SilentDelivery: Practical Timed-delivery of Private Information using Smart Contracts

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Abstract—This paper proposes SilentDelivery, a secure, scalable and cost-efficient protocol for implementing timed information delivery service in a decentralized blockchain network. SilentDelivery employs a novel combination of threshold secret sharing and decentralized smart contracts. The protocol maintains shares of the decryption key of the private information of an information sender using a group of mailmen recruited in a blockchain network before the specified future time-frame and restores the information to the information recipient at the required time-frame. To tackle the key challenges that limit the security and scalability of the protocol, SilentDelivery incorporates two novel countermeasure strategies. The first strategy, namely silent recruitment, enables a mailman to get recruited by a sender silently without the knowledge of any third party. The second strategy, namely dual-mode execution, makes the protocol run in a lightweight mode by default, where the cost of running smart contracts is significantly reduced. We rigorously analyze the security of SilentDelivery and implement the protocol over the Ethereum official test network. The results demonstrate that SilentDelivery is more secure and scalable compared to the state of the art and reduces the cost of running smart contracts by 85%.

Index Terms—Blockchain, Smart Contract, Timed Information Delivery, Information Privacy, Timed Release, Secret Sharing.

1 INTRODUCTION

Rapid advancements in Internet and service technology have led to a proliferation of information exchange happening in the cyberspace. Timed information delivery service (TIDS) refers to a class of service that enables an information sender to make a piece of private information arrive at an information recipient during a chosen future time-frame. Many scenarios require timed delivery of information in real-world. For example, courier services allow clients to select a predetermined time-frame during which their mail can be delivered. The ability of TIDS to control the arrival time of sensitive information and knowing precisely when information arrives can be crucial for many businesses and enterprises. Imagine a situation in which Alice would like her business proposal to arrive at the corporate headquarter exactly during the board meeting time. Here, an early arrival of the proposal could potentially leak her idea to her competitors while a late arrival will remove Alice’s proposal out of the competition. While there are numerous services (e.g., Boomerang [1] and Postfity [2]) that provide pre-scheduled timed delivery of information, current implementations of timed information delivery services (TIDS) are heavily centralized. These services require the users to entirely trust the centralized servers and their security properties are solely limited to a single point of trust. More importantly, even in scenarios when the service providers are trustworthy, the services are still prone to unpredictable security breaches or insider attacks that are beyond the control of the service providers [3], [4]. On the other hand, the emergence of Blockchain technologies such as Ethereum [5] and Smart contracts [6] provides significant potential for new security designs that support a decentralized implementation of TIDS to overcome the single point of trust issues associated with centralized approaches.

In this paper, we present SilentDelivery, a secure, scalable and cost-efficient protocol for implementing timed information delivery services (TIDS) in a decentralized blockchain network. SilentDelivery employs a novel combination of threshold secret sharing [7] and decentralized smart contracts [6]. The protocol maintains shares of the decryption key of the private information of an information sender using a group of mailmen recruited in a blockchain network before the specified future time-frame and restores the information to the information recipient at the required time-frame. Here, the benefits of employing blockchains and smart contracts are threefold: (a) SilentDelivery establishes a permissionless TIDS marketplace atop well-established public blockchains (e.g., Ethereum), allowing any interested party to join the service community as a mailman. Information senders and mailmen can thus simply leverage the native cryptocurrencies of blockchains for payment and settlement; (b) SilentDelivery inherits the two key security properties persistence and liveness of public blockchain backbone [8] and hence, both senders and mailmen cannot deny any information (e.g., recruitment relationship) recorded in the blockchain (persistence). They are protected from selective denial of service attacks and can always change the blockchain state with valid transactions (liveness); (c) Inspired by recent work on blockchain-based secure multi-party computations [9], [10], [11], SilentDelivery protects the fairness of TIDS and handles any misbehavior against the protocol by using the

1. E.g., UPS customers can pick a 2-hour time frame for ensuring a confirmed delivery. https://www.ups.com/us/en/help-center/sr/ups-my-choice-delivery-window.page
2. https://www.rapidparcel.com/timed-delivery/
cryptocurrencies pre-locked in smart contracts as security *deposits* and their confiscation as *penalty*. Hence, rational participants of the protocol are always incentivized to honestly follow the protocol. However, a naive design of the protocol, where each message is delivered by a single mailman, may result in both low service availability (i.e., the single mailman accidentally loses data or network connection) as well as lead to a single point of trust (i.e., anyone that manages the decryption key may collude with the single mailman). Therefore, *SilentDelivery* delivers each message with a group of *n* mailmen. Each mailman manages a share of the decryption key as well as a copy of the encrypted message. As long as at least *t* (*t* < *n*) mailmen manage shares well, the message would be successfully delivered without getting prematurely disclosed.

Here, the use of blockchains and smart contracts also leads to two key challenges that impact the security and scalability of the protocol. First, for the sake of fair trade, the protocol requires senders and mailmen to conclude recruitment relationships via smart contracts but the transparency of smart contracts makes it difficult to conceal the relationships before the future time-frame which challenges the service security in multiple aspects. Second, due to the use of threshold secret sharing, the protocol requires senders to recruit a group of *n* mailmen to gain higher service availability which involves *O(n)* transaction fees for carrying out the interactions between the *n* recruited mailmen and smart contracts. Hence, given a large *n*, the cost for running the service could be more than what most users can afford, making the approach difficult to work in practice. *SilentDelivery* incorporates two novel countermeasure strategies to tackle these two challenges, respectively. The first strategy, namely *silent recruitment*, recruit each mailman for a sender *silently* without the knowledge of any third party while still making it possible for the recruitment relationship to be revealed to the smart contracts during a future time-frame. Moreover, a mailman recruited via *silent recruitment* cannot prove the hidden recruitment relationship to any party, including the information recipient and other mailmen. Hence, *silent recruitment* could significantly reduce the attack surface by making any potential adversary unable to differentiate a small group of mailmen that deliver a specific message from other mailmen inside the large mailmen community who have registered in the smart contracts. The second strategy, namely *dual-mode execution*, makes the protocol run in a lightweight mode by default, where the non-scalable regulations are cut off to reduce the cost of running smart contracts significantly. When a dispute occurs, any recruited mailman reserves the ability to switch the protocol to a heavyweight mode by rebinding the removed regulations with smart contracts to redress and penalize any fraudulent or dishonest behavior, just as if these regulations were never decoupled.

In a nutshell, this paper makes the following key contributions:

- To the best of our knowledge, *SilentDelivery* is the first practical decentralized approach designed for *TIDS* that is secure, scalable and cost-efficient.
- *SilentDelivery* is a pure decentralized approach designed for a trustless environment, without requiring any trusted party.
- *SilentDelivery* completely isolates the service execution from the state of sender after the service has been set up, without requiring any assistance from the sender side.
- *SilentDelivery* employs the *silent recruitment* strategy to reduce the attack surface of *TIDS* and employs the *dual-mode execution* strategy to reduce the service cost.
- We rigorously analyze the security of *SilentDelivery* and implement the protocol over the Ethereum official test network. The results demonstrate that *SilentDelivery* is more secure and scalable compared to the state of the art and reduces the cost of running smart contracts by 85%.

