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CoinLayering: An Efficient Coin Mixing Scheme for Large Scale Bitcoin Transactions

Ning Lu*†, Yuan Chang*, Wenbo Shi*, and Kim-Kwang Raymond Choo‡, *Senior Member, IEEE*
*College of Computer Science and Engineering, Northeastern University, Shenyang, China
†School of Computer Science and Technology, Xidian University, Xi'an,China
§Department of Information Systems and Cyber Security, Department of Electrical and Computer Engineering, and Department of Computer Science, The University of Texas at San Antonio, San Antonio, TX 78249, USA

Abstract—Coin mixing can be used to preserve identity privacy of Bitcoin owners, by engaging a set of middlepersons (i.e., Mix) to temporarily hold the transacting Bitcoins and remove the linkage between the transacting parties. However, existing schemes are generally not scalable due to limitations associated with the anonymity set, and self-credibility. In this paper, we propose an efficient coin mixing scheme (hereafter referred to as CoinLayering). To achieve strong anonymity, CoinLayering randomly selects two sets of middlepersons to respectively execute Bitcoin holding and Bitcoin trading. The seller can also select lower-loaded sets of middlepersons in the shortest time possible. We also design two coin mixing protocols, CoinLayering-PA and CoinLayering-PB, to mitigate the risk due to misbehaving middlepersons and $Supervisor$. We then mathematically prove that CoinLayering achieves both strong anonymity and self-credibility, and evaluate its performance to demonstrate its scalability.

Index Terms—Blockchain, Bitcoin, Identity privacy, Coin mixing, Large scale Bitcoin transactions

1 Introduction

The interest in cryptocurrency, and particular Bitcoin, is partly evidenced by the increasing number of such currencies and the trading volume [1]. For example, as of Dec 5, 2020, there are reportedly 7,863 cryptocurrencies, in 33,925 markets, with a market capitalization of USD 571,589,849,765 (and Bitcoin dominates approximately 62.46% of the market)[1]. In other words, the volume of Bitcoin transactions is significant. Similar to other consumer technologies, there are underlying security and privacy challenges in Bitcoin and other cryptocurrencies [2], [3]. For example, since all Bitcoin transactions can be publicly audited in the blockchain, one can perform an analysis of the distributed ledger, using the heuristic cluster to analyze transaction data, and infer the true identities of transaction parties. The exposure of the user's identity can lead to other attacks, such as stealing of the user's Bitcoins [4], [5]. One high profile incident occurs in July 2017, where the leakage of nearly 31800 users' information on Bithumb (e.g., email address and mobile phone number) facilitated the exfiltration of billions of South Korean won, the official currency of South Korea [6]. This necessitates the protection of identity privacy of transacting parties in the Bitcoin marketplace.

Manipulating the ownership of Bitcoins to obfuscate the interlinkage of transacting parties (also known as coin mixing) is one approach used to protect user identity privacy. Specifically, in such an approach, coin mixing usually allows Bitcoin sellers to engage a set of middlepersons to temporarily hold on to their coins and further blind the transaction. As shown in Fig. 1, all sellers send their Bitcoins and buyers' identity information to the middlepersons and entrust them to complete the transactions. Consequently, the sellers and buyers are not linkable to each other.

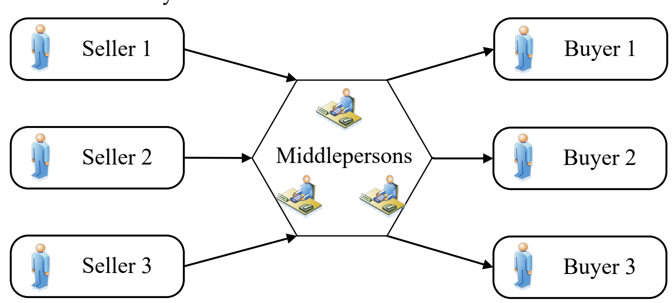

Fig. 1. Coin mixing: A brief overview

There are, however, several challenges in the implementation of coin mixing, particularly if we also take into consideration the constantly evolving threat landscape and the scale of Bitcoin trading.

1) *Strong anonymity*. In an attempt to violate the identity privacy of transacting parties, an adversary can guess the buyer-seller relationship to bypass the coin mixing system. This is an attack that affects most of the existing schemes. Normally, the increase in the mixing scale can improve the difficulty of guessing the relationship and thus effectively defend against such an attack. Here mixing scale is also regarded as the anonymous set, which is mainly associated with the maximum number of simultaneous acceptable anonymous transactions during the interval that the system completes a coin mixing. Apparently, the larger the anonymous set, the stronger the anonymity could achieve. For example,

Both Wenbo Shi and Kim-Kwang Raymond Choo are the corresponding authors (e-mail: shiwb@neuq.edu.cn, raymond.choo@fulbrightmail.org)

1. https://coinmarketcap.com/ (last accessed Dec 5, 2020).

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TABLE 1
A comparative summary of CoinLayering and other existing schemes

Functions		[7], [8]	[9]	[10]	[11], [12], [13]	[14]	[15], [16]	CoinLayering
Strong anonymity		×	×	×	×	√	×	√
Scalability	Low execution time	√	√	√	√	×	√	√
	Less bandwidth overheads	×	×	×	×	√	×	√
Self credibility	Anti-denial service	×	×	√	√	√	√	√
	Preventing collusion	√	×	√	√	√	×	√
	Preventing theft	√	√	√	√	√	×	√

merging multiple transactions into one transaction can obscure the seller-buyer relationships to some extent, but its effectiveness is subjected to the constraints of Bitcoin's maximum transaction size (e.g., 100KB). In other words, existing schemes generally can only take as input few transactions and this reduces the difficulty of correctly guessing the mapping between both buyer and seller [7], [8], [9], [10]. Alternatively, we can choose to direct all transactions to an explicit middleperson, say Mix, in order to efficiently separate the buyer from the seller. However, the compromise of Mix would make it easier to guess buyer-seller relationships in not one, but many transactions [11], [12], [13]. Therefore, how to achieve enhanced anonymity to against such an adversary is a challenge, and this is the one we seek to address.

2) *High scalability*. A practical coin mixing scheme needs to be able to scale up (significantly) when needed, and it does not appear to be the case in existing schemes. For example, randomly selecting middlepersons to perform mixing tasks can reduce the risk of colluding peers, but it comes at the cost of execution efficiency and consequently scalability [14]. In the case of a significantly large number of transactions, the schemes in [7], [8] can only take a transaction and serially execute the mixing tasks. Such a design has time and performance implications. Confined to the limited processing capacity in terms of bandwidth and computation resources, the middleperson in the schemes of [12], [13] becomes a performance bottleneck, which can also lead to denial of service (DoS). Therefore, CoinLayering is designed to achieve high scalability.
3) *Self credibility*. Coin mixing allows the middleperson to take control of the users' Bitcoins, which in itself is a risk. For example, to improve efficiency, existing schemes such as those in [15], [16] introduced a third-party to act as the middleperson. However, this requires blind trust in this middleperson to be doing the right thing (e.g. not to steal the user's Bitcoins, not to collude with an adversary and/or leak information about the transaction) [12], [13]. Therefore, CoinLayering includes a mechanism to penalize misbehaving middlepersons, and consequently, achieve self-credibility.

Specifically, in our proposed CoinLayering (see also Table 1), we introduce a $User - Mix - Supervisor$ based system model, in which the $Supervisor$ is authorized by the government (e.g. a central bank, banking regulator, or financial intelligence unit), and responsible for the middlepersons' ($Mixes$) task assignments. We assume Mix to be some organization (e.g. a financial institution), which profits by hosting the sellers' Bitcoins and trading them with the buyers. To achieve strong anonymity, and motivated by the observation that the leakage of seller-buyer relationship can potentially occur during the holding and trading actions, these actions are delegated to two different $Mixes$, and the $User$ can randomly select both $Mixes$ and utilize different identities interact with them, which secures the transaction's privacy and further facilitates the growth of anonymous set. Also, to achieve high scalability, we design an efficient $Mixes$ selection algorithm, which can determine the $Mixes$ that meet the $User$'s requirements (e.g., privacy and efficiency) in the shortest time possible. We also consider that in a real-world deployment, either the Mix or the $Supervisor$ may attempt to steal the User's Bitcoins. Thus, to be able to penalize a misbehaving Mix, we design a coin mixing protocol under a semi-trusted Mix (hereafter referred to as **CoinLayering-PA**), which uses group signature to disclose the identities of misbehaving $Mixes$ to facilitate subsequent penalties. To penalize a misbehaving $Supervisor$, we design a coin mixing protocol under a semi-trusted $MixSupervisor$ (hereafter referred to as **CoinLayering-PB**), which employs the security threshold signature to replace the supervisor and make up the cost difference.

In the next section, we will introduce relevant background materials and the related literature. In Sections 3 and 4, we will give an overview of CoinLayering and the secure coin mixing protocol, respectively. Then, we will present our security and performance evaluations in Sections 5 and 6. The last section concludes this paper.

2 Relevant Background and Literature

2.1 Background

In a typical coin mixing scheme, there exists a middleperson set M, a seller s and a buyer b. The coin mixing procedure $F(s, b)$ can be formalized as follows:

$$F(s,b) = f_1(s,M) \bullet f_2(M,b), \tag{1}$$

where $f_1(s, M)$ is used to remove the link between the seller and transaction Bitcoins. This compounds the challenge of a middleperson in inferring the origin of these Bitcoins, and $f_2(M, b)$ is used to ensure accurate delivery to the right buyers.

A practical coin mixing scheme should satisfy the following requirements, even when dealing with large-scale Bitcoin transactions:

- Strong anonymity. To improve the difficulty of guessing, the anonymity set should be as large as practical.
- DoS resilience. Under normal circumstances, the middlepersons would be available to provide mixing

services to users, failing which the middlepersons must be held accountable.
- Low execution time. The execution time should be minimized.
- Minimal bandwidth overhead. To avoid service degradation due to network congestion, the bandwidth overhead should be as minimal.
- Preventing collusion. In the event that middleperson collude, either among themselves or an external adversary, to disclose the seller-buyer relationship, there must be a mechanism to identify and penalize these misbehaving middlepersons.
- Preventing theft. The middlepersons cannot steal the users' Bitcoins.

2.2 Related Work

There have been attempts to design anonymous cryptocurrencies, such as Zerocash [17] and Monero [18]. Although such anonymous cryptocurrencies are promising, they are not as widely adopted as Bitcoin. Hence, in this paper we will only focus on coin mixing that can be deployed in Bitcoin (or other similar cryptocurrency). According to the system structure, existing Bitcoin mixing schemes are either completely centralized or completely decentralized.

