An Anonymous Trust-Marking Scheme on Blockchain Systems

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Abstract—During the Coincheck incident, which recorded the largest damages in cryptocurrency history in 2018, it was demonstrated that using Mosaic token can have a certain effect. Although it seems attractive to employ tokens as countermeasures for cryptocurrency leakage, Mosaic is a specific token for the New Economy Movement (NEM) cryptocurrency and is not employed for other blockchain systems or cryptocurrencies. Moreover, although some volunteers tracked leaked NEM using Mosaic in the CoinCheck incident, it would be better to verify that the volunteers can be trusted. Simultaneously, if someone (e.g., who stole cryptocurrencies) can identify the volunteers, then that person or organization may be targets of them. In this paper, we propose an anonymous trust-marking scheme on blockchain systems that is universally applicable to any cryptocurrency. In our scheme, entities called token admitters are allowed to generate tokens adding trustworthiness or untrustworthiness to addresses. Anyone can anonymously verify whether these tokens were issued by a token admmitter. Simultaneously, only the designated auditor and no one else, including nondenominated auditors, can identify the token admitters. Our scheme is based on accountable ring signatures and commitment, and is implemented on an elliptic curve called Curve25519, and we confirm that both cryptographic tools are efficient. Moreover, we also confirm that our scheme is applicable to Bitcoin, Ethereum, and NEM.

I. INTRODUCTION

Cryptocurrencies (cryptoassets) such as Bitcoin, Ethereum, and NEM have attracted attention in various aspects, such as the large market capitalization and the use of smart contracts. Because of a cryptocurrency’s decentralized structure, there is merit in fault tolerance and anyone can check the content of transactions; thus, a certain level of transparency is guaranteed. However, cryptocurrencies have been used for crimes because of their anonymity and have become a target of cyberattacks as their value increases. Furthermore, since it seems difficult to stop suspicious transactions such as unauthorized withdrawals or exchanges before they happen, it is important to consider countermeasures after cryptocurrencies are stolen.

During the Coincheck incident, which recorded the largest damages in cryptocurrency history in 2018, some volunteers tracked leaked New Economy Movement (NEM) cryptocurrencies using Mosaic, which is a NEM-specific feature allowing a self-made token to be sent on the NEM blockchain. These volunteers sent Mosaic to addresses that received leaked NEMs from Coincheck addresses and warned the recipients that these should not be exchanged for other cryptocurrencies or legal currencies. A criminal can discard such marked addresses, so it can be seen as a cat-and-mouse game. It was not recognized that a large amount of NEM was exchanged via legally authorized exchanges. The criminal finally exchanged stolen NEM via a self-made exchange established on the dark web (hidden service) until the removal of the system on March 18, 2018. Thus, the effectiveness of tokens in preventing the spread of leaked NEMs is admitted. Because theft of cryptocurrencies has become a real risk, it seems effective to employ tokens as countermeasures for cryptocurrency leakage. However, there are issues to be solved:

• Mosaic is a specific token for NEM, and it is not employed for other blockchain systems or cryptocurrencies.
• There is no way to check whether the volunteers can be trusted.
• If someone (e.g., who stole cryptocurrencies) can identify the volunteers, then that person or organization may be targets of them.

From a functionality standpoint, it seems effective to add trustworthiness to addresses, but the Mosaic token instead adds untrustworthiness to addresses. For example, if an address is authorized by adding a token for trustworthiness, then anyone can recognize it by checking whether the token is included in the corresponding transaction.

One might think that claims, which are defined in the ERC-725/ERC-735 Ethereum Identity Standard\(^1\) could be used to add and remove tokens. When a user wants to deploy smart contracts, a claim issuer (who may or may not be the user) can add some information relative to the user’s identity, and it can be verified as a credential. However, anonymity of claim issuers is not a primary subject of the standards; thus, it cannot be directly employed for our usage. One naive solution is to

