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# Anonymous, Secure, Traceable, and Efficient Decentralized Digital Forensics

Meng Li , Senior Member, IEEE, Yanzhe Shen , Guixin Ye , Jialing He , Member, IEEE, Xin Zheng , Zijian Zhang , Senior Member, IEEE, Liehuang Zhu , Senior Member, IEEE, and Mauro Conti , Fellow, IEEE

**Abstract**—Digital forensics is crucial to fight crimes around the world. Decentralized Digital Forensics (DDF) promotes it to another level by channeling the power of blockchain into digital investigations. In this work, we focus on the privacy and security of DDF. Our motivations arise from (1) how to track an anonymous-and-malicious data user who leaks only a part of the previously requested data, (2) how to achieve access control while protecting data from untrusted data centers, and (3) how to enable efficient and secure search on the blockchain. To address these issues, we propose Themis: an anonymous and secure DDF scheme with traceable anonymity, private access control, and efficient search. Our framework is boosted by establishing a Trusted Execution Environment in each authority (blockchain node) for securing the uploading, requesting, and searching. To instantiate the framework, we design a secure and robust watermarking scheme in conjunction with decentralized anonymous authentication, a private and fine-grained access control scheme, and an efficient and secure search scheme based on a dynamically updated data structure. We formally define and prove the privacy and security of Themis. We build a prototype with Ethereum and Intel SGX2 to evaluate its performance, which supports processing data from a considerable number of data providers and investigators.

**Index Terms**—Access control, blockchain, decentralized digital forensics, efficiency, privacy, SGX2, security, watermark.

## I. INTRODUCTION

CRIMES have been raging all over the world. A report from the World Health Organization says that violence-related injuries kill 1.25 million people every year, which constitute 2.23% of all deaths [1]. To fight crimes, investigators resort to a variety of forensics expertise. However, traditional forensics methods suffer from low efficiency that delays the investigation progress. With the advancement and ubiquitousness of portable equipments, e.g., smartphones, electric vehicles, and drones, Digital Forensics (DF) enables investigators to timely gather and analyze evidence from data provides to carry out efficient investigations [2], [3], [4]. DF not only prevents victimization, but contributes to reducing violence and injustice, as well as building safe and resilient cities [5]. Therefore, it is counted as a key to fight against crimes in the information era.

*Decentralized Digital Forensics (DDF)*, as we name it so for the first time, promotes the investigation process by invigorating DF with publicity, immutability, and verifiability due to the recent development of blockchain [6], [7]. As depicted in Fig. 1, a data provider collects data by using their equipment and sends captured data (potential evidence) to a blockchain; an investigator aperiodically requests data from the blockchain; after collaborating with a group of professionals on analyzing the data, the investigator files a report to the court to reach a verdict. DDF also facilitates complex investigations that span international borders and collaboration between different legal systems [4], [8].

Although DDF offers many benefits, it still encounters privacy and security issues [9], [10], e.g., user anonymity [11], data confidentiality [12], [13], unauthorized access [14], and intentional data leakage [15]. Some DDF schemes are proposed to solve the problems [15], [16], [17]. They build a forensics model and a threat model, design a protocol based on cryptographic primitives to protect privacy and security, and carefully integrate the protocol with the underlying blockchain network. Despite their targeted advantages, some issues still remain unresolved, which lead to our **three motivations** as follows.

*M1: Decentralized Anonymous Authentication (DAA) with strong traceability.* We notice a new attack called partial-data leakage attack where a malicious investigator leaks only a part of requested data to a blackmarket. Meanwhile, since we are constructing a digital forensics scheme based on blockchain,

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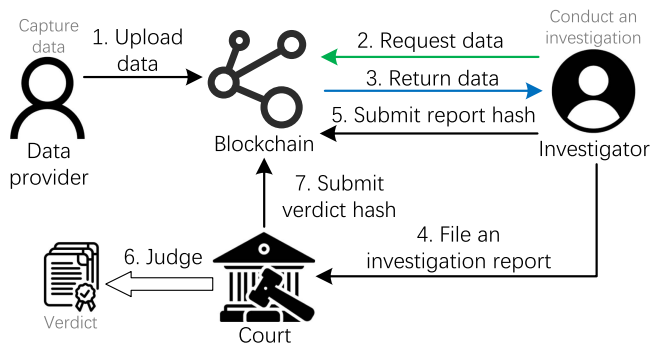


Fig. 1. Sketch model of DDF.

it is natural to rely on decentralized anonymous authentication [18] for user anonymity. However, among existing DAA schemes, Decentralized Anonymous Credential (DAC) [18] does not consider traceability and CanDID [19] does not mention how to reveal the real identity of a malicious user. Eunomia [15], a DDF scheme for vehicular networks, defends against data leakage attack, but it only works if the whole data is leaked.

**M2: Access control secure against untrusted data centers.** DDF can leverage Attribute-Based Encryption (ABE) to realize access control where data providers encrypts a message based on a set of attributes and a data user with relevant attributes can decrypt the ciphertext [20]. However, DDF data providers are not familiar with attributes. In fact, it is not necessary for them to know such information, thereby, there is no need for them to encrypt data with ABE. Meanwhile, authorities, i.e., data centers, may modify, add, or delete data intentionally or unintentionally [21], [22] due to various reasons, e.g., program glitches, security vulnerabilities, and misbehaving staff. Therefore, we consider the authorities to be untrusted. However, among recent decentralized access control schemes, Droplet's data providers have to know the public key of the data user they want to share their data with [23] and APECS's intermediary edge computing servers can still decipher the data [24]. Eunomia also exposes plaintext data to authorities.

**M3: Efficient and secure query processing.** It should be possible for investigators to request a data search by using predefined conditions, e.g., keywords and ranges. Such a search requires a secure index and a secure token for data privacy, but data users and investigators do not share keys, which is a requirement in searchable encryption and query processing schemes. Next, we notice that the authorities may return tampered or incomplete results for the same reasons above, thereby violating the expected security of the blockchain [26]. Therefore, result authenticity, i.e., correctness and completeness, is not guaranteed. Last, since the arrival time of data is uncertain, the authorities, as blockchain nodes, cannot generate an index that covers all the data quickly. Therefore, the index has to be efficiently updated. Among recent work of query on blockchain, GEM<sup>2</sup> Tree [25] and vChain [26] do not protect query privacy. Eunomia strenuously traverses all blocks to find the matched data. The aforementioned

motivations and problems induce **four technical challenges** in styling anonymous, secure, and traceable DDF.

**C1: From the anonymity vs. traceability perspective, how to preserve anonymity while defending against partial-data leakage attack in an anonymous environment?** Data providers who value identity privacy will not contribute if anonymity is not guaranteed. Anonymous authentication reduces such concerns, but creates a breeding ground for partial-data leakage attacks from malicious investigators. Hence, it is challenging to trace traitors in an anonymous environment.

**C2: From the access control vs. data privacy perspective, how to leverage ABE while keeping the data secure from the untrusted authorities?** ABE-based access control grants data providers a great power of autonomy by encrypting the data with access structure and distributing secret keys to data users. In DDF, data providers cannot take such a responsibility and investigators (data users) do not communicate with all the data providers for a key. Even if we transform the encryption phase to the authorities as Eunomia did, we still suffer from potential data breach. Hence, it is challenging to securely perform ABE on untrusted authorities.

**C3: From the efficiency vs. security perspective, how to conduct efficient and secure search on blockchain when there are enormous sources.** In an open DDF system, the sheer amount of data will be uploaded in a temporally unpredictable manner. Such data puts forward a high requirement of efficient search on blockchain, i.e., the design of a data structure adapting to blockchain. Furthermore, we cannot sacrifice security for efficiency. Hence, it is challenging to search on blockchain efficiently and securely.

**C4: From a formalization perspective, how to formally define and prove privacy and security for DDF?** Our target DDF scheme is basically a security protocol including parties, functions, attacks, and goals. Different from standard cryptographic protocols, it needs careful adjustments when capturing privacy and security in DDF.

To tackle these challenges, we build a framework based on Trusted Execution Environment (TEE) [27], [28] and consortium blockchain [29]. We leverage three carefully bridged primitives to propose a novel DDF scheme Themis. It provides traceable anonymity, private access control, and efficient search. Specifically, data providers register with authorities (blockchain nodes) to obtain a DAC by using a threshold signature scheme [30], [31]. They upload encrypted data to an authority equipped with an enclave. The enclave decrypts the ciphertext and produces (updates) a secure index [32] to generate a dynamically updated index tree [25]. Only the root hash instead of the entire tree is stored in a smart contract. Investigators send a data request to an authority that searches the tree with the request. If there is a match, the enclave verifies key, embeds the key into matched data [33] by using an improved watermarking scheme, and then performs ABE [20]. We frame three key contributions as follows.

- We put forth the concept of DDF and propose a security framework based on TEE and blockchain. Specifically, we define and defend against the partial-data leakage attack,

assume the authorities to be untrusted, and search on blockchain efficiently and securely.

- We design a secure and robust watermarking scheme in conjunction with decentralized anonymous authentication, a private and fine-grained access control scheme, and an efficient and secure search scheme with a dynamically updated data structure.
- We formally define and prove the privacy and security. We build a prototype based on the pioneering Ethereum and SGX2. We conduct extensive experiments to evaluate performance while comparing with existing work.

The remainder of this paper is organized as follows. We review some related work in Section II. Section III introduces some preliminaries. Section IV formalizes the problem. In Section V, we elaborate Themis, followed by the privacy and security analysis in Section VI and performance evaluation in Section VII, respectively. Finally, we provide some discussions in Section VII and conclude the paper in Section IX.

## II. RELATED WORK

### A. DF

A typical DF process consists of several key steps, such as evidence acquisition and duplication, evidence analysis, and result presentation [2]. An investigator collects data from crime scenes and witnesses by using professional acquisition tools, and send the data to an analyst for systematical analysis to look for potential evidence. During the analysis, different techniques including automatic detection image recognition, and image reconstruction, are used to process a large number of digital files. Based on an analysis report and proper crime reasoning, the investigator produces an investigation report.

Garfinkel [3] stated that we were in the ‘‘Golden Age of Digital Forensics’’ (1999-2007) when DF could magically see into the past and into the criminal mind. But it was coming to an end. This is because the collected data come in different formats and ciphertexts, and they cannot be analyzed with tools of the time. Next, the author proposes a plan for an improvement in research through the adoption of systematic approaches for representing forensic data and performing forensic computation.

