**TENET: Towards Self-sovereign and Fair Multi-party Computation Ecology Empowered by Decentralized TEE Network**

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**Abstract**

Recently, blockchain has been adopted across a increasing range of domains, e.g., supply chain finance, digital government. The confidentiality of smart contracts has now become a fundamental and crucial demand for practical applications. However, while new privacy protection techniques are emerging, how to securely enable Multi-party Computation (MPC) in confidential smart contracts is understudied. State-of-the-art solutions suffers on high on-chain cost, low flexibility and security thus can hardly reach general users.

This paper proposes TENET, a pluggable and configurable confidential smart contract framework. TENET identifies the pitfalls for supporting off-chain MPC-enabled confidential smart contracts by leveraging TEE network and proposes corresponding treats, e.g., anonymously negotiate MPC among apriori-unknown participants, atomically and fairly distribute the MPC outputs, and securely evaluate an MPC program with a constant on-chain transactions. TENET manages to secure an MPC by only 3 transactions. In our evaluation on both examples and real-world applications involving 2 to 11 parties, TENET cost 0.55-0.98X gas (0.91X on average) against the state-of-the-art.

**1 Introduction**

While blockchains are rapidly developed and adopted in privacy-sensitive domains, e.g., medicine and finance industries, the privacy issues of blockchains 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. Unfortunately, despite the importance of smart contract privacy, most of the existing blockchains are designed without privacy by nature [19,32]. 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. Traditionally, researchers aim to achieve confidentiality of sender’s private data and the execution of the transaction by using cryptographic solutions [5,7,14] or solutions based on trusted execution environment (TEE) [8,23]. Recently, some new works extend the privacy to multi-party scenarios, where they adopt Multi-party Computation (MPC) [30,31] or TEE [17,26] to make data of a party confidential to other parties in a transaction.

**Limitations.** While MPC-based solutions suffers on low scalability and performance (e.g., they use heavy cryptographic techniques such as non-interactive zero-knowledge proofs or general MPC), current TEE-based solutions also suffers from various deficiencies: they do not support apriori-unknown parties negotiating with others to join a MPC program; parties in their system are not self-sovereign to their private data (i.e., TEE encrypts and holds parties’ private data thus parties cannot access their private data without the help of TEE); do not achieve stateless of TEE (i.e., TEE and parties have to long-time persisting the execution state or transaction-specific data); do not achieve standard fairness of output distribution.

**Our design.** In this work, we propose TENET, a novel system that leverages a decentralized TEE network to support complex multi-party confidential smart contracts on established blockchains, such as Ethereum [32]. We emphasize that TENET does not only address the deficiencies of current solutions above, but is also high efficient and available. It can be easily integrated into legacy blockchain and hence is ready to use today.

**Contributions.** Our main contributions are as follows:

- We design a novel confidential smart contract framework, TENET, which supports multi-party programs and is interoperable with existing blockchains, i.e. operating multi-party private inputs from both on-chain and off-chain, and parties in our framework are self-sovereign to their data, i.e., parties can always access their data from blockchain without the help of TEE.
Table 1: A Comparison of TENET with related works. The symbols ×, ∅, ⊗ and ● refer to non-related, not match, partial match and full match respectively. "Self-sovereign" means whether party can access their private data without TEE. "Stateless" means whether the TEE network needs to persist states of confidential smart contracts. "Financial fairness" means that honest parties can always get collaterals in presence of adversary. "(Standard) Output fairness" means parties can get their outputs in almost the same time.

| Approach      | Adversary | min(#TX) | Self-sovereign | Negotiation | Confidentiality | Stateless | Fairness |
|---------------|-----------|----------|----------------|-------------|-----------------|----------|----------|
|               | Parties   | TEE Executors |               |             |                 |          |          |
| Ekiden [8]    | 1*        | m − 1     | O(1)           | ○           | ×               | ●        | ○        |
| Confide [18]  | 1*        | [m/3]     | O(1)           | ○           | ×               | ●        | ○        |
| Bhavani [28]  | n         | m − 1     | O(1)           | ○           | ×               | ●        | ○        |
| Hawk [17]     | n         | X         | O(n)           | ○           | ○               | ●        | ●        |
| FastKitten [11]| n         | 1*        | O(n)           | ○           | ○               | ●        | ●        |
| LucidiTEE [26]| n         | m − 1     | O(1)           | ●           | ●               | ●        | ●        |
| TENET         | n         | m − 1     | O(1)           | ●           | ●               | ●        | ●        |

- We propose an protocol to support anonymous MPC negotiation among apriori-unknown parities and standard fair distribution of MPC outputs in presence of a byzantine adversary who can corrupt all parties and all-but-one TEE executors.

- We have applied TENET in several industrial applications. TENET has managed to securely evaluate MPC programs in O(1) transactions and lower gas cost against state-of-the-art.

