CLOAK: Enabling Confidential Smart Contract With Multi-Party Transactions

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Abstract—In recent years, as blockchain adoption has been expanding across a wide range of domains, e.g., supply chain finance, digital asset, etc., the confidentiality of smart contracts has now become a fundamental demand for practical applications. However, while new privacy protection techniques are emerging, how existing ones can best fit development settings is understudied. State-of-the-art solutions lack architectural support - in terms of programming interfaces - thus are hardly able to reach general developers.

This paper proposes CLOAK, a pluggable and configurable framework for developing and deploying confidential smart contracts. The key capability of CLOAK is to allow developers to implement and deploy practical solutions to multi-party transaction (MPT) problems, i.e., to transact with secret inputs and states owned by different parties, by simply specifying it. To this end, CLOAK allows users to specify privacy invariants in a declarative way, automatically generate runtime with verifiably enforced privacy and deploy it to the existing platforms with TEE-Blockchain architecture, enabling the MPT. Additionally, we identify the pitfalls in achieving MPT, and provide the treat, i.e., non-deterministic negotiation and fair publication of MPT results. In our evaluation on both examples and real-world applications, developers manage to deploy business services on blockchain in a concise manner by only developing CLOAK applications, developers manage to deploy business services on blockchain.

We believe the insights learned from CLOAK will pave the way for general purpose multi-party privacy-preserved computation achieved by harmonizing TEE and blockchain.

Index Terms—confidential smart contract, privacy-preserved computation, multi-party computation

I. INTRODUCTION

With rapid development of both permissionless and permissioned blockchains, privacy issues have now become one of the top concerns for smart contracts, i.e., keeping transaction inputs and contract states as secrets to non-relevant participants. In many of the practical applications, privacy is an essential property to achieve, e.g., avoiding malicious arbitrage on cryptocurrency, protecting sensitive information in a cooperative business, etc. Unfortunately, despite the importance of smart contract privacy, most of the existing blockchains are designed without privacy by nature [29], [44]. For example, miners of Ethereum verify transactions in a block by re-executing them with the exact input and states. Consequently, private data is shared within the entire network.

Confidential smart contract. To address the aforementioned problem, researchers have proposed various confidential smart contract solutions. In general, these approaches fall into two categories based on cryptography techniques and trusted hardware, respectively. For the former class of approaches, techniques including ring signature, homomorphic encryption and zero-knowledge proof (ZKP) are adopted to achieve anonymity and privacy [8], [9], [11], [23]. For the latter, Trusted Execution Environment (TEE), e.g., Intel SGX, is used to provide confidentiality and trustworthiness [12], [26]. More specifically, TEE is able to reveal sealed transactions and execute them in enclaves, hiding input and contract states with a verifiable endorsement from the hardware manufacture.

Limitations. However, while both classes of solutions provide architectural capabilities to enforce confidential lifecycles of transactions, they are non-sufficient for the development of practical applications. Fig. 1 describes a scenario of procurement bidding among multiple enterprises in supply chain applications. Specifically, each participant submits its secret bid. The core enterprise selects a winner with the lowest bid and pays the second-lowest bid through updating the winner’s balance. For cryptography-based solutions, developers are required to implement a set of off-chain multi-party computation programs and on-chain verification smart contracts, as indicated by [11]. On the other hand, TEE-based solutions allow developers to implement general smart contracts with secrets owned by only one side in a single transaction. Consequently, the implementation needs to process one source of confidential bid input at a time, cache intermediate bids and generate final states when the bidding is completed. In summary, the literature of confidential smart contracts can hardly fit in the
practical multi-party transactions, i.e., transactions with secret inputs and states owned by different parties.

**Challenges.** Handling multi-party transactions on blockchain faces the following challenges:

**C1: Development cost for confidentiality.** Developing a confidential smart contract is time-consuming and error-prone due to the lack of programming support. Given a privacy specification, the development commonly requires embedding low-level controls into implementations for business logic. Consequently, it becomes less flexible for developers to understand and maintain such contracts.

**C2: Interoperability with existing blockchains.** Existing solutions to confidential smart contract are mostly blockchain-specific, i.e., designed for a specific blockchain, thus can hardly fit into general application domains with potentially different underlying blockchains.

**C3: Secure and trusted multi-party transaction.** Practical confidential use cases often require efficient processing on secrets from multiple parties, which has not been well-supported by existing solutions. The fundamental challenge is to guarantee the security of the transaction itself and deliver the verifiability for relevant participants as well.

**Contributions.** In this paper, we formalized the Multi-party Transaction problem on blockchain for the first time. We also designed the CLOAK framework as a practical development and deployment solution. CLOAK allows developers to annotate privacy invariants in contract source code. It checks the privacy specification consistency and do the rest to enable notate privacy invariants in contract source code. It checks and deployment solution. CLOAK designed the CLOAK system properties in Section VI, and how to send MPT with SGX. Finally, we evaluate CLOAK in Section VIII. We have applied CLOAK in several industrial applications, including supply chain, e-governance and more. CLOAK has managed to vastly simplify the implementation of confidential transactions with less deployment gas cost.

**Organization.** This paper is organized as follows. Section II introduces the background knowledge of our research. Section III formally defines the multi-party transaction problem. Section IV shows the overview of CLOAK. Then, we introduce how to develop confidential smart contract supporting MPT in Section V, how to deploy CLOAK generated code and analyzes system properties in Section VI, and how to send MPT with CLOAK SDK in Section VII. Finally, we evaluate CLOAK in Section VIII, discuss the research impact, limitations and improvements in Section IX, and conclude in section XI.

**II. BACKGROUND**

**Blockchain and smart contract.** Blockchain is an emerging technology, famously known for its used in popular cryptocurrencies. Smart contracts of blockchain, e.g. Ethereum [44], are account-like entities that can execute general purpose computation, e.g. receive transfers, make decisions, store data and interact with other contracts.

With smart contracts in place, applications that could previously only run through a trusted intermediary can now operate in a fully decentralized fashion and achieve the same functionality with comparable reliability. However, the blockchain and smart contract platforms lack transaction capacity, exceed computation cost, and are vulnerable in data privacy.

**Trusted execution environment.** Trusted execution environment (TEE) is a type of trusted hardware, designed to protect the confidentiality and integrity of computations, while issuing proofs - known as attestations - of computation correctness.

![Fig. 2. Interaction between server and user for establishing mutual trust](image)

Intel SGX is a specific TEE technology having been adopted as a powerful tool to enhance blockchain [12], [37]. Fig. 2 shows well-adopted practices in applying SGX [1], [37]. To compute well-adopted practices in applying SGX, ensuring that SK / PK is trusted generated in enclave (an isolated secure execution environment running pre-audited code). Then, the User sends ciphertext of x and a symmetric key k to SGX. SGX decrypts the ciphertext inside the enclave to get x and computes f(x, s), where s is the internal secret state of SGX. Finally, SGX returns the ciphertext of y encrypted by k. In this manner, the User can trust the confidentiality and correctness of computation without trusting operating system and applications of the Server.

**Multi-party computation.** Multi-Party Computation (MPC), also named as Secure Multi-Party Computation (SMC or SMPC), constructs cryptographic protocols to allow different parties to jointly compute a target function without revealing their input secrets to each other. MPC was first introduced by Yao in the 1980s [47]. It has been intensively researched in the past three decades. MPC protocols can be formalized using the following formula:

\[ f(x_1, x_2, ..., x_n) \Rightarrow y_1, y_2, ..., y_n \]

There are three critical properties for an MPC protocol:
• Correctness: Each party $P_i$ obtains correct output $y_i$ (even if some parties misbehave).
• Confidentiality: Each party $P_i$ knows $y_i$ without knowing $\{x_j, y_j | i \neq j\}$ except what can be derived from $x_i, y_i$ itself.
• Fairness: Corrupted parties receive their own outputs iff the honest parties have received their own outputs.