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\(^1\)See [https://erc725alliance.org/](https://erc725alliance.org/) or [https://github.com/ethereum/EIPs/issues/735](https://github.com/ethereum/EIPs/issues/735)
employ anonymous signatures such as ring signatures [34], especially linkable ring signatures [4], [25], [27], [37], [38], [40], which have been widely used to add anonymity in cryptocurrencies such as Monero [30]. This solution assumes that there are token admitters who are trusted; i.e., they are recognized as entities that can issue tokens but are not allowed further responsibilities. They generate a signature and include the signature on a transaction. In the signed message, anyone can check whether the address is authorized or unauthorized by verifying the signature. This method does not choose the underlying blockchain system. Moreover, anyone can anonymously check whether a token admmitter generates a signature. This naive solution looks promising, but an issue of anonymity arises. For example, if an address will behave maliciously using a trustworthiness token, then the trustworthiness of the corresponding token admmitter should be reduced. Moreover, if some users who have addresses deny the addition of a token for untrustworthiness, then the corresponding token admmitter needs to be traced. However, there is no way to identify the corresponding token admmitter if (linkable) ring signatures are employed. Thus, it seems effective to consider auditors, who can identify token admitters from signatures.

Another naive solution is to employ group signatures [15]. In this scenario, a group manager issues signing keys to users. A user generates a signature, and a verifier verifies the signature anonymously, i.e., checks whether the signer is a group member. If an accident happens, the group manager can identify the signer using a secret key. However, this centralized structure does not match decentralized blockchain systems. If we consider permissioned blockchain systems, then there is an additional access control layer and it may allow us to prepare such centralized organizations. However, it restricts the coverage of the system.

Our Contribution: In this paper, we propose a trust-marking scheme on blockchain systems explained as follows:

- The trust-marking scheme is universally applicable to any cryptocurrency, and works even in public blockchains.
- Token admitters can anonymously issue tokens for either trustworthiness or untrustworthiness to addresses by generating accountable ring signatures [11], [21], [23], [43].
- Token admitters designate an auditor when they issue tokens, and only the auditor can identify who issued the tokens.

As building blocks, we employ accountable ring signatures [11], [21], [23], [43], which can be seen as a generalization of ring and group signatures (See Section [11]). To our knowledge, an attempt to employ accountable ring signatures as tokens has not previously been made, although ring signatures have been widely employed in blockchain systems. By checking accountable ring signatures, anyone could anonymously check whether a token admmitter generated a signature. Moreover, because of anonymity, even if someone who stole cryptocurrencies wanted to retaliate against the corresponding token admmitter, that person or organization would not be able to identify the token admmitter. If an accident happened, only the designated auditor could identify the signer. In other words, our scheme preserves decentralized structures, because nondesignated auditors cannot break anonymity. We also consider a case in which a token admmitter revokes trustworthiness or untrustworthiness tokens. Subsequently, only the actual token admmitter can issue a trustworthiness or untrustworthiness token. The fact that two tokens were issued by the same token admmitter is revealed but still the token admmitter is anonymous.

We implemented our scheme using the Bootle et al. accountable ring signature scheme [11] and the Pedersen commitment scheme [32], employed Curve25519 [10]. To confirm whether our scheme is universally applicable to any cryptocurrency, we selected Bitcoin, Ethereum, and NEM for capturing various features.

Related Work: The word “Tokens” has been widely used in other blockchain systems. Here, for the sake of clarity and for explaining the difference from our work, we introduce these works as follows. Basically, a token is a non-sensitive surrogate value which is replaced from sensitive elements (this replacement procedure is so-called tokenization), and is employed for privacy-preserving payment system. Here, token is regarded as cryptocurrency itself. To name a few: Zerocoin [28], Zerocash [7], Confidential Assets [33], QuisQuis [16], and Zether [12].

For adding auditability (as in our scheme), Androulaki et al. [3] proposed a privacy-preserving and auditable token management system for permissioned blockchain systems such as Hyperledger Fabric [2]. The Androulaki et al. system architecture is somewhat similar to our scheme where users, issuers, and auditors are defined (in their paper a certifier and a registration authority are also defined). Briefly, users own tokens that represent some real-world assets. They wish to exchange their tokens with other users in the network. Issuers are authorized to introduce tokens (as in token admitters in our scheme). Auditors inspect transactions of users. One big difference from our work is that they did not consider anonymity of issuers. Moreover, in their system, auditors are not designated at each token generation phase where each user is assigned an auditor at registration time and that this assignment is immutable. Yuen [44] also proposed a private, authenticated and auditable consortium (i.e., partly private) blockchain. The system considers sender/recipient privacy, where the identity of a sender/recipient of a transaction is not revealed to any third party, and transaction privacy, where the content of the transaction is not revealed to any third party. In addition, auditability is introduced, where the auditor can recover the sender identity, recipient identity and/or the