The rest of this paper is organized as follows: We start by introducing preliminaries in Section 2. In Section 3, we present a strawman protocol for *TIDS* that involves public recruitment relationships as well as a high service cost. We then analyze the two challenges and present the attack methods and design goals. In Section 4, we propose the *SilentDelivery* protocol and presents the two countermeasure strategies, namely *silent recruitment* and *dual-mode execution*. In Section 5, we rigorously analyze the security and cost of *SilentDelivery*. We implement and evaluate the protocols over the Ethereum official test network in Section 6. Finally, we discuss related work in Section 7 and conclude in Section 8.

2 Preliminaries

In this section, we discuss the preliminaries about smart contracts and introduce the key cryptographic tools used in our work. While we discuss smart contracts in the context of Ethereum [6], we note that our solutions are also applicable to a wide range of other smart contract platforms. We summarize the key notations that will be used in this section and in the rest of this paper in Table 1.

2.1 Smart contracts

There are two types of accounts in Ethereum, namely External Owned Accounts (EOAs) and Contract Accounts (CAs). To interact with the Ethereum blockchain, an user needs to own an EOA by locally creating a pair of keys. Specifically, the public key *pkEOA* can generate a 20-byte address *addrEOA* to uniquely identify the EOA and the private key *skEOA* can be used by the user to sign transactions or other types of data. Then, any user can create a smart contract by sending out a contract creation transaction from a controlled EOA. The 20-byte address *addr(CA)* of the created smart contract is generated in a deterministic and predictable way and becomes the unique identity of the contract account (CA).

A smart contract (or contract, *C*) in Ethereum is a piece of program created using a high-level contract-oriented programming language such as *Solidity*. After compiling into a low-level bytecode language called Ethereum Virtual Machine (EVM) code, the created contract is packaged into a transaction, which is then broadcasted to the entire Ethereum network formed by tens of thousands of miner nodes. Following the Proof-of-Work (PoW) consensus protocol [12], all the miners in Ethereum competitively solve
TABLE 1: Summary of notations.

| notation | description |
|----------|-------------|
| S        | an information sender |
| M        | a mailman |
| R        | an information recipient |
| C        | a smart contract |
| C.fun()  | function fun() within contract C |
| =>       | transmit messages via private off-chain channels |
| addr(*)  | an 20-byte address of an EOA or a CA |
| hash(*)  | an keccak hash value |
| List(*)  | a list of objects |

2.2 Transaction fees

In order to either deploy a new contract or call a deployed contract in Ethereum, one needs to spend Gas, or transaction fees. Based on the computational work of the transactions or smart contracts executed by miners, a part of Ethereum needs to be spent in order to purchase an amount of Gas, which is then paid to the miner that creates the new block. The Gas system is important for Ethereum as it helps incentivize miners to stay honest, nullify denial-of-service attacks and encourage efficiency in smart contract programming. On the other hand, the Gas system requires protocols, especially the multi-party ones, to be designed with higher scalability in Ethereum. This is due to the fact that even a single-round multi-party protocol could spend a lot of money to run in case of a large number of participants.

2.3 Off-chain channels

In Ethereum, nodes forming the underlying P2P network can send messages to each other via off-chain channels established through the Whisper protocol [13]. By default, messages are publicly broadcast to the entire P2P network. The Whisper protocol enables two important functionalities: (1) message filtering functionality that enables an EOA to set up a filter to only accept interested messages marked with a specific 4-byte topic (e.g., the topic could be TIDS); (2) private channel functionality that enables two EOAs to establish private off-chain channels to exchange messages with either symmetric or asymmetric keys. Concretely, any EOA can locally generate a pair of asymmetric Whisper keys and reveal the public Whisper key by storing it into the transparent TIDS smart contract, which allows other EOAs to initialize private off-chain channels. In the rest of this paper, we assume that the private off-chain channels are secure and we omit the detailed settings of off-chain channels. Also, to make it easier to distinguish on/off-chain interactions, we denote private off-chain communication between two EOAs and public on-chain function invocation transactions with symbols \( \rightarrow \) and \( \Rightarrow \), respectively. It is worth noting that off-chain communication costs no money while on-chain transactions charge transaction fees.

2.4 Cryptographic tools

The design of SilentDelivery employs several key cryptographic tools: (1) \((t,n)\)-threshold secret sharing [2] is used to split the decryption key of the private information into \( n \) shares, among which any \( M \) shares could recover the key but \( t - 1 \) or fewer shares fail to do that. Specifically, we denote the key split and key restoration as \( \text{shares} \leftarrow \text{SS.split(key,}[t,n]\text{)} \) and \( \text{key} \leftarrow \text{SS.restore(shares,}[t,n]\text{)} \), respectively. (2) We use the Keccak 256-bit hash function supported by Ethereum and it is denoted as \( \text{hash(*)} \). (3) We use the ECDSA signature supported by Ethereum. Specifically, a EOA (i.e., signer) can sign any message with its private account key \( sk_{\text{EOA}} \) via JavaScript API and get signature \( vrs \leftarrow \text{sig(hash(message))} \). Later, other EOAs or CAs can recover the address of the signer EOA (i.e. addr(signer)) via JavaScript API or Solidity native function and get \( \text{addr} \leftarrow vf(hash(message), vrs) \). The signature \( vrs \) can be either privately delivered via off-chain channels or publicly announced via the blockchain.

3 A STRAWMAN PROTOCOL

We first describe the timed information delivery service (TIDS) as a three-phase process. We then propose a strawman protocol that implements TIDS using threshold secret sharing and smart contracts. We analyze the key limitations of the strawman protocol in terms of its security and scalability and finally, we present the attack methods.

3.1 TIDS as a three-phase process

We describe the TIDS problem as a three-phase process:

- **TIDS.send**: The information sender (or signer, \( S \)) sends her private information with a time-frame and the identity of information recipient (or recipient, \( R \)) to the TIDS service provider (i.e., mailmen in our protocol).
- **TIDS.pend**: The TIDS provider preserves the private information before the specified time-frame.
- **TIDS.deliver**: The TIDS provider delivers the private information to the recipient during the specified time-frame.