Organization. This paper is organized as follows. Section 2 introduces how TENET advances the related work. Section 3 shows the challenges and overview of TENET. Then, we model the data-logic separation model of MPC-enabled confidential smart contract adopted by TENET in Section 4 and how to securely evaluate an MPC program by TENET protocol in Section 5. Section 6 illustrates how to enable our framework on existing blockchains. Finally, we evaluate TENET in Section 8, discuss the research impact, limitations and improvements in Section 9, and conclude in section 10.

2 Related Work

In this section, we focus on research efforts related to our work from two lines separately, TEE-enforced confidential smart contract and MPC-enabled smart contracts. Table 1 shows the difference between TENET and representative related works.

TEE-enforced confidential smart contract. Ekiden [8, 27], Confide [18] and CCF [23] execute consensus algorithm among TEE devices to consistently execute revealed private transactions in TEE, thus confiding transaction parameters, returns, and contract state. While Confide [18] additionally holds EVM and WASM in SGX to support more kinds of contracts, CCF [23] supports users to run any typescript or C++ based application. TENET differs with these approaches in several key aspects. First, all these three approaches require TEE to encrypt and manage private inputs and states of contracts. Users therefore cannot access their own data without the help of TENET. Instead, in TENET, all private data are confidentially persisted on blockchain making users access and manage their data in a self-sovereign manner. Second, TENET also achieves the statelessness of both the TEE network and users by freeing them from persisting transaction-specific keys and data. Finally, while both these three schemes depend on a committee consisting of SGX to achieve consensus, TENET does not require TEE devices to hold heavy consensus algorithm among them and the TEE devices even have no interaction in evaluating transactions, including MPC programs.

MPC-enabled smart contract. Related works combining multi-party computation and smart contracts fall into two categories, MPC-based and TEE-based solutions. MPC-based works like [22, 30, 31] allows m-round MPC with penalties over Bitcoin, but relies on the claim-or-refund functionality which requires complex and expensive transactions and collaterals thus making these solutions impractical. TEE-based solutions usually introduce the TEE as an trusted third party. Specifically, Hawk [17] theoretically suggests a TEE-based manager receiving private inputs from multiple parties and output results to blockchain. FastKitten [11] commits m-round MPC results on blockchain and additionally achieves the collateral fairness when malicious parties or operator occurs. Thuraisingham et al. [28] achieve standard fairness of distributing MPC outputs by requiring each party to hold a TEE device and cooperate with an public board, e.g., blockchain. TENET distinguishes from these work in multiple aspects. In terms of security, while most of current works require limited malicious subjects in the system, TENET ensure the security of the system under all malicious parties and all-but-one malicious TEE executors. Moreover, while LucidiTEE lacks collateral system to punish malicious parties and FastKitten [11] adopts an improved challenge-response protocol to punish both malicious parties and the unique TEE operator therefore achieve financial fairness, TENET achieve financial fairness in presence of multiple TEE executors. Furthermore, TENET achieves the standard fairness in delivering MPC outputs. In terms of efficiency, current schemes adopting TEE to enhance MPC require at least O(n) high money-cost [30, 31] and time-consume transactions [11] for
collaterals and so on, thus suffering on high-cost. TENET only requires $O(1)$ transactions in normal cases.

3 TENET Design

In this section, we present the overview of our novel confidential smart contract framework TENET. We first highlight several key challenges towards a practical, self-sovereign, and secure off-chain MPC-enabled confidential smart contract economy and our corresponding designs. Then, we give a glance at the whole architecture and introduce the workflow of TENET to help parties evaluate an MPC program.

3.1 Design challenges of TENET

Harmonizing TEE and blockchain for building an MPC-enabled confidential smart contract framework requires us to solve the following main challenges.

3.1.1 Achieve self-sovereign data management of parties

Previous works about TEE-blockchain systems rely on TEE to persist or manage the private data of parties. Specifically, Ekiden [8], Confide [18] and LucidiTEE [26] store contracts’ secret data (e.g., code, inputs, states) by encrypting data with keys only known by TEE. Consequently, a party even cannot access its own private data without help of TEE. Besides that, other works [11, 26] focus on supporting MPC function in a one-time vision, i.e., enclaves are newly initialized for the specific function. To achieve confidentiality and security (e.g., fairness) under this setting, these works usually update states in TEE, commit outputs on-chain, and deliver the ciphertext of outputs and corresponding keys off-chain. These works indicate that parties have to persist these keys all the time in case they need to decrypt the on-chain ciphertext or re-compute the ciphertext to prove the correspondence between the ciphertext and the off-chain delivered plaintext. However, considering a long-running TEE oracle network, it is a disaster for both the network and parties participating quantity of MPC programs to persist keys and data of each MPC program. Our goal is to keep the autonomy of parties, i.e., parties access their private data and specify the privacy policy of their data in a self-sovereign manner, making TEE an on-demand privacy policy enforcer.

\[ C_{d_i} := \text{Enc}_{k_d^i}(d_i), \text{Enc}_{pk_i}(k_d^i), P_i \]