Caviglione et al. [4] pointed out that developments in DF forensics were in a difficult situation since its evolution is seriously challenged by the increasing popularity of digital devices and the heterogeneity of the hardware and software platforms. The majority of forensic software is not applicable to identify anomalies in an unattended way. Therefore, one of the major challenges for DF is the design of tools and techniques to process the data and report possible evidences to investigators for further investigation.

### B. DDF

Cebe et al. [16] stated that connected and smart vehicles would provide valuable data to stakeholders, e.g., maintenance companies, vehicle manufacturers, drivers, and insurance companies. They designed a framework Block4Forensic for managing vehicular data. The framework combined a public key

TABLE I  
KEY NOTATIONS OF THEMIS

Notation	Definition
DF, DDF	Digital Forensics, Decentralized Digital Forensics
DAA	Decentralized Anonymous Authentication
DAC, <i>cre</i>	Decentralized Anonymous Credential
ABE	Attribute-Based Encryption
TEE	Trusted Execution Environment
SGX	Software Guard eXtensions
PPT	Probabilistic Polynomial-Time
DP, IN	Data Provider, Investigator
AU, EV, CB	Authority, enclave, consortium blockchain
$\lambda$ , <i>key</i>	Security parameter, secret key
$\mathbb{A}$ , $S$ , <i>sk</i>	Access structure, attribute set, secret key
$SK$ , <i>k</i>	Secret key set, secret key
$\{h_1, \dots, h_v\}$ , <i>h</i>	pseudo-random hash function, hash function
$n_0, n_1, n_2$	Number of AUs, number of DPs, number of INs
<i>d</i> , <i>wd</i> , <i>pwd</i>	Data, watermarked data, a part of <i>wd</i>
<i>ed</i> , <i>dm</i> , <i>hv</i>	Encrypted data, data message, hash value
<i>tk</i> , <i>kp</i> , <i>dr</i>	Token, key proof, data request
$\mathcal{B}$ , <i>L</i>	Indistinguishable Bloom filter, length of $\mathcal{B}$
<i>rr</i> , <i>er</i> ,	Request result, encrypted request result
<i>ev</i> , <i>puk</i> , <i>prk</i>	Enclave, public key, private key
$\text{Tx}_2^{\text{Upl}}$ , $\text{Tx}_3^{\text{Upl}}$	Data uploading (root updating) transaction
$\text{Tx}_3^{\text{ReqD}}$ / $\text{Tx}_3^{\text{ReqG}}$	Data request deny/grant transaction
$\mathcal{A}$ , $\mathcal{C}$ , $\Pi$	Adversary, challenger, Themis scheme

infrastructure (i.e., pseudonym certificates) with a permissioned blockchain to establish privacy-preserving membership. They proposed a fragmented ledger to preserve diagnosis records and maintenance reports. However, the authors just propose a framework design but do not give a concrete implementation.

Li et al. [17] proposed a blockchain-based vehicular DF scheme BB-VDF consisting of accountable protocols and privacy-preserving techniques. They modeled the warrant state as a finite state machine and realized the state transition via a smart contract. They used distributed key generation in a threshold cryptosystem to require an investigator to have at least  $t$  decryption shares to decrypt the requested data. They also designed a distributed key-policy ABE scheme to realize the access control. However, BB-VDF scheme does not address anonymity or traceability.

Li et al. [15] presented a blockchain-based vehicular DF scheme Eunomia with anonymity, access control, and traceability. Different from BB-VDF, they modeled a forensics procedure as a finite state machine. They leverage decentralized anonymous credentials [21] to provide user anonymity. They adopted a ciphertext-policy ABE [20] to realize access control. They defended against data leakage by executing an interactive protocol between an authority and a investigator to securely watermark the investigator’s secret key into the requested data [34]. However, Eunomia cannot defend the partial-data leakage attack or provide result authenticity.

Themis’s promotion over existing work is threefold. First, Themis provides traceable anonymity where honest data providers and investigators remain anonymous but malicious investigators who leaks (even just a part of) data will be tracked. Existing work [15] can only trace the tractor when the whole data is leaked. Second, Themis achieves private access control where authorities control investigators’ access to data but cannot access the plaintext data directly. Third, Themis enables efficient and

TABLE II  
COMPARISON ON MODEL, PRIVACY, SECURITY, AND FUNCTIONALITY WITH EXISTING WORK

Property	Decentralized	Anonymity	Unlinkability	Private Access Control	Authentication	Strong Traceability
Block4Forensic [16]	Partial <sup>a</sup>				✓	
BB-VDF [17]	Partial <sup>a</sup>			Partial <sup>b</sup>	✓	
Eunomia [15]	Partial <sup>a</sup>	✓	✓	Partial <sup>b</sup>	✓	Partial <sup>c</sup>
Themis	✓	✓	✓	✓	✓	✓

<sup>a</sup>: There is a centralized and trusted third party. <sup>b</sup>: It only provides access control. <sup>c</sup>: It can only trace a traitor who leaks all the requested data.

secure search on blockchain where the index of uploaded data is being efficiently and securely updated on both the authorities and the smart contract. We compare Themis with existing work in Table II in Section VI.

### III. PRELIMINARIES

#### A. Threshold Signature

A threshold signature scheme is constructed upon a signature scheme [30] and a distributed key generation protocol [31]. It consists of four algorithms as follows:

Gen( $1^{\lambda_1}$ ): given a security parameter  $\lambda_1$ , outputs a private key  $prk$ ,  $n$  shares of  $prk$  denoted as  $\{prk_1, prk_2, \dots, prk_{n_0}\}$ , and a public key  $puk$ .

Sign( $prk_i, m$ ): given a private key share  $prk_i$  and a message  $m$ , outputs a signature  $\sigma_i$ .

Comb( $\sigma_1, \sigma_2, \dots, \sigma_t$ ): given  $t$  partial signatures  $\sigma_1, \sigma_2, \dots, \sigma_t$ , outputs a combined signature  $\sigma$ .

Verify( $puk, m, \sigma$ ): given a public key  $puk$ , a message  $m$ , and a signature  $\sigma$ , outputs 1 if  $\sigma$  is a valid signature on  $m$ , and 0 otherwise.

#### B. Ciphertext-Policy Attribute-Based Encryption

A Ciphertext-Policy Attribute-Based Encryption (CP-ABE) scheme [35] consists of four algorithms as follows:

Setup( $1^{\lambda_2}$ ): given a security parameter  $\lambda_2$ , outputs a public key  $mpk$  and a master secret key  $msk$ .

Encrypt( $mpk, \mathbb{A}, m$ ): given the public key  $mpk$ , an access structure  $\mathbb{A}$ , and a message  $m$ , outputs a ciphertext  $ct$ .

KeyGen( $msk, \mathcal{S}$ ): given the master secret key  $msk$  and a set of attributes  $\mathcal{S}$ , outputs a secret key  $sk$ .

Decrypt( $mpk, ct, sk$ ): given the public key  $mpk$ , a ciphertext  $ct$ , and a secret key  $sk$ , outputs a message  $m$  in the message space  $\mathcal{M}$ .

#### C. Digital Watermarking

A robust digital watermarking scheme [33] consists of three algorithms:

KGen( $1^{\lambda_3}$ ): given a security parameter  $\lambda_3$ , outputs a secret key  $key$ .

Embed( $key, m$ ): given a secret key  $key$ , a message  $m$ , generates a watermark  $wm$ , embeds  $wm$  into  $m$ , outputs a watermarked message  $m'$ .

Extract( $key, m'$ ): given a secret key  $key$  and a watermarked message  $m'$ , outputs a watermark  $wm$ .

#### D. Privacy-Preserving Query Processing

A privacy-preserving query processing scheme consists of five algorithms.

Initialize( $1^{\lambda_4}$ ): given a security parameter  $\lambda_4$ , outputs an encryption key  $k_0$ , secret keys  $\mathcal{SK} = \{k_1, k_2, \dots, k_{v+1}\}$ ,  $v + 1$  pseudo-random hash functions  $\mathcal{H} = \{h_1, h_2, \dots, h_{v+1}\}$ , a hash function  $h$ .

Enc( $k_0, di$ ): given the secret key  $k_0$  and a data item  $di$ , outputs a ciphertext  $ci$ .

IndexGen( $\mathcal{SK}, \mathcal{H} = \{h_1, \dots, h_v, h_{v+1}\}, h, m$ ): given the secret keys  $\mathcal{SK}$ , the set of pseudo-random hash functions  $\mathcal{H}$ , the hash function  $h$ , and an data item  $di$ , outputs a secure index  $\mathcal{B}$ . Specifically, the index  $\mathcal{B}$  has  $L$  twins and each twin stores either 0 or 1.  $\mathcal{H}$  determines which cell stores 1.  $di$  is hashed to  $L$  twin cells  $\mathcal{B}[h(di)][h(h_{v+1}(h_i(di)) \oplus r_{\mathcal{B}})] = 1$  where  $i \in [1, v]$  and  $r_{\mathcal{B}}$  is a random number.

TokenGen( $\mathcal{SK}, \mathcal{H}, h, q$ ): given the secret key set  $\mathcal{SK}$ , the pseudo-random hash functions  $\mathcal{H}$ , the hash function  $h$ , and a query  $q$ , outputs a token  $tk$ .

Search( $\mathcal{B}, tk$ ): given a secure index  $\mathcal{B}$  and a token  $tk$ , outputs a bit. Specifically, the  $tk$  is hashed into  $\mathcal{B}$  to check if it exists in  $\mathcal{B}$ :  $\mathcal{B}[h(tk)][h(h_{v+1}(h_i(tk)) \oplus r)] = 1$  for  $i \in [i, v]$ .

Dec( $sk, ci$ ): given a secret key  $sk$  and a ciphertext  $ci$ , outputs a data item  $di$ .

#### E. Intel SGX2

Software Guard eXtensions (SGX) is a hardware extension of Intel Architecture that enables an application to establish a protected execution space, i.e., an enclave [36], [37], [38]. SGX stores enclave pages and SGX structures in the protected memory called Enclave Page Cache (EPC). SGX guarantees confidentiality of code/data and detection of an integrity violation of an enclave instance from software attacks [36]. SGX allows one to verify that a piece of software has been correctly instantiated on the platform via attestation.

With SGX, developers can build trusted modules inside an application to protect secrets. Some works have been devoted to developing a security framework based on SGX. For instance, PrivacyGuard [39] leverages smart contracts and TEE to help data owners' control over the access and usage of their private data. SecGrid [40] leverages SGX to ensure that grid utilities efficiently perform rich functionalities on users' private data while guaranteeing their privacy.

