameworks**: The scalability, privacy, and traceability challenges were addressed by [26] through a scalable blockchain-based framework implementing Byzantine fault tolerance.

2.5. Blockchain Preserving Digital Evidence

Maintaining evidence integrity is an essential element required in the case of IoT forensics. And blockchain's immutability and auditability make it the perfect platform for this use case. Studies emphasize the following:

1. **Chain of Custody**: Blockchain provides evidence storage and transfer in a secure way where almost every action done on data is recorded [11].
2. **Privacy Preservation**: Blockchain keeps the data sensitive by restricting access to the data to only authorized users.
3. **Scalability**: Largely, this was made possible by the fact that blockchain, with its hash tree functionalities, is capable of processing large volumes of data, thus making it possible to store

and manage the hefty forensic evidence [27].

Also, blockchain solves the problem of insider threats and provenance validation, making sure that evidence is true and the information is valid enough to be used in a court trial [28].

2.6. Future Work and Limitations

Unfortunately, there are some challenges associated with implementing blockchain in IoT forensics. Interoperability, real-time data processing, and the scalability of the blockchain network all offer additional discussion [29]. Furthermore, it complicates the adoption of blockchain IoT forensics with the lack of standardized frameworks.

Coming up with robust, scalable blockchain frameworks that work well for IoT environments is something that future research should aim to achieve. Cyber-attack prediction and prevention can further be boosted with integration into machine learning techniques [14].

2.7. Conclusion

Blockchain turns out to be the solution to these IoT forensic challenges, as the literature highlights. Blockchain can significantly improve data integrity, data security, and traceability in an IoT environment to provide a reliable environment for forensic investigations. However, general research and application are still required to fully realize it's potential.

3. Research Methodology

A qualitative research methodology is used in this study to explore the use of blockchain technology in IoT forensic investigation to preserve digital evidence. Due to the multidisciplinary nature of the research topic, a comprehensive methodological framework was developed that would cater to the research objectives and questions from the aspects of cybersecurity, digital forensics, and blockchain technology.

3.1. Research Approach

The study is deductive in nature, deriving its theories and framework from existing research for blockchain's potential realization in IoT forensics. Systematic exploration of the theoretical concepts is guaranteed by the deductive approach, which guarantees the systematic exploration of the theoretical concepts and extensive literature reviews. This analysis offers a number of insights that aid with answering specific research questions and validating findings through theoretical and thematic analysis [30].

3.2. Research Design

A qualitative research design aimed to give us in-depth knowledge of the topic. Key aspects of the design include:

1. **Exploratory Research**: The analysis with themes and the detection of gaps between the already existing studies make this method useful for the investigation of underexplored areas [31], like studying blockchain on the basis of IoT forensics.
2. **Descriptive Research**: This method describes, through processes and frameworks in the domain of digital evidence preservation, how blockchain can improve the integrity and security of evidence data [32].
3. **Thematic Analysis:** Based on patterns and recurring ideas in the literature, themes were identified and coded, and the advantages and challenges of blockchain in blockchain forensic investigation are well structured [33; 58].

3.3. Data Sources

Reliable academic databases such as IEEE, Scopus, and ScienceDirect were used as secondary data. These sources included peer-reviewed journals, technical reports, and conference proceedings in blockchain, IoT forensics, and digital evidence preservation.

3.4. Thematic Analysis Procedure

The thematic analysis followed a structured process: [58]

1. **Data Familiarization**: In this paper, literature was reviewed to extract common themes and ideas on blockchain and IoT forensics.
2. **Coding**: Concepts (blockchain's role in assuring the integrity and traceability of the data) were coded open and axial.
3. **Theme Identification**: Themes were identified that highlighted blockchain as reliable and scalable, and the impact was on forensics.

3.5. Expanded Methodology

Article Screening Process:

- Initial search yielded 287 articles.
- Title/abstract screening reduced to 124.
- Full-text review finalized 57 articles.

Quality Assessment Criteria:

- Peer-reviewed status from IEEE, Scopus, etc., [2018–2024].
- Citation count [greater than 5 for older papers]
- Relevance score [0-5 scale]

Inclusion Criteria:

1. Relevance to IoT forensics/blockchain.
2. Empirical/review studies.

Exclusion Criteria:

3. Non-English publications.
4. Theoretical papers without applied findings.

4. Findings and Results

This study examines the relevance of blockchain technology to protecting the integrity of digital evidence in IoT forensic investigations using thematic analysis. The thematic analysis helped to identify the critical patterns and relationships in the literature and showed that blockchain could be a vehicle to solve security, reliability, and traceability-related issues in the forensic process of IoT. It discusses these findings systematically and discloses which themes and evidence were exposed in the analysis.