3.2 The strawman protocol

We first propose a strawman protocol that implements TIDS using threshold secret sharing and smart contracts. We sketch the strawman protocol in Fig. 3 and present the formal description in Fig. 4. Specifically, the regulations of the strawman protocol are programmed as an agent contract \( C_{\text{agent}} \) through which a sender can recruit a
group of Ethereum accounts to jointly take the role of the TIDS provider. We name each account serving for TIDS a mailman, M. The protocol demands each mailman M to register itself to the agent contract $C_{agent}$ via \texttt{newMailman(whiskey, } \Xi \text{deposit)}, where whiskey is a public Whisper key used to establish a private communication channel with the mailman using the Ethereum Whisper protocol and $\Xi$deposit represents the amount of Ether($\Xi$) that will be locked in $C_{agent}$ as a security deposit. We can understand that there is a recruitment agreement at $C_{agent}$, which goes into effect only when it has been signed by both a sender and a mailman, so that the registration of a mailman in this context means that the mailman has signed on a recruitment agreement and has promised to serve for future senders without violating the protocol. Otherwise the $\Xi$deposit will get confiscated. We next describe the three phases of the strawman protocol in detail.

**TIDS.send:** Sender S first creates a $key$ as well as a $receipt$, splits $key$ into $shares$ via secret sharing and encrypts both her private information (or $info$) and $receipt$ with $key$. Sender S then sets up a new service with $C_{agent}$ via \texttt{newService()} and specifies the service details including a future time-frame [day, slot], parameters $[t,n]$ for secret sharing and addresses (i.e., $addr(*)$) of both recipient R and a list (i.e., $List(*)$) of randomly selected registered mailmen. In addition, sender S also commits the values of $shares$ and $receipt$ by submitting their hash values (i.e., $hash(*)$) to $C_{agent}$ and locks an amount of Ether as $\Xi$remuneration to pay the mailmen. Finally, through private off-chain channels, sender S assigns each recruited mailman a $share$ and transmits the encrypted $[info,receipt]$ to recipient R. Here, the submission of addresses of selected mailmen implies that sender S has signed the recruitment agreements with these mailmen and has promised to pay $\Xi$remuneration for a successful service. From then on, the agreements signed by both sides come into force.

**TIDS.pend:** If any recruited mailman discloses its maintained $share$ before the time-frame, any mailman obtaining this $share$ will be able to report the premature disclosure of this $share$ to $C_{agent}$ via \texttt{reportPremature()}. With $hash(share)$ stored in $C_{agent}$, this function will be able to verify this report and divide $\Xi$deposit of the accused mailman to the informer as well as sender S in case of a true report. Here, the reward is split for the purpose of preventing malicious mailman from intentionally reporting itself with a different account and get back its locked deposit before disclosing the maintained $share$ to other parties. As a result, a malicious mailman can only obtain a negative payoff of performing premature disclosure unless it colludes with sender S or receives additional payment (i.e., bribery). We believe that the collusion share does not happen as it brings no benefits for sender S. We will discuss the latter situation as the bribery attack in section 3.4.

**TIDS.deliver:** During the time-frame, each mailman reveals its maintained $share$ to $C_{agent}$ via \texttt{revealShare()}. Recipient R, after restoring $key$ and decrypts $[info, receipt]$, receives $info$ and notifies the arrival of $info$ by revealing receipt to $C_{agent}$ via \texttt{revealReceipt()}. Finally, each honest recruited mailman can either keep serving for future senders without requesting withdrawals or stop working and withdraw $\Xi$deposit and accumulated $\Xi$remuneration from $C_{agent}$.

### 3.3 Limitations and challenges

We identify two challenges that significantly limit the security and scalability of the strawman protocol.

5. In case that a party getting the disclosed $share$ owns no mailman account, the party can report the disclosure by informing the $share$ to a mailman and share the reward with the mailman. The fairness can be guaranteed by deploying a smart contract that takes both disclosed $share$ from the party and an amount of deposit from the mailman as inputs. The smart contract can verify the input $share$ with $hash(share)$ retrieved from $C_{agent}$ and then both reward the party with the locked deposit and send out a transaction to call \texttt{reportPremature()} that rewards (larger than deposit) the mailman.
3.3.1 Premature revelation of recruitment relationships

In the strawman protocol, a recruitment agreement (or agreement) is first signed by a registered mailman and then signed by a sender. After that, the agreement comes into force at step 2 while at the same moment the included recruitment relationship (or relationship) is made known to all via the uploaded addresses of recruited mailmen, namely \( \text{List}(\text{addr}(M)) \). Later, the protocol ends at step 9, allowing each honest recruited mailman to make withdrawals. After revisiting this procedure, we observe that the relationships were getting revealed much earlier than necessary. Specifically, the relationships were made public at step 2 while only at step 9, namely the settlement stage, it becomes necessary for \( C_{\text{agent}} \) to know \( \text{List}(\text{addr}(M)) \) to approve withdrawals. Such a premature revelation of relationships endangers the security of TIDS in two aspects.

First, it has been widely recognized that the anonymity offered by blockchain networks is not strong \(^{14} \) and therefore, premature revelation helps an adversary locate recruited mailmen before \( \text{TIDS.deliver} \). Specifically, for the sake of anonymity, one may create a new Ethereum account to be a mailman. However, this new account must have been transferred an amount of Ether by an existing account in order to call \( \text{newMailman()} \) and pay \( \text{Zdeposit} \). In case that the information of the owner of the existing account has been disclosed at public places such as a forum, the anonymity of the mailman account has been breached via the connection of the two accounts. An adversary could then leverage the disclosed information about the existing account to attack the new mailman account. This significantly weakens the underlying protections of the mailmen offered by the large-scale anonymous Ethereum P2P network. In an ideal scenario when no information about the relationships is disclosed, from the view of an adversary, all the registered mailmen have equal probability to be recruited by a sender.

Second, in case of a recruited mailman seeking collusion with any other party, the premature revelation helps the mailman prove its relationship to that party, which further promotes the success of the trading between these mutually distrusted two parties. What makes the problem more challenging is that the relationships may get revealed through side information, other than just \( \text{List}(\text{addr}(M)) \). For instance, even if we conceal \( \text{List}(\text{hash}(\text{share})) \) in step 2, due to the public \( \text{List}(\text{hash}(\text{share})) \), a mailman can still prove its relationship by revealing its maintained \( \text{share} \). To make matters worse, even if the strawman protocol has forbidden any premature disclosure of \( \text{shares} \) through \( \text{reportPremature()} \), it is still possible for a sophisticated mailman to bypass this restriction by offering a zero-knowledge proof \( \pi \) \(^{15} \) to demonstrate that the mailman knows the pre-image of \( \text{hash} \) \( \text{(share)} \) (i.e., \( \text{share} \)), without revealing \( \text{share} \), thus being able to prove its relationship without being penalized. Therefore, to overcome this difficulty, we need a solution that can conceal both \( \text{List}(\text{addr}(M)) \) and all possible side information (e.g., \( \text{List}(\text{hash}(\text{share})) \)) before \( \text{TIDS.deliver} \) while still making \( \text{List}(\text{addr}(M)) \) get back in \( C_{\text{agent}} \) during \( \text{TIDS.deliver} \) to help \( C_{\text{agent}} \) process withdrawal requests.