In our design, parties’ private data are stored as a well-designed cryptographic commitments and managed by an on-chain data contract. Although private data of smart contracts can be typed as `string`, `uint`, etc., without losing generality, we construct the commitment of data $d_i$ private to $P_i$ as the above structure, where $k_d^i$ refers to a one-time symmetric key for encrypting the private data $d_i$, $pk_i$ refers to the public key of $P_i$, and $P_i$ refers to the address of party $P_i$. We note that $k_d^i$ is not only traditionally used for accumulating performance of the public key encryption using $pk_i$, but also used for achieving standard fair distribution, which will be explained in detail in Section 5. Obviously, in any time, parties can directly access their private data $d_i$ on blockchain by decrypting $C_{d_i}$, while that a TEE device can read $d_i$ only when the party $P_i$ consciously reveals $d_i, k_d^i$ to the TEE. In this way, TEE devices become just oracles that are only in charge of trustfully evaluating MPC instead of persisting and managing parties’ private data at the same time.

3.1.2 Allow anonymous negotiation among parties

Most of current works [11, 28] assume that the setting of an MPC, such as involved parties and target function, has already been known at the beginning of the protocol, thus the protocol always starts from an specified setting. However, there are definitely some scenarios where a party interested in joining an MPC has no idea about the identities of other parties, e.g., a public auction where anonymous bidders independently join an auction according to their interests and cannot a priori know the identities or total number. This is what we called anonymous negotiation. Even worse, since TENET introduces multiple TEE Executors to improve availability of our system, it also makes the anonymous negotiation non-trivial since different Executors against a single MPC proposal may settle in different MPC settings. Specifically, considering several parties compete to join an MPC proposal, these parties broadcast their participation interest to all Executors and each Executor adopts a deterministic rule such as “first come first selected” to select parties. However, this intuitive method will lead to inconsistency of both MPC proposal id and selected parties among Executors. For example, when a party broadcast an MPC proposal, assuming three parties $p_1, p_2, p_3$ broadcast their participation interests $i_1, i_2, i_3$ to join the proposal and each Executor independently generate an id for identifying the proposal and selects two parties corresponding to the earliest received two interests. First, independently generating the proposal id will duplicate the proposal thus not only against its proposer’s wishes but also scattering the potential participants thus making it difficult to gather required participants for a single proposal. Second, since the messages can be arbitrarily delayed, dropped or reordered by byzantine TENET Executors, an enclave $e_1$ of an Executor receiving $i_1, i_2, i_3$ will settle on $i_1, i_2$ while another enclave $e_2$ receiving $i_2, i_3, i_1$ will settle on $i_2, i_3$, which leads to inconsistency. Although LucidiTEE [26] mitigates this problem by requiring parties to join a computation by publicly posting data binding transactions on-chain, it leads to $O(n)$ transactions, and also leaks parties’ identities during the negotiation.

In this paper, we propose an anonymous negotiation protocol Proc\_anego to support apriori-unknown parties anony-
mously negotiating with others to reach a consensus of MPC setting among both themselves and multiple Executors without introducing a heavy consensus algorithm among these Executors. The basic idea is to utilize the consensus of blockchain. Specifically, a party broadcasts an MPC proposal to start a negotiation protocol. Each Executor receiving the proposal independently generates a deterministic id for the proposal to avoid the duplication of proposal id. Then, any party interested in the proposal can broadcast its signed interest attaching the proposal id to join the proposal. When the negotiation finishes, all Executors try to publish their settled MPC settings on a blockchain. Although an adversary can lead to inconsistency of settled parties among off-chain Executors, only a unique proposal of these proposals will be confirmed on the blockchain. Therefore, by requiring all Executors to proceed next steps according to the confirmed MPC proposal, we achieve a final consistency among these TENET Executors. Finally, our negotiation protocol not only achieves anonymity of parties but also requires only a constant 1 transaction on-chain.

3.1.3 Achieve standard fairness of output distribution

In a TEE-Blockchain system, besides that the outputs of the off-chain smart contracts are valid only when they are committed on the blockchain [8, 17], more security requirements arises in multi-party scenarios. First, the revealing of outputs should be atomic with the confirmation of the outputs’ commitments on-chain to avoid rewind attack [8], e.g., an adversary corrupting multiple Executors can feed different inputs to different Executors. If in a protocol the outputs are revealed but have not been confirmed, the adversary can selectively publish one of its preferred outputs. Second, even though the atomicity is preserved guaranteeing that all parties finally receive their own confirmed private data, different parties receiving their corresponding data at different times will also lead to attacks. e.g., a party knowing prior to other parties that the MPC result will increase the value of a stock can get unfair advantages in earning money from this information. To solve this problem, Bhavani et al. [28] first achieves standard fairness, i.e., parties of MPC get their private data at the same time but require each party to hold a TEE device interacting with a blockchain. LucidiTEE [26] looses the requirements of Bhavani [28] to that only some of parties hosts TEE devices, however, just achieves Δ-fairness, i.e., parties get their private data during a limited Δ period, where the Δ equals to the time of generating Proof-of-publication of a key-releasing transaction, which is at least exceeds the time to confirm a transaction on a blockchain.