Since SGX imposes limitations regarding memory commitment and reuse of enclave memory, Intel introduces SGX2 to extend the SGX instruction set to include dynamic memory management support for enclaves [27], [28]. SGX2 instructions offer software with more capability to manage memory and page

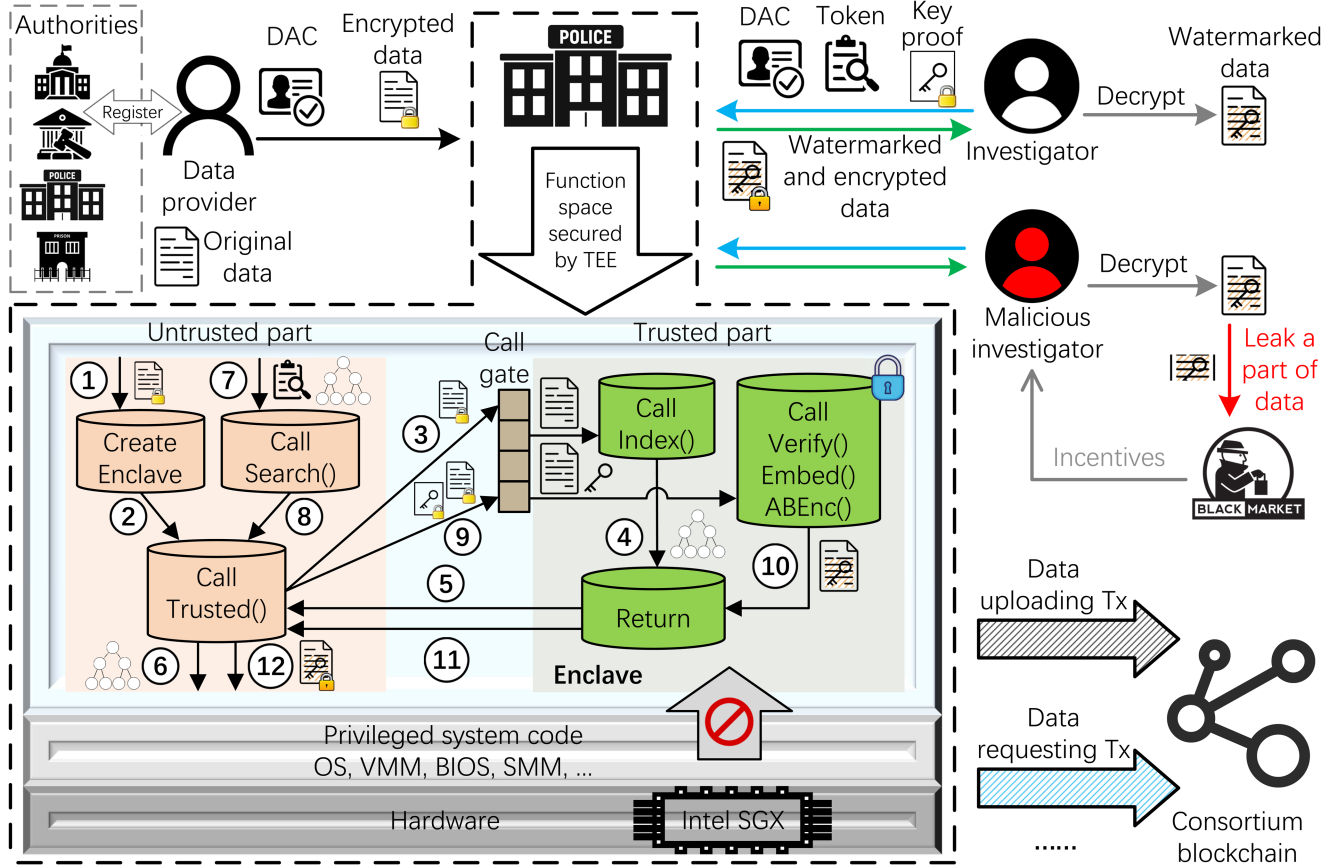


Fig. 2. Architectural vision of Themis.

protections from inside an enclave while preserving the security of the SGX architecture and system software.

#### F. Consortium Blockchain

As an underlying technique in Bitcoin [6], blockchain is a public ledger recording transactions among untrustworthy users in a decentralized network. The transactions are packed into separate blocks by a set of nodes using a predefined consensus algorithm, and the blocks are sequentially linked into a chain by their cryptographic hashes. Consortium blockchain is a specific blockchain maintained by a group of authorized entities. Only qualified parties are allowed to access the blockchain. It aims to secure transactions between users who do not fully trust each other but work collaboratively toward a common goal. Its consensus process is controlled by the authorized entities. Some noted consortium blockchains are Hyperledger Fabric, EEA, and Corda.

### IV. PROBLEM STATEMENT

#### A. System Model

The system model of Themis consists of four types of entities: Data Provider, Investigator, Authority, and Consortium Blockchain. We display the architectural vision of Themis in Fig. 2 and list the key notations in Table I.

**Data Provider (DP)** is a person who holds a device with sensing capabilities. She/he uploads to an authority the data that is captured by the device to provide potential evidence. Such an act is beneficial to uphold justice, which is rewarded by the police. DP can be a device that is installed in a fixed place or cruising along a route, e.g., a CCTV camera and autonomous vehicle. A DP first registers to a group of authorities to compute a DAC  $cre$  for anonymity. Next, the DP encrypts data  $d$  into  $ed$ , uploads a data message  $dm = (cre, ed)$  and a hash value  $hv$  of  $ed$  to an authority.

**Investigator (IN)** is a professional who performs an investigation task to solve a civil/criminal case. She/he registers to obtain a DAC  $cre$  and registers to their department for a set of attributes  $\mathcal{S}$ , a secret key  $sk$ , and a secret key set  $\mathcal{SK}$ . The IN computes a token  $tk$  and a key proof  $kp$ , and sends a data request  $dr = (cre, tk, kp)$ , and a  $hv$  of  $dr$  to an authority. After receiving an encrypted request result  $er$  from the authority, the IN decrypts  $er$  to obtain request result  $rr$ . The IN cooperates with other professional and continues to request data from the blockchain if necessary. After the case is solved, the IN sends a reporting transaction  $Tx^{Rep}$  to the blockchain.

**Authority (AU)** is an institute related to digital forensics, such as police department, transportation department, hospital, legislative council, prison, and court. Each authority acts as a blockchain node to maintain a consortium blockchain. When receiving a data message, an AU authenticates its DP, computes

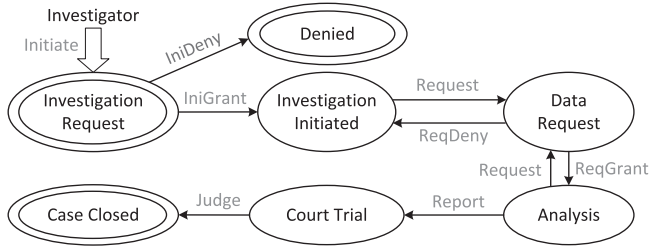


Fig. 3. State machine model of DDF.

a secure index, stores the encrypted data from DPs in a local database, and broadcasts a data uploading transaction  $Tx^{UpI}$  to the blockchain. After receiving a data request, an AU authenticates its IN, searches the database, verifies the IN's key, embeds the key into matched data, encrypts the watermarked data, returns an encrypted request result  $er$  to the IN, and broadcasts a data requesting transaction  $Tx^{Req}$ . After a case is closed and a trial is concluded, the court broadcast a judging transaction  $Tx^{Jud}$ . Specifically, each AU is initiated with a TEE, i.e., SGX2 enclave (EV), to secure the index building, key verification, key embedding, and encryption, such that they cannot acquire the plaintext of uploaded data.

**Consortium Blockchain (CB)** is a blockchain that is maintained by authorities. The CB records the data transactions, such as  $Tx^{IniG}$ ,  $Tx^{IniD}$ ,  $Tx^{UpI}$ ,  $Tx^{ReqG}$ ,  $Tx^{ReqD}$ ,  $Tx^{Rep}$ , and  $Tx^{Jud}$ . We model DDF as a finite state machine and record state transitions in a smart contract. There are seven states as depicted in Fig. 3.

We choose a consortium blockchain to lay the foundation of the whole system because the consortium blockchain is a permissioned blockchain that only allows qualified parties to maintain the blockchain. Therefore, it suits digital forensics where several authorities who do not fully trust each other need to collaborate to manage forensics data while being incompatible with the centralization of private blockchains or arbitrary participation of public blockchains.

### B. Threat Model

We adopt the classic honest-but-curious assumption for most internal entities. A part of INs and AUs may act maliciously. A malicious IN launches three attacks. **Partial-data leakage attack**: leaking a part of data, i.e., a corrupted investigator crops a picture and leaks the cropped picture to a blackmarket. A malicious AU can launch a data tampering attack and a data ignoring attack. **Tampering attack**: tampering with the returned data that is stored in the local dataset. **Ignoring attack**: ignoring some stored data during data search.

*Definition 1 (Attacks)*: Given a dataset  $\{d_1, d_2, \dots, d_{n_1}\}$ , a watermarked dataset  $\{wd_1, wd_2, \dots, wd_{n_1}\}$ , two secret keys  $sk, key$ , a secure index  $\mathcal{T}$ , a data request  $dr$ , an ABE public key  $pk$ , and a malicious IN with a data request  $dr$  and a secret key  $sk$ , partial-data leakage attack  $Att^L$ , tampering attack  $Att^T$ , and ignoring attack  $Att^I$  are defined:

$$Att^L : \mathcal{T} \times \{dr\} \rightarrow \{wd_j | Search(\mathcal{T}, dr) = \{c_i\},$$

$$Dec(pk, c_i, sk) = Embed(key, d_i), \exists wd_i : wd_j \subset wd_i\},$$

$$Att^T : \mathcal{T} \times \{dr\} \rightarrow \{wd_j | Search(\mathcal{T}, dr) = \{c_i\},$$

$$Dec(pk, c_i, sk) = Embed(key, d_i), \nexists wd_i : wd_j = wd_i\},$$

$$Att^I : \mathcal{T} \times \{dr\} \rightarrow \{wd_j | Search(\mathcal{T}, dr) = \{c_i\},$$

$$Dec(pk, c_i, sk) = Embed(key, d_i), \{wd_j\} \subset \{wd_i\}\}.$$

Given a secure index  $\mathcal{T}$  and a data request  $dr$ , the search result is  $Search(\mathcal{T}, dr) = \{c_i\}$  and the decryption of each  $c_i$  belongs to the original dataset: the partial-data leakage attack  $Att^L$  returns a set of cropped watermarked data  $\{wd_j\}$  where each  $wd_j$  is a part of the original watermarked data  $wd_i$ , the tampering attack  $Att^T$  returns a set of tampered watermarked data  $\{wd_j\}$  where every  $wd_j$  does not belong to the original watermarked dataset, and the ignoring attack  $Att^I$  returns a set of watermarked data  $\{wd_j\}$  which is a subset of the original watermarked dataset.