2Briefly, Bitcoin adopts UTXO (unspent transaction output) while Ethereum and NEM adopt account based transaction models. Bitcoin and Ethereum adopt PoW (Proof of Work) while NEM adopts PoI (Proof of Importance). Our scheme is applicable regardless of these features.
transaction amount. That is, the audit target is different from our purpose. Küsters et al. [22] also considered accountability in permissioned blockchains. They insisted that all parties know each other, and hence, accountability incentivizes all parties to behave honestly. We would like to insist that accountability is also important in public blockchains, and we mainly consider this setting as mentioned above. Garman et al. [17] proposed a decentralized anonymous payment system in the public blockchain. The system is capable of enforcing compliance with specific transaction policies. They considered a coin tracing scheme where individual coins can be marked for tracing. Briefly, all of the information needed to trace the output coins is encrypted under the existing key for the input coin commitments, and all of this output is encrypted by authority’s public key. One big difference from our work is that they did not consider both trustworthiness and untrustworthiness.

Camenisch et al. [13] proposed a delegatable anonymous credential system. An (attribute-based) anonymous credential is a set of attributes certified to a user by an issuer. A user can prove the possession of a credential via a zero-knowledge proof system by creating a fresh token. Then, the user can select which attributes need to be included when the token is created. Because credentials are typically issued in a hierarchical manner, Camenisch et al. considered delegatability of credentials to hide information revealed from the chain of issuers. Moreover, they consider an application of the system to a permissioned blockchain. Basically, in the system users spontaneously generate tokens to prove the possession of a credential. On the other hand, in our scheme users (addresses) are forcibly evaluated and issued a token.

Zhong et al. [46] proposed a system that signs cryptocurrency transactions by linkable group signatures [29]. The system enables us to trace a payer’s identity in consortium blockchain based anonymous cryptocurrencies in case a payer misbehaves in the system. The anonymity can be retained if a user behaves honestly.

Token-based traceability systems also have been considered. For example, Westerkamp et al. [42] proposed a blockchain-based supply chain traceability system using smart contracts. A non-fungible token (NFT), which is an identifiable token reflecting digital goods or physical goods, is standardized in ERC-721 [3]. It corresponds to a batch of physical goods. Watanabe et al. [41] proposed a token-based traceability system based on a directed acyclic graph (DAG). They insisted that NFT is expected to be able to represent complicated operations in traceability systems, everyone needs to easily confirm the history of the circulation of tokens related to each product. Their system allows us to efficiently retrieval of past histories. In these use cases, tokens are basically used for tracing a product’s provenance. On the other hand, our scheme evaluates (un)trustworthiness of addresses themselves.

Ometh et al. [31] proposed a system that adds (un)trustworthiness to addresses where a special address (as in a token admiter of our scheme) sends a few Bitcoin to them as a token. As differences from our work, they considered Bitcoin only and did not consider anonymity of the token admiter.

II. Preliminaries

Accountable Ring Signatures: In blockchain systems, a transaction is signed by a secret key connected with an address. According to applications, anonymous signatures (as the underlying signature scheme) and a decentralized structure are required. Thus, ring signatures [34] rather than group signatures are employed, especially in the cryptocurrency context. The ring signatures enabled a signer to sign anonymously. Each user generated a public verification key and a secret signing key, selected a ring that is a set of verification keys, and generated a signature on behalf of the ring. A verifier could verify whether the signer was a member of the ring. Unlike pseudonyms, ring signatures provide unlinkability (i.e., even if the same signer generated two signatures, nobody would know those signatures were generated by the same signer) and unforgeability (defined as in digital signatures) (see [8] for the detailed security definition). To prevent double spending in privacy-preserving cryptocurrencies, linkable ring signatures [4], [25], [27], [37], [38], [40], providing weak anonymity compared with that of ring signatures, were employed, e.g., in CryptoNote [39] (see [38] for the detailed security definition of (one-time) linkable ring signatures). A ring confidential transaction (RingCT) [30], [37], [45] employed a similar cryptographic technique.