MPC protocols are built on several cryptographic primitives, such as Garbled Circuit [48], Oblivious Transfer [34] and Secret Sharing [17], and more. In comparison to TEE-based solutions with the same function, MPC is underperforming with low computational performance and high data bloat.

III. Multi-party Transaction

In this section, we propose a new privacy problem of confidential smart contract in blockchain called Multi-party Transaction (MPT) and elaborate on the reasoning behind the development of CLOAK.

Multi-party transaction. As the formula below shows, $f$ is a target function of the MPT which takes inputs $x_i$ and contract old state $s_i$ from $n$ parties, $n(n > 1)$, and outputs results $r_i$ (e.g., return value), contract new state $s'_i$ and MPT proof. All $s_i$ have been committed by cryptography commitment on blockchain before computing $f$, e.g., store the hash or ciphertext of $s_i$ on-chain, etc. All $s'_i$ will also be committed after. We note $s_i$ commitment as $C(s_i)$ or $C(s)$ for all $s_i$ commitments and do the same to $s'_i$ and $s'$.

$$f(x_1, ..., x_n, s_1, ..., s_n) \Rightarrow r_1, r_2, ..., r_n, s'_1, ..., s'_n, proof$$

An MPT should satisfy four properties, of which three are inherited from MPC, with a newly introduced property verifiability:

• Correctness: Each party $P_i$ obtains correct output $r_i, s'_i$ (even if some parties misbehave).
• Confidentiality: Each party $P_i$ knows $r_i, s'_i$ without knowing $\{x_j, r_j, s_i, s'_j | i \neq j\}$ except what can be derived from $x_i, r_i, s_i, s'_i$ itself.
• Fairness: Corrupted parties should receive their own outputs iff the honest parties have received their own outputs.
• Verifiability: With proof, all nodes can verify that the commitment of the new state $s'_i$ and the return value $r_i$ is the correct result of a function $f$, which takes unknown $\{x_j | j = 1..n \land j \neq i\}$ and $\{s_j | j = 1..n \land j \neq i\}$ from $n(n > 1)$ parties, where all $\{s_i | i = 1..n\}$ match their pre-committed values on the blockchain.

Why is verifiability a critical property? In MPC, even though participants acknowledge the transaction and record the result on blockchain, it is hard for other nodes to verify it. Consequently, other nodes will regard the MPC results as normal immutable data, indicating the loss of MPC’s widespread trust. However, we would like to highlight practical applications where a non-involved party - e.g., regulation authority - needs to verify the both MPC settings, process and results. This unanswered gap promotes the development of MPT.

The MPT for general-purpose computation, e.g., confidential smart contract, neural network training, etc., is an emerging need in both academic and industrial fields. Under the pressure of both tightening supervision and increasing user privacy awareness, public verifiability becomes a urgent requirement for services to gain trust from users and regulators, which paves the way for their widespread use.

![Fig. 3. A general model for implementing MPT](image-url)

The model for achieving MPT. We have insight into the existence of a general model for achieving MPT, which is shown in Fig. 3 $F$ is a target function $f$ which clearly expresses the computation logic. $P$ is a privacy policy, which expresses the privacy specification, e.g., what is the secret data and who are the participants. The enforcer $E$ receives private data, runs $F$, publishes result $y$, enforces $P$ in the whole process and generates a proof $proof$. $V$ is a verifier, which believes the enforcement by verifying the binding $(E, P, F, y)$ by $proof$. Therefore, everyone can trust the result when the following is satisfied.

$$V.verify(proof,E,P,F,y) = true$$

Obviously, current solutions for MPT fit the model. For MPT solutions based on cryptography techniques, we are supposed to combine MPC and ZKP [35], in which users compute target function jointly by MPC and generate ZKP proof, then send the result with the proof on-chain. For these solutions, $F$ is expressed by MPC program framework [7]. $P$ is inherently expressed by API calls, e.g., feeding public variables as public arguments of ZKP proof circuits [24] or annotating private variables as secrets in coding MPC program, in which the variable will be secretly shared to other parties [7]. Since the program is distributively executed on parties’ local machines, $E$ is those local machines. $V$ is the ZKP verifier. For MPT solutions based on trusted hardware, e.g., TEE devices, $E$ consists of the trusted hardware. While $F$ and $P$ are expressed by specific task-friendly languages, $E$ is responsible to execute $F$, enforce $P$ and generate a proof. $V$ is the corresponding proof verifier.

As mentioned before, while cryptographic solutions of MPT lack on practicality and versatility, TEE meets the gap. Therefore, we adopt TEE to implement the model. It is worthy of note that the model and its implementation of achieving MPT can be adapted to general verifiable privacy-preserved computation when expanding the number of MPT participants $n$ to $n \geq 1$. 
We will answer the questions on (a) how to help developers express $F$ and $P$ in an intuitive manner (against C1) in Section VII and (b) how to design TEE-based MPT solutions which is interoperable with existing blockchains (against C2) and (c) how to achieve the MPT with security and trustworthiness wanted (against C3) in Section VI.

IV. CLOAK FRAMEWORK OVERVIEW

In this section, we model the target TEE-Blockchain architecture that CLOAK work with, introduce the workflow of CLOAK and illustrate how it enhances the TEE-Blockchain architecture to support confidential smart contract including MPT under the assumptions, threat model we adopted.

A. Target TEE-Blockchain Architecture

An TEE-Blockchain architecture is modeled as a system:

$$A_{TBC} := [C|!E]|BC$$

Here C is a user/client sending transactions, e.g., a digital wallet. $E$ is a node with TEE. There can be multiple C and $E$ nodes (indicated by $!$). BC is a blockchain on which the data are available to all C and E. Current platforms, e.g., Oasis [12], [39], CCF [57], all meet $A_{TBC}$.

B. Workflow of CLOAK

We designed the CLOAK framework to enable confidential smart contract supporting MPT on $A_{TBC}$. Fig. 4 shows the workflow of CLOAK. It is mainly divided into three phases, development, deployment and transaction. In the development phase, we provide a domain-specific annotation language for developers to express privacy invariants. Developers can annotate privacy invariants in a Solidity smart contract intuitively to get a CLOAK smart contract. The core of the development phase is CLOAK Engine, it checks the correctness and consistency of the privacy invariants annotation, then generates the verifier contract $V$, private contract $F$, and the privacy policy $P$. In the deployment phase, CLOAK helps developers deploy generated $V$, $F$, $P$ to specified $A_{TBC}$, i.e., deploying the $V$ to the $BC$, the $F$ and $P$ to $E$ and the transaction class to be held in CLOAK SDK. In the transaction phase, users use transaction class of CLOAK SDK to interact with the $BC$ and $E$ to send MPT transactions. We will introduce these three phases in Section VI and VII in detail respectively.

C. TEE-Blockchain Architecture with Integrated-CLOAK

CLOAK equips $A_{TBC}$ in a pluggable manner. To be more specific, CLOAK brings new features to $A_{TBC}$ to get enhanced system $A'_{Cloak-TBC}$, where $C, E$ and $BC$ are enhanced to be CLOAK Clients ($C$), CLOAK Executor ($E$) and CLOAK Blockchain ($BC$) respectively.

$$A'_{Cloak-TBC} := [C|!E]|BC$$

CLOAK Blockchain. A CLOAK Blockchain is a general purpose smart contract enabled blockchain with deployed CLOAK infrastructure contracts, i.e., CLOAKPKI and CLOAKService.