3.3.2 A tradeoff between scalability and availability

We observe that the non-scalable design of the strawman protocol leads to \( O(n) \) gas cost for a sender to recruit \( n \) mailman, which makes the protocol hard to scale in practice. There are two places in the strawman protocol that make the gas cost go with \( O(n) \). First, at step 2, after sender \( S \) uploads \( \text{List}(\text{addr}(M)) \), an amount of gas needs to be spent in \( C_{\text{agent}} \) to change the state of each recruited mailman and bind this mailman with this service. Second, at step 6, each recruited mailman needs to spend an amount of gas to reveal its maintained \( \text{share} \) to \( C_{\text{agent}} \) so that the \( \text{share} \) can be verified through the \( \text{hash} \) \( \text{(share)} \) in \( C_{\text{agent}} \) and made known to recipient \( R \). Obviously, the simplest way of reducing gas cost would be recruiting fewer mailmen. However, given a fixed \( t \) regarding \( (t,n) \)-threshold secret sharing as well as a fixed probability that a single \( \text{share} \) gets lost, a larger \( n \) results in a higher probability of recovering \( \text{key} \) at protocol step 7, namely higher availability of TIDS \(^{16} \). This shows the tradeoff between scalability and availability of the TIDS. To address this, we propose a redesign of the protocol so that the non-scalable regulations within \( C_{\text{agent}} \) can be removed while the removed regulations can still constrain the behaviors of protocol participants just as if these regulations are still bounded with \( C_{\text{agent}} \) in blockchain.

3.4 Attack methods

Two attack methods can be used to disclose the private information before the prescribed time-frame. Specifically, we assume that there exists an adversary seeking the premature disclosure of private information before the future time-frame. For instance, Alice’s competitors may want to learn the content of her business proposal before the board meeting time. It is easy to see that such premature disclosure could happen when an adversary acquires enough shares of the decryption key from the recruited mailmen before the time-frame. The adversary can employ two methods to achieve this goal. The first attack method is based on subverting the security of the protocol by creating a large number of EOAs leading to a Sybil attack \(^{17} \) to gain a disproportionately large influence in getting recruited as a mailmen and recovering the decryption key from the shares in the mailmen. The second attack method is based on creating a monetary reward to bribe the recruited mailmen to disclose the key shares prior to the release time. We refer to it as the Bribery attack.

4 The \text{SilentDelivery} Protocol

In this section, we start by introducing our key ideas for tackling the challenges that limit the strawman protocol. We then present the proposed \text{SilentDelivery} protocol and focus on its two novel countermeasure strategies, namely \text{silent recruitment} and \text{dual-mode execution}. We sketch the \text{SilentDelivery} protocol in Fig. 5 and formally describe it in Fig. 4 and Fig. 5.
4.1 Tackling the challenges

We observe both similarities and differences in tackling the two challenges presented in Section 3.3. Regarding similarities, both the two challenges demand a way for removing data from the agent contract Cagent while they also need the removal to be rolled back when a certain condition is reached. Specifically, a solution for the first challenge, namely the premature revelation of recruitment relationships, should remove recruitment relationships from Cagent before TIDS.deliver and later reveal the relationships to Cagent during TIDS.deliver. Similarly, a solution for the second challenge, namely the tradeoff between scalability and availability of TIDS, should remove non-scalable regulations from Cagent and later reveal these regulations to Cagent in case of any violation of them occurred. The main differences between them are twofold: (1) the removed relationships should be concealed against any third party while the removed regulations should still be made public; (2) the rollback of the removal of relationships is inevitably driven by the arrival of time-frame while the rollback of the removal of regulations is driven by violations of these regulations, which is completely avoidable when the recruited mailmen are honest.

By keeping these similarities and differences in mind, in SilentDelivery, we design two different countermeasure strategies for tackling the two challenges. As illustrated in Fig. 3, the first countermeasure strategy is implemented as a silent recruitment component within the TIDS.send phase. The key idea behind it is to consider the relationships also a type of private information that demands timed delivery, so both senders and mailmen should sign their recruitment agreements secretly and their signatures should also be protected with the key split into shares. The second countermeasure strategy, namely dual-mode execution, allows the protocol to be executed in two different modes. Specifically, we cut the non-scalable regulations out of Cagent and re-organize them as a supplementary contract Csup. By default, when recruited mailmen honestly follow the removed regulations, the protocol goes with its lightweight mode without involving any O(n) on-chain interactions. If any recruited mailman violates the removed regulations, any honest mailman can rebind the removed regulations (i.e., Csup) with Cagent to penalize the violations, which turns the protocol into the heavyweight mode and results in a pay-cut. Thus, the penalty of misbehaviors and the pay-cut induced by the heavyweight mode can incentivize recruited mailmen to stay honest, making the protocol stays at its lightweight mode with O(1) gas cost.

4.2 Silent recruitment

Before presenting the TIDS.send phase, it is worth noting that SilentDelivery demands each mailman to create a list of [privkey, pubkey] key pairs for a list of future time-frames [day, slot], maintain all the privkeys by itself and submit all the pubkeys to the agent contract Cagent during registration via newMailman(). A private key in a dedicated key pair is designed to be revealed by the mailman at a prescribed time point. Besides the onion planed to be decrypted, there will be no other information protected by the private key. In other words, the private key is designed to never be reused. During TIDS.send, sender S first deploys a switch contract Csup, which contains a single function deploySupplementary(). Just like the name implies, through Csup, any honest mailman can deploy the supplementary contract Csup and turn the protocol from the default lightweight mode into
Epoch-0 [reporting premature]:
1. A mailman $M$ does the following and the protocol jumps to epoch-2.
   1.1. $\Rightarrow C_{sw}.deploySupplementary(addr(C_{sw}), C_{sup}, vrs_{sup})$.
   1.2. $\Rightarrow C_{sup}.reportPremature(index, privkey)$.

Epoch-1 [lightweight mode]:
2. Each mailman $M$ reveals its $privkey$.
3. Recipient $R$ gets $shares \leftarrow D(privkeys, onions)$.
4. If $|shares| \geq t$, recipient $R$ does the following and the protocol jumps to epoch-6.
   4.1. Restore key $\leftarrow SS.restore(shares, [t,n])$ and obtain $[info, receipt] \leftarrow D(key, [info, receipt])$.
   4.2. $\Rightarrow C_{agent}: recipientReceipt(receipt, addr(S), addr(C_{sw}))$.
   Otherwise, the protocol goes to epoch-2.