4.1. Thematic Reports

4.1.1. Theme 1: Blockchain as a Trustworthy System for IoT Forensic Investigations

Maintaining the integrity, confidentiality, and traceability of evidence derived from heterogeneous devices poses major challenges for IoT forensic investigations. The immutable and decentralized ledger characteristic of blockchain technology suits very well as a repository of forensic evidence [21].

Key Findings:

Decentralized Data Storage: Threats such as a single point of failure are mitigated by blockchain,which distributes evidence across nodes [23].

Enhanced Traceability: Timestamps of blockchain transactions maintain a strong chain of custody[12].

Tamper-Proof Data: After being recorded, blocks are unmodifiable unless the consensus is obtained,thus evidence is preserved [10].

Like traditional blockchain, blockchain enables the use of permissioned [or consortium] blockchains to restrict access to authorized users and thus enforce confidentiality [22].

4.1.2. Theme 2: Blockchain for Preserving Integrity and Traceability of IoT Forensic Evidence

Ensuring the integrity, traceability, and confidentiality of digital evidence remains one of the most pressing challenges in IoT forensic investigations. Due to the distributed, heterogeneous, and resource-constrained nature of IoT ecosystems, traditional digital forensic mechanisms often fall short in maintaining a secure and reliable evidentiary chain. Blockchain technology offers a robust alternative, providing immutable, transparent, and decentralized infrastructures that are particularly suited for evidence management.

1. Immutability and Tamper Resistance

Blockchain records data in cryptographically linked blocks, making any subsequent alteration computationally infeasible without network consensus. This ensures that once digital forensic evidence is logged onto the blockchain, it remains unmodified throughout the lifecycle of the investigation. Each evidence interaction is logged with a unique cryptographic hash, preserving its integrity and supporting admissibility in legal contexts [9].

2. Chain of Custody Automation

One of the most significant advantages of blockchain in forensics is its capacity to automate the chain of custody [CoC] through smart contracts. These contracts embed forensic access policies and automatically log access events, ensuring transparency and reducing the risk of human error or unauthorized intervention [11]. Every read, write, or export action is recorded with a timestamp and digital signature, thus maintaining an auditable trail of evidence handling.

3. Distributed Replication and Fail-Safe Evidence Storage

In conventional storage systems, evidence is vulnerable to data loss due to single-point failures or insider threats. Blockchain's decentralized architecture replicates forensic records across multiple nodes, ensuring redundancy and high availability even under adverse conditions. This is particularly advantageous in hostile or cross-border environments where infrastructure reliability is variable [18].

4. Access Control and Confidentiality via Permissioned Blockchains

IoT forensic data often includes sensitive information, such as personal identifiers or healthcare records. To protect confidentiality, permissioned or consortium blockchains restrict data access to authorized parties only. This selective transparency preserves evidentiary integrity while ensuring compliance with data privacy regulations like GDPR and HIPAA [22].

5. Legal Admissibility and Evidentiary Trust

The blockchain's auditability and verifiability bolster the legal admissibility of digital evidence. Blockchain logs can satisfy requirements under legal standards such as the U.S. Federal Rules of Evidence 1Rule 902[14], which permits self-authenticating digital records if integrity can be established. Moreover, blockchain aligns with ISO/IEC 27043 principles for digital forensic investigations, offering a procedural framework that supports evidentiary trust [45].

4.1.3. Theme 3: Blockchain in Forensic Processes

The integration of blockchain in forensic investigations addresses critical gaps in traditional methodologies.

Provenance Tracking: Furthermore, blockchain assuring evidence origin and movement ensuring secured [28].

Chain of Custody [CoC]: Evidence permanently stored, modified by smart contracts embedded in blockchain that automate and secure the CoC processes, preventing alteration of evidence throughoutthe investigation [24].

Likewise, the inherent transparency of blockchain means all stakeholders in the forensic investigation have access to trustworthy, immutable records and thus trust in forensic investigations themselves [12].