CLOAK Clients. A CLOAK Client is a party with CLOAK SDK, marked as $C$. $A$ is able to compile CLOAK smart contracts, deploy generated code and send MPT. We expect $C$ to be lightweight, allowing both mobile and web applications.

CLOAK Executors. A CLOAK Executor is a party holding TEE with the CLOAK runtime in it, marked as $E$. A $E$ processes requests from $C$, runs contracts in $E$’s TEE and generates proofs proving the correctness of state updates. A key management module in CLOAK runtime generates two key pairs, i.e., $(PK_{enc},SK_{enc})$ for encryption and $(PK_{sig},SK_{sig})$ for identity verification. The module also registers $PK_{enc},PK_{sig}$ with the IAS report on $BC$ and delivers $SK_{enc},SK_{sig}$ to new $E$.

The TEE can be instantiated by any comparable products with attestation capabilities, e.g., [13], [22], [30]. Anyone with a TEE can deploy CLOAK runtime to become a $E$, contributing to the liveliness and scalability of CLOAK service. $E$ is corresponding to $\tilde{E}$ in the model for implementing MPT.

For narrative consistency, we will use $\tilde{E}$ to refer to $E$ below. Finally, all $\tilde{E}$ form a CLOAK network, marked as $\tilde{E}$, which hold common $(PK_{enc},SK_{enc}),(PK_{sig},SK_{sig})$ and do not need cooperation except relaying broadcast messages during handling a MPT.

D. Assumptions and Threat Model

We assume the adversary can observes global network traffic and may reorder and delay messages arbitrarily. The adversary can compromise the operating system and the network stack of all-but-one $\tilde{E}$, while cannot compromise any TEE device itself. Therefore, users can trust the TEE integrity attested by Intel IAS. On compromised $\tilde{E}$, the adversary can reorder messages and schedule processes arbitrarily.
While a client $C$ need not to execute contracts themselves or hold TEE, we assume honest $C$ trust their own code and platform, but not other $C$. CLOAK does not (and cannot reasonably) prevent contracts from leaking secrets intentionally or unintentionally through software bugs.

E. Security Goals

Briefly, CLOAK aims to support execution of general-purpose confidential smart contracts with MPT while enforcing the following security properties:

Consistency. At any time, the blockchain stores a single sequence of state transitions consistent with the view of each compute node.

Confidentiality. During a period without any compromised TEE, CLOAK guarantees that the contract state, MPT inputs, return values are kept secret to their owners. CLOAK additionally allows the MPT promoter to specify anonymity level of participants during the negotiation, while the participants addresses are finally public when the MPT is done.

Fairness. A new state resulted in by MPT should be updated on-chain while return values being all delivered unless the CLOAK system being totally unavailable.

Verifiability. Everyone can verify that the contract state transitions are resulted by the MPT among given participants, with given inputs from multiple parties and claimed return values.

V. DEVELOP CONFIDENTIAL SMART CONTRACT

To handle the challenge C1, i.e., helping developers specify what is private data and what privacy policy the data should follow, we developed a domain-specific language. The language allows developers to annotate privacy invariants intuitively at the place where the data are defined.

A. The CLOAK Language

CLOAK language is a domain-specific annotation language for confidential smart contract; it allows developers to declare the identity of a owner and annotate the owner of private data. CLOAK language is implemented based on Solidity [19] which is one of the most influential smart contract languages [20].

Fig. 5 shows the syntax of CLOAK language; it consists of (memory) locations, data and privacy types, expressions, statements, functions, and contracts. In order to focus on key insights, CLOAK is deliberately kept simple.

Locations ($L$) consist of contract field identifiers, function arguments and local variables (‘id’, alphanumeric strings), and mapping entries ($L[e]$).

A type declaration ($\tau @\alpha$) in CLOAK consists of a data type ($\tau$), and a privacy type ($\alpha$) specifying the owner of a construct. Privacy types consist of me, a pseudo-address indicating public accessibility (all), a pseudo-address indicating TEE accessibility (tee) and identifiers (covering state variables, array elements and mapping key tags). For readability, we often omit all, writing $\tau$ instead of $\tau @ all$. Besides the well-known data types (the bool and uint256), CLOAK supports addresses indicating accounts (address), and binary data capturing signatures, public keys and ciphertexts (bin). In addition, types include mappings, i.e., mapping($\tau_1 \rightarrow \tau_2 @ \alpha_2$) (resp. arrays $\tau @ \alpha$) and named mappings, i.e., mapping(address[id $\rightarrow$ $\tau @ \alpha$]) (resp. named arrays address[id]).

Verifiability. Everyone can verify that the contract state transitions are resulted by the MPT among given participants, with given inputs from multiple parties and claimed return values.

B. Privacy Invariants Specification

1) Invariants specification exemplified: With CLOAK language, users can intuitively specify the MPT in Fig. 1 as a CLOAK smart contract, the .cloak file in Listing 1.

In line 2, the developer can declare the key of balances as a temporary variable k, then specifies that the corresponding value is owned by the account with address k, e.g., balances[tenderer] is owned by the tenderer in line 23. In line 3, the developer specifies mPrice to be public.
In line 6-7, to handle an uncertain number of suppliers, the developer declares owners \( p \) and their owned data separately in two dynamic arrays. In line 10, the return value \( sPrice \) is owned by the winner. In line 12-13, the developer reveals private data to another owner, which is forced by CLOAK to avoid unconsciously leaking private data. In line 14-24, it computes the lowest price, the second lowest price, and the winner. The computation is based on the operation between private data from different parties, e.g., \( \text{bids}[i] < \text{sPrice}, \text{balances[tenderer]} += \text{sPrice} \).

```contract
SupplyChain {
    mapping(address !k => uint @k) balances;
    uint @all mPrice;

    function biddingProcure(
        address ![p] parties,
        uint @[p] bids,
        address tenderer
    ) public returns (address winner, uint @winner sPrice) {
        winner = parties[0];
        sPrice = reveal(bids[0], all);
    for (uint i = 1; i < parties.length; i++) {
        if (bids[i] < mPrice) {
            winner = parties[i];
            sPrice = mPrice;
        mPrice = bids[i];
    } else if (bids[i] < sPrice) {
        sPrice = bids[i];
    } }
    balances[tenderer] -= sPrice;
    balances[winner] += sPrice;
}
```

Listing 1. CLOAK smart contract of bidding procurement

2) Type system exemplified: We now discuss the type system. We present core rules of CLOAK’s type system (illustrated shortly) in Fig. 6.

We write \( \Gamma \vdash e : \tau @\alpha \) (resp. \( \Gamma \vdash L : \tau @\alpha \)) to indicate that expression \( e \) (resp. location \( L \)) is of type \( \tau @\alpha \) under the typing context \( \Gamma \). We write \( g \vdash \prod_{i=1}^{n} \tau_i @\alpha_i \rightarrow \tau @\alpha \to \forall F: \beta \) to express that the \( i \)th argument of a native function \( g \) is of type \( \tau_i @\alpha_i \), the return value is of type \( \tau @\alpha \), where \( \alpha, \alpha_1, \ldots, \alpha_n \in \{ \text{me, all, id} \}, \) the function type of \( F \) which \( g \) belongs to is \( \beta \in \{ \text{pub, ct, mpt} \} \). We write \( \Gamma \vdash P \rightarrow \Gamma' \) to indicate that statement \( P \) is well-typed and transforms the typing context \( \Gamma \) to \( \Gamma' \), capturing that \( P \) might declare new variables and thereby modifies the context.