In this paper, we achieve the standard fairness of MPC outputs distribution without requiring parties to hold TEE themselves. We assume that there are several TENET Executors independently holding their own TEE device to serve all parties, and all TEE devices synchronize a common key pair to form a network. To achieve standard fairness, we require each of these TEE devices to independently release the one-time symmetric key of outputs’ commitments only when it is verified that the outputs’ commitments have been confirmed on the blockchain. Therefore, since parties can independently and directly communicate with each Executor, these parties can get the released keys to decrypt their outputs’ commitments at the same time as long as at least one Executor honestly proves to its TEE device that the commitments have been confirmed.

3.1.4 Resisting adversary with minimal transactions

To resist parties from aborting in the middle of the protocol, it’s common that current works adopt various challenge-response mechanisms to punish parties departing the protocol. However, these mechanisms [11] require parties to deposit collaterals on-chain for evaluating an MPC program each time, thus leading to at least $O(n)$ transactions. This high on-chain cost makes these solutions impractical.

In this paper, we adopt different mechanisms to resist malicious parties and Executors respectively. For malicious parties, we adopt a challenge-response mechanism similar with [11]. However, in our mechanism, each honest party is only required to globally deposit coins once then join any MPC program unlimited times. For TENET Executors, we do not require Executors to deposit coins like [11] but require multiple Executors to serve parties so that our protocol will proceed when at least one Executor is honest. As result, we only require minimal 3 transactions in normal cases while achieving byzantine adversary resistance, anonymous negotiation, and standard fair distribution.

3.2 Architecture and workflow

Integrating all mentioned key designs, we propose a novel TENET framework $A_{TENET-BC}$ to enable an MPC-enabled confidential smart contract on a blockchain. As is shown in Figure 1, the $A_{TENET-BC}$ includes two components: TENET Blockchain (BC). A blockchain with deployed TENET contract (i.e., $TC$, as is shown in Algorithm 1). Essentially, $TC$ manages the config (e.g., public key and account address) of the TENET Network, parties’ coins and public keys, and life cycles of all MPC proposals.

TENET Network (E). A TENET Network (E) consists of multiple TENET Executors. Each Executor $E$ holds a TEE device $E$ that runs the TENET enclave program (i.e., Algorithm 2) and is able to evaluate MPC programs. All those TEE devices synchronize with each other to hold a common account ($adr_E$, key$E$) and key pair ($pk_E$, sk$E$).

We assume smart contracts are implemented based on Data-logic separation model, which has been widely adopted in both academic papers [7, 17, 26] and industrial smart contracts [21]. We will elaborate it in detail in Section 4. Accord-
Design Idea and Workflow

The workflow of Cloak, a development framework of general-purpose confidential smart contract e.g., ENET Contract 

1.1
1.2
2
3.2
3.3

T ENET

ENET Blockchain

ENET Contract

R/W

Data Contract

Privacy Policy

Logic Contract

Enclave

Executor (E)

Figure 1: The framework and overall workflow of TENET. The TENET blockchain has deployed TENET contract for managing life cycles of MPC proposals. The TENET network consists of multiple TENET Executors E. Each E holds a TEE device running a TENET enclave program E. An MPC-enabled smart contract consists of a data contract \( V \) on-chain (persisting data and verifying state transition), a logic contract \( F \) (expressing business logic), and a privacy policy \( P \) (expressing the privacy specification of \( F \)) and binds \( F \) with the \( V \).

... going to the model, each MPC-enabled smart contract includes three parts: (i) a data contract \( V \) that is responsible for storing data and verifying state transition, (ii) a logic contract \( F \) that holds the function logic of several MPC programs, and (iii) a privacy policy \( P \) that specifies the privacy requirements of each MPC program and binds the \( V \) and \( F \).

After the TENET Network E has been initialized, all parties can verify the correct initialization of TEE devices and get the common public key \( pk_E \) of E. We assume that the data contract \( V \) has been deployed to the blockchain and the logic contract \( F \) and \( P \) have been deployed to the TENET Network. Figure 1 shows the workflow of TENET. All parties follow a TENET protocol \( \pi_{TENET} \) to interact with the BC and E to evaluate an MPC program. To quickly grasp the key process without diving into complex symbols, we first explain the protocol in natural description. The protocol \( \pi_{TENET} \) can be divided into four phases, where a global setup phase happens only once for all parties and other three phases happen in valuating an MPC program each time. We will briefly travel through these phases and then introduce them in detail at 5.

- (0) Global setup phase: \( \pi_{TENET} \) first requires all parties globally blocking their coins on BC before they joining any MPC. Specifically, parties deposit their coins to the network E’s common address \( adr_E \). The collaterals of each MPC will be deducted from these coins.