4.1.4. Theme 4: IoT Forensic Investigation Procedures

The complexity of IoT forensic investigations requires systematic procedures to address challenges such as limited storage capacities and dynamic device behaviors. Blockchain integrates seamlessly with IoT forensic workflows, ensuring:

- Evidence collection and storage in immutable formats.
- Easy retrieval and verification of data during analysis.
- Real-time tracking of evidence interactions using blockchain timestamps [2].

Blockchain's scalability helps IoT forensic investigations as each hash tree supports storing huge amounts of forensic evidence without degrading performance [27].

4.1.5. Theme 5: Blockchain Performance in IoT Forensics

The performance of blockchain technology in forensic applications demonstrates its ability to:

- Enhance security through cryptographic verification of blocks.
- Support high-volume evidence storage through scalable architectures.
- Facilitate real-time updates to evidence records, reducing investigation timelines [26].

Recently, blockchain integration with IoT environments has been proven to increase the cost efficiency and reliability of forensic applications, as shown by comparative studies [25].

In a related context, Arshad et al. [2025] [61] show how Big Data analytics and AI integration in online streaming platforms enable real-time optimization and personalized services, illustrating the broader potential of data-driven intelligence to enhance system performance—paralleling how similar techniques could augment forensic evidence handling efficiency.

4.2. Case Illustration: Blockchain in Medical IoT Forensics

A hospital's IoT-connected insulin pump system was compromised, with unauthorized dosage changes logged on a Hyperledger Fabric permissioned blockchain. Forensic investigators retrieved immutable records via cryptographic hashing, identifying an insider threat. Blockchain's timestamping and Chain of Custody [CoC] validated evidence integrity in court, demonstrating operational benefits [11; 24].

4.3. Limitations and Challenges of Blockchain in IoT Forensics

Despite its strengths, blockchain technology in IoT forensics faces hurdles:

- **Scalability Issues**: High transaction volumes strain networks [9].
- **Energy Consumption**: Proof-of-Work algorithms are impractical for IoT devices [27].
- **Interoperability**: Heterogeneous devices lack standardized protocols [37].
- **Legal Admissibility**: Conflicts exist between blockchain immutability and GDPR's 'right to be forgotten' [40].
- **Data Privacy**: Public blockchains may expose sensitive forensic data [50]
- **Forensic Tool Compatibility**: Most digital forensic tools lack native blockchain support [51]
- **Cost Barriers**: Enterprise blockchain solutions require significant infrastructure investment [52]

4.4. Case Study: Blockchain in Smart Home Forensics

A recent smart home intrusion case demonstrated blockchain's evidentiary value. Attackers compromised IoT security cameras, altering footage. A private Ethereum blockchain logged all device interactions with cryptographic hashes, enabling investigators to:

- Verify unaltered timestamps of suspicious activities
- Trace the attack path across multiple devices
- Maintain an immutable chain of custody for court proceedings

This case highlights blockchain's ability to preserve evidence integrity in distributed IoT environments [49].

4.5. Conclusion

Blockchain's transformative potential in IoT forensic investigations is highlighted through the thematic analysis. Blockchain improves the reliability and efficiency of forensic processes by addressing the challenges of the integrity of evidence, security, and traceability. Integration with IoT forensics not only mitigates existing vulnerabilities but also formulates the first step towards a more robust and scalable forensic framework.

5. Discussion and Conclusion

5.1. Research Questions to be discussed

This research contributes a novel synthesis of blockchain capabilities and IoT forensic needs. Unlike prior studies that treat these domains in isolation, our thematic framework integrates core blockchain properties—immutability, decentralization, and traceability—with procedural and evidentiary requirements in digital forensics. This convergence addresses a key gap in the literature and enables a more robust forensic paradigm.

This thematic analysis in this work highlighted the critical role blockchain technology can play in making the vulnerabilities and challenges of IoT forensics reliable. Blockchain provides a robust means of safeguarding digital evidence from tampering and both internal and external threats. Furthermore, the significance of forensic procedures and the guarantees that blockchain provides in IoT forensic investigations is analyzed. Based on findings from thematic analysis and literature review, the research questions are addressed.

RQ1: How can blockchain technology support digital forensic investigation, especially IoT forensic investigations?

IoT forensics refers to evidence gathering from devices, systems, and the IoT network environment. Two significant challenges in preserving evidence presented in IoT systems that require defending devices from internal or external threats of tampering or misuse are highlighted in the literature. The extracted evidence data must be correctly maintained [with privacy and managed identity], especially organized around effective forensic investigations.