Fig. 6 shows the expression rules. The provable equal \( \alpha \) and \( \alpha' \) will be recorded as a same owner (Fig. 6a). The type rule for assignments \( L = e \) (Fig. 6b) requires (a) typing the target location \( L \) as \( \tau @\alpha \), (b) the expression \( e \) as \( \tau @\alpha' \), and (c) \( \alpha = \alpha' \lor \alpha' = \text{all} \). To avoid type errors, we must explicitly reclassify expression private to \( \alpha \) to another owner \( \alpha' \) (Fig. 6c).

Fig. 7 shows the function rules recognizing the function type. We denote the unified owner set of \( g \)’s expressions as \( \alpha_o = \{ \alpha_1, \ldots, \alpha_n \} \). For example, \( g \) include \( \tau_1 @\text{all}, \tau_2 @\text{id}, \tau_5 @\text{me}, \tau_7 @\text{all} \). Given \( \text{me} \) equals id (by Fig. 6a) thereby \( \alpha_o = (\text{all, me}) \). The functions type of \( F \) which \( g \) belongs to is typed as public transaction (pub) if \( \alpha_o = \{ \text{all} \} \), conditional transaction (ct) if only one private expression exists but not owned by \( \text{me} \), and MPT (mpt) if \( g \) involves variables from different parties.

Taking a CLOAK smart contract, CLOAK ignores the annotation to checks the Solidity validation first, then builds an Abstract Syntax Tree (AST) for further analysis. It adopts rules in Fig. 6 to infer expression owners and recognize function type by Fig. 7. Then, CLOAK checks privacy invariants consistency, e.g., prohibiting developers from implicitly assigning private data to variables owned by others.

For example, in Listing 1 line 6-7, the developer declares the address array \_parties’s elements as \( p \), and annotates the \_bids’s elements being private to \( p \) respectively. Therefore, CLOAK requires the run-time length of \_parties equals it of \_bids. Next, in line 20, the run-time owner of \_bid[i], i.e., \_parties[i], is different from the owner of \text{sPrice}, thus CLOAK infers the function being mpt.

C. Enforcement Code Generation

1) Privacy policy generation: After checking AST, CLOAK generates a privacy policy \( P \) for the contract. To formally explain \( P \), we model the privacy policy of an annotated private data \( \alpha_d = (id_d, \tau @\alpha) \), where \( id_d \) is the identifier of \( d \). We define a complete set of all sets consisting of \( \alpha_d \) as \( \mathcal{P}_U \).

\[
\mathcal{P}_f = \{ id_f, \text{type}_f, \mathcal{P}_X, \mathcal{P}_R, \mathcal{P}_M, \mathcal{P}_O \}
\]

is the privacy policy model of a function \( f \), where \( \text{type}_f \in \{ \text{mpt, ct, pub} \} \), and \( \mathcal{P}_X, \mathcal{P}_R, \mathcal{P}_M, \mathcal{P}_O \in \mathcal{P}_U \). Specifically, \( \mathcal{P}_X \) means inputs, which includes function parameters with specified \( \mathcal{P}_d \); \( \mathcal{P}_R \) records the \( \mathcal{P}_d \) of state variables that the \( f \) needs for execution; \( \mathcal{P}_M \) means \( \mathcal{P}_d \) of state variables that the \( f \) will mutate; \( \mathcal{P}_O \), which means return or output, records the \( \mathcal{P}_d \) of all return variables.

We model the privacy policy of a CLOAK smart contract \( c \) as \( \mathcal{P}_c = \{ \mathcal{P}_S, \mathcal{P}_F \} \), where \( \mathcal{P}_S \in \mathcal{P}_U \) and \( \mathcal{P}_F \) is a collection
of function privacy policy, i.e., \( \mathcal{P}_F = \{ \mathcal{P}_i^k | i = 1..n \} \). \( n \) is the number of functions in \( c \). Finally, \( \mathcal{P}_c \) becomes the \( \mathcal{P} \) in the model for achieving MPT.

2) Contract code generation: After generating \( \mathcal{P} \), CLOAK generates a service contract \( F \) and verifier contract \( V \). While leaving the computation logic in \( F \), CLOAK generates \( V \) to verify the result and update the state. Algorithm 1 shows the structure of \( V \). \( V \) first initializes the address of the pre-deployed CloakService contract, i.e., the cloak. Then, \( V \) has a new function \( f' \), transformed from the MPT function \( f \) in .cloak. The \( f' \) verifies the MPT proof \( proof \), assigns new state \( C(s') \) when \( proof \) evaluates true, e.g., biddingProcure in Algorithm 1.

Algorithm 1: Verifier contract generated by CLOAK

```plaintext
Function constructor(config)
    // contract creation by developer
1  fHash ← config.fHash // The hash of \( F \)
2  pHash ← config.pHash // The hash of \( \mathcal{P} \)
3  cloak ← config.cloakService
4  Proposals ← []

Function propose(id, proposal)
    // called by TEE with \( TX_p \)
5  if !Proposals[id] then
6      Proposals[id, proposal] ← proposal
7      Proposals[id].status ← WAIT_EXEC
8  end

Function biddingProcure(proof, read, state')
    // generated \( f' \), called by TEE with \( TX_{mpt} \)
9  state ← getStateArray(read)
10 sHash ← Hash(state)
11 if cloak.verify(proof, fHash, pHash, sHash) then
12    setState(state')
13    Proposals[id].status ← COMPLETE
14 end
```

The CloakService is shown in Algorithm 2 which is an infrastructure contract and should be pre-deployed by CLOAK service provider. The CloakService holds the service config of CLOAK, e.g., the \( PK_{enc} \) and \( PK_{sig} \) of \( \hat{E} \), etc. CloakService also holds utility functions, e.g., verify, which verifies \( proof \) to ensure the validity of the state transition.

Algorithm 2: Cloak service contract

```plaintext
Function register(report, ePk, sPk)
    // called by Cloak service provider
1  PK_{enc} ← ePk // for encryption
2  PK_{sig} ← sPk // for identity verification
3  REP_{as} ← report

Function verify(proof, fHash, pHash, sHash)
    // called by \( f' \), verify the proof
4  expProof, \{fHash, pHash, sHash\} ← \{fHash, pHash, sHash\}
5  if proof = expProof then
6    return true
7  end
8  return false
```

VI. DEPLOY CONFIDENTIAL SMART CONTRACT

In this section, we first introduce how to plug in CLOAK to \( \mathcal{A}_{T_{BC}} \) and deploy the generated contract to \( A_{Cloak\text{-}T_{BC}} \) (handling C2). Then, we illustrate how to achieve secure and trusted MPT by introducing two protocols we proposed, i.e., the non-deterministic MPT negotiation protocol and the fair result publication protocol (handling C3).

A. Initialize global infrastructure

Before sending MPT, the service provider of CLOAK should perform a one-time initialization to enable CLOAK on \( \mathcal{A}_{T_{BC}} \). Specifically, a client of \( \mathcal{A}_{T_{BC}} \) can download CLOAK SDK to become a \( C \). Any \( C \) can decide whether to become a service provider. The service provider is supposed to deploy the infrastructure contracts - the CloakPKI and CloakService - on the \( BC \) to enhance it as the \( BC \). Any \( C \) can deploy CLOAK runtime to TEE to become a \( \hat{E} \). Multiple \( \hat{E} \) form a CLOAK network \( \hat{E} \). By calling register of CloakService in Algorithm 2, a \( \hat{E} \) registers \( PK_{enc} \) and \( PK_{sig} \) with an Intel Attestation Service (IAS) if the keys has not been registered, finishing the global initialization thereby get \( A_{Cloak\text{-}T_{BC}} \).