- (1.1 – 1.2) Negotiation phase: A party broadcasts an MPC proposal to E without knowing other parties’ identity a priori. Each TEE E in E starts a anonymous negotiation protocol independently. First, each E deterministically generates an id for the proposal and broadcasts the signed proposal with the id to all parties. If a party is interested in or required by the proposal, it responds by broadcasting an acknowledgment to E where the acknowledgment includes signed commitments of the party’s parameters to the MPC proposal. Each E keeps parties’ acknowledgments until the negotiation phase timeouts or collected acknowledgments meet the settlement condition of negotiation phase. Then, each E independently sends a \( TX_p \) to BC. \( TX_p \) publishes the settled MPC proposal with parties’ identities and parameters’ commitments. Therefore, we achieve the anonymity of parties since parties cannot know identities of other parties until these TEE devices settle the proposal. Besides, although different E may settle at different parties or parameters’ commitments, only one of these published \( TX_p \) will be confirmed on-chain thus ensuring the final consistency. The \( TX_p \) also deducts collaterals of all parties for the MPC proposal in case one of them aborts the MPC after the negotiation succeeds.

- (2) Execution phase: When \( TX_p \) has been confirmed on BC, each party involved in \( TX_p \) broadcasts their signed inputs (i.e., parameters and old states) to E. Upon receiving these inputs, each E first verifies Proof-of-Publication \(^2\) (PoP) \(^3\) of \( TX_p \) to ensure that \( TX_p \) has been confirmed on BC, which indicates that collaterals of parties have been deducted \(^1\) and parties cannot change their parameters. Then, each E checks that collected parties’ inputs meeting their commitments in \( TX_p \). In case a E does not receive inputs from some parties, the E needs to determine whether these parties failed to send inputs or its E behaved maliciously (e.g., by dropping messages). We resist malicious Executors and parties in different ways. To resist malicious Executors, since we introduce multiple Executors in our system, we do not punish specific E because we assume that there is at least one Executor honestly following the protocol so that the department of some malicious Executors do not disturb the proceeding of honest Executors in E. Moreover, to avoid that malicious Executors may drop parties’ inputs to cheat its E to mistakenly punish some honest parties, we require a E to punish malicious parties only if its Executor proves that these parties have publicly challenged but did not respond their inputs. This proof is generated by performing a improved challenge-response protocol via the blockchain: one E publicly challenges these parties on BC. Upon the challenge transaction \( TX_{cha} \) is confirmed,

\(^1\) Practically, a E can send \( TX_p \) as well as other transactions when it has not seeing a \( TX_p \) with the same id sent to BC to avoid the redundancy

\(^2\) A proof constructed for proving that a transaction has been confirmed on a blockchain. We use the same algorithm as \(^3\) [11].

\(^3\) In other words, all parties have enough balance in their globally deposited coins and indeed deducts collaterals required by the specific MPC.
the challenged parties need to respond publicly on BC by posting a response transaction $TX_{resp}$ with the ciphertext of their inputs. If all challenged parties respond, each $E$ can extract plaintext of their inputs and continue with the protocol execution. If these parties did not respond, each $E$ forwards the respective blocks as a transcript to its $E$ to prove that these parties misbehaved, so that each $E$ sends a punish transaction $TX_{pun}$ to refund collaterals deducted by $TX_p$ to all honest parties and stop the protocol. Otherwise, if all parties’ inputs have been successfully collected, $E$ evaluates the MPC program to get outputs (i.e., return values and new states). 

3.3 Adversary model

$\pi_{\text{Tenet}}$ is followed by $n$ parties and a Tenet network consisting of $m$ Executors $E$ to enforce the off-chain MPC program. We uses TEE to ensure the confidentiality and integrity of $\pi_{\text{Tenet}}$. Although we prototype $\pi_{\text{Tenet}}$ based on an TEE instance, i.e., SGX, our design is TEE-agnostic. In this paper, we consider a strong byzantine adversary who can not broken the confidentiality and integrity of TEE itself but are able to corrupt all parties and all-but-one Tenet Executors.

Exemplified by SGX, we first note that although recent research showed some attacks against TEE, the confidentiality and integrity guarantees of TEE devices is still trustworthy. Specifically, we assume that $E$ has full control over the machine and consequently can execute arbitrary code with root privileges. First, we consider memory-corruption vulnerabilities [2] against TEE. While memory corruption vulnerabilities can exist in the enclave code, a malicious $E$ must exploit such vulnerabilities through the API between the host process and the enclave. For the enclave code, we assume a common code-reuse defense such as control-flow integrity (CFI) [1, 6], or fine-grained code randomization [12] to be in place and active. Then, we consider architectural side-channel attacks (e.g., based on caches [3]) that can expose access patterns from SGX enclaves (and therefore our Tenet prototype). However, the community has developed several software mitigations [15, 24, 25] and new hardware-based solutions [10, 20] against these side-channel attacks. A more serious Micro- architectural side-channel attacks like Foreshadow [4] can extract plaintext data and effectively undermine the attestation process Tenet relies on, leaking secrets and enabling the enclave to run a different application than agreed on by the parties; however, the vulnerability enabling Foreshadow was already patched by Intel [16]. Therefore, since existing defenses already target SGX vulnerabilities and since Tenet’s design is TEE agnostic (i.e., it can also be implemented using ARM TrustZone or next-generation TEEs), we consider mitigating side-channel leakage as an orthogonal problem and out of scope for this paper so that the confidential and integrity of TEE devices is still trustworthy. Therefore, users can trust the TEE integrity attested by Intel Attestation Service.