Completely decentralized based schemes. Maxwell $et.al$ [9] proposed a coin mixing scheme (Coinjoin), in which a large number of peer nodes in the blockchain are engaged as middlepersons. To remove the link between the seller and the buyer, a middleperson is required to combine multiple transactions into one transaction. However, the middleperson may be able to infer relevant transaction information and collude with each other during the node negotiation process. Hence, Ruffing $et.al$ [7] proposed CoinShuffle, which shuffles the output address. Such an approach prevents the middleperson from learning information about the buyer associated with the transaction. To reduce the number of communication rounds, they proposed CoinShuffle++ [8]. To ensure the resilience of the system in the event of attacks or node failure, Ziegeldorf $et.al$ [19] proposed CoinParty. The latter uses both secure multiparty computing protocol and threshold signature technology to improve robustness. However, it requires the middleperson to be online all the time, and it is vulnerable to DoS attacks. Moreover, subject to the constraints of Bitcoin's maximum transaction size, it only allows one to input few transactions. In other words, the anonymous set is small. To overcome these limitations, Maxwell $et.al$ [14] proposed Xim, which allows the seller to randomly and anonymously select middleperson so as to conceal the real task execution position. Such an approach increases the difficulty of guessing the mapping between buyer and seller, and is resistant to DoS attacks. However, it needs take several hours to complete a coin mixing task, and clearly is not scalable.

Completely centralized based schemes. Bonneau $et.al$ [15] proposed the centralized MixCoin scheme, in which all transactions are handled by a middleperson (Mix) in order to separate the buyer from the transaction Bitcoins. While it can prevent the Mix from stealing the User's Bitcoins, it does not prevent the Mix from leaking transaction information. Thus, Valenta $et.al$ [16] used blind signature to remove the relationship between the buyer and the transaction. However, in their approach, the Mix can steal the User's Bitcoins. Inspired by eCash, Heilman $et.al$ [11], [12] designed an anonymous cryptocurrency (TumbleBit), which is compatible with Bitcoin. TumbleBit uses both blind signatures and smart contracts to ensure security during transactions between Users and $Mixes$. The Mix in TumbleBit uses multi-party secure computing's cut-and-choose method to remove the link between the seller and the Mix. Ferretti $et.al$ [20] improved TumbleBit, in order to be used for anonymous payments on private chains. In a separate work, Liu $et.al$ [13] respectively adopted group transaction to reduce the possibility of Bitcoins stolen by $Mixes$ and ring signature to accurately deliver the transaction to the buyer. However, the exposure of Mix will ease the correct guessing of the buyer-seller relationships. In addition, for large scale transactions, they are also vulnerable to DoS attacks due to the performance bottleneck of Mix.

Unlike the above discussed approaches, our proposed CoinLayering adopts the $User - Mix - Supervisor$ based system model. In the model, the $Supervisor$ (a central node) is only responsible for lightweight task assignment and regulation, and thus removes the risk of being a performance bottleneck. Also, $Mixes$ are randomly selected to implement coin mixing so as to improve anonymity.

TABLE 2
A summart of notations

Notation	Description
Mix	The mixing server
$Supervisor$	The mixing server's supervisor
BB	bulletin boards
(x_i, y_i)	The private/public key pair of Mix_i, $y_i = g^{x_i}$
ID_i	Mix_i's identity
E_i	Mix_i's escrow address
K_i	Mix_i's private address
E	$Supervisor$'s total escrow address
p_i	Mix_i's modulus
$\vec{A}_i^k$	The attribute score vector of Mix
$\vec{w}$	The user-defined query preference weight
DA	The dominance graph first-level data
CL	The ordered candidate table CL
RS	The result table RS
k_1, k_2	The ordered candidate and the result table's length
h	The highest total score
T_1, T_2, T_3, T_4	Four time limits for the mixing phase
I, O	Input address I, output address O
V_i	Mix's commitment to $Users$
W	An escrow voucher from Mix
$nonce_i$	The random number to prevent replay attacks
f_i	The Mix's mixing fees
b	Blind factor for blinding messages
U, U^*	$User$'s two identities
tx_i	Bitcoin transactions
b_i	Lagrange interpolation
T	Key update algorithm time slice
ρ	The queuing intensity
LQ	The average queue length
L_i	Mix_i's current queue length
BC	The total value of the current transaction

3 Our Proposed CoinLayering

In this section, we present the system model and the respective system components and features, the $Mixes$ selection approach to guarantee execution efficiency, and two potential threats faced by CoinLayering. Table 2 summarizes the notations used in this paper.

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3.1 System model

As is previously discussed, to increase the difficulty of guessing the seller-buyer relationships and further achieve the strong anonymity in large scale Bitcoin transactions, CoinLayering allows for the random selection of $Mixes$ and separation of holding and trading action assignment to the different $Mixes$. Also, to achieve scalability, CoinLayering allows $User$ to select multiple available $Mixes$ in the shortest time possible. Specifically, we introduce a $User - Mix - Supervisor$ based coin mixing scheme. It requires all $Mixes$ to compete for the coin mixing task. $Supervisor$ is tasked with $Mixes$ assignments and regulation, which is responsible for recommending the most appropriate k candidate $Mixes$ that are able to satisfy the $User$'s requirements. Then, $User$ selects two lightly loaded $Mixes$ as the ultimate performers in a random fashion. Moreover, to minimize communication overhead, we introduce a $Bulletin\ Board$ to broadcast relevant information. The system model in CoinLayering is represented in Fig. 2.

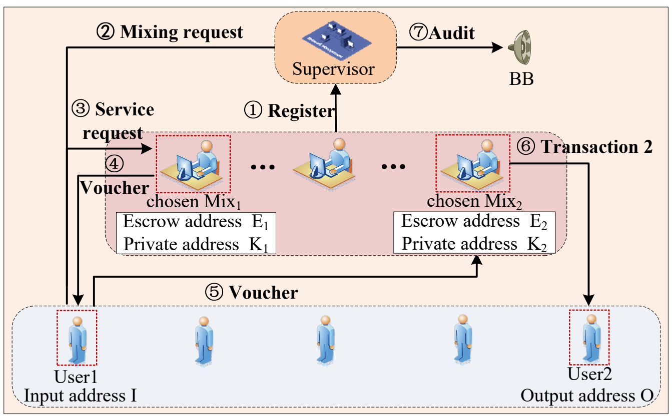

Fig. 2. System model in CoinLayering

- **User** is the seller in a transaction. To protect its identity privacy, it would initiate a coin mixing request to Mix and select two lightly loaded $Mixes$ from k candidates.
- **Mix** provides the coin mixing service, on a fee-for-service basis. To be more competitive, Mix reveals its operation status data to $supervisor$.
- **Supervisor** is responsible for recommending the k candidate $Mixes$ to $User$, making up the cost difference between $Mixes$ and monitoring $Mixs$' behaviors to prevent theft (conceptually similar to the banking regulator, or the trusted government department). Apparently, as the central controller, $Supervisor$ may even be a chock point of the system capacity due to the shortage of resource, in the face of large scale Bitcoin transactions. The advent of cloud service, however, offers a new appealing option to support coin mixing service over the Blockchain. It provides an opportunity to design a feasible $Supervisor$ without resource constraints. In addition, the pay-per-use nature of cloud service provides incentives to encourage the blockchain administrators to deploy mixing service. Consequently, migrating $Supervisor$ to the cloud becomes more of a natural choice.
- **Bulletin Board (BB)** is used to broadcast public information, including communications between $Users$ and $Mixes$.

Under ideal conditions, CoinLayering works as follows:

Step 1: Mix sends a registration request to the $Supervisor$. Upon successful registration, Mix can provide mixing services for users.

Step 2: $User$ makes a mixing request to $Supervisor$, which recommends k candidate $Mixes$ to the $User$. On being accepted, $User$ selects two $Mixes$ from k candidates. Let Mix_1 and Mix_2 respectively denote these two chosen $Mixes$.

Step 3: $User$ makes service requests to the two $Mixes$. $Mixes$ receive the requests and then send the commitment V as the reply. $User$ transfers Bitcoins from address I to escrow address E_1 of Mix_1, and then builds a transaction $tx_1 : I \rightarrow E_1$ (recorded in BB).

Step 4: Mix_1 confirms the transaction from BB and sends a voucher W to $User$.

Step 5: $User$ receives voucher W and sends it to Mix_2.

Step 6: Mix_2 receives voucher W and builds a transaction $tx_2 : K_2 \rightarrow O$, where K_2 is the private address of Mix_2.

Step 7: After the mixing is completed, the $Supervisor$ audits the $Mixes$ by reviewing the BB and recycles the amount in all the escrow addresses E_i to its total escrow address E. It also transfers the same Bitcoins to the private address of Mix_2 according to tx_2's record. $Supervisor$ audits once within a certain time.

One may argue that, once the two $Mixes$ collude with each other, the $User$'s identity privacy may still be leaked. However, the possibility of such an event occurrence is relatively low. The reasons can be stated as follows. Firstly, without being aware of each other, the candidate $Mixes$ have been designated to $User$ by the $Supervisor$. In this case, it is difficult for them to collude in advance. Secondly, the $User$ can further optionally select two $Mixes$ from the candidates according to its security requirements, which further increases the collusion between these $Mixes$ difficulty.

3.2 Mix Selection

In CoinLayering, we adopt the multiple supplier selection strategy to improve the difficulty of guessing the seller-buyer relationships, i.e., on one hand $Supervisor$ needs select k appropriate candidate $Mixes$ according to $User$'s performance and security requirements (e.g., the execution efficiency and credibility), on the other hand $User$ needs randomly select two lightly loaded $Mixes$ from these candidates. Obviously, in CoinLayering, the results of Mix selection not only affects the quality of coin mixing, but also its execution time. This requires that $Mixes$ selection is able to satisfy all $Users$' requirements in the shortest time possible. But, there are two problems to achieve this goal. Firstly, the diversity of $Users$' requirements makes it difficult to match. For example, some $Users$ focus on mixing fees, while others on service efficiency (both are contradictory). Secondly, considering $Supervisor$ cannot obtain the $Mixes$' status information (or underlaying network) in real time,

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numerous concurrent asynchronous mixing tasks would make a few $Mixes$ in k candidates be over-allocated. Once the $User$ designates such Mix as an ultimate performer, this would cause it to a long wait. In this case, as for this $User$, whether or not to reselect a Mix is a hard decision. For these, we first formulate the candidate Mix selection problem, and then design an efficient algorithm to solve it. Moreover, we utilize $M/M/k$ queueing based prediction to give the optimal decision.

Definition 1 (Mix service). Given a Mix_i, its Mix service is measured by multiple attributes that are of interest to $User$ (including bandwidth, acceptance rate, service efficiency, credibility, etc.), which can be expressed as $p_i = \{ID_i, f_i, \vec{A_i}\}$, where ID_i denotes the identity of Mix_i, f_i denotes its mixing fee, and $\vec{A_i}$ denotes its attribute vector. The attribute vector is $\overrightarrow{A_i} = \left[A_i^1, A_i^2, ..., A_i^k\right]$, where $A_i^k \in [0, 100]$ denotes the score of k^{th} attribute.