According to [13], blockchain's inherent functionality with data integrity, privacy preservation, and confidentiality rules it out as an indispensable instrument for evidence preservation. The chain of custody [CoC] is supported by blockchain, where evidence is collected, stored, and verified, and access is restricted. Blockchain, as [11] proposes, allows for evidence verification and storage in a tamper-proof ledger. Depending on access and security requirements, each model provides its own blockchain model, like consortium, permissioned, and permissionless. For example, a consortium blockchain limits access to authorized team members to guard privacy and ensure the integrity of the evidence data.

According to [28], authorized access, integrity, confidentiality, and traceability are key for IoT forensic investigation. The attributes of these are guaranteed by blockchain technology that prevents data modification or erasure by unauthorized users. Timestamps and team verification are used to store data blocks and to trace them. Furthermore, the nature of blockchain is distributed and therefore permits access to multiple distant locations, which provides sound evidence monitoring and court presentation seamlessly [12]. Beyond forensics, Zaman et al. [2022] [62] present a blockchain-based land record management system for Pakistan that employs smart contracts to automate property registration, ensuring tamper-resistant and transparent ledger operations—demonstrating blockchain's versatility in safeguarding critical records. By creating an immutable system that does not get altered, blockchain provides both the confidentiality and integrity that courts demand.

Integration of blockchain and IoT forensics increases evidence preservation and investigation. Digital forensics [DF] gives us a basic template to determine where the evidence is, while blockchain secures and organizes the evidence we have gotten from the devices that have been compromised. [35; 36] deplore the problem of evidence data tampering or loss and describe how data integrity and no unauthorized access can be ensured with blockchain. Blockchain is an indispensable solution for many IoT forensic investigations due to its properties.

RQ2: How can blockchain improve the efficiency and integrity of digital evidence gathered during the IoT forensic investigation process?

It uses immutable, audited, and verified consensus chains to improve evidence preservation and ensure the integrity of the data. [9] Currently validates each data block prior to storage and stores its modification as a new block, preserving the evidential reliability. The main benefits of blockchain for IoT forensics [10] are its accountability, transparency, and auditability. Cryptographic hash functions allow investigators to ensure evidence integrity and thereby improve trustworthiness.

By studying traces of data from the IoT, forensic investigations seek to identify when and to what malicious activity has occurred. However, issues arise from an unregulated IoT environment as well as from no security standards among device manufacturers [37]. Investigations of IoT networks connected to cloud systems get further complicated [38]. By increasing trust, integrity, and immutability of evidence preservation, blockchain addresses these challenges [27].

Forensics is supported by blockchain because of data provenance, integrity, and traceability by cryptographic validation. In addition, it has the capability for an organization to store large amounts of evidence data [23]. The resilience of blockchain guarantees tamper-proof data, reliable and verifiable, which contributes to the confidence of forensic investigators. These features place blockchain as a key solution to problems inherent in conventional forensic processes.

5.2. Policy Implications for Blockchain in IoT Forensics

The integration of blockchain into IoT forensics necessitates policy frameworks to address three critical areas:

1. **Standardization**: Regulatory bodies [e.g., ISO, NIST] must develop guidelines for blockchain-based evidence admissibility in court, including hash verification protocols [12].
2. **Cross-Border Collaboration**: Mandate FIPS 140-2-compliant encryption for interoperable forensics[41].
3. **Funding**: Pilot programs in smart cities [e.g., Barcelona's blockchain-based surveillance] [42].

5.3. Regulatory Challenges and Global Standardization

The absence of unified legal frameworks poses significant barriers to blockchain adoption in IoT forensics. Key challenges include:

1. Jurisdictional Conflicts:

- The EU's General Data Protection Regulation [GDPR] mandates data erasure under Article 17[”Right to be Forgotten”], which conflicts with blockchain's immutability [43].
- In contrast, the U.S. Federal Rules of Evidence [FRE] permit blockchain records if they meet authenticity standards [FRE 902[14], but lack IoT-specific guidelines [44].

2. Standardization Gaps:

- While ISO/IEC 27043:2015 provides general forensic investigation principles, it does not address blockchain-specific requirements [45].
- Emerging efforts by NIST [e.g., IR 8202] outline blockchain use cases but stop short of forensic standards [46].