Although strong anonymity (meaning no entity can identify the actual signer) is an attractive and effective security in a privacy-preserving context, it may cause unexpected incidents (e.g., signers may behave maliciously because they will not be identified). In group signatures, a group manager has the power to track a signer, but this ability is too strong, and the group manager can become a big brother. In particular, its centralized structure does not match the structure of blockchain systems.

Xu and Yung [43] proposed accountable ring signatures as a generalization of ring signatures and group signatures. As in ring signatures, each user generated a public verification key and a secret signing key. Openers generated own public key and secret opening key. A user made a ring (a set of verification keys), designated an opener public key, and generated a signature using his or her own signing key. A verifier verified whether a signer was contained in the ring, and only the designated opener could identify the actual signer. Later, Bootle et al. formalized the security definitions. In particular, they considered signature hijacking attacks [35] and provided the function that allowed the opening result to be publically verified [6]. Bootle et al. also provided a concrete accountable ring signature scheme with a logarithmic signature size of the number of ring members. The Bootle et al. scheme is based on the Camenisch-Stdalger signature scheme [14] and the Groth-Kohlweiss one-out-of-many proofs of knowledge [19].
It was secure under the decisional Diffie-Hellman (DDH) assumption (in prime-order groups), which is widely recognized as a standard cryptographic assumption. Moreover, assuming the hardness of the DDH problem allows us to employ Curve25519 \(^{10}\) to implement the scheme\(^{11}\). In contrast, Lai et al. \(^{23}\) showed a relationship between sanitizable signatures and accountable ring signatures and proposed an accountable ring signature scheme with a constant signature size. One downside of the scheme is that it employed composite-order bilinear groups. As an alternative, Kumawat et al. \(^{21}\) proposed another accountable ring signature scheme from indistinguishability obfuscation \((\text{iO})\) \(^{2}\) which is recognized as one of the extremely strong cryptographic tools. Thus, we mainly followed the Bootle et al. scheme in this paper.

**Definition 1 (Syntax of Accountable Ring Signatures \(^{11}\))**:
- **Setup\((1^\lambda)\)**: The setup algorithm takes as input a security parameter \(\lambda \in \mathbb{N}\) and outputs a common parameter pp.
- **OKGen\((\text{pp})\)**: The opener key generation algorithm takes as input pp, and outputs an opener public key opk and a secret key osk.
- **UKGen\((\text{pp})\)**: The user key generation algorithm takes as input pp, and outputs a user public key pk and a secret key sk.
- **Sign\((\text{opk}, M, R, \text{sk})\)**: The signing algorithm takes as input opk, a message to be signed \(M\), a ring \(R\), and sk and outputs a ring signature \(\sigma\). We assume that the corresponding pk is contained in \(R\).
- **Verify\((\text{opk}, M, R, \sigma)\)**: The verification algorithm takes as inputs opk, \(M\), \(R\), and \(\sigma\) and outputs 1 (accept) or 0 (reject).
- **Open\((M, R, \sigma, \text{osk})\)**: The opening algorithm takes as inputs \(M\), \(R\), \(\sigma\), and osk and outputs pk of the signer and its proof \(\pi\) or \(\bot\) otherwise.
- **Judge\((\text{opk}, M, R, \sigma, \text{pk}, \pi)\)**: The judge algorithm takes as inputs opk, \(M\), \(R\), \(\sigma\), pk, \(\pi\), and outputs 1 (meaning that \(\sigma\) is generated by sk corresponding to pk) or 0 otherwise. If \(\sigma\) is not valid or \(\text{pk} \not\in R\), then output 0.

Correctness is defined as a standard manner such that, if all keys are honestly generated and a signature is honestly generated using them, then the verification of the signature always outputs 1. Beside correctness, Bootle et al. defined four security notions: full unforgeability, full anonymity, traceability, and tracing soundness. Full unforgeability ensures that an adversary who may corrupt all-but-one users and openers cannot produce a forged signature, proof that the signature is valid, and proof with a verification key that the noncorrupted user is accepted by the Judge algorithm. Full anonymity ensures that an adversary who may have all signing keys (and secret keys of nondesignated openers, as discussed later) cannot distinguish whether two signatures are generated by the same signing key.\(^{5}\) Traceability ensures that designated openers can always identify the actual signer and can produce valid proof for their identification. Tracing soundness ensures that a signature cannot trace two different signers. See \(^{11}\) for the formal security definitions.