Definition 2 ($User$'s preferences). Each $User$ may have different preferences. For example, some $Users$ may focus on the mixing price, while others on service efficiency. Given a $User_j$, we formally define the top k query as $Q_j = \{f_j, \overrightarrow{w_j}\}$ [21], where f_j denotes the highest mixing fee accepted by $User_j$, $\overrightarrow{w_j} = \left[w_j^1, w_j^2, ..., w_j^k\right]$ denotes the weight vector of $User_j$'s preferences and $\sum_m w_j^m = 1$.

Definition 3 (Aggregate function). Given a Mix_i and a $User_j$, the matching degree MD_i^j between Mix_i and $User_j$ can be computed through the following aggregation function. After receiving the $User$'s mixing request, $Supervisor$ refers to $Mixes$' service information in BB, and returns the top k $Mixes$ with the highest aggregation value to $User$.

$$MD_i^j = \overrightarrow{A_i} \bullet \overrightarrow{w_j} \tag{2}$$

Mix selection algorithm. When the number of $Mixes$ is larger, it is impossible to rapidly compute each aggregate value for them. An efficient solution is to filter those conspicuously unsuitable $Mixes$ and simplify the constraint condition. For this, we introduce the Domination Graph (DG), which can show the dominance relationship of each Mix's attributes [22]. When all attributes of $\vec{A_i}$ are greater than $\vec{A_j}$, we consider that $\vec{A_i}$ dominates $\vec{A_j}$. $\vec{A_i}$ is placed on the first layer and $\vec{A_j}$ is placed on the next layer. Obviously, $Mixes$ in the first few layers are what $Users$ require. In this, we can easily filter a part of $Mixes$ with too low attributes by means of DG. Considering that the first layer has more dominance relationships, its $Mixes$ would have higher priority, i.e., more in line with $Users$ requirements. Thus, we start from the first layer departure and meantime combine with mixing costs to select Mix. The process of searching top-k $Mixes$ is depicted in Algorithm 1.

The time complexity of this algorithm mainly depends on the number of Mix accessed in the domination graph. It can be expressed as $o(|S|)$, where S is the set of r_i, and r_i denotes the accessed Mix. Considering that S belongs to multi-level structure, we define the set $S_1 = \left\{r_i^1 \middle| r_i^1 \in Layer_1\right\}$, where r_i^1 denotes the node in $Layer_1$. Suppose h_1 is the Mix with highest score in $Layer_1$, and $S_2(h_1) = \left\{r_i^2 \middle| r_i^2 \; is \, the \, leaf \, of \, h_1\right\}$. We search the second-highest Mix in $S_2(h_1)$. By that analogy, we infer that $|S_1 \cup S_2(h_1)| \leq o(|S|) \leq |S_1 \cup S_2(h_1) \cdots \cup S_k|$, where k denotes the number of queried layers.

Waiting decision strategy. Because $Supervisor$ cannot see the service queue length of $Mixes$, it may recommend those overloaded ones to $User$. In the context of random influence, once $User$ unconsciously chooses such $Mixes$, it has to wait a significant amount of time. A straightforward strategy is to immediately reselect another Mix from the k candidates. But, compared to the waiting, it may take more time due to the high processing overhead of Mix switching. It also highlights the waiting decision that becomes a key step in improving the system efficiency. Another alternative strategy is to achieve good load balancing and avoid the overloaded candidate $Mixes$. Toward this end, the number of candidate $Mixes$ k should be as more as possible. However, excessive candidate $Mixes$ cannot only increase the administration overhead of $Supervisor$, but also its computation overhead. In this, it is necessary to determine the most suitable value of k, i.e. , find an optimal k without incurring $Supervisor$ overload, which ensures that this amount of $Mixes$ cannot only complete the relevant tasks, but also require least waiting time for $User$.

We use the $M/M/k$ queuing theory to model the least number of $Mixes$ involved in CoinLayering, where k denotes the least number of $Mixes$ providing mixing services for $Users$. Suppose that $User$ arrives at a Poisson flow with a parameter λ, and coin mixing service time also follows a Poisson distribution with parameter μ. Note that, the time series of user arrival is a sequence of i.d.d. random variables, which is the same as mixing service. In the $M/M/k$ queuing system, there are two factors affecting k: one is the queuing intensity $\rho = \frac{\lambda}{k\mu}$; another is the reduced-length of queue with the increase of k. The former is used as a reference to account for the relationship between the number of $Users$ entering the system per unit time and the greatest number of $Users$ served by $Mixes$. Generally speaking, for the system, $\rho < 1$ is the most reasonable. This is because, when $\rho \geq 1$, the number of entering $Users$ is more than the number of acceptable $Users$. In this case, it would bring about the long waiting queues and the overburdened $Mixes$, which makes the system unstable. Based on it, on the condition of given λ and μ parameters, we can infer $k > \frac{\lambda}{\mu}$. The latter reflects the impacts of increasing k on the queue length. To achieve the best benefits, how to increase k has the biggest impact on decreasing the average queue length LQ. From the queuing theory, the average queue length is $LQ = \frac{(\lambda/\mu)^k \times \lambda \times \mu}{(k-1)! \times (k \cdot \mu - \lambda)^2} \times P_0$, where $P_0 = [\sum_{n=0}^{k-1} \frac{(\lambda/\mu)}{n!} + \frac{(\lambda/\mu)}{k!}(\frac{k\mu}{\mu-\lambda})]^{-1}$ denotes the probability that all $Mixes$ are free. Based on it, k search issue can be formulated as $\max\limits_{k=1 \ldots n}\left(\frac{LQ_{k+1}-LQ_k}{LQ_k-LQ_{k-1}}\right)$. Through combining

Algorithm 1 Mix selection based on DG

```
Input: DG, User query parameter w⃗, aggregate function f
Output: Top-k Mixes, result table RS
BEGIN
  CL ← f(DA, w⃗);    //the dominance graph first-level data DA
  RS ← r from the CL;    //the ordered candidate list CL
  For k1 < k2 dolength
    For each child C of r do    //the highest total score r
      If All parent nodes of C ∉ CL Then
        CL ← k(C, w⃗);
      End If
      RS ← r ;
    End For
  End For
END
```

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above factors, $Supervisor$ eventually searches a feasible k.

After k has been determined, the waiting decision process can be stated as follows: when $User$ sends the service request to a busy Mix_i, Mix_i would inform the $User$ of the current queue length L_i. If $L_i \leq LQ$, we recommend $User$ to wait; otherwise, it should choose some other $Mixes$, where LQ denotes the average queue length. It's worth noting that, although the operations of Mix_1 (responsible for performing group signatures) and Mix_2 (responsible for verifying group signature) are different, their computation costs are almost the same, which would be proved in the experimental evaluation section. This means that we do not have to distinguish them in design waiting decision strategy.

3.3 Potential Threats

For simplicity, the above strawman design assumes all components to be honest and well behaved. Once relax these assumptions, CoinLayering would face the following potential threats. To fix these threats and enhance its self-credibility, we respectively devise the corresponding coin mixing protocols in Section 4.

Semi-trusted *Mixes*. To maximize their self-interest, Mix may record $Users'$ transaction information in the background, and sell them to the adversary. Moreover, it is likely to steal $Users'$ Bitcoins without providing any service. Furthermore, the lazy Mix would deliberately delay the service time. Therefore, it is necessary to disclose the identities of misbehaved $Mixes'$ and further punish them.

Semi-trusted *Supervisor*. Because "enemy within" exists, $Supervisor$ may be not completely honesty. For example, the misbehaved insider may steal $Users'$ Bitcoins and make false accounts to cover up its behavior. More complicated, it may some compromise $Mixes$ to obtain their private keys and further steal Bitcoins. Therefore, it is desired to limit the $Supervisor$'s behaviors and thus prevent from its stealing.

4 Secure Coin Mixing Protocol For CoinLayering

In this section, we first describe a coin mixing protocol to prevent Mix's semi-honest, termed as CoinLayering-PA. And on this basis, to further solve the $Supervisor$'s semi-honest behavior, we design a more secure coin mixing protocol termed as CoinLayering-PB.

4.1 CoinLayering-PA

The primary principle of CoinLayering-PA design can be stated as follows: to secure the ownership of Bitcoins, $Mixes$ that host $Users'$ Bitcoins must mark the vouchers with signatures; to prevent from Bitcoins stolen, $Mixes$ are required to provide the deposit to $Supervisor$; to prevent Mix from colluding with adversaries to leak information, the interaction between $Mixes$ should be blinded; to urge lazy $Mixes$, $Users$ are allowed to set time constraint. Guiding by this principle, we combine the Schnorr signature and congruence based group signature technologies to proof the Mix's escrow Bitcoins. The choice is due to the following: (1) it can insure the anonymous between $Mixes$, i.e., Mix_1 cannot see the identity of Mix_2 when verifying the signature, and further prevent them from colluding with each other. (2) It allows $Mixes$ dynamically joining and exiting, which is more applicable for large scale transactions. (3) It has less computation, and makes the entire protocol more efficient.

As is shown in Fig. 3, there are three phases in our protocol: registration, mixing and audit. Only when Mix puts up rent deposit can eligible for rendering mixing service. When $Users$ request coin mixing service, the time limits T_i for the service is attached. If $Mixes$ accept the request, it must be completed within T_i. After the escrow operation, Mix_1 signs the blind message as a voucher. $Users$ can require Mix_2 to complete transaction by virtue of this voucher. During the execution of a transaction, we allows $User$ to terminate transaction under these conditions: if $Users$ want to terminate the transaction after received the commitments from $Mixes$, they just have to wait until after the T_4; if $Users$ want to terminate the transaction after constructed $tx_1 : I \rightarrow E_1$, it only needs to change the output address O to I and ID_2 to ID_1 in the message m'. Then, certificate W is handed over to Mix_1 for verification, which can facilitate it to construct the transaction $tx_2 : K_1 \rightarrow I$, and further recover the transaction. In addition, considering $User$ need pay for mixing service, as the number of coin mixing increases, its financial burden would grows. In this case, we design an incentive mechanism. Its basic idea is that $Supervisor$ authenticates $Users'$ applications and then provides some rebates for users who continuously mixed coins. Limited by the space, we will depict in Appendix A.