Users can authenticate the TEEs of \( \hat{E} \) by \( REP_{as} \) and build secure channel with \( \hat{E} \) by \( PK_{enc} \) and \( PK_{sig} \). CLOAKPKI is a Public Key Infrastructure (PKI). While knowing the addresses of parties of biddingProcure, CLOAK get the registered encryption key of each party from CloakPKI, so as to encrypt private data by their owners’ public keys.

B. Deploy generated contract-specific code

A client \( C \), as a developer, uses CLOAK SDK to deploy the generated \( V \), \( F \), \( \mathcal{P} \) of CLOAK smart contract. Specifically, CLOAK SDK deploys \( V \) to \( BC \) first. With the \( PK_{enc} \) from CloakService, the \( C \) builds secure channel with \( \hat{E} \), deploys \( F \), binds the \( \mathcal{P} \) and the address of \( V \) with the deployed \( F \). When \( C \) receives the success response signed by \( PK_{sig} \) of \( \hat{E} \), the contract-specific deployment is well-done.

C. Non-deterministic MPT Negotiation

A challenge of achieving MPT is that the participants of an MPT need to agree on an MPT setting under non-deterministic settings, e.g., complex real-world needs include asynchronous network, identity anonymity, and uncertain number of participants until the negotiation settled. For example, any party interested in joining biddingProcure of a tenderer can freely participate in the MPT, but following an accepted MPT setting, e.g., specified duration or anonymity level. We propose a Non-deterministic MPT Negotiation protocol \( Proc_{noneg} \) which supports participants agreeing on a MPT proposal under real-world settings.

As is shown in Fig. 8, given a participants set \( Z \) (a set of \( C \) participating of the MPT), a blockchain \( BC \) and a CLOAK network \( \hat{E} \). \(|\hat{E}| = m \) and \(|Z| = n \), where \( n,m > 1 \). The \( Proc_{noneg} \) allows \( Z \) to reach a consensus on an MPT proposal and commit \( x_i | i = 1..n \) on-chain as a \( PROOF_{participants} \).

1) A promoter generates an MPT proposal \( p = \langle c,f,l,r \rangle \) and broadcasts unsigned \( C(p) = Enc_{PK_{enc}}(p) \) to \( \hat{E} \),
D. Fair Result Publication

Achieving fair and automatic publication of MPT results, i.e. return values \( r_i \) and new state \( s' \), is another challenge \([12]\). This encourages us to design the Fair Result Publication Protocol \( \text{Proc}_{fapub} \), shown in Fig. 9.

1) Each \( \mathcal{E}_j \in \mathcal{E} \) reads and verifies \( \text{PROOF}_{\text{participants}} \), decrypts \( \pi' \) of \( TX_P \) to get \([\text{Addr}_i|i=1..n], x_i, e \) and \( f \), then constructs a normal transaction \( tx_p = c.f([x_i|i=1..n]) \) inside TEE. \( \mathcal{E}_j \) synchronizes the old state \( C(s) \) of \( \mathcal{V} \) according to \( \mathcal{P}_f \) of the called \( f \), then executes \( tx_p \) to get returns \( r_j \) and new state \( s' \) in TEE.

2) Each \( \mathcal{E}_j \in \mathcal{E} \) gets \( k_r \) from \( TX_P \) and broadcasts signed \( C(r_i) = \text{Enc}_{PK_i}(idp, \text{Enc}(k_r, r_i))[i=1..n] \). Each \( P_i \) decrypts the \( C(r_i) \), then broadcasts a receipt, \( \text{REC}_i = \text{Enc}_{PK_{enc}(idp)} \).

3) Upon collecting all \( \text{REC}_i \), each \( \mathcal{E}_j \in \mathcal{E} \) constructs a proof \( = \{\text{hash}(P), \text{hash}(F), \text{hash}(C(s))\} \), then sends a signed \( TX_{mpt} = V.f'(\text{proof, P}_X, C(s')) \) to update \( V \)'s state on \( BC \).

4) Upon receiving the \( \text{PROOF}_{\text{publication}} \) of \( TX_{mpt} \), each \( \mathcal{E}_j \in \mathcal{E} \) broadcasts \( k_r \) to \( \mathcal{P} \).

![Fig. 9. Fair result publication protocol: Proc\textsubscript{fapub}](image)
and balances[\text{winner}]). \(E_j\) first broadcasts the ciphertext of the return values (the public winner and encrypted sPrice private to \text{winner}) by \(C(r_i) = Enc_{PK}(id_p, Enc(k_r, (\text{winner}, Enc_{PK_{Private}(sPrice)})) | i = 1..n.\) Confirming that all participants have received \(C(r_i)\), \(E_j\) calls \(V\).hiddingProcure to updates the new states on BC. When the new state is confirmed, \(E_j\) publishes the \(k_r\), so that the winner can get the sPrice.

E. Property Analysis

1) Confidentiality: For non-participants of the MPT, i.e. \(P \notin \bar{P}\), \(P\) can collect all off-chain messages of two protocols, on-chain \(TX_p\) and \(TX_{\text{mpt}}, V\). Among the data \(P\) collected, \(p\) is deliberately published by \(E\) for calling participants (Proc\text{noneg-S2}). \(Addr_i\) \(i = 1..n\) are consciously revealed (Proc\text{fapub-S3}) since the negotiation has been settled and we enforce the address being public in type systemY\|E. With the help of secure channel built by \(PK_i, PK_{\text{enc}}, PK_{\text{sig}}, P \notin \bar{P}\) cannot know the \(x_i\) in \(TX_p\) (Proc\text{noneg-S4}), \(r_i\) (Proc\text{fapub-S2}), or \(s, s_i\) in \(TX_{\text{mpt}}\) (Proc\text{fapub-S3}). For participants, i.e. \(P_i \in \bar{P}\), each \(P_i\) additionally knows \(x_i, r_i, s_i\) than non-participants. However, as we ignore data leakage leads by code itself, \(P_i\) cannot know \(\{x_j, r_j, s_j, s_j' | j \neq i\}\). In a word, the confidentiality holds against both non-participants and participants.

2) Consistency: Our insights for achieving great consistency is that instead of requiring a \(E\) to distinguish stale state from current state, CLOAK relies on the blockchain to proactively reject any update based on a forged, stale, or duplicated input.

Specifically, to make the MPT proposal consistent, we consider potential message delays or reordering due to asynchronous network assumption or malicious Selective Deny/Delay Attack, with which different \(E\) may receives different \(ACK_i\) thereby adopts different participants and inputs in \(p'\) (Proc\text{noneg-S4}). We require \(V\) accepting \(TX_p\) with unique \(id_p\) to ensure the consistency of the \(p'\), which settles final \(Addr_i\) \(i = 1..n, k_p, k_r, etc\). To make the MPT results consistent, the \(V\) first authenticates the identity of \(E\), then verify that the hashes of \(P, \bar{F}\) and the old state \(C(s)\) in the proof and \(V\) match (Proc\text{fapub-S3}), where the matching of the old state hash is to avoid duplication or outdated state transition.

3) Fairness and Atomicity: Essentially, Proc\text{fapub} is a two-phase protocol. Only when all \(C(r_i)\) are received by \(P_i \in \bar{P}\) and the corresponding \(TX_{\text{mpt}}\) is confirmed on the blockchain, \(E\) announces the \(k_r\). Although a \(E\) may launch Isolation Attacks against its TEE, which prevent the TEE from releasing \(k_r\), the smooth broadcast of \(k_r\) must be guaranteed because at least one \(E \in \bar{E}\) is honest. Moreover, since any \(P_i\) with TEE can deploy the CLOAK runtime to become a \(E\), the smooth publication of \(k_r\) can be further ensured, which finally achieves fairness of MPT results delivering [4].