Furthermore, we assume that the adversary can compromise all parties and all-but-one $E$. On compromised parties or $E$, the adversary can control the operating system and network stack so that is able to schedule processes as well as reorder and delay messages arbitrarily.

While parties need not to execute contracts themselves or hold TEE, we assume honest parties only trust their own code and platform, and all attested TEE devices.

4 Data-logic Separation Model

As is mentioned before, in Tenet, while the data of smart contracts are persisted on blockchain, contract logic is held in TEE devices, which indicates a data-logic separation (DLS) model, i.e., decoupling the contract data and logic. The DLS empowers developers to update the transaction logic of contracts without migrating legacy data, and therefore is widely adopted in both academics and industry. Specifically, a DLS typically split an contract to a data contract $\mathcal{U}$ and logic contract $\mathcal{F}$, where $\mathcal{U}$ persists contract storage and $\mathcal{F}$ holds transaction logic and interact with $\mathcal{U}$ to manipulate data. While in normal scenarios both these two contracts are deployed on a
same blockchain, we improve interfaces and data structures of the $\mathcal{V}'$ in DLS and deploy the $\mathcal{F}$, one transaction logic of which is an MPC program, to our TENET Network $\mathcal{E}$.

4.1 Data contract

In TENET, a data contract $\mathcal{V}'$ is deployed on $\mathcal{BC}$ for managing contract storage including all parties’ private data. $\mathcal{V}'$ persists each party’s private data in the structure of commitments elaborated in Section 3. Here we ignore the details of the data contract but model it by three functions:

- $C_r \leftarrow \mathcal{V}'.getStates(f)$: get the current state commitments of $\mathcal{V}'$ read by $f$ in execution.
- $\mathcal{V}'.setStates(f, C_r)$: set current state commitments to new commitments $C_r$ only when the transaction is sent by $\mathcal{E}$.
- $\{1/0\} \leftarrow \mathcal{V}'.verify(f, H_C)$: verify that the hash of the array of all parties’ current state commitments (i.e., $\text{Hash}([C_n|1..n])$) matches its claimed value $H_C$ in the transaction, i.e., it’s a valid state transition from current states.

4.2 Logic contract

A logic contract $\mathcal{F}$ holds several transactions, some of which are MPC programs. To evaluate each MPC program, TEE devices $\mathcal{E}$ collect private parameters from multiple parties and replace the state of $\mathcal{F}$ to current state of $\mathcal{V}'$, then evaluate the MPC program of $\mathcal{F}$ based on the collected parameters and current states to get MPC outputs, i.e., return values and new states.

4.3 Privacy Policy

Since TEE devices $\mathcal{E}$ need to read states of $\mathcal{V}'$ before evaluating any MPC program of $\mathcal{F}$, TEE devices must aware about the read and write sets of each MPC program of $\mathcal{F}$. For this reason, we first add $\mathcal{V}'.getStates$ (resp. $\mathcal{V}'.setStates$) to expose interfaces for reading (resp. writing) states of $\mathcal{V}'$ in transaction granularity, then, inspired by [26], bind a privacy policy $\mathcal{P}$ to note privacy needs of $\mathcal{F}$.

\[
\begin{align*}
\text{Verifier} & \quad \mathcal{V}_{\mathcal{addr}} := \{0, 1\}^* \\
\text{Name} & \quad n := [a - zA - z0 - 9];+
\end{align*}
\]

\[
\begin{align*}
\text{Party} & \quad \mathcal{P} := \{0, 1\}^* \\
\text{Function} & \quad \mathcal{P}_f := \\
& \quad \{ \\
& \quad \text{Param } \mathcal{P}_r := (n : \mathcal{P}) \mid \mathcal{P}^* \\
& \quad \text{Read } \mathcal{P}_r := (n : \mathcal{P}) \mid \mathcal{P}^* \\
& \quad \text{Write } \mathcal{P}_r := (n : \mathcal{P}) \mid \mathcal{P}^* \\
& \quad \text{Return } \mathcal{P}_r := (n : \mathcal{P}) \mid \mathcal{P}^*
\}
\]

A privacy policy $\mathcal{P}$ is modeled as the above. The $\mathcal{P}$ of an $\mathcal{F}$ can be split into two parts, contract-specific and function-specific parts. For contract-specific part, the Verifier refers to the address of its corresponding verifier contract $\mathcal{V}'$ on blockchain. The Name refers to the name of managed state variable in $\mathcal{V}'$. The Party refers to parties’ addresses. For each function’s policy $\mathcal{P}_f$, there are four elements, Param, Read, Write and Return. The Param ($\mathcal{P}_r$) refers to transaction parameter variables of the function $f$. The Read ($\mathcal{P}_r$) refers to states variables needed to be read in evaluating $f$. The Write ($\mathcal{P}_r$) refers to states variables updated in evaluating $f$. Each variable is denoted by the tuple $(n : \mathcal{P})$, containing its name $n$ and the address of its owner $p$ (i.e., the party that the variable private to). If the owner party of the variable is unknown at the time of specifying the computation, we write $(n : \mathcal{P}^*)$, and the unknown party will be settled and revealed after the anonymous negotiation protocol in Section 3 finished.