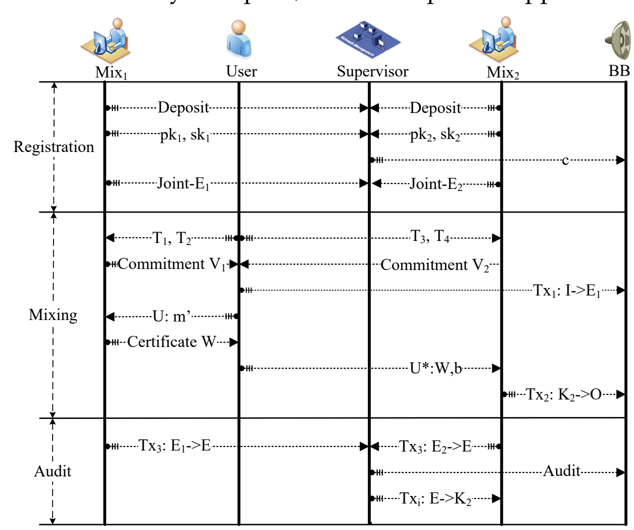

Fig. 3. CoinLayering-PA.

4.1.1 *Registration phase*

In this registration phase, Mix must put up the deposit and its private address with enough Bitcoins. There are three sub-sets of the condition: proof of Bitcoins, join and exit.

Proof of Bitcoins: Only if the following conditions are fulfilled would the $User$ be qualified as a Mix: hold enough Bitcoins so as to provide mixing services to $User$, and possess sufficient bandwidth and computation resources so as to complete coin mixing task. When the above conditions are met, it needs further register itself to $Supervisor$. It firstly signs $ECDSA$ for one of his own private addresses K and waits for $Supervisor$'s verification. Once successful, it would provide the deposit to $Supervisor$'s total escrow address E. After $Supervisor$ receives the deposit and publishes the $User$'s service information (e.g., its reputation and service efficiency) on BB, the $User$ is registered successfully. This means that it is officially upgraded to a Mix.

Join: $Supervisor$ sends a modulus p_i to each Mix. Each Mix generates its own private key x_i, and calculates its own public key $y_i = g^{x_i} \bmod p_i$. Then, speak its y_i and ID and meantime send them to $Supervisor$. If Mix has a malicious move, $Supervisor$ can be held accountable according to its identity. To prevent Mix from messing up, Mix needs to prove by knowledge sign that it owns the private key x_i and submits the corresponding public key y_i [23]. Mix selects a random number r_i, and computes $c_i = H(Time||y_i||g||g^{r_i})$, $s_i = r_i - c_i \cdot x_i$, where $Time$ is a timestamp. After $Supervisor$ receives c_i and s_i, it verifies that $c_i = H(Time||y_i||g||g^{s_i}{y_i}^{c_i})$. If the equation is true, $User$ can prove $y_i = g^{x_i} \bmod p_i$. $Supervisor$ constructs the Chinese remainder theorem congruence $c = y_i \bmod p_i$ according to y_i and p_i of each Mix [24], and compute $c = \sum_{i=1}^{k} y_i \cdot P_i \cdot P_i'$ and post it on the BB. Among them, $P = \prod_{i=1}^{k} p_i, P_i = P/p_i$. P_i' satisfies the integer solution of $P_i \cdot P_i' = 1$.

Exit: When Mix exits, $Supervisor$ conducts a transaction audit. If the audit result is correct, the public key y_i of Mix is changed by $Supervisor$, the new c is calculated and updated on BB, so that the Mix cannot perform the legal group signature.

4.1.2 Mixing Phase

In the mixing phase, $User$ reached an agreement with Mix. If Mix agrees to provide the service, it needs to provide a commitment to $User$. When $User$ initiates the transaction tx_1, Mix_1 needs to give it a group-signed voucher W. After Mix_2 verifies W, it would build tx_2 to complete the coin mixing. Mixing phase including the following steps.

Step 1: $User$ wants to make a transaction tx_0:I(input address)$\rightarrow O$ (output address). For this, it first randomly selects two from the recommended k $Mixes$, and creates two identities U and U^*. Then, as U, send both T_1 (Time limit for transaction $I \rightarrow E_1$) and T_2(Time limit for signing message m') to Mix_1. And meantime, as U^*, send both T_3 (Time limit for sending voucher W) and T_4 (Time limit for transaction $K_1 \rightarrow O$) to Mix_2.

Step 2: If Mix_1 accepts the mixing request, it needs to send the commitment $V_i = \{nonce_1, T_1, T_2, sign\{T_1||T_2||nonce_1\}x_1\}$ to the user. The sign is the group signature [1] based on Schnorr signature with parameter c. For a message m, Mix_1 chooses a random number r, and calculates $s_1 = g^r \bmod p_i$, $s_2 = H(m) \cdot x_i - r$. (p_i, s_1, s_2) is the signature. $Nonce$ is a random number to prevent the replay attack. The same is true for Mix_2.

Step 3: When $User$ authenticates V_i, the public keys y_1, y_2 of the $Mixes$ are recorded. $User$ first calculates $y_i = c \bmod p_i$ according to the information disclosed by the group c, and then judges whether the equality $s_1 \cdot g^{s_2} = {y_i}^{H(m)}$ is true, which can determine the validity of the signature V_i.

Step 4: $User$ builds the transaction $tx_1 : I \rightarrow E_1$ (announced on the BB), and generates $m = \{O||ID_2||nonce_3\}$, a random number b as the blinding factor, and calculates $m' = m \cdot b^{y_2}$. Finally, send m' to Mix_1.

Step 5: Mix_1 confirms the transaction tx_1 and signs $W = sign\{m'\}_{x_1}$ to $User$ by group signature. W is the voucher used to communicate with Mix_2. For Mix_1, a transaction tx_1 corresponds to a signature. If Mix is excessively signed, it will be discovered and punished by $Supervisor$ in audit phase.

Step 6: $User$ U changes his identity to U^*, posts voucher W on BB and sends $\{W, b, O, ID_2, nonce_3\}$ to Mix_2 to verify the voucher.

Step 7: Mix_2 first verify the group signature to obtain m', remove the blindness of b and y_2 to obtain m^*, and compare with the m. If they are consistent, Mix_2 build the transaction $tx_2 : K_2 \rightarrow O$, where K_2 is the private address of Mix_2. Otherwise, Mix_2 rejects the voucher.

Change of $User$'s identity belongs to data obfuscation at the network layer. To prevent adversary from obtaining identity and privacy information by discovering the network topology, researchers have proposed that the blockchain can be used on networks with privacy protection features, such as Tor [26]. Another type of digital currency known for privacy is Monero, which uses an anonymous communication scheme I2P [27]. Compared to the Tor protocol, the same network link is used to send and receive data. I2P uses multiple links to send data and Accepting data can better hide IP and prevent transaction the traceability through network layer information [28] .

4.1.3 Audit Phase

In the audit phase, Mix's denial of service needs be monitored by $Supervisor$. In addition, transaction differences between $Mixes$ need be made up of auditing signatures.

Denial of service audit: For Mix's denial of service behavior, we use the form of $User$ disclosure for auditing. If E_1 refuses to sign m' message after generating $tx_1 : I \rightarrow E_1$, $User$ only needs to take the record of Mix_1's commitment V_1 and tx_1 to expose. If $tx_3 : K_2 \rightarrow O$ is refused after Mix_2 verifies the credential W, $User$ only needs to hold the commitment V_2 and the voucher W of the Mix_2 to expose. $Supervisor$ confirms the disclosure. If there is a denial of service in Mix, $Supervisor$ will deduct the deposit and mark the corresponding Mix by ID, and Mix's reputation will decrease. Once the score of tags is too low, the $Supervisor$ has the right to force the malicious Mix to exit group.

Signatures audit: $Supervisor$ compares whether the number A of $Mix's$ signatures is less than or equal to the number B of corresponding host transactions. If $A > B$,

1. It is well established that, in the traditional group signature, the verifier can distinguish whether the two signatures come from the same signer. In this, one may argue that once a $User$ selects the same $Mixes$ multiple times in a row, the selected Mix_2 is able to guess the genuine identity of $User$ correctly. However, on one hand the probability of such case is very small, because our adopted load balancing techniques could avoid assigning multiple tasks to the same $Mixes$; on other hand aiming at this problem, the researchers have proposed a more secure group signature technique [25], which is shown in Appendix B.

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Mix is considered as malicious one. Then, $Supervisor$ would deduct the mixed consumption and its deposit, and meantime force it out of the group. Finally, $Supervisor$ builds $tx_3 : E_i \rightarrow E$ to recycle Bitcoin of all escrow addresses E_i to the total escrow address E of $Supervisor$. For honest $Mixes$, $Supervisor$ sends mixing consumption to their private addresses.

4.2 CoinLayering-PB

When $Supervisor$ makes up the cost difference between $Mixes$, it may steal Bitcoins. To prevent such behavior, CoinLayering-PB should allow the transactions between $Mixes$ be carried out by themselves. For this, we use threshold signature technology to insure the security of this operation. The choice is due to the following: (1) secure. For a Mix's operation, only when a majority of $Mixes$ support can be completed. (2) Fault-tolerant. Even under the condition that 1/3 $Mixes$ are compromised, it can normally work. (3) Efficiency. $Supervisor$ can provide a large number of parameters for the threshold signature process in advance. Moreover, to prevent private keys from being compromised and thus protect $Mixes'$ Bitcoins, we also improve the group signature. To sum up, as is shown in Fig. 4, the improvements in CoinLayering-PB are mainly in the following phases, compared to CoinLayering-PA.

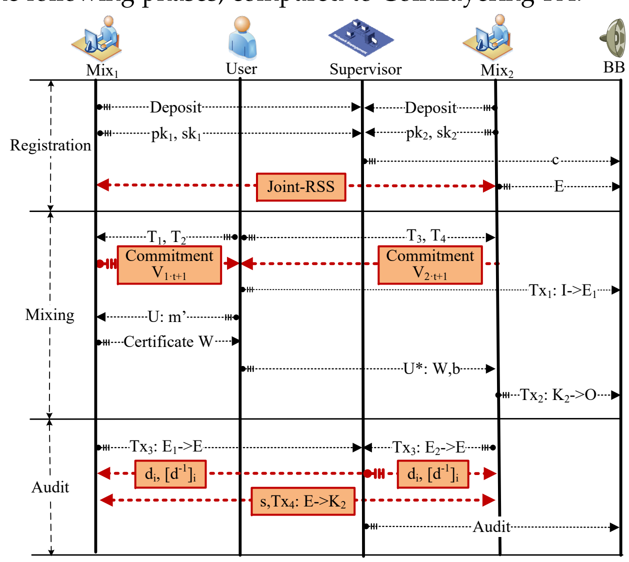

Fig. 4. CoinLayering-PB. The operations in red rectangles are ones distinct from CoinLayering-PA.

In the registration phase, each Mix's escrow address should be generated by itself. We use secure $Joint - RSS$ to achieve it. The detailed process is as follows:

Step 1: Each Mix gets the share k_i of the key k by secure $Joint-RSS$, which is based on Shamir Key Sharing (SS). It can divide a key into n key shares. As long as 2/3 participants are online, the original key can be restored through the key share.

Step 2: Mix computes the public key k_iG(announced on the BB, and the escrow address is $E_i = Hash(k_iG)$.