We also consider a **collusion attack** between AU and IN, where the two colluding parties share information to disclose the identity and data of a DP.

### C. Design Objectives

We provide formal security definitions by using cryptographic experiments (games) [41]

**Privacy** is twofold. (1.1) **Anonymity**: the real identity of DPs/AUs is kept anonymous against  $\mathcal{A}$  when they are uploading/requesting data to/from the CB. Assume  $\mathcal{DP} = \{dp_1, dp_2, \dots, dp_{n_1}\}$  is a set of DPs' pseudo identities,  $\mathcal{IN} = \{in_1, in_2, \dots, in_{n_2}\}$  is a set of INs,  $\mathcal{A}$  is Probabilistic Polynomial-Time (PPT) adversary,  $\mathcal{C}$  is a challenger,  $\Pi$  is the proposed Themis scheme, and  $\lambda_0$  is a security parameter. We define a *DP-anonymity experiment*  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0)$  as follows:

1. Setup:  $\mathcal{C}$  prepares  $\mathcal{DP}$  and  $\mathcal{IN}$ .
2. Execution:  $\mathcal{C}$  executes  $\Pi$  with  $\mathcal{DP}$  and  $\mathcal{IN}$ .
3. Challenge:  $\mathcal{C}$  chooses a random  $k \in \{1, 2, \dots, n_1\}$  and sends  $dp_k$  to  $\mathcal{A}$ .
4. Guess:  $\mathcal{A}$  outputs a value  $k'$ .  $\mathcal{A}$  wins if  $k' = k$ .

We compute a DP-anonymity advantage of  $\mathcal{A}$  in correctly guessing  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0)$ . We denote it by

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0) = \left| \Pr[k' = k] - \frac{1}{n_1} \right|.$$

Similarly, the experiment  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Any-IN}}(\lambda_0)$  is defined where the target set is  $\mathcal{IN}$ ,  $\mathcal{C}$  chooses  $k$  from  $[1, n_2]$  and  $\mathcal{A}$  outputs  $k' \in [1, n_2]$ .  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-IN}}(\lambda_0) = |\Pr[k' = k] - \frac{1}{n_2}|$  under no collusion attack; and  $|\Pr[k' = k] - \frac{1}{n_2-1}|$  otherwise.

*Definition 2 (Anonymity)*:  $\Pi$  achieves anonymity if

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0) \leq \text{negl}(\lambda_0), \text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-IN}}(\lambda_0) \leq \text{negl}(\lambda_0).$$

(1.2) **Unlinkability**: two data uploading/requesting transactions sent by the same DP/IN are indistinguishable to  $\mathcal{A}$ . We define a *DP unlinkability experiment*  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1)$  as follows:

1. Setup:  $\mathcal{C}$  prepares  $\mathcal{DP}$  and  $\mathcal{IN}$ .
2. Execution:  $\mathcal{C}$  executes  $\Pi$  with  $\mathcal{DP}$  and  $\mathcal{IN}$ .  $\mathcal{A}$  generates two data  $d_0, d_1$ , and sends them to  $\mathcal{C}$ .



3. Challenge:  $\mathcal{C}$  chooses a random  $k \in \{1, 2, \dots, n_1\}$ , prepares  $\{dm_1, dm_2, \dots, dm_{n_1}\}, dm'_k$ , and sends them to  $\mathcal{A}$ .  $dm_k$  and  $dm'_k$  are computed by the same DP.

4. Guess:  $\mathcal{A}$  outputs a value  $k'$ .  $\mathcal{A}$  wins if  $k' = k$ .

An Experiment  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-IN}}(\lambda_0, \lambda_1)$  is defined regarding  $\{dr_1, dr_2, \dots, dr_{n_2}\}$  and  $dr'_k$ . We define  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1) = |\Pr[k' = k] - \frac{1}{n_1}|$ .  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{Unl-IN}}(\lambda_0, \lambda_1) = |\Pr[k' = k] - \frac{1}{n_2}|$  under no collusion attack; and  $|\Pr[k' = k] - \frac{1}{n_2-1}|$  otherwise.

**Definition 3 (Unlinkability):**  $\Pi$  achieves unlinkability if

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1) \leq \text{negl}(\lambda_0) + \text{negl}(\lambda_1),$$

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{Unl-IN}}(\lambda_0, \lambda_1) \leq \text{negl}(\lambda_0) + \text{negl}(\lambda_1).$$

**Security** contains two objectives. (2.1) **Private access control.** The plaintext data is protected from AUs. The accesses to data from unqualified INs are denied. We define an *AU-private access control experiment*  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2)$  as follows:

1. Setup:  $\mathcal{C}$  prepares  $\mathcal{DP}$  and  $\mathcal{IN}$ .
2. Execution:  $\mathcal{C}$  executes  $\Pi$  with  $\mathcal{DP}$  and  $\mathcal{IN}$ .  $\mathcal{A}$  generates two data  $d_0, d_1$ , and sends them to  $\mathcal{C}$ .
3. Challenge:  $\mathcal{C}$  chooses a random bit  $b \in \{0, 1\}$ , computes a ciphertext  $c_b$  of  $d_b$ , and sends  $c_b$  to  $\mathcal{A}$ .
4. Guess:  $\mathcal{A}$  outputs a bit  $b'$ .  $\mathcal{A}$  wins if  $b' = b$ .

We define  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{PAC-IN}}(\lambda_0, \lambda_2)$  as follows:

1. Setup:  $\mathcal{C}$  prepares  $\mathcal{DP}$  and  $\mathcal{IN}$ .  $\mathcal{A}$  sends  $\mathcal{S}_A$  to  $\mathcal{C}$  who returns  $sk_A \leftarrow \text{KeyGen}(msk, \mathcal{S}_A)$  to  $\mathcal{A}$ .
2. Execution:  $\mathcal{C}$  executes  $\Pi$  with  $\mathcal{DP}$  and  $\mathcal{IN}$ .  $\mathcal{A}$  generates two data values  $d_0, d_1$ , and sends them to  $\mathcal{C}$ .
3. Challenge:  $\mathcal{C}$  chooses a random bit  $b \in \{0, 1\}$ , chooses  $m_b$  for some  $dm$ , outputs its ciphertext  $c_b$  for its  $er$ , and sends  $c_b$  to  $\mathcal{A}$ .
4. Guess:  $\mathcal{A}$  outputs a bit  $b'$ .  $\mathcal{A}$  wins if  $b' = b$ .

We define  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2) = |\Pr[k' = k] - \frac{1}{2}|$  and  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{PAC-IN}}(\lambda_0, \lambda_2) = |\Pr[k' = k] - \frac{1}{2}|$ .

**Definition 4 (Private Access Control):**  $\Pi$  achieves private access control if

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2) \leq \text{negl}(\lambda_0, \lambda_2),$$

$$\text{Adv}_{\mathcal{A}, \Pi}^{\text{PAC-IN}}(\lambda_0, \lambda_2) \leq \text{negl}(\lambda_0, \lambda_2).$$

(2.2) **Authentication.** The identity of DPs and INs should be authenticated. We define an *authentication experiment*  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Aut}}(\lambda_1)$  as follows:

1. Setup:  $\mathcal{C}$  prepares  $\mathcal{DP}$  and  $\mathcal{IN}$ .
2. Execution:  $\mathcal{C}$  executes  $\Pi$  with  $\mathcal{DP}$  and  $\mathcal{IN}$ .  $\mathcal{A}$  is given  $1^{\lambda_1}$  and oracle access to  $\text{Sign}(prk_i, \cdot)$ .  $\mathcal{A}$  can only submit queries to at most  $w$  signing oracles.
3. Guess:  $\mathcal{A}$  outputs  $(m, \sigma)$ .  $\mathcal{A}$  wins if  $m \neq \mathcal{Q}$  and  $\text{Verify}(pk, m, \sigma) = 1$ , denoted by  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Aut}}(\lambda_1) = 1$ .

**Definition 5 (Authentication):**  $\Pi$  achieves authentication if

$$\Pr[\text{Exp}_{\mathcal{A}, \Pi}^{\text{Aut}}(\lambda_1) = 1] \leq \text{negl}(\lambda_1).$$

**Efficiency** refers to efficient performance, i.e., the computational costs, communication overhead, and gas costs (in Ethereum) should be as low as possible.

**Function** refers to strong traceability where Themis can track the IN who leaks a part of watermarked data  $pwd$ .

## V. PROPOSED SCHEME

### A. Overview

There are eight phases in Themis, namely system initialization, entity registration, data uploading, data requesting, analyzing, reporting, trailing, and traitor tracing. We use an end-to-end example to show the general process of DDF. A group of local administrative institutes, as AUs, establish a CB. Alice, as a DP, witnessed a bank robbery and took two pictures of a suspect with her smartphone. Given a Themis app on her smartphone, Alice registers to AUs to acquire a DAC. Then, Alice uploads the two pictures to the CB by sending two encrypted photos and the DAC to a local police department, i.e., an AU. The local police department verifies the DAC, decrypts the encrypted data into the enclave, computes a secure index, encrypts the data, and stores the ciphertext in its local database. If more data arrived later, an index tree is built and updated. A crime investigator Bob, as a DU, initiates an investigation on the robbery. He sends a DAC, a token, and a key proof to the police department. The police department verifies the DAC and the key proof, searches corresponding data, watermarks Bob's key into the matching data within an enclave, and sends watermarked-and-encrypted data back to the CPI. As for analyzing, reporting, and trailing, we follow the idea of [16] and [15]. If Bob leaks requested data, the authority can trace back to Bob by extracting his key from the leaked data.

### B. System Initialization

Before any security protocols are preset, a secure enclave EV  $ev_i$  is installed at each AU  $au_i$  ( $1 \leq i \leq n_0$ ). A pair of private key and public key  $(prk_{ev_i}, puk_{ev_i})$  is generated for  $ev_i$  by SGX Seal method.  $\Omega = (S, E, D)$  is an asymmetric encryption scheme with a security parameter  $\lambda_0$ .