4) Configurability: The Proc\text{noneg} of CLOAK is configurable. A promoter is sovereign to configure the negotiation timeout \(t\), anonymity level between participants, and the requirement of pre-transaction pledge of an MPT in \(p\), etc. Obviously, the \(t\) must be reasonable, because the negotiation can achieve agreement only when enough participants approving \(p\) and replying \(ACK_i\). For transaction pledge, the promoter can add a variable in \(p\) to set up the pledge amount, then \(E\) identifies the variable and adds transaction pledge phase before Proc\text{fapub}. The promoter can also designate specific addresses in \(p\) to be pre-qualified participants of MPT.

5) Availability: For \(A'_{\text{LOAK-TBC}}\) since the availability of BC has been guaranteed in assumption, we mainly consider the CLOAK network \(E\) with naturally devices failure and under DOS Attack, in which an adversary may frequently send proposals without finishing Proc\text{noneg} and Proc\text{fapub}.

For the whole CLOAK network \(E\), although multiple \(E\) need synchronizing keys in initialization, they serve without collaboration in MPT handling. The downtime of all-but-one \(E\) affect nothing on the overall service stability. Furthermore, any user can maintain a TEE device, become a \(E\) by deploying the CLOAK runtime, and join the \(E\) improving the availability of CLOAK network.

We can also adopt techniques to mitigate the influence caused by DOS attack. The adversary can be identified by account address and blocked by \(E\) for \(\Delta\) time, as adopted in [12], [14]. \(\Delta\) can be a pre-defined system variable and vary from the type of dishonest behaviors.

Unlike payment services, e.g. mixing, an MPT can be irrelevant to financial industry and make it difficult to measure the value of private data. Therefore, we don’t require mortgage funds to join Proc\text{noneg} in default. Because no deposit is required, even if the CLOAK service is down - cannot processing MPT transactions - it will not cause property losses to the participants. Nevertheless, it’s also easy to require parties to deposit funds to \(E\) managed addresses before Proc\text{noneg} starts, which has been well studied [10]. When there is a deposit, it is sufficient to set up a timeout recovery mechanism. Therefore, the availability of CLOAK services can be guaranteed.

6) Other Properties: We analyze the Anonymity additionally here. During Proc\text{noneg} and Proc\text{fapub}, all messages broadcasted among \(E\) and \(\bar{P}\) are ciphertext without sender and receiver tags, which indicates that only the message receiver can try to decrypt the ciphertext, get the correct data structure and then knows that they are the receiver. Furthermore, by padding the protocol messages to constant size, the non-receiver users of messages also have no idea about which protocol phase or MPT proposal the message belongs to. Consequently, for \(P_i \notin \bar{P}\), \(P_i\) cannot decrypt messages; thus only knows that they are not the receiver. For \(P_i \in \bar{P}\), the participants’ addresses \(Addr_i\) is consciously revealed (resp. encrypted by \(PK_i\)) independently in \(p'\) Proc\text{noneg-S4} in default (resp. if the \(p\) sets up the anonymity between participants).

For now, the owners declared by address variables in CLOAK smart contract is enforced to be public, which leaks \{\(Addr_i\) | \(i = 1..n\} \) by on-chain \(TX_{mpt}\). However, we note that the problem is not technically difficult. We can mitigate this by processing MPT in batches and updating \(V\)’s state once,
or solve it by support confidential owner address which is encrypted by $PK_{enc}$ and stored the ciphertext on-chain.

In a nutshell, CLOAK achieves off-chain unlinkability between an MPT proposal, participants’ addresses and protocol messages, but on-chain linkability between an MPT proposal and participants’ addresses, where the on-chain linkability can be easily solved by allowing confidential owner address or processing MPT in batches in layer-2.

### VII. TRANSACT WITH CLOAK

With configured nodes IP and ports of the $BC$ and $\mathcal{E}$, users, i.e., $C$, can send private transactions, including MPT, with CLOAK SDK. In this section, we introduce the critical contract-specific part of CLOAK SDK, which is generated by CLOAK and used by users to send MPT transparently.

#### A. Verify the Integrity of MPT Implementation

When participating in an MPT for the first time, all participants $P \in \mathcal{P}$ should independently verify the integrity of $\mathcal{F}, \mathcal{P}, \mathcal{V}$ and agree on them first. To this end, each $P$ gets the source code of the CLOAK smart contract form the URL announced by the developers, compiles the CLOAK smart contract and compares the hash of the generated $\mathcal{F}, \mathcal{P}, \mathcal{V}$ with their announced hashes on $BC$. When the hashes match, all $P$ audit the business logic of the CLOAK smart contract as their need and decide whether to trust it.

We note that publishing the CLOAK smart contract by URL meets the benefits of the developer, since the more users know the code and trust the code, the more users use the code and send MPT, by which the developer can earn the gas reward. The developer can also publish the code by IPFS [4], third-party service or other public bulletin board, as used in [10], [41], to improve the availability of the source code.

#### B. Generate Contract-specific Transaction Class

When $P \in \mathcal{P}$ trust the CLOAK smart contract, they can use CLOAK to generate a contract-specific transaction class. Algorithm 3 shows the generated transaction class for SupplyChain. First, each transaction class has a $initialize$ function. The $initialize$ is called by $P \in \mathcal{P}$ for connecting deployed CLOAK infrastructures on $BC$ in lines 1-6 and creating a contract $Contract$ instance with contract-specific configuration in lines 7-11, e.g., addresses of $\mathcal{V}, \mathcal{F}$. When the generated code of the CLOAK smart contract has not been deployed, the $initialize$ will deploy the code if it is needed in lines 8-9. Then, since $P \in \mathcal{P}$ can hardly handle ciphertext and implement aforementioned protocols by themselves, CLOAK generates an all-in-one API, $biddingProcure.biddingProcure$ encapsulates the complex interaction between $C$, $BC$ and $\mathcal{E}$, e.g., send a proposal, building secure channel with $\mathcal{E}$, following $Proc_{moneg}$ and $Proc_{lapub}$, decrypting the $C(r_i)$ by $k_r$ and new state $C(s'_i)$ by $SK_i$, etc..

### Algorithm 3: Transaction class generated by CLOAK

**Function $initialize(V,F,P)$**

// check infrastructure contracts
$PKI, Service, Contract \leftarrow \text{null, null, null}$

if $\not{\mathcal{BC}. CloakPKI} \text{ or } \not{\mathcal{BC}. CloakService}$ then

return false;

end

$PKI \leftarrow \mathcal{BC}. CloakPKI_{addr}$;

Service $\leftarrow \mathcal{BC}. CloakService_{addr}$;

// check or deploy contract-specific code

if $\not{\mathcal{BC}. V} \text{ or } \not{\mathcal{F} \text{ or } \mathcal{E}}$ then

$BC.V.(hash(F), hash(P), Service_{addr})$

$\mathcal{E}. deploy(F, P, V_{addr})$

end

Contract.$\{V, F\} \leftarrow \{BC.V_{addr}, \mathcal{E}. F_{addr}\}$

**Function $biddingProcure(x_i, proposalID, propose)$**

// check whether it need propose a new MPT

if propose then

$f \leftarrow \text{'biddingProcure'}$

$r \leftarrow \text{getRandom()}$

// allow other proposal settings

t $\leftarrow$ propose.t

$p \leftarrow <\text{Contract.V.f.t.r}>$

$id_p \leftarrow Proc_{moneg}(p)$

else // is for participating an MPT

$id_p \leftarrow \text{proposaID}$

end

$r_i \leftarrow \text{follows} \ Proc_{moneg}(id_p, x_i). Proc_{lapub}()$

$s'_i \leftarrow \text{gets and decrypts} C(s'_i)$ of $BC.V$

return $r_i, s'_i$

#### C. Send MPT by Transaction Class

With the transaction class, a $P \in \mathcal{P}$ can interact with the $\mathcal{V}$ on $BC$ and the $\mathcal{F}$ in $\mathcal{E}$ by the created class instance $Contract$. The back-end of transaction class processes and broadcasts all protocol messages by providers. If a message is MPT related, it will be broadcasted to $\mathcal{E}$, which encrypts the message with $PK_{enc}$ and sends it to pre-configured $\mathcal{E}$. Otherwise, the transaction will be normally sent to the pre-configured nodes of $BC$. This way, $P \in \mathcal{P}$ can interact with the transaction class ignoring the back-end CLOAK. Therefore, sending an MPT is as intuitively as sending a normal public transaction, which make it practical and useful.