Step 3: Total escrow address $E = Hash(\sum_{i \in T} b_i k_i G), b_i = \prod_{i \in A, i \neq j} \frac{j}{j-i}$.

The specific contents of $Joint - RSS$ are as follows: each participant Mix_i takes itself as the center and selects a random secret value $k_i{}^0$. Then, construct a polynomial $f_i(x)$, and execute SS to get the share of $k_i{}^0$. $Mix_j(1 < j < n)$ receives the $f_i(j)$ sent by the remaining $n-1$ participants $U_i(1 < i < n, i \neq j)$ and calculates $k_i = \sum_1^n f_i(j)$ as the key share; to ensure the correctness of $f_i(x)$ sent by Mix_i. Each Mix_j can get $k_i{}^0G$, $a_i{}^lG$. Mix_j can calculate $k_i{}^0G = f_i(x)G = \sum_1^n i^l(a_i{}^lG)$. If the equation is true, the key share received by Mix_i is correct. Meantime, the secret by the participants is $k = \sum_1^n k_i{}^0$, the secret-sharing $k_i = \sum_1^n f_i(j)$.

In the mixing phase, the group signature of the Mix is a very important step. If the private key of the Mix is leaked, not only the identity of the Mix will be forged, but the Bitcoin in the escrow address will also be at risk. It is very important to prevent the private key of Mix from leaking. We have improved the group signature as follows:

During the t time period, the private key of Mix_i is $x_{i \cdot t}$. At time $t+1$, the private key $x_{i \cdot t+1} = x_{i \cdot t}{}^2 \bmod (p_i - 1)$. At the same time, the key update algorithm will erase the key in time t immediately after the private key in time $t+1$ is generated. If $t = T$, the private key is output as an empty string. When the time slice runs out, group members need to regenerate a pair of keys.

The user's group signature $s_1 = g^r \bmod p_i$, $s_2 = H(m) \cdot x_{i \cdot t} - r$. For group signature verification, first the verifier calculate $y_i = c \bmod p_i$ according to the information disclosed by the group c, and then judge whether the equality $s_1 \cdot g^{s_2} = {y_i}^{H(m) \cdot 2^t}$ is true to determine the validity of the signature.

In the audit phase, all escrow addresses are generated by the Mix and the $Supervisor$ cannot operate on the escrow address. But this does not affect the $Supervisor$ auditing Mix. If a malicious Mix privately forwards the Bitcoin in the escrow address, and it will be discovered during the audit phase. $Supervisor$ will punish dishonest Mix, deduct the deposit and cancel its identity. During the audit phase, $Supervisor$ removes all $Mixes$ with malicious behavior. Mix wants to get the corresponding Bitcoin from the escrow address. Divided into the following steps.

Step 4: Each $Supervisor$ initiates a transaction $tx_i : E_i \rightarrow E$. All Bitcoins are transferred to the total escrow address.

Step 5: The $Supervisor$ calculates the Bitcoins that the Mix should receive and announces the audit results on the BB. The $Supervisor$ generates the key d, $[d^{-1}]$ and calculates the key share d_i, $[d^{-1}]_i$ through the SS. $Supervisor$ will assign them to each Mix.

Step 6: Mix initiates its own transaction $tx_4 : E \rightarrow K_i$, and computes $e = H(tx_i)$. With $(x, y) = d_iG$ and $R = x$, each Mix computes $s_i = ([d^{-1}]_i) \cdot (e + k_i \cdot R)$ and puts s_i on the BB.

Step 7: The Mix can get the $s = \sum_{i \in T} b_i s_i, b_i = \prod_{i \in A, i \neq j} \frac{j}{j-i}$, so it can use s to legally sign transaction tx_i.

5 Security Analysis

This section mainly analyzes the security of Coinlayering, including strong anonymity, anti-denial service, signature unforgeability and backward security.

Theorem 1 (Strong anonymity)**.** *In CoinLayering, it is difficult for an adversary to guess the buyer-seller relationship.*

Proof. To enhance the anonymity of Bitcoin owners, coin mixing system is responsible for cutting off the relationship between seller and buyer thoroughly. For this, to hide the target transaction A from the adversary, it can make other transactions that take place simultaneously with A as the misled items, which consist of the anonymous set. Apparently, the larger the anonymous set, the stronger the anonymity is. In addition, suppose that there are N_1 buyers and N_2 sellers during the interval that the system completes a coin mixing. Under ideal condition, for any pair of seller and buyer, the probability of getting it right is $1/(N_1 * N_2)$. In other words, the upper bound of anonymous set is $(N_1 * N_2)$.

Based on the above, if the anonymous set of CoinLayering can achieve $(N_1 * N_2)$, it possesses the strong anonymity. To prove it, we take the following two steps: (1) the connection between seller and buyers in CoinLayering is less enough and (2) the size of anonymous set $(N_1 * N_2)$ is large enough. For the first step, in CoinLayering, because the adversary cannot detect the $User$'s choice and the connection between Mix_1 and Mix_2 is also cut off by group signature, their interactive process cannot be directly observed by the ledger, and this maximizes the difficulty of guessing the relationship between the buyer and the seller. One may argue that, once Mix_1 and Mix_2 collude with each other or the adversary colludes with a small number of $Users$, the guessing probability can be enhanced. However, considering the Mix selection and economic cost, the occurrence probability of such situations is very low. For the second step, because CoinLayering has an effective load balance result through Mix selection, it can normally run under the large scale Bitcoin transactions as long as plentiful of $Mixes$ are involved. To sum up, the strong anonymity in CoinLayering has been proofed. □

Theorem 2 (Anti-denial service)**.** *In CoinLayering, any $Mixes$ who refuse to provide services would be exposed.*

Proof. When $User$ sends the timestamps T_1, T_2 or T_3, T_4 to a Mix τ, τ normally requires issuing a commitment to $User$ after accepting the request. However, once τ is a semi-honest Mix in CoinLayering, three unexpected cases are exhaustive. (1) If τ does not respond, $User$ can choose another Mix after the timeout. In this case, τ would not get any benefit from it except for the waste of time. (2) If τ denies the mixing service after hosting Bitcoins and reject to provide a voucher for the $User$, $Supervisor$ would audit the number of τ's vouchers during the audit phase. In this case, τ would lose its mixing qualification and be charged the deposit. (3) If τ provides the $User$ with a voucher, it refuses to transfer the escrow Bitcoin. The commitment and voucher will be evidence of the denial of service. In the context of Blockchain, τ cannot deny its behavior. For the above, if a semi-honest Mix actively refuses to serve the $User$, the Mix can not get any extra benefits and meantime its malicious behavior would be exposed. □

Theorem 3 (Unforgeability)**.** *In CoinLayering, the adversary cannot forge any $Mixes'$ identities to provide users with false services.*

Proof. In CoinLayering, the group signature is used to cut off the relationship between $Mixes$, and the threshold signature is used to secure the transactions. In this, once an adversary A forges these two signatures, it can forge Mix's identity and defraud its Bitcoins. To prove the unforgeability of CoinLayering, we just need prove the following subproblems: the group signature is unforgeable and the threshold signature is unforgeable.

(1) Group signature unforgeability. Assume to the contrary that there exists an adversary A who can forge the group signature with a non-negligible probability P_0, under the random oracle model. In CoinLayering, we use $s_i^1 \cdot {g_i}^{s_i^2} = {y_i}^{H(m||r_i)}$ to verify the validity of Mix_i's signature. For convenience, we term s_i^1 and s_i^2 together as s_i and let $h_i = H(m||r_i)$. In this, to satisfy the above equation, the main work of A is to search s_i and h_i. To simulate the searching process, we construct a challenger B to respond to adversary A's queries. The whole procedure can be divided into 3 steps. Step 1: select a Mix_i as the forged object. After A sends the key query O_{CKey} relevant with Mix_i to B, B randomly selects $x_i \in Z_p$ to calculate $(pk_i, sk_i) = (g^{x_i}, x_i)$, and then let Mix_i join the group, in which the group parameter c is updated by $Superivsor$. Step 2: acquire the Mix_i's signature. After A sends a plaintext message m to B, B uses the Schnorr signature technique $\sigma = (m, s_i^1, s_i^2)$ to compute the m's signature, where $s_i^1 = g^{r_i} \bmod p_i$, $s_i^2 = (H(m||r_i) \cdot x_i - r_i)$, and r_i is a random number. To acquire more of the Mix_i's signatures, A can choose different messages and analyze them. Step 3: forge the Mix_i's signature. After A forges the signature $sign\{m\}$ and sends it to B, B verifies whether such signature is valid. Once the forged signature $sign\{m\}$ cannot be certified false through a series of queries, A's forgery succeed and it can only be regarded as Mix_i. In this case, without loss of generality, we further assume that A can forge two signatures (m, r_i, h_i, s_i) and (m, r_i, h_i^*, s_i^*). Based on them, we can derive ${g_i}^{s_i} = r_i \cdot y_i^{h_i}$ and ${g_i}^{s_i^*} = r_i \cdot {y_i^*}^{h_i^*}$. Going a further step, we can use $G_1 =< g >$: $x_i = (s_i - s_i^*)(h_i - h_i^*)^{-1}$ to calculate the discrete logarithm x_i of y_i. However, this is the Discrete Logarithm Problem (DLP), i.e., there exists no polynomial time algorithm to search a feasible x_i under given (g, g_i^x). This means that such adversary A does not exist, which contradicts the precondition.

(2) Threshold signature unforgeability. In CoinLayering, the threshold signature is a combination of $ECDSA$ and Shamir's Secret Sharing (SS). The $ECDSA$ signature can be computed as $s = d^{-1}(e + r \cdot k)$, where d is the private key of Mix, and k is the temporary key generated during signature calculating. Going a further step, by using SS technique, d and k are divided into sub-keys respectively, and then issue them to the varied $Mixes$. Suppose that an adversary A can control the first t $Mixes$, and further monitor their sub-keys. To prove the unforgeability of the threshold signature, we simulate the threshold signature process, and further certify that adversary A cannot utilize these t $Mixes$ to recover the $ESCDA$ signature s. The simulation process is as follows. After obtaining the t $Mixes'$ sub-key $(d_1^*, d_2^* ... d_t^*)$ and $(k_1^*, k_2^* ... k_t^*)$, A can use interpolation formula to calculate $R = k_i^* G (1 \leq i \leq t)$ and then calculate sub-signature $s_i^* = ([d^{-1}]_i^*) \cdot (e + k_i^* \cdot R)$ $(1 < i < t)$ through broadcasting

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R to honest $Mixes$. Considering that $ECDSA$ is a secure signature technique, to forge the signature s, A can only resort to the sub-signature s_i. According to Shamir's secret sharing, d and k are t-order polynomials, i.e., only when more than t sub-keys are collected can A obtain d and k. Since s is generated by d and k, it is $2t$-order polynomial, and thus A requires collecting $2t$ s_i. Because each Mix stores a sub-key, A needs compromise more than $2t$ $Mixes$, which contradicts the preassumption. Thus, the Threshold signature cannot be forged. □

Theorem 4 (Forward security)**.** *In CoinLayering, if the adversary gets Mix's private key, the system is still safe and trusted.*

Proof. In CoinLayering, even if Mix reveals its current private key x_i to the adversary A, A is also unable to retrieve the previous information and further reveal $User$'s privacy. To prove it, we just need prove the following points: the forward security of the Mix's private key and the forward security of the group signature.