**Remark**: The syntax and security definitions of accountable ring signatures given in Bootle et al. \(^{11}\) considered only one opener. However, because of our usage, e.g., a signer designates an opener, it is natural to consider plural openers.\(^{6}\) According to this modification, we also need to modify the security definition in which nobody except the designated opener can break anonymity; i.e., an adversary of anonymity is allowed to obtain secret keys of nondesignated openers.

This modification does not affect security. Let \(\ell\) openers be defined. Then, the adversary is allowed to corrupt (i.e., is allowed to know the secret keys of) at most \(\ell - 1\) openers. In the security proof of anonymity, just guessing the noncorrupted opener is enough, and its probability is at least \(1/\ell\).

The Bootle et al. scheme is secure in the common reference model (i.e., a common parameter pp needs to be honestly generated). We discuss how to generate pp in our scheme later.

**Commitment**: A commitment scheme Com consists of three algorithms. The ComSetup algorithm takes as input a security parameter \(\lambda \in \mathbb{N}\) and outputs a common reference string crs. The Commit algorithm takes as inputs crs and a message \(M\) to be committed and outputs a commitment \(C\) and a decommit dec. The ComOpen algorithm takes as inputs crs, \(C, M\), and dec and outputs 1 (meaning that \(C\) is a commitment of \(M\)) or 0 otherwise. A commitment scheme provides both hiding (no information of \(M\) is revealed from \(C\)) and binding (\(C\) is not opened to two \((M, \text{dec}) \neq (M', \text{dec}')\)) properties. In our implementation, we employ the Pedersen commitment scheme \(^{32}\) which provides computational binding (under the discrete logarithm (DL) assumption) and perfect hiding. We remark that crs needs to be generated honestly. We discuss how to generate crs in our scheme later.

**Common Reference String**: In the Bootle et al. accountable ring signature scheme, \(h_1, \ldots, h_n \in \mathbb{G}\), where \(\mathbb{G}\) is a group of prime order \(p\), and a public key of the ElGamal encryption scheme \(ek = g^\tau\), where \(\tau \in \mathbb{Z}_p\), need to be honestly generated. That is, nobody knows \(\log_g h_1, \ldots, \log_g h_n\), and \(\tau\). If there is no central authority, i.e., in permissionless blockchains, we need to consider how to generate them. In the Pedersen scheme, the ComSetup algorithm outputs crs = \((g, h)\) where \(g, h \in \mathbb{G}\) are generators. For \(M \in \mathbb{Z}_p\), the Commit algorithm randomly chooses dec \(\in \mathbb{Z}_p\) and

\(^{5}\)As a similar primitive, Zhang et al. \(^{47}\) proposed revocable and linkable ring signatures. One big difference from accountable ring signatures is linkability, where anyone can link whether two signatures are generated by the same signing key.

\(^{6}\)As a similar primitive, multi-opener group signatures have been proposed \(^{9},^{18},^{26}\) where plural openers identify the signer as a threshold manner.
computes $C = g^M h^{\text{dec}}$. The ComOpen algorithm outputs 1 if $C = g^M h^{\text{dec}}$ holds and 0 otherwise. Here, crs needs to be generated honestly, i.e., nobody knows $\log_g h$.

We assume that the generator $g$ is publicly specified and we employed the generator of Curve25519 defined by the $x$-coordinate is 9 [24]. We employed the multi-CRS setting [20]. We assumed that a token admitter $i$ chose $\tau_i \in \mathbb{Z}_p$, computed $ek_i = g^{\tau_i}$, and broadcast $ek_i$ to other token admitters. Simultaneously, the token admitter $i$ proved the knowledge of $\tau_i$ via a zero-knowledge proof system. Finally, $ek$ is defined as $ek = \sum ek_i$. We also assumed that all token admitters did not collude. $h_1, \ldots, h_n$ and $h$ also could be generated similarly.