Epoch-2 [switching mode]:
5. $M \Rightarrow C_{sw}.deploySupplementary(addr(C_{sw}), C_{sup}, vrs_{sup})$.
6. Mailmen reveal their maintained $privkeys$ to public and collect $privkeys$ from others.
7. If $|shares| \geq t$, mailmen should do the following, which makes the protocol enter epoch-3.
   7.1. Compute key $\leftarrow SS.restore(shares, (t,n))$ and $List(index, vrs_{s}, vrs_{m}) \leftarrow List(D(key, [index, vrs_{s}, vrs_{m}])))$.
   7.2. $\Rightarrow C_{sup}.revealIdentity(List(index, vrs_{s}, vrs_{m}))$.
   Otherwise, the protocol jumps to epoch-6.

Epoch-3 [heavyweight mode]:
8. $M \Rightarrow C_{sup}.revealPrivkey(index, privkey)$.
   At the end of epoch-3, the protocol goes to epoch-4.

Epoch-4 [reporting absent/fake]:
9. $M \Rightarrow C_{sup}.reportAbsent(index)$.
10. $M \Rightarrow C_{sup}.reportFake(index)$.
   At the end of epoch-4, the protocol goes to epoch-5.

Epoch-5 [second revelation]:
12. Recipient submits the receipt through $\Rightarrow C_{agent}.recipientReceipt(receipt, addr(S), addr(C_{sw}))$.
   At the end of epoch-5, the protocol goes to epoch-6.

Epoch-6 [settlement]:
13. Depending on how the protocol terminates, the protocol participants can request withdrawals at $C_{agent}$.

Fig. 5: TIDS.pend and TIDS.deliver in SilentDelivery. They together form the dual-mode execution.

The heavyweight mode. Since the only transaction that is allowed to be sent by $C_{sw}$ creates $C_{sup}$, the address of $C_{sup}$ is deterministic and can be computed by sender $S$ at protocol step 1. After that, sender $S$ selects mailmen and sets up a service with $C_{agent}$ without disclosing any (side) information revealing recruitment relationships. Similar to the selection of mailmen in the strawman protocol, the selection of mailmen in the Silent Recruitment is also random. This is a straightforward way of defending against adversaries that try to leverage a few accounts to possess the majority of mailmen recruited by a particular sender. From then on, silent recruitment is executed via private channels in the form of a three-way handshake. Specifically, sender $S$ initials the handshake by giving each mailman the two contracts $C_{sw}$ and $C_{sup}$ a signature $vrs_{sup}$ regarding the two contracts and an index assigned to the mailman. Upon getting contacted, each mailman verifies the correctness of service information and sends back a signature $vrs_{m} \leftarrow sig(hash(addr(C_{sw}), index))$ to sender, which implies that the mailman has agreed to take charge of this service. Upon receiving mailman’s signature, sender $S$ also generates a signature $vrs_{s} \leftarrow sig(hash(addr(C_{sw}), index, vrs_{sm}))$, which says that sender $S$ has agreed to recruit the signer of $vrs_{m}$ in this service. Then, similar to the strawman protocol, sender $S$ creates $shares$ of a key and a receipt. However, unlike the strawman protocol, these $shares$ are not directly given to mailmen. Instead, at protocol step 8, each $share$ is iteratively encrypted with $l$ pubkeys from $l$ different recruited mailmen, where $l$ is a parameter determined by sender $S$ at protocol step 2. In this way, each $share$ is turned into an onion and its recovery needs $privkeys$ maintained by $l$ mailmen. This design allows the premature disclosure of a $share$ to be verified through pairing the disclosed $privkeys$ with the pubkeys in $C_{agent}$, instead of having to rely on hash that reveals recruitment relationships. Finally, through private channels, sender $S$ broadcasts all these onions, transmit a list of encrypted tuple $[index, vrs_{s}, vrs_{m}]$ to each recruited mailman and encrypted $[info, receipt]$ to the recipient. With the signatures $vrs_{sm}$ and $vrs_{sl}$, both mailmen and recipient will be able to verify the received messages and request the sender to resend the messages if needed.

4.3 Dual-mode execution

Next, we present the dual-mode execution, which incentivizes mailmen to make the protocol get executed in the lightweight mode, reducing the service cost from $O(n)$ to $O(1)$. We design the dual-mode execution to include six epochs spreading across the TIDS.deliver phase. Specially, we consider the TIDS.pend phase as epoch-0, during which any mailman can switch the default lightweight mode to the heavyweight mode by deploying $C_{sup}$ via $C_{sw}$ and
report a prematurely disclosed privkey. Specifically, the protocol allows any mailman, who knows the identity of a mailman recruited by a particular sender and also obtains the corresponding privkey used by that mailman to encrypt the onion for that sender, to report a premature disclosure. Later, if the reported privkey is proved to be correct or the suspected mailman becomes absent in epoch-4, the reporter could receive a monetary reward from the security deposit paid by the suspected mailman as the incentive, and the rest of the confiscated security deposit will be used to compensate for the cost of mode switching. In contrast, if the reported privkey is proved to be incorrect after the suspected mailman has revealed the corresponding privkey in epoch-4, the reporter who is also a mailman, will lose the locked security deposit. The security deposit will be used to compensate for the cost of mode switching.

Then, in epoch-1, if the recruited mailmen honestly obey the non-scalable regulations shifted from $C_{agent}$ to $C_{sup}$ by revealing their privkeys to recipient $R$ via private channels, $R$ will be able to recover key and acquire info and receipt, which makes the protocol reach a successful termination and jump to epoch-6, namely the settlement stage. In case that some mailmen violate the regulations in $C_{sup}$ and result in a failure of recovering key, the protocol will enter epoch-2, during which any honest mailman can switch the protocol into the heavyweight mode (i.e., epoch-3) by deploying $C_{sup}$ via $C_{sw}$. After that, the recruited mailmen reveal privkeys to all via Whisper protocol, decrypt onions to shares, recover key from shares and finally acquire the list of tuple $\langle index, vrs_s, vrs_m \rangle$. Each tuple can prove a recruitment relationship to $C_{sup}$ by revealing by an agreement signed by a mailman via $vrs_m$ and by a sender via $vrs_s$. If the key can not get recovered, the protocol researches a failed termination and jumps to epoch-6. During epoch-3, the protocol is executed in the heavyweight mode, demanding each recruited mailman to reveal its privkey to $C_{sup}$ via revealPrivkey(). Furthermore, any absent or fake privkey that were not appropriately submitted during epoch-3 will be identified as misbehavior and reported during epoch-4, resulting in the dishonest mailman to lose $Ξdepositor$. After that, epoch-5 provides the second chance of making the protocol end with success, though in heavyweight mode. Finally, during epoch-6, if the service is failed, each mailman could withdraw its deposit and the sender could withdraw remained fee anytime after epoch-5. Otherwise, the service is successful. Each mailman, with no misbehavior, could withdraw its deposit, remuneration or reporting award. In case that the protocol terminates via lightweight mode, mailmen need to follow step 6 and 7.1 to prove relationships to request withdrawals. The sender could withdraw remained fee anytime after epoch-5.

5 Security and cost analysis

We next analyze the security of SilentDelivery in terms of its termination, attack resilience and availability properties. After that, we analyze the cost of SilentDelivery.