(1) Forward security of the Mix's private key. In CoinLayering, given a Mix_i, its private key x_i is associated with the time period j, i.e., x_i would change over time. For this, we utilize $x_{i.j+1} = x_{i.j}^2 \bmod (p_i - 1)$ to update the private key. Because this one-way key updating function is based on large prime factorization of $p_i - 1$, in the limited time available, the adversary cannot use the current key $x_{i.j}$ to calculate the previous key $x_{i.j-1}$.

(2) Forward security of the group signature. Given a Mix_i, suppose that its private key x_{ij} at the time period j is leaked. If the adversary A tries to forge the group signature at time period $j-1$, it needs make the equation $r_i \cdot g_i{}^{s_i} = y_i{}^{2^{j-1}H(m)}$ true through searching two valid values of both r_i and s_i. According to Theorem 3, only when the private key $x_{i.j-1}$ has been acquired can r_i and s_i be found. Yet, due to the forward security of x_{ij}, A cannot calculate $x_{i.j-1}$. This means that, the signature at $j-1$ is still secure. □

6 Performance Evaluation

In this section, we focus on the proof of scalability in CoinLayering. For this, we first use the theoretical analysis to demonstrate its efficiency. Then, build simulations platform to perform extensive experiments so as to supplements the above analysis results.

6.1 Theoretical Evaluation

We use the mathematical analysis to evaluate the computation costs of encryption (En), square operation (S), modular multiplication (M), modular exponentiation (E), hash function (H) and elliptic curve scalar multiplication (R). Firstly, considering that the main computation work of Mix is to complete group signature, to measure the Mix's load in CoinLayering, we conduct a theoretical evaluation on the involved group signature. Secondly, to demonstrate the efficiency, a theoretical evaluation of the entire protocol is necessary.

(1) In CoinLayering, we combine the Congruence based Group Signature with Schnorr Signature, termed as $CGSSS$. We choose the Forward Secure Group Signature ($FSGS$) [29] to compare with ours, both of which are capable of prevent $Mixes$ from colluding, i.e., have the same security level. The former uses Mix selection to make $Mixes$ unable to collude with each other; the latter increases the interaction with $Supervisor$ in signature generation stage to prevent collusion.

Table 3 shows the comparison result, which contains five Stages: Key Update (KU), Member Joining (MJ), Member Revocation (MR), Signature Generation (SG) and Signature Verification (SV). Let n be the number of Mix in the signature. In the key update stage, each Mix needs to update its own key $x_{i\cdot t+1} = x_{i\cdot t}{}^2 \bmod (p_i - 1)$. Because each Mix is updated at the same time, it is an (S) operation. In the member joining stage, $Supervisor$ adds each registered Mix to the congruence, and compute $c = \sum_{i=1}^{k} y_i \cdot P_i \cdot P_i'$, which is (nE) operations. In the member revocation stage, $Supervisor$ modifies the public key $y_i = y_i{}^2 \bmod p_i$ corresponding to the exit member and recalculates the public key c, which is $(E+nM)$ operation. In the signature generation stage, Mix chooses a random number r, and computes $s_1 = g^r \bmod p_i$, $s_2 = (H(m) \cdot x_i - r)(\bmod p_i)$, which is a $(E+M)$ operation. In the signature verification stage, Mix calculates $s_1 \cdot g^{s_2} = y_i{}^{H(m)}$ to verify the correctness of the signature, which is a $(2E+M)$ operation. Compared with $FSGS$, $CGSSS$ has advantages in the calculation of the key update stage and member joining stage. Firstly, $FSGS$ requires all $Users$ to update their private keys simultaneously, but $CGSSS$ could allow $Users$ to update their private keys according to their own requirements, which can effectively reduce its computational overhead. Secondly, whenever a new Mix joins, $CGSSS$ only requires $Supervisor$ to recalculate the group public key c_{new} and then issue them to the $Mixes$, but $FSGS$ requires the new one to interact with all other $Mixes$, and update their parameters. In particular, even under the condition that part of $Mixes$ cannot receive the public key c_{new}, the interactions among the remaining $Mixes$ can run normally in $CGSSS$. This cannot only reduce the computation cost, but also minimize the bandwidth overhead. In brief, $CGSSS$ is more efficient. Especially, as more and more $Mixes$ join in the Bitcoin marketplace, it has better characteristic of scalability.

TABLE 3
Theoretical analysis and comparison between the group signatures $CGSSS$ and $FSGS$

Stages	CGSSS	FSGS
Key Update	S	$2S$
Member Joining	nM	$n(M+E)$
Member Revocation	$E+nM$	$E+nM$
Signature Generation	$E+M$	$2E+M$
Signature Verification	$2E+M$	$2E+M$

(2) We choose two typical schemes to compare with CoinLayering. Coinparty [10] is a decentralized structure coin mixing scheme, which also uses threshold signatures in the scheme. Zerocoin [30] is a centralized structure coin mixing scheme with excellent privacy protection.

Table 4 shows the computation costs of CoinParty, Zerocoin and CoinLayering. Let n be the number of Mix in the protocol. In CoinLayering, there is no operation to encrypt the message. In the registration phase, each $User$ generates the key $y_i = g^{x_i} \bmod p_i$ and a knowledge signature $c_i = H(Time||y_i||g||g^{s_i}y_i{}^{c_i})$, which include

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$n(E + H + M)$ operations. In addition, to ensure the security of key sharing, Mix needs perform Joint-RSS, which includes $n(3R)$ operations. In the mixing phase, Mix and $User$ need to generate group signature $s_1 = g^r \bmod p_i$ and $s_2 = H(m) \cdot x_i - r$, and meantime verify the group signature $s_1 \cdot g^{s_2} = {y_i}^{H(m)}$ twice, which include $n(6E+4H+4M)$ operations. In addition, $User$ blinds the message $m' = m \cdot b^{y_2}$, which includes nE. By adding the above analytical results together, CoinLayering mainly includes $n(8E + 5H + 4M)$ operations. Different from CoinLayering, CoinParty needs spend more time on encryption and elliptic curve scalar multiplication, and ZeroCoin needs to spend more time on modular exponentiation. Yet, in terms of security and scalability, CoinLayering has more advantages. Firstly, compared to CoinParty, although it brings more elliptic curve scalar multiplication operations, it can guarantee the transaction security through the secure key sharing, even under the condition that a large number of malicious nodes share wrong key sharing. Secondly, compared to ZeroCoin, it has stronger anonymity. As a centralized scheme, ZeroCoin is more vulnerable to bandwidth attack, which restricts its scalability.

TABLE 4
Theoretical analysis and comparison between CoinLayering and others

Operations	CoinParty	ZeroCoin	CoinLayering
Encryption	$(n^2)_{En}$	0	0
Modular Multiplication	$(8n)_M$	$(9n)_M$	$(4n)_M$
Modular Exponentiation	$(4n)_E$	$(12n)_E$	$(8n)_E$
Hash	$(4n)_H$	$(n)_H$	$(5n)_H$
Elliptic Curve Scalar Multiplication	$(10n)_R$	0	$(3n)_R$

6.2 Experimental Evaluation

We firstly measured the computation time of CoinLayering-PA and CoinLayering-PB respectively, including the group signature and threshold signature. Furthermore, we evaluate the overall performance of CoinLayering. Specially, investigate its computation and storage overheads, as the number of blocks increases. Calculation time refers to the actual running time of various operations, including modular multiplication T_M, modular exponentiation T_E, hash T_H and elliptic curve scalar multiplication T_R. All of the experiments are performed on the server with Intel 2.6GHz i7-4720 CPU, 8GB RAM and Windows XP. We use JPBC (Java Pairing-Based Cryptography Library) library to implement our concerned cryptographic techniques, in which RSA modulus in the selected accumulator is 1024 bits and hash function is SHA-256.

6.2.1 On The Performance of CoinLayering-PA

As congruence-based group signature (i.e., $CGSSS$) is the main cryptographic technique that is simultaneously involved in the CoinLayering-PA's registration phase and mixing phase, we focus on testing its computation time. According to Section 6.1, such group signature is divided into five stages: MJ, MR, KU, SG and SV. Fig. 5 investigates the computation costs at different stages. The experimental results are consistent with our theoretical evaluation results. Compared with the existing secure group signature $FSGS$ [29], the advantages of CoinLayering-PA are mainly reflected in the following stages. In KU stage, compared with CoinLayering-PA, $FSGS$ requires one more squaring operation, but there is no significant difference in

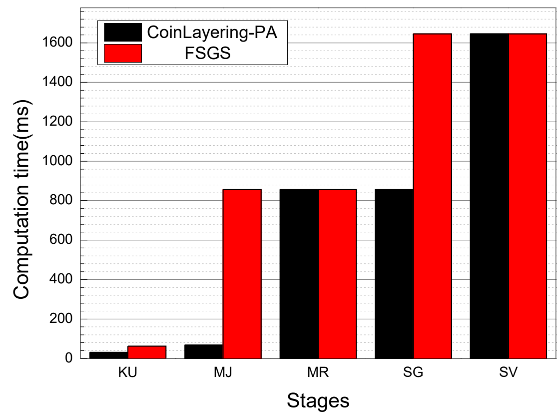

Fig. 5. Comparison between CoinLayer-PA and FSGS

their computation costs, because the squaring operation is lightweight. In MJ stage, because the computation cost of E is relatively higher, as the $Mixes$ increase, the computation cost of $FSGS$ is about to get even larger, i.e., the difference between CoinLayering-PA and $FSGS$ would also become larger. In SG phase, to ensure security, $FSGS$ requires $Supervisor$ to perform a E operation, which also increases the computation cost.

6.2.2 On The Performance of CoinLayering-PB

To secure the Bitcoin transactions between $Mixes$, CoinLayering-PB adds threshold signature to CoinLayering-PA. In this, we first test the computation costs of threshold signature in CoinLayering-PB. Then, measure the computation time of CoinLayering-PB's entire process and compare it with other protocols (including CoinParty [10] and Zerocoin [30]).