5 TENET Protocol

After the data contract $\mathcal{V}'$, logic contract $\mathcal{F}$ and privacy policy $\mathcal{P}$ of an MPC-enabled contract having been deployed, $\mathcal{P}_{\mathcal{ENET}}$ is used to evaluate MPC programs of $\mathcal{F}$. In this section, we illustrate how $\mathcal{P}_{\mathcal{ENET}}$ achieves anonymous negotiation and standard fair distribution in evaluating an MPC program $f$.

5.1 TENET Protocol Details

As explained in Section 3, our protocol $\mathcal{P}_{\mathcal{ENET}}$ proceeds in four phases. In global setup phase, all parties verify the integrity and correctness of TEE devices in TENET Network $\mathcal{E}$ then deposit coins to $\mathcal{E}$ common address $\text{adr}_E$ and register their, the parties’, public keys $\text{pk}_E$ on blockchain. Then, evaluating each MPC program requires three phases. During a negotiation phase, all parties negotiate to join an MPC and finally one $\mathcal{E}$ of $\mathcal{E}$ commits settled MPC proposal with parties’ inputs commitments and deducts their collaterals on-chain. After that, an execution phase follows for collecting plaintext inputs (i.e., parameters and old states) from parties and executing MPC with inputs in enclave to get outputs. When the execution finishes, the protocol enters a distribution phase to commit outputs and release the decryption key of outputs commitments when the output commitments have been confirmed on blockchain to complete the MPC and refund collaterals. We stress that after synchronizing with other devices to get the network common keys ($\text{sk}_E, \text{pk}_E$) and accounts ($\text{adr}_E, \text{key}_E$), each $\mathcal{E}$ proceeds $\mathcal{P}_{\mathcal{ENET}}$ to evaluate an MPC program without cooperating with each other during the protocol.

To explain the protocol steps in depth, we use the following symbols to simplify the expression. As is shown in Figure 2, given a blockchain $\mathcal{BC}$, a party set $\mathcal{P}$, and a TENET Network $\mathcal{E}$, where $|\mathcal{E}| = m$ and $|\mathcal{P}| = n$. Since $\mathcal{P}_{\mathcal{ENET}}$ involves data from different parties, we use $d_i$ to refer to data related to $\mathcal{P}_i$ (e.g., $x_{i,s_i,k_i^j}$), we use $d$ to refer to an array $[d_{i|1..n}]$ including all

\footnote{TENET Executors will only be responsible for relaying messages broadcast in the network during the protocol.}
$d_i$ from $n$ parties (e.g., $x, s, k'$). For operation based on these data, we similarly let $H_d$ refers to $\text{Hash}(d_i)$ and $H_{\bar{d}}$ refers to $\text{Hash}(\{d_i\}_{1:n})$ (e.g., $H_C$ refers to $\text{Hash}(C_{\bar{c}}))$. However, for $\text{Hash}(\{d_i\}_{1:n})$, we refer it as $H_d$ (e.g., $H_C, H_{\bar{C}}$). Notably, for common values among all parties (e.g., the unique $\mathcal{P}, f$), the operation on these value is normal (e.g., $H_{\bar{d}}$ refers to $\text{Hash}(\bar{P})$). The detailed interactions is displayed in Figure 2. Algorithm 1 describes the TENET contract and Algorithm 2 describes the TENET enclave program $\mathcal{E}$.

5.1.1 Global setup phase

All parties verifying that the TENET Network $\tilde{E}$ has been correctly initialized are required to register their public keys and deposit coins to the TENET contract $TC$ on blockchain before executing any MPC program off-chain. Specifically, as shown in Figure 2, before using TENET, a party $P_i$ is supposed to globally register its public key $pk_i$ and deposit some coins with amount $Q$. We stress that each party only needs to do it once.

5.1.2 Negotiation phase

A negotiation phase uses the anonymous negotiation protocol ($\text{Proc}_{\text{anego}}$) to guide parties to anonymously reach a agreement on an MPC proposal and commit their parameters $x_i$ on-chain. $\text{Proc}_{\text{anego}}$ proceeds in two steps:

S1: One party who wants to call an MPC broadcasts an MPC proposal $p = (f, q, t_n)$ to $\tilde{E}$. $f$ refers to the MPC program in $\mathcal{F}$ to call, $q$ refers to required collateral for punishing malicious parties and $q \leq Q$. $t_n$ means the required deadline of finishing the negotiation phase. Then, each $\mathcal{E}$ independently but deterministically computes hash of the MPC proposal $p$ to be the $p$’s id $id_p$ and broadcasts the signed $(id_p, p)$ to parties. Since each parties communicates with all TEE devices $\mathcal{E}$ in $\tilde{E}$ in secure channels, each party thus has no idea of other parties’ identities according to the broadcast messages in the network.