5.1 Termination

A fair trading should guarantee that honest service requestors only need to pay service fee when the prescribed service is successful and honest service providers always receive service fee when the prescribed service is successful. As illustrated by Fig. 5, the protocol can always terminate by reaching epoch-6. During the settlement stage, fairness is guaranteed in the following ways:

1. The $Ξremuneration$ is only charged from sender $S$ when the service is successful and is only paid to honest mailmen who have no detected misbehavior.

2. As described in protocol step 1, 9 and 10, $Ξdepositor$ is confiscated only when a recruited mailman fails to protect its privkey before TIDS.deliver or fails to properly reveal privkey during TIDS.deliver. In other words, since the privkeys are necessary for reporting recruited mailmen and are only known by the recruited mailmen, it becomes difficult for any party, including senders and recipients, to unjustly accuse a mailman by abusing the reporting functions. This property was not achieved in the strawman protocol, where a dishonest sender always owns the ability to swindle $Ξdepositor$ of a recruited mailman because the share reported through reportPremature($share$) is not uniquely known by the mailman, but also by the sender.

5.2 Attack resilience

For analyzing the attack resilience, we assume that there exists an adversary seeking the premature disclosure of private information $info$ before the future time-frame. There are two approaches to launch such an attack, namely mailman Bribery attack [18] and Sybil attack [17]. Before presenting the details, we denote the threshold of secret sharing as $t$, the layer of onion as $l$, the security deposit charged to a single mailman as $d$, the number of innocent mailmen as $v$, the number of malicious mailmen as $x$ and the percentage of malicious mailmen as $p_A$.

The silent recruitment realized in SilentDelivery makes it difficult for an adversary to succeed via bribery as there is no information regarding the recruitment relationships that can help the adversary distinguish whether a mailman has been recruited or not.

However, a powerful adversary may identify the identities of some mailmen recruited by a particular sender by launching side-channel attacks. Then, the adversary could deploy a smart contract with a fund larger than the
security deposit $d$ and use this smart contract as bait to bribe a mailman to obtain a specific private key. Since the fund in the bribery contract is larger than the security deposit, a rational mailman may choose to reveal the private key to the bribery contract to increase its profit. We now analyze the cost to successfully acquire the private information before the prescribed time-frame via bribery attack.

**Lemma 1.** An adversary needs to spend an amount of $tdl$ to bribe mailmen for successfully obtaining the private information before the prescribed time-frame, where $t$ denotes the threshold, $l$ denotes the layer of onion and $d$ denotes the security deposit charged to a single mailman.

*Proof.* An adversary should aim at restoring key before the prescribed time-frame, which means at least $t$ shares should be obtained. To obtain a single share, the adversary needs to deploy $l$ bribery smart contracts to collect private keys from $l$ different mailmen, which, due to the existence of the reporting premature mechanism, will cost $ld$. Therefore, the cost of obtaining $t$ shares will be $tdl$. □

With Sybil attacks [17], an adversary can create an arbitrary amount of Ethereum accounts and register all these accounts to $C_{agent}$ as mailmen.

**Lemma 2.** The minimum amount of security deposit that an adversary needs to deposit to obtain $t$ shares on average via controlled mailmen would be $(l - 1)vd$, where $v$ denotes the number of registered mailmen not controlled by the adversary and $d$ denotes the security deposit charged to a single mailman.

*Proof.* The situation refers to step 2 of the $TIDS.send$ phase in $SilentDelivery$ protocol, where the registered mailmen can be divided into two groups, namely the (malicious) ones controlled by an adversary through Sybil attacks and the (innocent) ones not controlled by the adversary. By denoting the number of innocent mailmen as $v$ and the number of malicious mailmen as $x$, we get

$$p_M = \frac{x}{x + v} \Rightarrow x = \frac{vp_M}{1 - p_M} \quad (1)$$

where $p_M$ denotes the percentage of malicious mailmen. To obtain a single share, all the $l$ mailmen providing privkeys for recovering this share from an onion should be selected from the malicious group, giving its probability $p_M^l$. Since there are $n$ shares in total, the overall process can be viewed as a Binomial distribution $B(n, p_M^l)$ with mean $np_M^l$. Then, the amount of security deposit $d$ that should be deposited by the adversary to obtain $M$ shares on average would be:

$$\hat{d} = \frac{xd}{np_M^l} \cdot t = \frac{vp_M}{1 - p_M} \cdot \frac{dt}{np_M^l} = \frac{vdt}{n} \cdot \frac{p_M^{1-l}}{1 - p_M} \quad (2)$$

Since the adversary cannot control $(v, d, t, n)$, to minimize $\hat{d}$, by setting $\frac{\partial \hat{d}}{\partial p_M} = 0$:

$$\frac{(1 - l)p_M^{1-l}}{1 - p_M} + \frac{p_M^{1-l}}{(1 - p_M)^2} = 0 \Rightarrow p_M = \frac{l - 1}{l} \quad (3)$$

Therefore, when $\hat{d}$ is minimized:

$$x = v \cdot \frac{l - 1}{l} \Rightarrow l = (l - 1)v \Rightarrow \hat{d}_{min} = (l - 1)vd \quad (4)$$

We emphasize that it is hard to entirely prevent bribery attack and Sybil attack, especially in permissionless blockchains. In this paper, we assume that an adversary has a bounded ability, which refers to a bounded amount of money to be invested in a specific attack. Hence, we can quantify the attack resistance with the amount of money that an adversary needs to spend.

The resilience against Sybil attack depends on three factors. Besides $l$, the two other factors are $v$, the number of registered mailmen not controlled by the adversary and $d$, the security deposit charged to a single mailman. In other words, resilience $\propto (l - 1)vd$, as in lemma 2. In practice, a sender can customize $l$ based on desirable Sybil attack resistance $\hat{d}_{min}$. Besides, to make the value of $l$ in a reasonable range, we may adjust the other two factors, namely $v$ and $d$. It may not be feasible to control $v$. However, it is possible to periodically adjust the value of $d$ based on the recent number of registered mailmen and a default value of $l$ that is not large (say $l = 5$). This is similar to periodically adjusting the mining difficulty in PoW blockchains such as the Bitcoin.

### 5.3 Availability

It is possible that a recruited mailman violates the protocol inadvertently, such as being absent during $TIDS.deliver$ due to unexpected network issues. Considering that the decentralized service providers, namely the mailmen are not as professional as a centralized service provider, a very strict protocol that demands each mailman to maintain 99.9%
availability would be unpractical and may make the bar of being a mailman too high. On the other hand, we would not want the bar to stay too low because otherwise each service needs to recruit a great number of mailmen to succeed. A good balance can be made when mailmen can maintain relatively high availability while TIDS can achieve very high availability, such as three nine or even four nine availability.