Specifically, for SupplyChain, as initialize has been called, the class has got the $Contract$. A $P \in \mathcal{P}$ sending an MPT calls $biddingProcure$ with plaintext secrets $x_i$ (party, bid, tenderer), the proposal ID of an ongoing MPT ($proposalID$), and the settings for new MPT proposal ($propose$). In lines 12-17, the $biddingProcure$ first follows $S1$-$S2$ of $Proc_{moneg}$ if propose is not empty indicating to promote a new MPT. Otherwise, it specifies $id_p$ with $proposalID$ to participate in an existing MPT. Then, $biddingProcure$ finishes the rest protocols and waits for the MPT’s result $r_i$ and $\mathcal{V}$’s new state $s'_i$ in lines 21-22. $r_i$ includes the plaintext winner and the plaintext (resp. without) $sPrice$ if $P$ is (resp. is not) the winner. If $P$ is the winner, $s'_i$ includes the plaintext of balances[winer], otherwise empty.
VIII. Evaluation

System implementations. We implement CLOAK language based on ANTLR [33]. The CLOAK runtime with a EVM [18] in it is developed based on OpenEnclave [32]. We deploy the runtime to SGX [13] to get E. We use Ganache-2.5.4 [42] to simulate BC, Solc-0.5.17 [16] to compile the generated V, F, P is expressed by JSON.

We note that the data structures that CLOAK does not support in the industrial contracts has been modified to basic Solidity value types to achieve the same function. Therefore, this does not affect the reliability of the conclusion. Methodology and setup. To evaluate the effectiveness of CLOAK, we propose 3 research questions.

- **Q1:** How does CLOAK language reduce the complexity of developing confidential compliant contracts?
- **Q2:** What’s the cost of enabling MPT on the blockchain with TEE-Blockchain architecture by using CLOAK?
- **Q3:** How does CLOAK perform when applied to real-world industrial contracts and scenarios?

The experiment is based on Ubuntu 18.04 with 6G memory and 2.3 GHz 8-Core Intel Core i9. Although the gas cost of a specific transaction is deterministic, it also varies from transaction arguments. Therefore, we send each transaction of CLOAK parsed contract 5 times with different arguments to get the average.

A. Development Simplicity

To answer Q1, we apply CLOAK on 9 contracts. The 9 contracts vary from LOC, scenarios, and privacy needs. Contracts business involves energy, education, finance, meditation, and blockchain infrastructure. Their LOC distributes from 25 to 1029, which is a representative distribution in Ethereum main chain [20]. Each of these contracts consists of at least two types of three functions, including public function, CT function, and MPT function at the same time.

| Name            | #Functions | #CLOAK | #V_{all} | MPT related | #F | #Y | #P |
|------------------|------------|--------|----------|-------------|----|----|----|
| PowerGrid        | 4(1, 1, 2) | 25     | 146      | 23          | 126| 72 |
| Bidding          | 4(0, 2, 2) | 44     | 148      | 38          | 123| 102|
| SupplyChain      | 6(0, 5, 1) | 68     | 249      | 36          | 145| 85 |
| Scores           | 6(0, 2, 4) | 77     | 339      | 57          | 211| 174|
| Insurance        | 8(2, 3, 3) | 89     | 356      | 52          | 271| 199|
| ERC20Token       | 11(4, 4, 3)| 112    | 347      | 56          | 218| 173|
| YunDou           | 14(10, 0, 4) | 279  | 501      | 166         | 361| 345|
| Oracle           | 22(19, 0, 3)| 326   | 413      | 93          | 190| 196|
| HTLC             | 39(31, 0, 8)| 1029 | 852      | 429         | 401| 443|

Table I shows the LOC of privacy-compliant code before and after using CLOAK. The LOC of CLOAK smart contract; the whole generated verifier contract V_{all}; generated service contract F, verifier contract V and privacy policy P for MPTs.

contract LOC in Solidity and 1.03-3.13X privacy policy in JSON. Therefore, CLOAK significantly reduces the development complexity of privacy in cryptography understanding and code implementation.

B. Initialization and Deployment Gas Cost

To answer Q2, we discuss the gas cost of deploying CLOAK infrastructure and transformed contracts. The transaction cost is particularly relevant as it directly corresponds to monetary expenses paid by the transaction sender.

Gas cost of initialization. As an example without loss of generality, we discuss the initialization gas cost of deploying the SupplyChain contract, depicted in Fig. 10.

In global initialization phase. CLOAK deploys the CloakService, and registers the key of E by calling registerWorker. This (moderate) cost is paid by CLOAK service provider, thus is mostly irrelevant.

Gas cost of deployment. In contract-specific phase, CLOAK deploys the transformed SupplyChain itself by SupplyChain.constr. As shown in Fig. 10, the deployment cost of the transformed SupplyChain is 2.1X to the original contract (the contract without considering privacy), shown in SupplyChian.constr. As this phase only occurs once per deployed contract, the cost is acceptable.

C. Transaction Cost

Gas cost of sending MPT. Fig. 11 shows the deployment cost of all example contracts. In small academic contracts, left to the vertical dash line, transformed contracts’ deployment gas is 2.1-4.2X to original contracts. For industrial contract - which is to the right of the vertical dash line - the transformed YunDou costs 1.25X gas to its original version while RandomOracle reduces to 0.6X and HTLC reduces to even 0.1X. With the deployment gas of original contract growing, the cost of transformed contracts relatively reduces and becomes more less. That is because CLOAK separates MPT from the complicated calculations. The transformed MPT only keeps updating
and verifying state variables on-chain. This result shows the great potential of CLOAK in its application to industrial-grade contracts.

![Graph of Gas Cost Comparison](image)

**Fig. 11.** Gas cost of contract deployment before and after CLOAK transformation

Fig. 12 shows the transaction costs of MPT. For all 9 contracts with different 27 MPTs, the transformed MPTs cost 0.81X to the original transactions on average, while the later has no confidentiality. Specifically, 19 of the 27 transformed MPTs cost lower than 0.85X, the lowest one is 0.35X, which happens in `setNewProposalTxInfo` of HTLC. The highest cost in the last 8 is 1.25X. Overall, we conclude that running transactions on transformed contracts are feasible at a moderate cost.

![Graph of Gas Cost Comparison](image)

**Fig. 12.** Gas cost of MPT before and after CLOAK transformation

**Latency of MPT.** As shown in Section VII, sending an MPT indicates multi-round off-chain communication among participants and confirmation of two on-chain transactions, i.e., $TX_p, TX_{mpt}$, thus, has longer legacy than normal transaction on blockchain. We specifically analyze the latency specifically below. For off-chain communication, a participant of MPT need 7 receive-and-broadcast off-chain rounds, including 3 of $Proc_{noneg}$ (S1, S2-S3, S4) and 4 of $Proc_{temp}$ (S1, S2, S3, S4). The MPT proposer takes 1 round additionally $Proc_{noneg}$-S1 for generating the proposal. For on-chain communication, the main latency happens in the confirmation of two transactions, $TX_p, TX_{mpt}$. These two transactions happen sequentially and each of them need to be fully confirmed, which cost 10 minutes to 1 hour in PoW, e.g., 1 hour (6 blocks) in Bitcoin.