Given a security parameter  $\lambda_1$ , a distributed key generation protocol [31] to generate a secret key  $prk = d$ , a public key  $pk = (n = pq, e)$ , and a polynomial  $f(x) = \sum_{i=0}^{t-1} a_i x^i$ , where  $e$  is a prime bigger than  $n_0$ ,  $de \equiv 1 \pmod{M}$ ,  $a_0 = d$ , and  $a_i$  ( $1 \leq i \leq t-1$ ) is random chosen from  $\{0, 1, \dots, M-1\}$ . At the end,  $n_0$  secret shares of  $prk$  are computed as  $prk_i^{ev} = f(i) \pmod{M}$ ,  $1 \leq i \leq n_0$ , a random value is chosen as  $v \in \mathcal{Q}_n$ , and  $n_0$  verification keys are computed as  $v_i = v^{s_i}$ ,  $1 \leq i \leq n_0$  [30]. Given a security parameter  $\lambda_2$ ,  $\text{Setup}(1^{\lambda_2})$  outputs a public key  $mpk$  and a master secret key  $msk$ . Given a security parameter  $\lambda_3$ ,  $\text{KGen}(1^{\lambda_3})$  outputs a secret key  $key$ . Given a security parameter  $\lambda_4$ ,  $\text{Initialize}(1^{\lambda_4})$  outputs secret keys  $SK = \{k_1, k_2, \dots, k_{v+1}\}$ ,  $v+1$  pseudo-random hash functions  $\mathcal{H} = \{h_1, h_2, \dots, h_{v+1}\}$ , and a hash function  $h$ . Here,  $h_i = \text{HMAC}(k_i, \cdot) \% L$  ( $1 \leq i \leq v$ ) where  $L$  is the length of the underlying indistinguishable Bloom filter  $\mathcal{B}$ ,  $h_{v+1} = \text{HMAC}(k_{v+1}, \cdot)$ ,  $h = \text{SHA256}(\cdot) \% 2$ .

All AUs determine the parameters (e.g., consensus algorithm, block generation time, node account deposit) for the CB. An Investigation Smart Contract (ISC) with a unique address  $\text{Add}_{\text{ISC}}$  is published.

Finally,  $msk$ ,  $key$ , and  $\mathcal{SK}$  are securely distributed to all enclaves. Public parameters  $pp = (\{puk_{ev_i}\}_{i=1}^{n_0}, v, \{v_i\}_{i=1}^{n_0}, pk, mpk, \mathcal{H}, h)$  are published.

### C. Entity Registration

A DP generates a pair of private key and public key  $(prk_{dp}, puk_{dp})$  and registers to a subset of  $t$  EVs  $\mathcal{EV} = \{ev_{i_1}, ev_{i_2}, \dots, ev_{i_t}\}$  for a DAC  $cre_{dp}$  as follows:

- DP generates a random registration message  $rm$  and submits  $erm = E(puk_{ev_{i_j}}, "Register" || rm)$  to  $ev_{i_j}$ .
- Each  $ev_{i_j}$  decrypts  $erm$  to obtain  $rm$ , signs the  $rm$  by computing a partial signature [30]

$$\sigma_{i_j} = rm^{2\Delta prk_{i_j}^{ev}}, \Delta = n_0!, \quad (1)$$

where  $prk_{i_j}^{ev}$  is the private key of  $ev_{i_j}$ .

- Each  $ev_{i_j}$  chooses a random number  $r$ , and computes a proof of correctness  $\pi_{i_j} = (z, hv)$  [30] where

$$v' = v^r, rm' = rm^{4\Delta r}, hv = h(v, rm^{4\Delta}, v_{i_j}, \sigma_{i_j}^2, v', rm'),$$

$$z = prk_{i_j}^{ev} hv + r.$$

- Each  $ev_{i_j}$  returns  $E(puk_{dp}, \sigma_{i_j} || \pi_{i_j})$  to the DP.
- DP decrypts the encrypted message from each  $ev_{i_j}$  and verifies each partial signatures  $\sigma_{i_j}$  [30] by checking

$$hv \stackrel{?}{=} h(v, rm^{4\Delta}, v_{i_j}, \sigma_{i_j}^2, v^z v_{i_j}^{-hv}, rm^{4\Delta z} \sigma_{i_j}^{-2hv}).$$

- If all the verification passes, DP combines the  $t$  partial signatures to get a full signature [30] by computing

$$\sigma_{dp} = \prod_{j=1}^t \sigma_{i_j}^{2\gamma_{0,i_j}^{AU}} \quad (2)$$

where  $\gamma_{0,i_j}^{AU} = \Delta \prod_{j' \in AU \setminus \{i_j\}} (0 - i_j) / \prod_{j' \in AU \setminus \{i_j\}} (i_j - j')$ . DP acquires the  $cre = (rm, \sigma_{dp})$ .

An IN registers to  $t$  AUs to acquire a  $cre$  similarly. In case of multiple data request, the IN sends multiple registration messages to AUs for multiple DACs. The IN with a set of investigation attributes  $\mathcal{S}_{in}$  registers to their department  $au$  to obtain a secret key  $sk_{in} \leftarrow \text{KeyGen}(msk, \mathcal{S}_{in})$  and  $\mathcal{SK}$ . An IN initiates an investigation from his/her department, which will grant or deny the request and send a grant transaction  $\text{Tx}_1^{\text{IniG}}$  or a deny transaction  $\text{Tx}_1^{\text{IniD}}$  with a timestamp  $ts$ :

$$\text{Tx}_1^{\text{IniG}} = ("IniGrant", ReqID, CaseID, ts, \sigma_{au}),$$

$$\text{Tx}_1^{\text{IniD}} = ("IniDeny", ReqID, Null, ts, \sigma_{au}).$$

### D. Data Uploading

The DP encrypts their data  $d$  to obtain  $ed = E(pub_{ev_i}, d)$  and sends a data message  $dm = (cre, ed)$  to the  $au_i$ .

Upon receiving  $dm$ ,  $au$  verifies its validity by computing

$$\sigma^e \stackrel{?}{=} rm^{4\Delta^2}.$$

If it passes,  $au$  sends a data uploading transaction to the CB:

$$\text{Tx}_2^{\text{Upl}} = ("Upload", cre, h(ed), ts, \sigma_{au_i}).$$

Next, the enclave  $ev_i$  produces a secure index as follows:

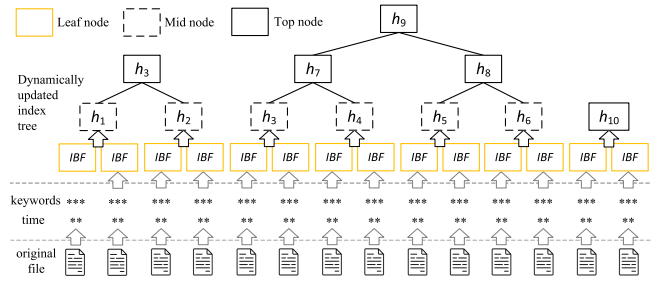


Fig. 4. Structure of dynamically updated index tree.

- Decrypt  $ed$  to obtain  $d = D(prk_{ev_i}, ed)$ ,
- Extract key information from  $d$  to acquire a set of items  $\mathcal{IT} = \{it_i\}$  where each  $it_i$  has a set of keywords and time. For example, a keyword can be “assault”, “murder”, “theft”, etc. Time can be “20221014”.
- Initialize an IBF  $\mathcal{B}_i$  and insert each keyword  $it_i$  into  $\mathcal{B}$  by converting it into a prefix family  $\mathcal{PF}_i = \{pr_{i_j}\}$  [32].
- Update  $\mathcal{PF}_i$  by encoding each prefix into a keyword. For example, assume the keyword is “assault” and  $\mathcal{PF}(4) = \{0100, 010*, 01**, ****, ****, ****, ***, ****, *****\}$ , encode each prefix in  $\mathcal{PF}(4)$  into “assault:0100”, “assault:010\*”, “assault:01\*\*”, “assault:0\*\*\*”, and “assault:\*\*\*\*”.
- Set for all  $j$  where  $rn_i$  being a random number:

$$\begin{aligned} \mathcal{B}_i[h_j(pr_{i_j})][h(h_{v+1}(h_j(pr_{i_j})) \oplus rn_i)] &= 1, \\ \mathcal{B}_i[h_j(pr_{i_j})][1 - h(h_{v+1}(h_j(pr_{i_j})) \oplus rn_i)] &= 0. \end{aligned}$$

At the end of each consensus period, a winning enclave  $ev^*$  is selected. Each  $ev_i$  that has produced a secure index sends  $(\mathcal{B}_i, rn_i)$  to  $ev^*$ . There are two cases for the index tree.

(1) If there is no index tree,  $ev^*$  produces an index tree (binary tree)  $\mathcal{T}$  as follows.

- Sort the  $n_1$  IBFs in a random order and prepare to build  $\mathcal{T}$  from the bottom to up. Each IBF is called a leaf node.
- Assume that  $\mathcal{B}_{new}$  is the father node of a left child node  $\mathcal{B}_{le}$  and a right child node  $\mathcal{B}_{ri}$ , for  $i \in [1, |\mathcal{B}|]$ , set

$$\begin{aligned} \mathcal{B}_{new}[i][h(h_{v+1}(i) \oplus rn_{new})] &= \\ \mathcal{B}_{le}[i][h(h_{v+1}(i) \oplus rn_{le})] \vee \mathcal{B}_{ri}[i][h(h_{v+1}(i) \oplus rn_{ri})]. \end{aligned}$$

- When the number of lead nodes reaches a predefined one, stop adding new leaf nodes and start producing a new tree (see Fig. 4 for an example).

(2) If there is already an index tree  $\mathcal{T}$ ,  $ev_i$  appends the new IBFs to  $\mathcal{T}$ . After the tree construction,  $ev^*$  shares the new index tree(s) with other AUs and update the root hashes  $\{rh_i\}$  in the ISC and send a root updating transaction:

$$\text{Tx}_3^{\text{Upd}} = ("Update", \{rh_i\}, \sigma_{au_i}).$$

### E. Data Requesting

The IN has a request  $q$  consisting of a sequence of keywords and time periods  $tp$  and generates a data request  $dr$  as follows.

- Convert  $tp$  into a minimum set of prefixes  $\mathcal{MS} = \{pr_i\}$  [32].

- Update  $\mathcal{MS}$  by encoding each prefix into a keyword.
- For each  $pr_i \in \mathcal{MS}$ , compute

$$tk = \{(h_j(pr_i), h_{v+1}(h_j(pr_i)))\}_{j=1}^v. \quad (3)$$

- Compute key proof  $kp = (puk_{in}, E(puk_{ev_i}, prk_{in}))$  and send  $dr = (cre, tk, kp)$  to an AU, say  $au_i$ .