3. Global Initiatives:

- The INTERPOL IoT Forensics Framework [2020] highlights blockchain's potential but notes interoperability hurdles [47].
- The EU Blockchain Observatory recommends amendments to GDPR for forensic exceptions [48].
- To address these gaps, we propose:
- Amending Article 17 of GDPR to exempt forensic blockchain logs.
- Expanding ISO/IEC 27043 with a blockchain annex [under development as ISO/IEC 27043-2].
- Cross-border agreements to recognize blockchain-based evidence under mutual legal assistance treaties [MLATs].

4. Implementation Timeline:

- Short-term [1-3 years]: Develop blockchain forensic guidelines [ISO/IEC 27043-2]
- Medium-term [3-5 years]: Establish cross-jurisdictional evidence sharing protocols
- Long-term [5+ years]: Implement global blockchain forensic standards [57]

5.4. Future Research Direction

1. **Hybrid Architectures**: Combining blockchain with edge computing for real-time forensics [53]
2. **Standardized APIs**: Developing universal interfaces for forensic tool integration [54]
3. **Lightweight Consensus**: Evaluating alternatives to PoW for resource-constrained IoT [55]
4. **Automated Evidence Analysis**: Machine learning for anomaly detection in blockchain logs [56]

5.5. Practical Implementation Guidelines

To operationalize the thematic findings and facilitate the adoption of blockchain technology in IoT forensic investigations, this section provides structured, actionable guidelines. These are intended for digital forensic practitioners, system architects, legal stakeholders, and policymakers seeking to integrate blockchain into forensic workflows while maintaining legal admissibility, technical reliability, and procedural compliance.

Drawing upon validated themes, case illustrations, and best practices from recent literature, five key domains of implementation are outlined below.

5.5.1. Blockchain Architecture Selection

Selecting the appropriate blockchain architecture is foundational to preserving digital evidence effectively. Based on forensic requirements for confidentiality, traceability, and controlled access:

- **Recommendation**: Deploy permissioned or consortium blockchain models, such as Hyperledger Fabric, rather than public or permissionless networks.
- **Rationale**: These models support controlled access to evidence, reduced consensus latency, and compliance with privacy regulations [e.g., GDPR, HIPAA] , as demonstrated in Brotsis et al.'s permissioned blockchain model for forensic metadata storage [24].
- **Example**: In the medical IoT case, Hyperledger Fabric enabled secure storage of insulin dosage logs accessible only to authorized investigators and hospital administrators [24].

5.5.2. Smart Contract Integration for Chain of Custody

Smart contracts can automate the enforcement of the Chain of Custody [CoC] by embedding logic into blockchain transactions.

- Recommendation: Develop smart contracts to:
- Record who accessed what evidence, when, and for what purpose.
- Restrict unauthorized evidence modification.
- Trigger alerts on anomalous access patterns.
- Rationale: Automating CoC reduces human error and ensures verifiable custody transitions, as outlined by Al-Khateeb et al. [1].
- Best Practice: Log every forensic interaction [e.g., acquisition, duplication, export] as a hashed event with digital signatures [1].

5.5.3. Interoperability with Forensic Tools

To ensure seamless adoption, blockchain systems must be interoperable with commonly used forensic toolkits [e.g., FTK, Autopsy, EnCase].

- Recommendation: Design and implement middleware APIs to bridge forensic platforms with blockchain storage layers.
- Standards Alignment: Use data exchange formats such as JSON-LD and maintain hash compatibility with SHA-256/SHA-3 standards.

- Ongoing Work: NIST's Draft API Standards for Blockchain Forensic Tools (SP 500-345] may offer future plug-and-play support [14].

5.5.4. *Legal and Regulatory Alignment*

Blockchain-based evidence management must align with evolving legal standards across jurisdictions.

- Recommendation: Ensure blockchain logs meet admissibility standards under:
- U.S. FRE 902[14]: Self-authenticating electronic evidence.
- EU GDPR [amended proposal]: Forensic exceptions to Article 17 "Right to be Forgotten."
- Guideline: Use append-only logs and include metadata attestation mechanisms (e.g., X.509 certificates) to verify chain integrity.
- Example: Akhtar and Feng demonstrated that blockchain-based forensic ledgers can improve evidentiary admissibility under conditions of chain integrity and verifiability [14].