**Lemma 3.** SilentDelivery can achieve three nine or even four nine availability when mailmen maintain 95% availability.

**Proof.** By denoting mailman availability as $A_T$, the service availability $A_S$ with parameters $[t, t, n]$ can be computed through the Cumulative Distribution Function of Binomial distribution:

$$A_S = 1 - \sum_{i=n-l+1}^{n} \binom{n}{i} P^i (1 - P)^{n-i}$$

(5)

where $P = 1 - A_T^l$ represents the probability that a share is lost. As illustrated in Fig. 6 when $[t, n] = [4, 10]$ and $A_T = 95\%$, we get $A_S = 99.9\% (99.99\%)$ by taking $l = 4$ (3).

We can see that there is a tradeoff between attack resilience and availability offered by SilentDelivery. A larger $l$ results in higher resilience against Sybil attacks while a smaller $l$ improves availability. We suggest using a smaller $l$ (e.g., $[t, n] = [3, 4, 10]$) when senders are less concerned about attacks regarding premature disclosure because a smaller $l$ can also reduce the number of recruited mailmen and thus $\Xi$remuneration that senders need to pay.

### 5.4 Cost analysis

We analyze the cost of SilentDelivery as follows:

**Lemma 4.** The SilentDelivery protocol has a total cost in the range of $O(1)$, $O(n)$ and the $O(1)$ lower bound could be reached as long as the participants are rational.

**Proof.** The total cost would reach the upper bound $c_{pp}$ when (1) the identities of mailmen are uploaded via `revealIdentity()` onto the blockchain and (2) the private keys are uploaded via `revealPrivkey()` onto the blockchain, namely,

$$O(c_{pp}) \rightarrow O(c_{id} \cdot n + c_{pk} \cdot n + c_{rem}) \rightarrow O(n)$$

(6)

where $c_{id}$ and $c_{pk}$ denotes cost of uploading per identity and private key and $c_{rem}$ represents the total cost of calling other functions. In contrast, the total cost would reach the lower bound $c_{low}$ when none of `revealIdentity()` and `revealPrivkey()` have been invoked, namely $O(c_{low}) \rightarrow O(c_{rem}) \rightarrow O(1)$. Both the functions are countermeasures against dishonest participants by fixing problems made by them and confiscating deposit paid by them, so the violators would gain no positive benefit but only a negative payoff. Considering that rational adversaries choose to violate protocols only when doing so brings them a positive payoff, rational participants would not choose to lose deposit, which in turn would push the total cost to reach its lower bound.

### 5.5 Discussion

#### 5.5.1 Deliberate disclosure

It is possible that an active adversary who does not care about his or her loss but does care about the loss of the sender, will deliberately make premature disclosure, thus making the gas cost $O(n)$ from $O(1)$. In this case, the security deposit of the adversary will be confiscated and the confiscated money will be used to compensate for the cost of mode switching. With this strategy, the overall gas cost could not reach $O(1)$, but it could be decreased by a certain amount of value. Though it is a challenging problem to guarantee $O(1)$ with such active adversaries, it is an interesting and important aspect of future research on this topic.

#### 5.5.2 Mailmen Collusion

If the mailmen are in collusion, they may be able to decrypt their shares and find out the sent information. The protocol allows any mailman to report a premature disclosure. The reporter could receive a monetary reward from the security deposit paid by the suspected mailman as the incentive. We design the incentive to incentivize mailmen to betray each other in collusion. For instance, if two mailmen (say A and B) exchange private keys, immediately after receiving private key B, mailman A could report the disclosure of both key A and B to earn security deposit from mailmen B and also prohibit future reports from mailmen B. As a result, it will never be a good idea to disclose any private key in collusion. However, if a mailman (say A) chooses to decrypt one layer of the onion and disclose only the decrypted onion without revealing the key, it will become difficult for other mailmen to verify the correctness of the decryption and hence, mailman A could not receive any monetary incentive to do this.

### 6 IMPLEMENTATION AND EVALUATION

In this section, we present the implementation and evaluation of the proposed SilentDelivery protocol. We programmed the protocol as smart contracts using Solidity, the most commonly used smart contract programming language. We also anonymously deployed the contracts to the Ethereum official test network `rinkeby` for evaluation purpose.

Similar to recent work on blockchain-based platforms [19, 20], the key focus of our evaluation is on measuring gas consumption, namely the amount of transaction fees spent in the protocol. This is due to the fact that the execution complexity in Ethereum is measured via gas consumption. It is worth noting that, in Ethereum, the amount of gas that a single transaction may spend is bounded by a system parameter and hence, the time overhead of executing functions inside smart contracts is small, usually in the scale of hundreds of milliseconds. In addition, we compare the gas consumption of SilentDelivery with that of Kimono [21], a recent project that also employed Ethereum to release private information.

8. addr($C_{sup}$): 0x4C8a2Ab68779d861D594A144A1a099a27E917e9
TABLE 2: Key functions and their cost in Gas and USD.

| Phase   | Step | Function                  | Gas     | USD    |
|---------|------|---------------------------|---------|--------|
| TIDS.send | 1    | deploy $C_{sw}$ newService | 616666  | $1.81  |
|         | 2    |                           | 83121   | $0.24  |
| Epoch-0 | 1.1  | deploySupplementary reportPremature | 2425356 | $7.10  |
|         | 1.2  |                           | 65317   | $0.19  |
| Epoch-1 | 4.2  | recipientReceipt          | 54291   | $0.16  |
| Epoch-2 | 5    | deploySupplementary revealIdentity | 2425356 | $7.10  |
|         | 7.2  |                           | 72678   | $0.21  |
| Epoch-3 | 8    | revealPrivkey             | 90689   | $0.27  |
| Epoch-4 | 9    | reportAbsent              | 65343   | $0.19  |
|         | 10   | reportFake                | 1280723 | $3.75  |
|         | 11   | informAgent               | 57042   | $0.17  |
| Epoch-5 | 12   | recipientReceipt          | 54291   | $0.16  |

6.1 Gas consumption of SilentDelivery

In TABLE 2 we list the key functions in the programmed smart contracts that interact with protocol participants during different phases of SilentDelivery and the cost of these functions in both Gas and USD. The cost in USD was computed through cost(USD) = cost(Gas)∗GasToEther∗EtherToUSD, where GasToEther and EtherToUSD were taken as their mean value during the first half of the year 2019 recorded in Etherscan 9 which are 1.67 ∗ 10−8 Ether/Gas and 175 USD/Ether, respectively. As illustrated by the results, in the lightweight mode, the completion of a service only requires a sender to deploy $C_{sw}$ ($1.81$) and set up a new service ($0.24$) during TIDS.send and a recipient to submit the receipt ($0.16$) during Epoch-1, which costs only $2.21$ in total. This cost is independent of the number of recruited mailmen, namely $O(1)$, so the tradeoff between security and scalability is eliminated and the scalability of TIDS gets significantly improved. In contrast, the heavyweight mode requires a sender to deploy $C_{sw}$ ($1.81$) and set up service ($0.24$) during TIDS.send and a mailman to deploy $C_{sup}$ ($7.10$) and reveal identities of all recruited mailmen during Epoch-2 ($0.21n$). It then requires all recruited mailmen to reveal prikeys during Epoch-3 ($0.27n$) and finally a recipient to submit the receipt ($0.16$) during Epoch-5. It thus costs $$(9.31 + 0.48n)$$ for completing a service that recruits $n$ mailmen. If any misbehavior occurs, the reporting functions can be invoked during Epoch-1 and Epoch-4 and the cost for calling these reporting functions will be deducted from $\Xi$deposit paid by protocol violators.