In a nut shell, the off-chain communication is negligible comparing with the confirmation time of $TX_p$ and $TX_{mpt}$ and the time for users deciding whether to participating a MPT manually.

**D. Real-world Contract Application**

To answer Q3, we apply CLOAK to 3 real-world contracts. All contracts have been used in industrial, and the LOC of HTLC is close to the max LOC in [20]. The details of those contracts and scenarios are as follows.

**YunDou.** YunDou is a consumption token contract similar to the ERC20. Users earn token through tourist actions and use points in hotels, shopping, and other places. YunDou supports co-managed accounts, which allow a group of accounts to vote for a proposed transfer transaction. However, limited by the smart contract, it’s hard to hide accounts’ identities and voters. In contrast, a developer with CLOAK could regard co-managed account as an MPT intuitively. While Table I and Fig. 11 show the convenience and low gas cost of developing YunDou with CLOAK, we additionally discuss the scalability of CLOAK implemented MPT here. We implement 2-n threshold voting logic with and without CLOAK separately. Without CLOAK, the privacy can not be preserved, and developers have to separate voting logic for 3 phases (propose transaction, vote for the transaction, settle transaction) to cooperate with other managers. With CLOAK, developers could express voting logic as MPT in a function, leaving CLOAK doing the rest. Fig. 13 shows the gas cost of 2-n threshold transfer transaction without (the sum of 3 phase without privacy) and with CLOAK. It’s easy for CLOAK to adapt to cooperation between 8 managers. Furthermore, the gas cost of threshold transfer with the CLOAK is also much lower.

![Graph of Gas Cost Comparison](image)

**Fig. 13.** Gas cost of multiparty transaction before and after transformed by CLOAK

**RandomOracle.** RandomOracle is an oracle contract responding to every unique query with a (truly) random number. Without privacy, the traditional solution to get verifiable random
number suffers from attacks \[6\]. With CLOAK, it’s easy to implement an MPT, which takes private inputs from different participants and hashes the concatenate input (or by other operation) to get a final random number.

In this scenario, a noteworthy thing is that CLOAK allows users to specify a timeout to receive private inputs from different participants. With CLOAK, participants can asynchronously and efficiently cooperate with other parties. Therefore, it’s more practical than MPC based solution \[13\], \[40\].

**HTLC.** HTLC is an open-source hash time lock contract. HTLC supports payments that use hash locks and timelocks and plays a very important role in the cross-chain transaction. In this implementation, the HTLC contract costs $5719 \times 10^4$ gas in deployment. It’s too big to be deployed in Ethereum as it exceeds the block gas limitation. The transactions of HTLC also endures on the high gas cost of on-chain computation.

With CLOAK, the high-cost transaction is transformed to run in TEE. As shown in Fig. \[11\] CLOAK leaves the new state verification and assignment functions on-chain, thus significantly reduces the deployment gas to $554 \times 10^4$ gas.

**IX. Discussion**

**Expanding to various languages and computations.** Although we take Solidity as a front-end language to express private data and computation logic, the insight behind CLOAK is essentially agnostic to language or computation. Furthermore, while annotating the data owner at where it was defined, it also limits the data structure by language expression ability. The language-agnostic design of CLOAK supports annotating owner for data hash, no matter what’s the data structure or where the data stored. Similarly, user could bind the private data with a code hash, which may express complex computation logic in other language, e.g., deep learning model.

**Limitations of current implementation.** For proof of concept, we have not supported all the Solidity features, e.g., return statement in the middle of the function body, annotation cross contract or library, etc. These limits mainly affect the development experience of developers. Developers have to develop under limited language features or modify the audited legacy code to meet CLOAK smart contract. We notes that the limits do not reduce the scientific advantage of our design and the effectiveness of our experiment.

**Expanding annotation system to meet real-world need.** In current syntax, the owner of private data is allowed to be \{tee, me, id\}, each of which limits the owner to a specific account. However, in the real-world, the owner could be a group or committee, which may have dynamic members. It’s noteworthy to say that we can definitely expand the ownership annotation system to support special owners. It’s also possible to allow a owner to transfer his ownership to others. CLOAK could match the plaintext secret with on-chain ciphertext, encrypt the secret with transferee’s public key and record the ownership transfer event on-chain.

**X. Related Work**

**Blockchain Privacy.** Zether \[9\] is the first privacy scheme oriented for the account model. It adopts special NIZK protocol, \(\Sigma\)-Bulletproof, to achieve anonymity and hiding transaction amount using Elgamal. Hawk \[23\], Arbitrum \[21\] designs a framework in which contracts are executed by several pre-registered credible managers. Managers are supposed to be tight-lipped, update contract state with proof of their honesty and get their gas excitation. Besides, Ekiden \[12\] reveals and executes private transactions in TEE to confide input, result and process data of contract. CCF \[37\] supports users to run any typescript or C++ based application in an TEE-based permissioned blockchain. CONFIDE \[26\] designs a key protocol to synchronize and hold a common public key between all SGX. It also holds EVM and WASM in SGX to support kinds of contracts. Both these two schemes depend on a committee consisting of SGX to achieve consensus. CONFIDE additionally provides CCLe, a language for developers to express which of data should be encrypted by SGX.

**Multi-Party Computation.** First, in terms of expressive ability, First, MPCL \[31\], Wysteria \[36\], SecreC \[5\], ObliVM \[25\], CCLe \[26\] only distinguishes values between public and private. CLOAK allows developer fine-grained annotate private values available to specific addresses. Second, while Fairplay \[27\], SecreC, and ObliVM do not support general loops with private conditions, CLOAK runs the target function in TEE thus is not limited. For security and verifiability, MPCL and Wysteria support values stored at only one participant and are vulnerable to tampering. In terms of scalability, even the State-of-the-art MPC system \[3\], \[43\] cannot actually be extended to the public blockchain. In contrast, CLOAK handles MPT by TEE, it is easy to adopt TEE cluster \[38\] to scale to MPT with large participants, amounts of data and complex computation logic.

**Privacy Policy Languages.** JFlow \[28\] introduces information flow annotations enforcing fine-grained and powerful access control. Jeewes \[2\], \[46\] and Jacqueline \[45\] are languages separating core logic from non-interference policy specifications. All these languages assume a trusted executor enforcing these policies. With CLOAK, although we adopt TEE with Non-broken device assumption, which is reliable enough, and we also propose practical measures to strengthen safety. Zkay \[11\] proposes language for annotating privacy owner to generate off-chain proof generator and on-chain verifier contract for user. Zkay is designed for NIZK-based verifiable computation framework. It has no ability to handle MPT and suffers from proof generation a lot. Finally, with CLOAK, we recognize MPT and achieve it through TEE-Blockchain architecture.

**XI. Conclusion**

In this paper, we have first formalized the problem of Multi-party Transaction and developed a novel framework CLOAK to plug in confidential smart contract supporting MPT to a blockchain with TEE-Blockchain architecture. During our evaluation of CLOAK in both examples and real-world smart contracts, we obtained the results that the LOC of developing CLOAK smart contract is 30% less than deployed ones, while the gas cost is reduced by 19%.
In conclusion, CLOAK allows developers to specify privacy invariants of MPT as smart contract annotations. It eliminates low-level, bug-prone, and time-consuming implementations for developers and achieves non-deterministic MPT negotiation as well as fair MPT results publication, thus paves the way for general purpose multi-party privacy-preserved computation.

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