$au_i$  first verifies the validity of  $dr$ . If it is not valid,  $au_i$  sends a request deny transaction to the CB; otherwise, it sends a request grant transaction:

$$\text{Tx}_4^{\text{ReqD}} = (\text{"ReqDeny"}, cre, h(tk), ts, \sigma_{au_i}),$$

$$\text{Tx}_4^{\text{ReqG}} = (\text{"ReqGrant"}, cre, h(tk), ts, \sigma_{au_i}).$$

Given  $tk$ ,  $au_i$  locally searches from the root  $\mathcal{B}_{rt}$  of  $\mathcal{T}$  and checks whether there exists a  $pr_i$  that satisfies for  $1 \leq j \leq v$ :

$$\mathcal{B}_{rt}[H_j(pr_i)][h(h_{v+1}(h_j(pr_i)) \oplus rn)] = 1.$$

If so,  $au_i$  processes  $tk$  against the left child node and right child node of the root. The process recursively applies to subtrees and stops when  $au_i$  determines  $tk$  matches no leaf nodes or at least one leaf node.  $au_i$  generates Merkle proofs  $\mathcal{MP}$  for the matching node.

Given a matching leaf node  $\mathcal{B}$ , we assume that  $au_i$  has stored the corresponding data  $ed$  locally. We will discuss in Section VIII about how we respond to IN if  $au_i$  does not have the requested data. Next,  $ev_i$  produces watermarked-and-encrypted data  $er$  as follows.

- Decrypt  $ed$  and  $kp$  to obtain data  $d$  and  $prk_{in}$ .
- Verify  $prk_{in}$  by checking if  $g^{prk_{in}} = puk_{in}$ .
- Code  $prk_{in}$  by using an improved embedding method to guarantee the recovery rate in traitor tracing. (Refer to VII.A for details on improvements.)
- Embed  $prk_{in}$  into  $d$  by computing  $d' = \text{Embed}(key, prk_{in} || d)$ .
- Determine the access structure  $\mathbb{A}$  for  $d$  and encrypt  $d'$  by computing  $er = \text{Encrypt}(mpk, \mathbb{A}, d')$ .

$au_i$  sends  $(er, \mathcal{MP})$  back to the IN. The IN verifies  $er$  and then decrypts  $er$  by computing  $rr = \text{Decrypt}(pk, er, sk_{in})$ .

### F. Analyzing, Reporting, and Trailing

Since this part is not our focus, we only provide a process sketch of it. After collecting enough data for the investigation, the IN carries out a professional and systematic investigation in cooperation with other forensics professionals. At the end of the investigation, the IN finalizes a When an investigation report  $rp$  and sends a reporting transaction to the CB:  $\text{Tx}_5^{\text{Rep}} = (\text{"Report"}, h(rp), ts, \sigma_{in})$ .

Afterwards, the court holds a trial handle down a verdict  $ve$  and close the case. Finally, the judge sends a judging transaction to the CB:  $\text{Tx}_6^{\text{Jud}} = (\text{"Judge"}, h(ve), ts, \sigma_{co})$ .

### G. Traitor Tracing

In this work, we assume that INs initiates a partial-data leakage attack by cropping a requested picture and leaking the cropped data. When the leaked data  $pwd$  is found, any

enclave will extract a watermark  $wm$  from  $pwd$  by computing  $wm = \text{Extract}(key, pwd)$ . Then, the enclave computes its corresponding public key to track the traitor.

The successful tracking probability depends on how much the traitor crops the picture as well as the length of the secret key. We will analyze it in Section VII.

## VI. PRIVACY AND SECURITY ANALYSIS

### A. Privacy

1) *Anonymity: Theorem 1.* Themis provides anonymity under the indistinguishability of the asymmetric encryption scheme  $\Omega$ .

*Proof.* For DPs, they register to  $t$  AUs to obtain  $t$  encrypted partial signatures  $\sigma_1, \sigma_2, \dots, \sigma_t$  that are further combined to be a full signature  $\sigma$ . Intuitively, the anonymity of DPs is guaranteed by protecting the link between  $\sigma_1, \sigma_2, \dots, \sigma_t$  and  $\sigma$ . Here, each set of  $\{\sigma_{i1}, \sigma_{i2}, \dots, \sigma_{it}\}$  is secured by E and sent from the  $t$  AUs to a DP.

AU or a colluding IN as the  $\mathcal{A}$ . The view of AU and the view of IN towards the message of a DP is the same because they can only observe DP's communication channel. Although AU processes DP's data messages, it cannot access the contents due to the secure enclave. We define two events for proving anonymity. (1) Event 11:  $\mathcal{A}$  successfully guesses  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0)$  (Section IV-C) by successfully breaking the asymmetric encryption  $\Omega$ . (2) Event 21:  $\mathcal{A}$  successfully guesses  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0)$  by randomly guessing the correct  $k$  [41]. We have the following inequality:

$$\begin{aligned} \text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-DP}}(\lambda_0) &= \left| \Pr[\text{Event 11}] + \Pr[\text{Event 12}] - \frac{1}{n_1} \right| \\ &= \left| \Pr[\text{PubK}_{\mathcal{A}, \Omega}(\lambda_0) = 1]^{t+1} + \frac{1}{n_1} - \frac{1}{n_1} \right| \\ &= \Pr[\text{PubK}_{\mathcal{A}, \Omega}(\lambda_0) = 1]^{t+1} \leq \text{negl}(\lambda_0). \end{aligned}$$

For INs, the proof is similar such that  $\text{Adv}_{\mathcal{A}, \Pi}^{\text{Any-IN}}(\lambda_0) = \frac{1}{2^{|\lambda_0|}} \leq \text{negl}(\lambda_0)$ . We have proved the anonymity goal in Definition 2.

2) *Unlinkability: Theorem 2.* Themis provides unlinkability under the indistinguishability of  $\Omega$  and Discrete Logarithm (DL) assumption.

*Proof.* For DPs,  $\mathcal{A}$  can break their unlinkability by either linking  $d_0$  and  $d_1$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1)$  or linking  $cre_{dp}$  and  $cre'_{dp}$ . Meanwhile, we require that DPs register to different AUs for a new DAC and assume that the number of AUs in the new registration is  $t^*$  ( $0 \leq t^* < t$ ). We define two experiments for proving unlinkability. (1) Event21:  $\mathcal{A}$  successfully guesses  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1)$  (Section IV-C) by successfully breaking the asymmetric encryption  $\Omega$  at  $\text{DP}_k$ . (2) Event 22:  $\mathcal{A}$  successfully guesses  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1)$  by breaking the signature scheme  $\Gamma$   $t^*$  times. (3)  $\mathcal{A}$  successfully guesses  $k$  in  $\text{Exp}_{\mathcal{A}, \Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1)$  by randomly guessing the correct  $k$ . In Event 22,  $\mathcal{A}$  has to locate the  $t^*$  new partial signatures first and then break their signing

keys. Therefore, we have the following equation:

$$\begin{aligned}
& \text{Adv}_{\mathcal{A},\Pi}^{\text{Unl-DP}}(\lambda_0, \lambda_1) \\
&= \left| \Pr[\text{Event 21}] + \Pr[\text{Event 22}] + \Pr[\text{Event 23}] - \frac{1}{n_1} \right| \\
&= \left| \Pr[\text{Event 21}] + \Pr[\text{Event 22}] + \frac{1}{n_1} - \frac{1}{n_1} \right| \\
&= \frac{\Pr[\text{PubK}_{\mathcal{A},\Omega}(\lambda_0) = 1]}{n_1} + \frac{\Pr[\text{Sig-forge}_{\mathcal{A},\Gamma}(\lambda_1) = 1]}{(\mathcal{C}_t^{\ell^*})^2} \\
&\leq \text{negl}(\lambda_0) + \text{negl}(\lambda_1),
\end{aligned}$$

which is negligible. For INs, the proof is similar such that  $\text{Adv}_{\mathcal{A},\Pi}^{\text{Unl-IN}}(\lambda_0, \lambda_1) \leq \text{negl}(\lambda_0) + \text{negl}(\lambda_1)$ . We have proved the anonymity goal in Definition 3.

## B. Security

1) *Private Access Control: Theorem 3.* Themis provides private access control under the indistinguishability of  $\Omega$  and the DLIN assumption on asymmetric pairing groups in the random oracle model [20].

*Proof.* Based on  $\text{Exp}_{\mathcal{A},\Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2)$ , from the AU's view, the uploaded data is encrypted by the DP and stored locally. If the data is requested by an IN, its ciphertext is processed within enclave, watermarked, and encrypted by the public key  $pk$ . We define two events for proving private access control. (1) Event 31:  $\mathcal{A}$  successfully guesses  $b$  in  $\text{Exp}_{\mathcal{A},\Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2)$  (Section IV-C) by successfully breaking the asymmetric encryption  $\Omega$ . (2) Event 32:  $\mathcal{A}$  successfully guesses  $b$  in  $\text{Exp}_{\mathcal{A},\Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2)$  by successfully breaking the ABE  $\Upsilon$ . (3) Event 33:  $\mathcal{A}$  successfully guesses  $b$  in  $\text{Exp}_{\mathcal{A},\Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2)$  by randomly guessing the correct  $b$ . Therefore, we have the following equation:

$$\begin{aligned}
& \text{Adv}_{\mathcal{A},\Pi}^{\text{PAC-AU}}(\lambda_0, \lambda_2) \\
&= \left| \Pr[\text{Event 31}] + \Pr[\text{Event 32}] + \Pr[\text{Event 33}] - \frac{1}{2} \right| \\
&= \Pr[\text{PubK}_{\mathcal{A},\Omega}(\lambda_0) = 1] + \Pr[\text{PubK}_{\mathcal{A},\Upsilon}(\lambda_0) = 1] \\
&\leq \text{negl}(\lambda_0) + \text{negl}(\lambda_2).
\end{aligned}$$

Based on  $\text{Exp}_{\mathcal{A},\Pi}^{\text{PAC-IN}}(\lambda_0, \lambda_2)$ , the IN's view is a little different for possessing a secret key  $sk_{\mathcal{A}}$  associated with  $\mathcal{S}_{\mathcal{A}}$ . We have the following equation:

$$\begin{aligned}
& \text{Adv}_{\mathcal{A},\Pi}^{\text{PAC-IN}}(\lambda_0, \lambda_2) \leq \frac{1}{2^{|\lambda_0|}} + (8Q+2)\text{Adv}_{\text{DLIN}}^{\beta}(\lambda_2) + \frac{(16Q+6)}{p} \\
&= \text{negl}(\lambda_0) + \text{negl}(\lambda_2),
\end{aligned}$$

where  $Q$  is the number of queries and  $p = \Theta(\lambda_2)$  is the order of the pairing group. Please refer to [20] for details. We have proved the private access control goal.