III. PROPOSED ANONYMOUS TRUST-MARKING SCHEME

In this section, we give our anonymous trust-marking scheme. As the first attempt, we simply added an audit functionality to CryptoNote [39], which provides anonymity in Monero. CryptoNote originally provided an audit functionality in which secret values were revealed outside the blockchain. However, we could not control who would audit it. Thus, we tried to change (linkable) ring signatures on CryptoNote to accountable ring signatures. Then, a signer who signed an address could designate an auditor and include the auditor public key on the signed message. Anyone who signed an address could designate an auditor and in-

Next, we define the message format to be signed as follows.
- Address of the target user.
- A flag indicating either trustworthiness or untrustworthiness.
- Public key of the designated auditor.
- Expiry time.
- Either a commitment or both the corresponding de-
- commitment and the hash value of the corresponding transaction (which are explained later).
- Any message, e.g., “This user appropriately sent transac-
- tions.” or “This user received cryptocurrencies *** that
- were leaked on CCYYMMDD from ***.”

We assume that a common parameter pp and a common reference string crs have been honestly generated (as mentioned in the Appendix). At the initial step, each token admitter runs $(\text{pk}_i, \text{sk}_i) \leftarrow \text{UKGen}(\text{pp})$. We denote $(\text{pk}_i, \text{sk}_i)$ as the $i$-th token admitter. Each auditor runs $(\text{opk}_j, \text{osk}_j) \leftarrow \text{OKGen}(\text{pp})$. We denote $(\text{opk}_j, \text{osk}_j)$ as the $j$-th auditor. Moreover, each token submitter generates an address for sending transactions.

We show the flow of our scheme in Fig. 1. The case in which a token admitter issues a token is as follows:

Token Admitter $i$:
1) Randomly chooses $\tau_{\text{link}}$ and runs $(C, \text{dec}) \leftarrow \text{Commit}(\text{crs}, \tau_{\text{link}})$.
2) Defines ring $R$ where $\text{pk}_i \in R$.
3) Designates an auditor $j$ and let $\text{opk}_j$ be the public key.
4) According to the message format, prepares a message $M$ to be signed. $M$ contains $C$ and $\text{opk}_j$.
5) Runs $\sigma \leftarrow \text{Sign}(\text{opk}_j, M, R, \text{sk}_i)$ and sends $(M, \sigma)$ to a token submitter.

The case in which a token admmitter revokes a token is as follows. Assume that the token admmitter has issued a token $\sigma'$ on $M$ on behalf of $R$, that $M$ contains a commitment $C$, and the token admmitter knows the corresponding $(\tau_{\text{link}}, \text{dec})$. In other word, no token admmitter can revoke a token unless the token was issued by myself.

Token Admitter $i$:
1) According to the message format, prepares a message $M$ to be signed. $M$ contains $(\tau_{\text{link}}, \text{dec})$ and the hash value of the transaction that $\sigma'$ is embedded.
2) Runs $\sigma \leftarrow \text{Sign}(\text{opk}_j, M, R, \text{sk}_i)$ and sends $(M, \sigma)$ to a token submitter.
Token Admitters

Generate a ring signature on a message:
- An address of the target user.
- A flag indicating either trustworthiness or untrustworthiness.
- A public key of the designated auditor.
- A commitment (or the corresponding decommitment).
- e.t.c.

Token Submitters

Blockchain

A token is embedded on a transaction.

Users

Generate a ring signature σ on a message:
- An address of the target user.
- A flag indicating either trustworthiness or untrustworthiness.
- A public key of the designated auditor.
- A commitment (or the corresponding decommitment).
- e.t.c.

Token Admitters

The designated auditor can identify the corresponding token admitter.

Designate an auditor

Fig. 1. Flow of our scheme

Next, the procedure for a token submitter is as follows:

Token Submitter:
1) If \( R \) contains unknown public key, then abort.
2) If \( \text{opk}_j \) is not a public key of auditors, then abort.
3) If the expiry time contained in \( M \) has passed, then abort.
4) If \( \text{Verify}(\text{opk}_j, M, R, \sigma) = 0 \), then abort.
5) Otherwise, embed \((M, \sigma)\) to the corresponding transaction and send the transaction.