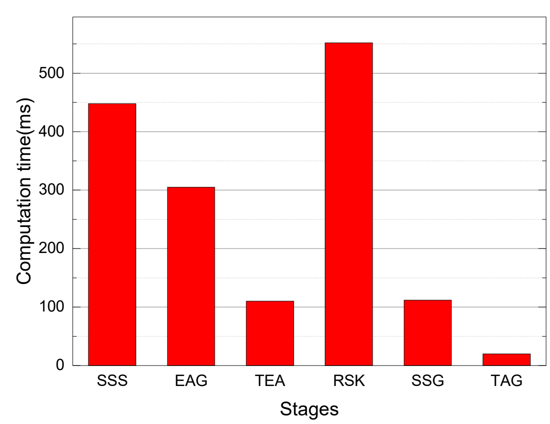

Fig. 6. Computation costs at different stages in threshold signature

In CoinLayering-PB, the threshold signature technique are mainly divided into the following stages: Security Secret Sharing (SSS), Escrow Address Generation (EAG), Total Escrow Address generation (TEA), Request Signature Key (RSK), Sub-Signature Generation (SSG), Threshold Signature Generation (TAG). In this, we investigate the computation costs at different stages, and the results are shown in Fig. 6. We can obviously observe that SSS and RSK stages take more time, but this does not affect the efficiency of transaction. The reasons can be stated as follows. Firstly, although Joint-SSS operation with high computation cost is required in SSS stage, it only requires performing once

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during the Mix registration. Secondly, since $In - SS$ operation with high computation cost is the main work of RSK stage, CoinLayering-PB allows the $Supervisor$ with abundant computing resources to perform it, instead of those over-loaded $Mixes$. This can effectively ensure the efficiency of transactions. From the above, even in the face of large scale transactions, Coinlayering-PB is scalable.

Coinlayering-PB mainly contains the following operations: M, E, H and R. For the convenience of functional analysis, we investigate the total running time of each operation, and the results are shown in Fig. 7, in which SUM denotes and the aggregation time of all operations. We can summarize the following interesting observations: (1) the computation cost of Coinlayering-PB is between CoinParty and ZeroCoin. This is because R operation would bring about the high computing overhead. In CoinLayering, R operation is performed 4 times, while 10 times in CoinParty. As for ZeroCoin, it is based on discrete logarithms and thus does not require R. (2) The computation cost of CoinLayering-PA is almost equal with CoinLayering-PB. This means that, the threshold signature is lightweight, and does not take up $Users'$ transaction time.

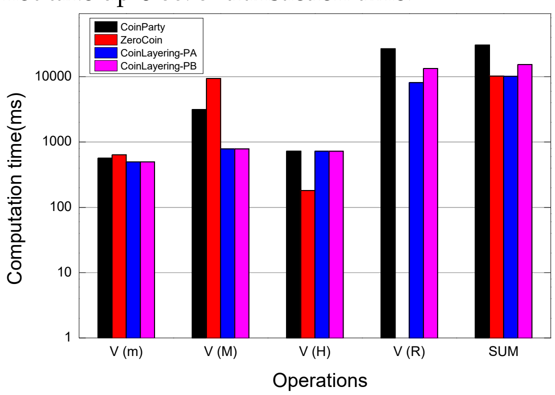


Fig. 7. Comparison between Coinlayering-PB and other protocols

6.2.3 On The Performance of CoinLayering

As the number of transactions increases, performance overhead of CoinLayering also grows. To ensure that CoinLayering can cope with the large scale Bitcoin transactions, here we focus on evaluating its scalability. Firstly, we investigate how the computation costs of varied entities (including $User$, $Supervisor$, Mix_1 and Mix_2) scale with an increasing number of transactions. We separate Mix_1 from Mix_2 during test execution, because their operations are different in mixing process. And we test the overall performance of CoinLayering and meantime compare it with CoinParty [10] and Zerocoin [30]. Secondly, considering that the number of network trips is an important factor affecting task execution time, we compare the communication amounts in the varied schemes. Thirdly, considering that the multiple copies of redundant storage in blockchain make it potential for the scalability issues, we aims to investigating the storage cost through varying the number of transactions. For the discrete logarithm-based signature and elliptic curve-based signature, we respectively fix 1024-bit and 256-bit.

Fig. 8 shows the computation costs of varied entities worked as a function of the number of transactions. For any entity, we measure its computation time through accumulating the running time of all its linear pair operations. From the evaluation results, we made the following observations. Firstly, it is evident that the computation cost of $User$ is low and its curve is almost flat. The reason is that, for the $User$, only a few operations are required to perform in CoinLayering. In general, its total computation cost is $2M+3E+H$, which includes registration cost $M+2E+H$ (mainly involve public key generation and knowledge signature) and mixing cost $E+M$ (involve message blinding). Secondly, though the computation cost in Mix_1 is slightly higher than Mix_2, their difference is not so much (belong to the same order of magnitude). This is because, judging by computational overhead only, compared to Mix_1, Mix_2 needs to only one more M. Thirdly, with the increasing of transactions, the computation cost of $Supervisor$ is also rising up. The increase of transactions requires more registered $Mixes$, which results in the surge of M operations. From the above, we can conclude that, in the face of large scale transactions, $Supervisor$ is more likely to be the bottleneck of the system. However, once we migrate it to cloud platform with super capacity, such issue would be well solved.

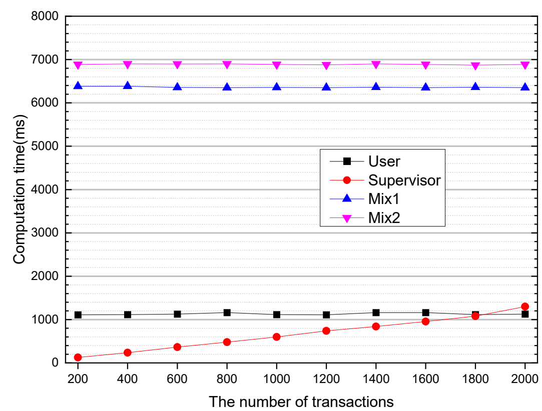


Fig. 8. Computation costs of varied entities by increasing the number of transactions

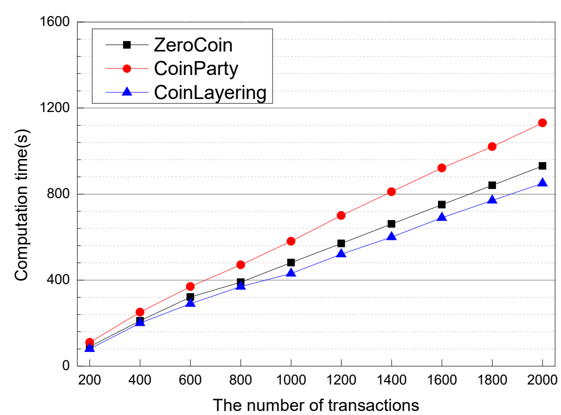
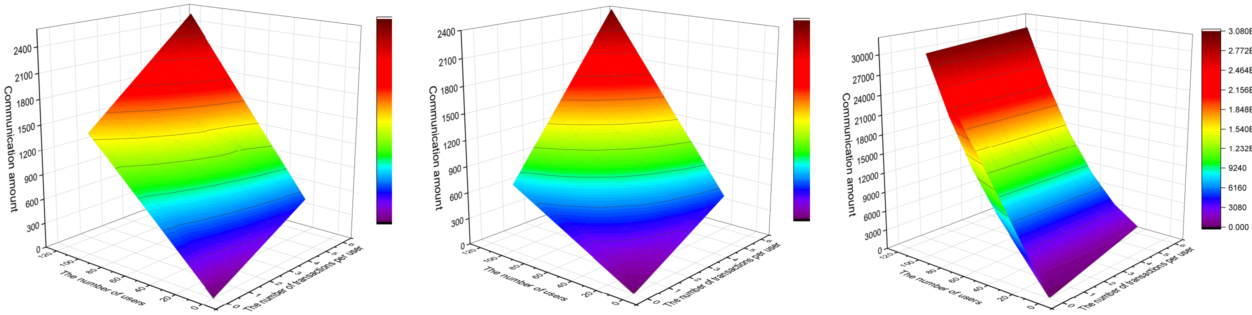


Fig. 9. Overall comparison between CoinLayering and other schemes

Fig. 9 shows how the overall computation cost varied as the number of transactions increases. For ease of comparison between the other schemes, we measure overall computation time through accumulating the trading time of each entity. In the simulation, trading time just refers to the spent time during mixing phase, considering that registration cost is produced only when the system is initialized or new $User$ joins. The evaluation results are summarized as follows. Firstly, no matter CoinLayering, Coinparty or Zercoin, the



(a) CoinLayering (b) ZeroCoin (c) CoinParty

Fig. 10. Communication amount by increasing the number of transactions.

overall trend of its computation cost is obviously rasing up, with the increasing of transactions. In CoinLayering, according to the conclusion from Fig. 8, $Supervisor$ is the major contributors to the increase of overall computation cost. For any new $User$, in Coinparty, other ones have to interact with it so as to generate the new signature, which adds additional $E + M$ operations. Zercoin requires all $Mixes$ to constantly interact with the new $User$ and perform E operation. Secondly, with the increasing of transactions, the computation cost of CoinLayering is higher than Coinparty and Zercoin, which is slightly different from Fig. 7. This is because, CoinLayering wouldn't require significant M,E and H operations in trading situations, and meantime its most time-consuming operation R takes place in the registration phase, which would not take up the trading time.

Fig. 10 shows the evaluation results for communication amount (i.e., the number of network trips), which is worked as a function of the number of $Users$ and the number of transactions. It is clear that, compared to CoinParty, both ZeroCoin and CoinLayering require less communication amount. The reason can be stated as follows. ZeroCoin adopts zero-knowledge proof technology and thus only requires three communications for one transaction; on this basis, CoinLayering adds one more interaction between two $Mixes$; CoinParty requires significant communications to generate threshold signatures and escrow addresses.

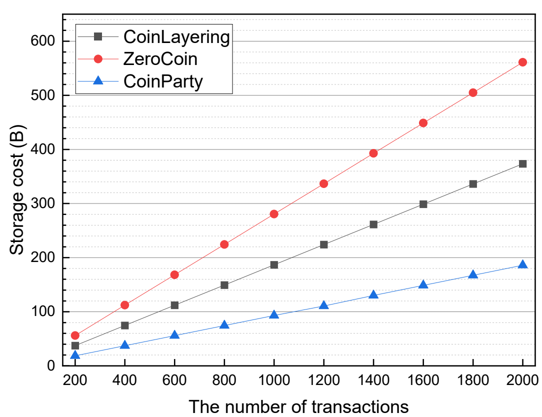


Fig. 11. Storage costs by increasing the number of transactions.