2) *Authentication: Theorem 4.* Themis provides authentication under the security of the standard RSA signature scheme

TABLE III  
KEY EXPERIMENTAL PARAMETERS

Parameter	Value	Parameter	Value
$n_0$	4	$n_1$	[100, 1000]
$n_2$	[100, 500]	$ prk^1 ,  puk^1 $	512, 512
$ prk^2 ,  puk^2 $	1024	$ mpk ,  msk $	512, 512
$ sk $	512	$ key $	512
$ k_i $	256	$v$	5
$h$	SHA256%2	$L$	10000

for  $t = w + 1$  in the random oracle model for  $h$ , where  $w$  is the number of corrupted AUs [30].

*Proof.* We have asked the AUs to register DPs and INs by signing their submitted message and generating a partial signature. Assume that there are  $w$  corrupted AUs and they try to forge a valid full signature  $\sigma$  given their  $w$  secret shares. We define one event for proving authentication. Event 4:  $\mathcal{A}$  successfully forges a full signature in  $\text{Exp}_{\mathcal{A},\Pi}^{\text{Aut}}(\lambda_1)$  (Section IV-C) by successfully breaking the signature scheme  $\Gamma$  for any uncorrupted AU from  $n_0 - w$  uncorrupted AUs. Therefore, we have the following equation:

$$\begin{aligned}
& \text{Adv}_{\mathcal{A},\Pi}^{\text{Aut}}(\lambda_1) = \Pr[\text{Event 4}] \\
&\leq (n_0 - w)\Pr[\text{Sig-forge}_{\mathcal{A},\Gamma}(\lambda_1) = 1] \leq \text{negl}(\lambda_1).
\end{aligned}$$

We have proved the authentication goal in Definition 4.  $\square$

We also compare Themis with existing work on model, privacy, security, and function in Table II. Only the proposed Themis provides all the design objectives.

## VII. PERFORMANCE EVALUATION

### A. Experiment Settings

**Dataset.** Since there are few sources of datasets on data uploading or requesting in digital forensics, we synthesized two plausible groups (DPs and INs) to simulate the uploading and requesting activities. Specifically, we created  $n_1$  DPs and  $n_2$  INs. Both of the two groups uploaded/requested data spontaneously in a predefined time period.  $n_1$  and  $n_2$  were drawn from two ranges to test scalability.

**Parameters.** We list the key experimental parameters in Table III, including the number of AUs  $n_0$ , number of DPs  $n_1$ , number of INs  $n_2$ , private key and public key  $(prk^1, puk^1)$  for signature scheme, private key and public key  $(prk^2, puk^2)$  for DPs and INs, public key and master secret key  $(mpk, msk)$ , secret key  $sk$ ,  $key$ ,  $k_i$  ( $1 \leq i \leq v + 1$ ), and hash function  $h_i$  ( $1 \leq i \leq v + 1$ ),  $h$ .

**Metrics.** We evaluated the computational costs and communication overhead for DP, IN, AU, and EV. Since Themis is a decentralized framework, we have chosen Ethereum to be the underlying platform and evaluate the basic blockchain performance including consensus time, transaction confirmation time, and gas costs. We also evaluated the scalability (response time for INs) and traceability (private key recovery rate after partial-data leakage) of Themis.

**Setup.** The implementation details of Themis are shown in Fig. 5. The hardware settings are listed in Table IV. We initialized

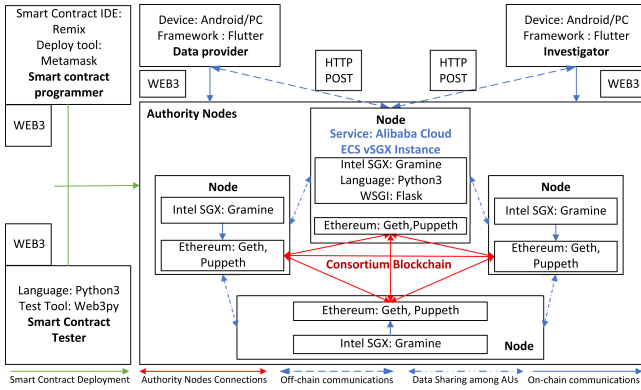


Fig. 5. Implementation details of DDF.

TABLE IV  
HARDWARE SETTINGS

Smartphone (Huawei Mate 40) as DP and IN	
CPU	Kirin 9000E
Memory	8 GB
Operating System	HarmonyOS
Server (ECS) as AU	
CPU	Intel Xeon 8269CY @2.50GHz
Memory	4 GB
Operating System	Ubuntu 20.04.6 LTS

Themis by installing SGX Driver, SGX SDK, SGX PSW, SGX DCAP, and Gramine on the AU's server, deploying the web application into enclave through Gramine. The blockchain test platform was Ethereum 2.0, and Geth was used to establish the Ethereum network. We instantiated four AU nodes, each with an Ethereum account, on four Alibaba Cloud ECS servers supporting SGX 2.0. The nodes communicated with each other through the LAN. We instantiated DP/IN on two smartphones, created a cross-platform application based on the Flutter framework. They communicated with AU through the HTTP protocol and interact with CB through the web3 protocol. We used Puppeth to create the genesis block. The consensus mechanism was Clique with a block creation time of 10 seconds. After the consortium blockchain started running, each blockchain node generated the node information. We wrote the smart contract using Remix and deployed the smart contract through MetaMask. We recorded the generated contract address and application binary interface, and then invoked the contract through the web3 protocol. We have uploaded the codes to <https://github.com/UbiPLab/Themis>.

For *watermark embedding*, we transform the 1024-bit public key into a symmetrical watermark by using even-parity Hamming encoding, padding, spread-spectrum encoding, XORing, double sampling, and flipping. We convert the host image to the YCrCb space and extract the Y component as the luminance matrix. We set the global embedding intensity to two and change each element of the luminance matrix to the initial value plus the global embedding intensity multiplied by the value of each element in the symmetrical watermark. We convert the new luminance matrix and the original host image's Cr and Cb components to an RGB image to generate the watermarked image. For *watermark extracting*, we convert the watermarked

image to the YCrCb space and extract the Y component as the luminance matrix. We use the local variance of the luminance matrix to calculate the mean square error minimization estimate of the watermark module to obtain the watermark module and then synchronize the watermark based on symmetry. We determine the watermark state based on the central limit theorem, decode the watermark and the mask matrix to obtain the public key information after group Hamming encoding, and then recover the original public key through Hamming decoding.

## B. Computational Costs

We analyze the computational costs for DP, IN, AU, and EV through counting their number of operations. We denote  $G_x$  as a general generation function to obtain  $x$ .

A DP's computational costs come from entity registration and data uploading, which includes: compute a public key  $pubk_{dp}$ , encrypt a registration message  $rm$ , decrypt  $t$  encrypted messages  $E(pubk_{dp}, \sigma_{i_j} || \pi_{i_j})$ , verify and combine  $t$  partial signatures  $\{\sigma_i\}$ , and encrypt data  $d$ . i.e.,  $(ex + E + D + (6ex + 2mu) + t * ex + (t - 1)mu) + E$ . The two phases cost the DP 0.69 s and 1.17 s.

An IN's computational cost mainly stem from entity registration and data requesting, which includes: the same operations as DP in entity registration, generate a token  $tk$ , compute a key proof  $kp$ , and verify and decrypt  $er$ . i.e.,  $(ex + E + D + (6ex + 2mu) + t * ex + (t - 1)mu) + TokenGen + E + ex + D$ . The two phases cost the IN 0.77 s and 16.32 s.

An AU's computational cost originate from system initiation, data uploading, and data requesting, which includes: initialize the CB, verifies  $n_1$   $dms$ , verifies  $n_2$   $drs$ ,  $n_2$  searches on the index tree, and generate Merkle hash proofs  $\{pf_i\}$ . i.e.,  $ln_{CB} + 2n_1ex + 2n_2ex + Search(\mathcal{T}, tk) + G_{\{pf_i\}}$ . The three phases cost the AU 64 ms, 4.82 s, and 5.12 s.

An EV's computational costs are from system initiation, entity registration, data uploading, data requesting, and traitor tracing, which includes: generate all the keys and functions, decrypt  $n_1 + n_2$  encrypted registration messages, sign  $n_1 + n_2$  registration messages, generate  $n_1 + n_2$  proofs, decrypt  $n_1$  encrypted data, generate  $n_1$  indexes, decrypt  $n_2$  encrypted data and key proofs, verify  $n_2$  secret keys, embed  $n_2$  times, encrypt  $n_2$  times, and extract the key. i.e.,  $(Gen + Setup + KGen + Initialize) + (n_1 + n_2)(D + 5ex + h) + (n_1(D + IndexGen) + G_{\mathcal{T}}) + n_2(2D + ex + Embed + Encrypt) + Extract$ .

The five phases cost the IN 0.93 s,  $25 * (n_1 + n_2)$  ms,  $6.88n_1 + 0.92$  s,  $7.59n_2$  s, and 0.17 s. The main measured values for execution time of each entity are listed in Table V.