Next, the procedure for a token verifier is as follows:

Token Verifier:
1) If the expiry time contained in \( M \) has passed, then abort.
2) Check the flag (for a trustworthiness token or an untrustworthiness token).
3) If \( M \) contains \( C \) and \( \text{Verify}(\text{opk}_j, M, R, \sigma) = 1 \), then consider the token embedded to the transaction to be valid.
4) If \( M \) contains \( (r_{\text{link}}, \text{dec}) \), then find the corresponding transaction that contains the corresponding \( C \) (via the hash value). If \( \text{Verify}(\text{opk}_j, M, R, \sigma) = 1 \) and \( \text{ComOpen}(\text{crs}, C, r_{\text{link}}, \text{dec}) = 1 \), then consider the token embedded to the transaction to be revoked.

Security Analysis: Due to the anonymity of accountable ring signatures, token admitters can issue tokens to addresses anonymously, and anyone can verify it. Only the designated opener can identify the token admitter from the signature. The designated opener can produce a proof of tracing, and due to the tracing soundness, a signature cannot trace to two different signers. In order to maintain anonymity of token admitters, we assume that an adversary who would like to identify the token admitter does not collude with the designated auditor and the token submitter. We emphasize that auditors and token submitters are not fully trusted, and are modeled as semi-trusted entities that follow the protocol descriptions. Due to the unforgeability, the address specified by a token admitter cannot be modified even by the corresponding token submitter because a target address is contained to a signed message. Moreover, token admitters have no way to produce untraceable signatures due to the traceability.

If two tokens are generated by the same token admitter, then they are linked via \( C \) and \( (r_{\text{link}}, \text{dec}) \). Because of the binding property, other token admitters cannot prepare \((r'_{\text{link}}, \text{dec'})\) where \( (r'_{\text{link}}, \text{dec'}) \neq (r_{\text{link}}, \text{dec}) \) that \( \text{ComOpen}(\text{crs}, C, r'_{\text{link}}, \text{dec'}) = 1 \) holds. Because of the hiding property, adding \( C \) as part of the message does not affect anonymity. We remark that token admitters can generate nonlinked tokens by randomly choosing \( C \). However, the designated auditor can identify token admitters even if they generate such nonlinked tokens. For example, a token verifier can ask the designated auditor who the actual token admitter is when the corresponding transaction is not found in the step 4. That is, token admitters have no merit to generate such
tokens, and thus we assume that a token verifier can always find the corresponding transaction if tokens are revoked.

IV. IMPLEMENTATION

In this section, we show our implementation results, in which the Bootle et al. accountable ring signature scheme [11] and the Pedersen commitment scheme [12]. We also employed Curve25519 [10] and checked that our scheme is applicable to Bitcoin, Ethereum, and NEM. We used MacBook Pro (2.3 GHz Intel Core i5, 16 GB 2133 MHz LPDDR3) and specified the ring size $N = 16$. According to this setting, we set $n = 4$ and $m = 2$ as defined in [11], where $N = n^m$. Then, the signature size is as follows: $(\log_2 N + 12)|G| + \frac{1}{3}(3\log_2 N + 12)|\mathbb{Z}_p| \approx 1.4kB$. In this setting, the running times of the Sign and Verify algorithms are given in Table I. We also show the running times of the Commit/ComOpen algorithms in Table II. From these implementation results, we can say that both cryptographic tools are reasonable in blockchain systems in terms of efficiency.

Next, we confirmed that our scheme is applicable in terms of both computational costs and remittance charge for Bitcoin, Ethereum, and NEM. We estimated them using the exchange rate on April 6, 2020. We implemented two cases:

1) We embedded a ring signature on the transaction directly. Then, one can check trustworthiness or untrustworthiness of a token unless the blockchain system is down. Owing to high availability of blockchain systems, it can be a merit of this case. On the other hand, we needed to embed 1612 bytes in Bitcoin, 1619 bytes in Ethereum, 1616 bytes in NEM, respectively, for a transaction. Because the embeddable data size is limited, it is a demerit of this case.

2) We embedded a hash value of a ring signature (and its messages) and a URL of an outside storage (e.g., Google Drive, Dropbox, and so on) or path of “hash-of-object” of a decentralized storage (e.g., InterPlanetary File System (IPFS) [3]), that preserves the ring signature. If SHA256 is employed as the hash function, then we can drastically reduce the data size (32 bytes) and it can solve the demerit of the first case. However, we needed to additionally require to confirm whether its hash value is the same as that of the embedded one after verifying the ring signature. Moreover, we need to assume that the outside storage is also available, and does not collude with other entities. Here, we simply assumed that the outside storage is semi-honest, i.e., it follows the protocol description.