5.5.5. *Example Workflow for Blockchain-Enabled IoT Forensics*

The following schematic describes a practical blockchain-enhanced forensic process:

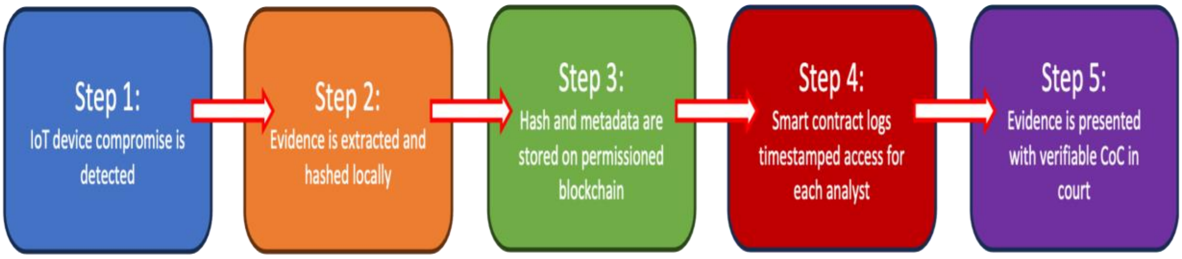
Step 1:
IoT device compromise is detected
Step 2:
Evidence is extracted and hashed locally
Step 3:
Hash and metadata are stored on permissioned blockchain
Step 4:
Smart contract logs timestamped access for each analyst
Step 5:
Evidence is presented with verifiable CoC in court

Figure 3. Blockchain-enhanced Forensic Process

Figure 3. Workflow for blockchain-enabled forensic evidence handling in IoT environments, integrating smart contracts and hash storage on a permissioned ledger.

Description of Steps:

1. **IoT Device Compromise Detected** – Anomaly or breach is identified in a smart device.
2. **Evidence Extracted and Hashed Locally** – Digital artifacts are collected and hashed at the edge or forensic lab.
3. **Hash and Metadata Stored on Blockchain** – Immutable record is created on a permissioned ledger.
4. **Smart Contract Logs Analyst Access** – Each interaction is recorded and authorized through smart contracts.
5. **Evidence Presented in Court** – Verified chain of custody is used for legal admissibility. This model aligns with experimental frameworks proposed for IoT evidence preservation [24].

Summary: Implementing blockchain in IoT forensics is not merely a technical decision—it is a multidisciplinary process that requires legal foresight, forensic precision, and architectural flexibility. The guidelines aboveprovide a pragmatic foundation for secure, scalable, and compliant deployment. Future advancements inregulatory frameworks and blockchain-forensics tooling will further streamline adoption and enhance trustin digital evidence handling [58].

5.6. Recommendations

Based on the thematic analysis and findings, the following recommendations are proposed for the integration of blockchain technology in IoT forensics:

1. **Evidence Storage**: Blockchain timestamps create a proof, hash, and reference to previous blocks so that there is consensus among authorized users. It is highly recommended for use in forensic investigations.
2. **Transparency and Accountability**: Blockchain creates a trail of where your data is being processed and allows each data block to have unique IDs that keep things transparent and accountable [hopefully].
3. **Data Synchronization**: Approved data blocks are synchronized by blockchain, so you can track modified or abrogated blocks, which helps in IoT forensic investigation.
4. **Chain of Custody**: The CoC is supported by blockchain, which provides evidence from acquisition to final reporting and provides for full forensic analysis.
5. **Security and Integrity**: Digital crime data is an ideal data storage candidate for blockchain, whose characteristics [transparency, authenticity, security, and auditability] make blockchain an ideal

solution for storing digital crime data.

6. **Standardization**: With regulatory challenges, establishing global standards for blockchain use in IoT forensic investigations can be done.
7. **Restricted Access:** To control information risk, we want blockchain networks to limit access to trusted participants.

5.7. Conclusion

This research demonstrates the value of blockchain technology in digital and IoT forensics. It analyzes the vulnerabilities of an IoT environment and how blockchain can overcome the problems. Through evidence integrity, privacy, and security, blockchain provides a perfect solution to the issues of IoT forensic investigations.

Thematic analysis and a literature review identify the use of blockchain in IoT forensics for preserving evidence and enhancing the process of forensics. The immutability, transparency, and reliability of blockchain make it central to overcoming the problems related to digital forensics. Future work includes practical implementations of the effectiveness of blockchain to preserve IoT forensic evidence for the trust and reliability of digital crime investigation.

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