Fig. 11 shows how the storage cost changed as the number of transactions increases. In coin mixing, the signatures and other credentials would be recorded on the chain. It is evident from the figure that the storage requirements in CoinLayering is higher than CoinParty, but far lower than Zerocoin. This is because CoinParty adopts the elliptic curve based threshold signature with the smaller length, but CoinLayering still requires a group signature, besides the 256-bit threshold signature. In ZeroCoin, it adopts the knowledge signature whose length is the same with the group signature of CoinLayering. In addition, it needs to first convert Bitcoin to 1024-bit Zerocoin, which enforces the need for the storage.

7 Conclusion

In this paper, we proposed an efficient coin mixing scheme for large scale Bitcoin transactions. The building blocks of our proposed CoinLayering scheme are as follows: a $User - Mix - Supervisor$ based system model (that allows $User$ to randomly select two $Mixes$ to respectively execute the Bitcoin holding and Bitcoin trading actions), a Mix selection algorithm (to ensure task completion), and two security coin mixing protocols (to mitigate the risk due to misbehaving middlepersons and $Supervisor$). Our security and performance evaluations demonstrated the utility of CoinLayering.

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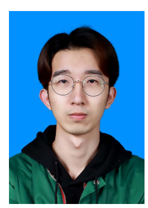
Ning Lu received the B.Sc. degree in Information and Computing Science from Inner Mongolia University, Huhhot, China, in 2006, M.S. degree from the Chongqing University of Posts and Telecommunications, Chongqing, China, in 2009 and Ph.D. candidate in State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2013. Now, he is a associated professor in Northeastern University. His current research interests include artificial intelligence security, data security and privacy protection, Denial of Service attack defense.



Yuan Chang received the BE degree in Computer Science and Technology from Shenyang Architecture University, Shenyang, China, in 2019. He is currently a postgraduate student in Northeastern University. His current research interests include cryptography, data security and privacy protection.

Wenbo Shi received the M.S. degree from the Inha University, Incheon, South Korea, in 2007 and the Ph.D. degree from the Inha University, Incheon, South Korea, in 2010. Currently he is a professor at Northeastern University at Qinhuangdao. His research interests include cryptographic protocol, cloud computing security, artificial intelligence security, data security and privacy protection, Denial of Service attack defense.

Kim-Kwang Raymond Choo (Senior Member, IEEE) received the Ph.D. in Information Security in 2006 from Queensland University of Technology, Australia. He currently holds the Cloud Technology Endowed Professorship at The University of Texas at San Antonio (UTSA). He was included in Web of Science's Highly Cited Researcher in the field of Cross-Field – 2020, and in 2015 he and his team won the Digital Forensics Research Challenge organized by Germany's University of Erlangen-Nuremberg. He is the recipient of the 2019 IEEE Technical Committee on Scalable Computing Award for Excellence in Scalable Computing (Middle Career Researcher), the 2018 UTSA College of Business Col. Jean Piccione and Lt. Col. Philip Piccione Endowed Research Award for Tenured Faculty, the British Computer Society's 2019 Wilkes Award Runner-up, the 2019 EURASIP Journal on Wireless Communications and Networking Best Paper Award, the Korea Information Processing Society's JIPS Survey Paper Award (Gold) 2019, the IEEE Blockchain 2019 Outstanding Paper Award, the Inscrypt 2019 Best Student Paper Award, the IEEE TrustCom 2018 Best Paper Award, the ESORICS 2015 Best Research Paper Award, the 2014 Highly Commended Award by the Australia New Zealand Policing Advisory Agency, the Fulbright Scholarship in 2009, the 2008 Australia Day Achievement Medallion, and the British Computer Society's Wilkes Award in 2008.

APPENDIX A: INCENTIVE STRATEGY

To attract more honest $Mixes$, CoinLayering pays several Bitcoins as the profit to them. For a $User$, with the increase of the transactions, the cost to pay for those mixing service would also grow linearly. But, this would bring severe economy burdens for this $User$, and further decrease the incentive to mix coin. In this, we provide an incentive mechanism termed as CoiInc, in which $User$ would acquire extra rewards as long as it persistently utilizes CoinLayering.

Only if the $User$ continuously purchases the mixing service can its costs be reduced by $Supervisor$. Given a time interval T_d, we term the $User$ that continuously purchases more than two mixing services during T_d as the continuous mixing $User$. In this, our proposed CoiInc contains two steps: applying for incentive subsidy and granting for incentive subsidy. The details can be depicted as follows:

Step 1: When $User$ purchases the coin mixing service more than once, it firstly performs the operation $tx_d^2 : I \rightarrow E_1$. And then calculates the difference T_s between the current transaction time and the last transaction time. If $T_s \leq T_d$, the $User$ submits the tx_d^2 record to $Supervisor$ and applies for incentive subsidy.

Step 2: Upon receiving the request, $Supervisor$ firstly verifies the tx_d^2 and record its input $User$'s address I. Then, use I to search the last transaction tx_d^1 in BB. Meantime, judge whether the $User$ I is eligible for the incentive subsidy through computing the time difference between tx_d^1 and tx_d^2. If it does, $Supervisor$ computes the amount of its incentive subsidy $f = BC \times b$ and then sends them to I, where BC denotes the total value of the current transaction, b denotes the proportion of incentive subsidy in BC. Normally, b is proportional to the number of mixing times during T_d.

It is worthy of note that, although $Supervisor$ can verifies the input $User$'s address during the second step, it is incapable of watching the privacy of seller-buyer relationship and thus cannot decrease the anonymous set. The reason is that, during the interaction with Mix_2, the identity of $User$ is different from that it interacts with $Supervisor$. Going a further step, $Supervisor$ is unable to guess the buyer associated with Mix_2, let alone the connection between the seller and buyer.

APPENDIX B: A MORE SECURE GROUP SIGNATURE TECHNIQUE

In this section, we mainly illustrate how to embed the existing secure group signature technique [25] into our proposed CoinLayering. To prevent the Mix from watching the $User$'s information in secret, it requires the value of elements in group signature to be changed every time. The details can be depicted as follows.

Step 1: $Supervisor$ generates the group's private key (p, q, d), where p and q are two random primes. Then, generate group's public key (n, e), where $n = p \times q$ and $e \times d = 1\ (\mathrm{mod} n)$. At last, assign a random prime number p_i for each $Mixes$ and meantime send it to the corresponding Mix.

Step 2: When Mix_i receives (g, n, p_i) from Supervisor, it calculates the Mix_i's public key $y_i = g^{x_i} \bmod n$ and sends it to $Supervisor$, where g is the generator of cyclic group, and x_i is Mix_i's private key .

Step 3: After receiving y_i, $Supervisor$ constructs the congruence $c = y_i \bmod p_i$ and then saves c's value in a private way.

Step 4: Mix_i uses its private key x_i to sign the message M. Then, calculate its signature $s_i = h(M||\xi) \cdot x_i \bmod n$ and send (M, ξ, s_i, p_i) to $Supervisor$.

Step 5: $Supervisor$ needs verify whether the signature is valid through $y_i = c \bmod p_i$ and $h(M||\xi) = s_i^{y_i} \bmod n$. If valid, it calculates group signature $C = (h(M||s_i||r_1||r_2))^d$, where $r_1 = p_i + \alpha h(M||\xi) \bmod n$ and $r_2 = (\alpha h(M||\xi))^e \bmod n$. And then, send $(M, \xi, s_i, C, r_1, r_2)$ to Mix_i.

Step 6: When a coin mixing deal starts, Mix_1 firstly sends the group signature (as a voucher) to $User$. To verify this group signature, $User$ then sends it to Mix_2. If $C^e = h(M||s_i||r_1||r_2)$, it is valid.

APPENDIX C: AN ILLUSTRATION EXAMPLE

In this section, for easy understanding of CoinLayering, we present illustrative examples for the main primitives (including Mix selection and coin mixing protocol). Under normal circumstances, the entire workflow of CoinLayering can be stated as follows.

TABLE 5
The $Mixes$' attribute scores

Mix_i	$\vec{A_1}$	$\vec{A_2}$	$\vec{A_3}$	$\vec{A_4}$
i=1	60	95	60	95
i=2	70	85	70	85
i=3	90	75	90	75
i=4	95	65	95	65
i=5	55	80	55	80
i=6	75	75	75	75
i=7	80	60	80	60
i=8	45	65	45	65
i=9	72	62	72	62
i=10	80	50	80	50

Step 1: The owner of Bitcoins demonstrates to $Supervisor$ that it is fully qualified for a Mix. When successful, it generates a private key. Assume that there are 10 $Mixes$ registered in $Supervisor$.

Step 2: $Supervisor$ evaluates each Mix and the relevant attributes are shown in Table 5. And meantime, $Supervisor$ records the $Mixes'$ keys and enables them to generate signatures.

Step 3: When $User$ initiates coin mixing, it first finds $Mixes$ that meets its requirements, i.e., sends its requirements $\vec{w} = (0.1, 0.1, 0.2, 0.6)$ to $Supervisor$.

Step 4: $Supervisor$ firstly analyzes the current queuing situation and calculates the least number of candidate $Mixes$ $k = 3$ and average queue length $LQ = 5$. And then, use Mix selection strategy to recommend 3 appropriate $Mixes$, whose attributes are $M_1 = (60, 95, 60, 95), M_2 = (70, 85, 70, 85), M_3 = (90, 75, 90, 75)$.

Step 5: $User$ randomly selects Mix_i recommended by $Supervisor$ and obtain its queue length L_i. If $L_i < LQ$, Mix_i can be specified as Mix_1 or Mix_2.

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Step 6: $User$ utilizes identity U to send $T_1(23), T_2(38)$ to Mix_1, and meantime utilizes identity $U*$ to send $T_3(53), T_4(68)$ to Mix_2. When accept the requests, Mix_1 and Mix_2 respectively send commitments V_1=$\{sign\{23||38||40ibuLn6jFDn3ZVF\}x_1$ and V_2=$sign\{53||68||OBtIKydiEpkkGjzw\}x_2$.

Step 7: $User$ uses identity U to build $tx_1 : I \rightarrow E_1$ before T_1 and sends $m' = (O||ID_2||tfGzh3NFYH0WDugN) \cdot b^{y_2}$ to Mix_1.

Step 8: Mix_1 checks transaction tx_1 and sends $W = sign\{m'\}x_1$ to U before T_2.

Step 9: $User$ utilizes identity U^* and sends W to Mix_2 before T_3.

Step 10: Mix_2 verifies W and builds $tx_2 : K_2 \rightarrow O$ before T_4. After the owner of address O receives the transaction tx_2, the $User's$ transaction is completed.

Step 11: $supervisor$ conducts an audit for each Mix every time t, which is used to check whether the number of transactions hosted by Mix is consistent with the number of issued certificates W.

Step 12: During the audit on $supervisor$, Mix_1 builds the transaction $tx_3 : E_i \rightarrow E$, and Mix_2 initiates threshold signature $s_i = ([d^{-1}]_i) \cdot (e + k_i \cdot R)$ on transaction $tx_4 : E \rightarrow K_2$ (including mixing fees).