**Bitcoin:** In Bitcoin, Bitcoin script is used to describe transactions. To embed data to a transaction, we can use OP_RETURN. Because it embeds 80 bytes of data at once, we needed to use 21 transactions for case 1 and 2 transactions for case 2 when Google Drive URL (66 bytes) or IPFS path (48 Bytes) is used. This result shows that we needed to consider some meta-information that connect two (or potentially more) transactions. One easy way to do this in case 2 is to employ the transaction identity (txid) which is a 32 byte value. We embed the URL to transaction 1, and embed the hash value of ring signatures and the txid of transaction 1 to transaction 2. If one would like to connect two transactions, it finds transaction 1 via the txid in transaction 2, downloads a ring signature and the corresponding message from either the Google Drive URL or the path of IPFS in transaction 1, checks whether the signature is valid, and also checks whether its hash value is the same as the hash value contained in transaction 2. Basically, this simple way works in case 1. Regarding remittance charges, it is changed according to the data size or the conditions of blockchains, and so on. Moreover, the transaction may not be confirmed depending on remittance charges. As a reference, we needed to spend 0.002 BTC (€13.74) if the transaction is confirmed within 5 min. Although our scheme is applicable to Bitcoin in terms of functionality point of view, there is a room for argument on such high remittance charges.

**Ethereum:** In Ethereum, we embedded a token to data space using the Ethereum wallet called MetaMask. Because we can use high availability of blockchain systems, and 1 transaction is enough for both cases, case 1 is better than case 2 for Ethereum. We needed to pay 70,332 gas for case 1. When we set a gas price of 2 gwei, it was 0.000093776 ETH (€0.015). This result showed that the remittance fee was reasonable; thus, we concluded that our scheme is applicable to Ethereum.

**NEM:** In NEM, the transaction/prepare-announce API is used for sending a transaction. To embed data to a transaction, we can use the message space. Because it embeds 1024 bytes of data at once, we needed to use 2 transactions for case 1 and 1 transaction for case 2. We can employ txid to connect two transactions as in the case 2 of Bitcoin. In NEM version 1, the remittance charge is estimated by $(\text{fee}(\text{XEM})) = (\text{MessageLength}/32 + 1) * 0.05(\text{XEM})$. We needed 2.80 XEM (€0.10) in case 1, and in case 2 we needed 0.25 XEM (€0.009) when Google Drive URL (66 bytes) is used and 0.20 XEM (€0.007) when IPFS path (48 bytes) is used, respectively. Because we do not have to connect two transactions, case 2 seems better than case 1 for NEM. This

| Algorithm         | Time (ms) |
|-------------------|-----------|
| Sign              | 13.7      |
| Verify            | 11.0      |

| Algorithm         | Time (ms) |
|-------------------|-----------|
| Commit/ComOpen    | 0.0072    |

We consider [36], which fixes the ring size to 11 in general.

See https://ipfs.io.
results showed that the remittance fee was reasonable; thus, we concluded that our scheme is applicable to NEM.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed an anonymous trust-marking scheme on blockchain systems based on accountable ring signatures and commitment, and confirmed that our scheme is applicable to Bitcoin, Ethereum and NEM considering both computational costs and remittance charges.

Since our system adds/revokes (un)trustworthiness to users (addresses), we further need to consider how to evaluate (un)trustworthiness of users (addresses) outside of our system. As a simple way, the (un)trustworthiness of users (addresses) can be assumed to be judged by external organizations such as an investigative organization, and is shared to token admitters. We leave considering such an evaluation system run outside of our anonymous trust-marking scheme as a future work of this paper. We simply assumed that if untrustworthiness is added to an address, then nobody makes a deal to the address. However, as a next step, it needs to more concretely consider how can token verifiers utilize such tokens during or after a cyber incident, and similiary need to more concretely consider how to utilize trustworthiness token. Considering a malicious outside storage are also left as future works.

Acknowledgment: This work was supported by JSPS KAKENHI Grant Number JP19H04107.

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