## C. Communication Overhead

We analyze the communication overhead for the four main entities. A DP submits  $t$  encrypted registration messages and a data message, i.e.,  $t|erm| + |cre| + |E| = 4.45$  MB. An IN submits  $t$  encrypted registration messages, a data message, and a data request  $dr$ . i.e.,  $t|erm| + |dr| = 0.25$  KB. Assume that all requests are valid and matched

TABLE V  
 COMPARISON OF COMPUTATIONAL COSTS

Scheme	System Initialization		Entity Registration			Data Uploading			Data Requesting			Traitor Tracing
	AU	EV	DP	IN	EV	DP	AU	EV	IN	AU	EV	EV
[16]	$\text{In}_B^{1a}$	n/a	$G_{cer}^{1b}$	$G_{cer}^{1b}$	n/a	$h + G_\sigma$	$n_1(h + G_\sigma)$	n/a	$n/m^{1c}$	n/a	n/a	n/a
[17] <sup>2a</sup>	$\text{In}_B + \text{Gen} + \text{Setup}$	n/a	$ex$	$ex$	n/a	$\text{Encrypt} + G_{root} + G_\sigma^{2b}$	$n_1 \text{Ver}_\sigma$	n/a	$H + 4G_\sigma + \mathcal{N} * G_{bres} + \text{PIR} + G_\pi + G_{SK} + \text{Decrypt}^{2c}$	$n_2(\text{Ver}_\sigma + G_{res} + G_\pi + G_\sigma + 4\text{Ver}_\sigma)^{2d}$	n/a	n/a
[15] <sup>3a</sup>	$\text{In}_{CB} + \text{Gen}_{cre} + \text{Setup}$	n/a	$2ex + mu + G_\pi + G_\sigma$	$2ex + mu$	$n_1 \text{Ver}_{Tx_1} + n_2 \text{KGen} + n_2 G_\sigma + n_2 \text{Ver}_{Tx_2}^{3b}$	$\text{Encrypt} + G_{cre} + \pi' + H_1 + H_2 + G_\sigma$	$n_1 \text{Ver}_{Tx_3}$	n/a	$G_{\pi'} + G_{\pi''} + G_{cre} + 2G_\sigma + \text{OT} + \text{Dec} + \text{Decrypt}$	$n_2 \text{Ver}_{Tx_4} + G_\sigma + \text{Encrypt}$	n/a	n/a
Themis	$\text{In}_{CB}$	$\text{Gen} + \text{Setup} + \text{KGen} + \text{Initialize}$	$(t + 7)ex + (t + 1)mu + E + D$	$(t + 7)ex + (t + 1)mu + E + D$	$(n_1 + n_2)(D + 5ex + h)$	E	$2n_1ex$	$n_1(D + \text{IndexGen}) + G_T$	$\text{TokenGen} + E + ex + D$	$n_2(2ex + \text{Search} + G_{\{pfi\}})$	$n_2(2D + ex + \text{Embed} + \text{Encrypt})$	Extract

1a: No indication of what blockchain. 1b: register to certification authority using vehicular public key infrastructure (IEEE 1609.2). 1c: Not mentioned.  
 2a: The function and notation that are same to ours do not always mean the same. 2b: root is a Merkle root computed from consecutive ciphertexts.  
 2c: DP leverages the private information retrieval (PIR) scheme [43] to retrieve the data from a distributed data storage system.  
 2d: AU computes a zero knowledge proof  $\pi$  by using the technique in [44] to approve that  $SK$  is indeed computed based on the authorized  $res$ .  
 3a: Same to 2a; 3b: AU conducts these operations.

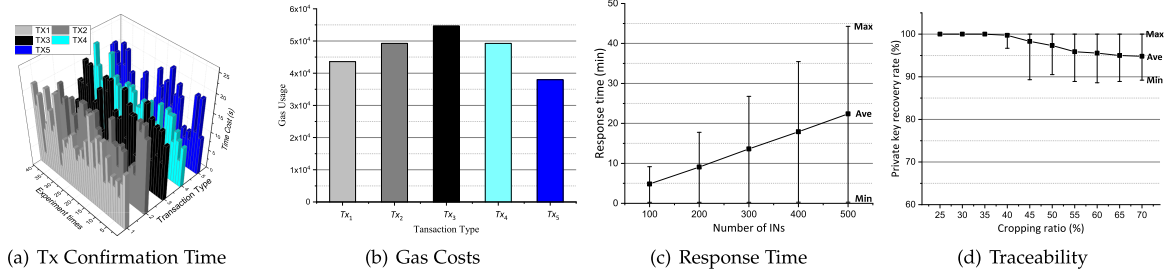


Fig. 6. Performance of themis.

with stored data, an AU sends  $n_2$  grant transactions,  $n_1$  data uploading transactions,  $n_2$  request grant transactions, and  $n_2$  results, i.e.,  $n_1|\text{Tx}^{\text{Upl}}| + n_2(|\text{Tx}^{\text{InG}}| + |\text{Tx}^{\text{ReqG}}| + |er| + |G_{\{pfi\}}|) = 0.43n_1 \text{ KB} + 4.41n_2 \text{ MB}$ . An EV sends public parameters,  $n_1 + n_2$  partial signatures and proofs,  $n_1$  indexes and random numbers,  $n_2$  encrypted results, and a public key of traitor IN. i.e.,  $|pp| + (n_1 + n_2)(|\sigma| + |\pi|) + n_1(|\mathcal{B}| + |rn|) + n_2|er| + |pubk_{in}| = 0.22n_1 \text{ KB} + 4.41n_2 \text{ MB}$ .

#### D. Basic Blockchain Performance

We set the block period to be 20 seconds. The real consensus time fluctuates around 20 seconds because of the hardware interference. The interval time between two transactions of six types is 1 s. Due to network delay and consensus mechanism, the average transaction confirmation time of transactions is approximately 13.34 seconds as shown in Fig. 6(a). We measure the gas cost of six types of transactions in Fig. 6(b). The average gas cost for  $Tx_1$  is about 43572. We set the gas price to be 1 Gwei (0.000000001 Ether) in the Themis blockchain, at the time of writing (May 1st, 2023), the exchange rate is \$1,870.76 USD per Ether. Each  $Tx_1$  costs about 0.000043572 Ether (0.08 USD).

#### E. Scalability

Scalability here refers to the response time of an IN between data requesting and result receiving, including blockchain search

time and communication delay. We evaluate the maximum, minimum, and average response time. In Fig. 6(c), the average response time increases with the number of INs, which is less than 5 minutes when  $n_2 = 100$ .

#### F. Traceability

The private key recovery rate (PKRR) of the watermarking module is affected by the cropping ratio  $cr$ . We set the ratio from 25% to 70% and randomly crop out a square in three pictures twenty times for each ratio. After watermark extraction, we compute how many bits of the IN's private key  $prk_{in}$  are recovered and record the average private key recovery rate. Results in Fig. 6(d) show that we can recover  $prk_{in}$  without error when  $cr \leq 35\%$ . When  $cr$  is 70%, the average PKRR is 94.8%.

#### G. Comparison With Existing Work

Since the existing work do not have EV in their system model, we incorporate the computational cost and communication overhead into the one of AU. The comparison results are listed in Tables V and VI. Although Themis does not exceed other schemes, still it empowers DPs and INs to securely share data against multiple attacks.

TABLE VI  
COMPARISON OF COMMUNICATION OVERHEAD

Scheme	System Initialization		Entity Registration			Data Uploading			Data Requesting			Traitor Tracing
	AU	EV	DP	IN	EV	DP	AU	EV	IN	AU	EV	EV
[16]	$ ln_B^{1a} $	n/a	$ id $	$ id $	n/a	$ m ^{1b} +  h  +  \sigma $	$ m  +  h  +  \sigma $	n/a	n/m	n/a	n/a	n/a
[17]	$ PK $	n/a	$ pk $	$ pk $	n/a	$ Tx^1 $	n/a	n/a	$ req  +  Tx^2  + N *  bres  +  PIR  +  Tx^4  +  Tx^5  +  Tx^6 $	$n_2( res  + Tx^3)$	n/a	n/a
[15]	$ pp $	n/a	$ Tx^1 $	$ A ^{3a}$	$n_2( sk  +  Tx_2 )^{3b}$	$ Ed  +  Tx_3 ^{3c}$	n/a	n/a	$ Tx_4  +  id  +  pk  +  L  + 2 \sigma  +  OT ^{3d}$	$n_2( Tx_5  +  Enc )$	n/a	n/a
Themis	$n_2 Tx^{hiG} $	$ pp $	$t erm $	$t erm $	$(n_1 + n_2)( \sigma  +  \pi )$	$ cre  +  E $	$n_1 Tx^{Up} $	$n_1( B  +  rn )$	$ dr $	$n_2( Tx^{ReqG}  +  er  +  MP )$	$n_2 er $	$ pubk_{in} $

1a: Blockchain creation related messages; no indication of what messages to send. 1b: messages to send; provide only integrity and authentication.  
3a: Set of attributes. 3b: AU sends the grant transaction. 3c:  $Ed$  is encrypted data. 3d:  $L$  is a download link for data retrieval.

## VIII. DISCUSSIONS

### A. Data Sharing Among AUs

If  $au_i$  does not have what an IN requests, we ask the AUs to share encrypted data in a peer-to-peer distributed file system, such as InterPlanetary File System (IPFS) [44].  $au_i$  sends back the identity of the AU that holds the corresponding data and an permission token  $tk$  to the IN. The IN passes  $tk$  to the AU, say  $au_j$ , which will return the data.

### B. Malicious Data Providers

Since DDF gathers data in a crowdsourcing way, it is likely that some DPs are malicious and uploads falsified data. Such data are fatal to investigations as they pretend to be authentic data that cloud INs' judgement. We have two countermeasures in this case. First, we can leverage some detection mechanisms running on the DDS apps regarding image [45] and video [46]. Second, once a data forgery is detected, we can adopt conditional privacy-preserving authentication [19], [47] to reveal the identity of the data provider to revoke their login permission. They will stand as the defense forefront of data uploading.

### C. Watermarking

The watermarking technique that we improved in this work is applicable to more than just decentralized digital forensics. For example, it can be used for copyright tracking, transfer recording, and access control. First, a digital watermark embedded in a pictorial work speaks for its owner and copyright. Second, when a watermarked item is transferred among different entities and embedded with a new watermark upon each transfer, the watermarks can be considered as a proof of transfer record. Third, we can embed several watermarks of different data users into an item to claim that such an item are only accessible to these data users. For the last two scenarios, we have to preset different areas for different watermarks to avoid extraction failures.

### D. Applicability

There are many real-world use cases where the proposed DDF approach is useful to transform and enhance existing digital forensics techniques, such as Criminal Digital Forensics (CDF) and Vehicular Digital Forensics (VDF). In CDF as well as VDF, the collection of data is key to cracking a criminal case and

determining liability. Our approach transforms existing DF techniques into collecting real-time data from multiple data sources in a distributed manner. In CDF, the management of potential evidence uploaded by data providers, e.g., determining which crime investigator can access the uploaded data and which crime investigator leaks data, is extremely important to advance the investigation process and fight crimes. Our approach enhances existing DF techniques by guaranteeing that only qualified data users can access corresponding data and prevent internal adversaries from leaking valuable evidence.

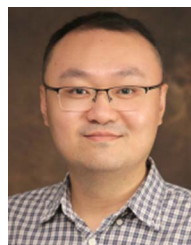
## IX. CONCLUSION

In this paper, we have proposed decentralized digital forensics based on TEE and blockchain to achieve traceable anonymity, private access control, and efficient search. To achieve the three goals, we integrate secure and robust watermarking scheme with decentralized anonymous authentication, realize fine-grained access control against malicious authorities, and facilitate efficient and secure search with a dynamically updated data structure. We formally define and prove the privacy and security. Experimental results exhibit its good practicability and efficiency.

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