The overall cost of using SilentDelivery in its lightweight mode is $2.21$ and the fee is charged for employing the solid decentralized security in Ethereum. It is worth noting that the fee was computed using a half-year average price of Ether and sometimes the price of Ether was insanely high. In practice, users could purchase Ether with much lower exchange rate, and the lower price could help reduce the cost of using SilentDelivery. We next analyze the relationship between the cost of using SilentDelivery and the scale of recruited mailmen. In lemma 2, we proved that the minimum amount of security deposit that an adversary needs to deposit to obtain $t$ shares on average via controlled mailmen would be $(l−1)vd$, which is independent of the number of recruited mailmen. In lemma 3, we get service availability 99.9% (99.99%) by taking the factor $l$ with 4(3). Also, we have seen that the overall fee in its lightweight mode is not increased when the number of recruited mailmen get scaled up. Therefore, an amount of 30 recruited mailmen (e.g., $[l, t, n] = [3, 4, 10]$) could give consideration to both security and cost. In future work, we will further decouple the security and cost of textitSilentDelivery from the scale of the participants of the protocol.

6.2 Comparison between SilentDelivery and Kimono

Next, we compare the gas consumption of SilentDelivery with that of Kimono 21. For the purpose of evaluating the scalability of the protocols, we tested the gas consumption of recruiting different numbers of mailmen in the two projects and displayed the results in Fig.7. As can be seen, compared with Kimono, the SilentDelivery protocol proposed in this paper is much more scalable and cost-effective. In contrast, the heavyweight mode requires a sender to deploy $C_{sw}$ ($1.81$) and set up service ($0.24$) during TIDS.send and a mailman to deploy $C_{sup}$ ($7.10$) and reveal identities of all recruited mailmen during Epoch-2 ($0.21n$). It then requires all recruited mailmen to reveal prikeys during Epoch-3 ($0.27n$) and finally a recipient to submit the receipt ($0.16$) during Epoch-5. It thus costs $$(9.31 + 0.48n)$$ for completing a service that recruits $n$ mailmen. If any misbehavior occurs, the reporting functions can be invoked during Epoch-1 and Epoch-4 and the cost for calling these reporting functions will be deducted from $\Xi$deposit paid by protocol violators.
7 RELATED WORK

7.1 Sending private information to a future time point
The study of timed release of private information began with May [22]. Since then, there have been extensive studies on this problem. One representative approach [23], [24], [25] protects private information with a time-lock puzzle, forcing recipients to solve a cryptographic puzzle to obtain the information. Nevertheless, the time for solving such puzzles is non-deterministic and as a result, the delivery time of the information can not be precisely controlled. Also, cryptographic approaches for timed data release come with a very significant computational cost and as such, these techniques are not scalable. Another well-studied approach [26], [27], [28] relies on a (semi-)trusted time server to release time trapdoors to recipients at specified future time points. These techniques involve a single point of trust and create a safety bottleneck. The recent emergence of blockchain technology [12] and smart contracts [6] have started the development of new decentralized approaches. One of the decentralized approaches [29], [30], [31] encloses private information with blockchain puzzles used in Proof-of-Work [12] and therefore minimizes the computational burden of the information senders as the blockchain puzzles are periodically solved by blockchain miners. However in such an approach, the involved heavy cryptographic primitives result in very high performance overhead [30], [32]. Another direction of recent decentralized techniques for timed data release [32], [33], [21] leverages smart contracts [6] to establish a decentralized virtual autonomous agent, through which an information sender could recruit a group of peers from the blockchain network as her mailmen to cooperatively maintain and deliver her private information to recipients. Here, the transparency of smart contracts makes it difficult to conceal any information recorded by the virtual agent and therefore challenges the service security in multiple aspects. Besides that, the cost of running smart contracts in this approach is proportional with the number of recruited mailmen, making it costly to recruit more mailmen to gain higher service availability. Our work in this paper tackles the key limitations of the state-of-the-art approaches using blockchain-based smart contracts and tackles two key challenges that significantly limit the security and scalability of the protocol. Through silent recruitment, SilentDelivery makes a mailman get recruited by a sender silently without the knowledge of any third party while still making it possible for the recruitment relationship to be revealed to the smart contracts during a future time-frame. Through dual-mode execution, SilentDelivery incentivizes mailmen to make the protocol get executed in the lightweight mode, reducing the service cost significantly. We rigorously analyze the security of SilentDelivery and implement the protocol over the Ethereum official test network. The results demonstrate that SilentDelivery reduces the cost of running smart contracts by over 85% and is more secure and scalable compared to the state of the art.

7.3 Using cryptocurrency as security deposits
There have been many recent efforts on blockchain-based protocol design that leverage cryptocurrency as security deposits to penalize unexpected behaviors and improve security. Andrychowicz et al. [37] used bitcoin to penalize anyone who unfairly aborts a secure multiparty computation (SMC). Kiayias et al. [38] proposed to use bitcoin as collateral to protect digital content. In [18], the authors use Ether as security deposits to provide verifiable cloud computing. Matsumoto et al. [39] used Ether as security deposits to enforce certificate authorities to be honest. Inspired by these previous efforts, SilentDelivery demands each mailman lock Ether in smart contracts as security deposits to penalize potential misbehaviors violating the protocol and thereby enforces recruited mailmen to stay honest.

8 CONCLUSION
This paper proposes SilentDelivery, a practical decentralized solution for cost-effectively implementing timed-delivery of private information. Our solution employs a novel combination of threshold secret sharing and decentralized smart contracts and tackles two key challenges that significantly limit the security and scalability of the protocol. Through silent recruitment, SilentDelivery makes a mailman get recruited by a sender silently without the knowledge of any third party while still making it possible for the recruitment relationship to be revealed to the smart contracts during a future time-frame. Through dual-mode execution, SilentDelivery incentivizes mailmen to make the protocol get executed in the lightweight mode, reducing the service cost significantly. We rigorously analyze the security of SilentDelivery and implement the protocol over the Ethereum official test network. The results demonstrate that SilentDelivery reduces the cost of running smart contracts by over 85% and is more secure and scalable compared to the state of the art.

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