S2: Receiving $(id_p, p)$, each $P_i$ interested in the MPC autonomously computes $C_{\mathcal{S}}$ (its parameter $x_i$’s commitment) and broadcasts a signed acknowledgement $ACK_i = (id_p, C_{\mathcal{S}})$ to $\tilde{E}$ before $t_n$. Each $\mathcal{E}$ receiving $ACK_i$ knows that $P_i$ is interested in the MPC proposal $id_p$ then, each $\mathcal{E}$ reads $TX_{id_p}^{\mathcal{S}}$ from the blockchain $BC$ to get $pk_i$, that will be used to compute the party $P_i$’s commitments in next steps. Each $\mathcal{E}$ keeps collecting $ACK_i$. Upon collected $ACK_i$ meet the settlement condition in $p$, $\mathcal{E}$ constructs the settled proposal $p'$. $p'$ expands $p$ with settled parties’ addresses $\bar{P}$ and their parameters’ commitments $C_{\mathcal{S}}$. Then, each $\mathcal{E}$ send a $TX_{\bar{P}}$ to try to confirm its settled $p'$ on blockchain before executing the MPC. Only when the $TX_{\bar{P}}$ is released, other parties can know who are also interested in the proposal. When a unique $TX_{\bar{P}}$ is confirmed on the $BC$, it also deducts $q$ collateral of each party from their coins respectively. Then, each $\mathcal{E}$ goes to execution phase. Otherwise, if the settlement condition is still not satisfied and the time exceeds $t_n$, the negotiation of the $p$ failed and each $\mathcal{E}$ stops the protocol.

5.1.3 Execution phase

This phase is used for collecting plaintext inputs from parties and executing the MPC to get outputs. It contains three steps:

S1: Upon one of these $TX_{\bar{P}}$ is confirmed on $BC$, each $\mathcal{E}$ verifies the Proof-of-Publication [11] of the $TX_{\bar{P}}, PoP_{\bar{P}}$. Then, each $\mathcal{E}$ reads $\mathcal{F}, f$-needed old state commitments $C_{\bar{c}}$ from $BC$. Meanwhile, each party $P_i$ knowing they are involved in the confirmed $TX_{\bar{P}}$ broadcasts their inputs (i.e., parameters $x_i$ and old states $s_j$) to $\tilde{E}$. Each $\mathcal{E}$ in $\tilde{E}$ receiving $P_i$’s inputs recomputes commitments of $x_i, s_j$ respectively to match them with their commitments $C_{\bar{c}}, C_{\bar{s}}$ read from $BC$. If all involved parties’ inputs are collected and matched, $\mathcal{E}$ goes to S3. Otherwise, if a $\mathcal{E}$ finds that some parties’ inputs mismatches their on-chain commitments, or have not receiving some parties’ inputs before $t_e$, $\mathcal{E}$ marks these parties as potentially misbehaved parties $P_M$ and returns $P_M$ to its host $\mathcal{E}$. Then, $\mathcal{E}$ calls challenge to sends $TX_{\text{cha}}$ to challenge all parties in $P_M$ on-chain. Then, the $\mathcal{E}$ goes to S2.

S2: When $TX_{\text{cha}}$ has been confirmed on-chain, honest parties in $P_M$ are supposed to send a $TX_{\text{res}}$ to publish ciphertext of their inputs $x_i, s_j$ on $BC$. All published $TX_{\text{res}}$ are required to be confirmed before block height $\tau_{\text{res}}$ otherwise will be regarded as invalid. Before the block height goes to $\tau_{\text{res}}$, the $\mathcal{E}$ waiting for challenge results reads published $TX_{\text{res}}$ and verifies its $PoP_{\text{res}}$. For a party $P_i$ in $P_M$, if the $\mathcal{E}$ successfully reads matched inputs from its responded $TX_{\text{res}}^{\mathcal{S}}$, the $\mathcal{E}$ removes $P_i$ from $P_M$. Otherwise, if $PoP_{\text{res}}$ shows that no $TX_{\text{res}}^{\mathcal{S}}$ is published or the inputs in $TX_{\text{res}}^{\mathcal{S}}$ are still mismatched, the $\mathcal{E}$ keeps $P_i$ in $P_M$. After that, if $P_M$ becomes empty, which means all inputs are collected, $\mathcal{E}$ goes to S3. On the contrary, if $P_M$ is not empty, which means the misbehavior of parties left is confirmed, $\mathcal{E}$ marks these misbehaved parties as $P_{\mathcal{M}}$. Then, $\mathcal{E}$ sends $TX_{\text{pun}}$. $TX_{\text{pun}}$ calls $BC.TC.punish$ to refund deducted collaterals of all parties to only honest parties in average and settle the MPC with ABORT.

S3: If all involved parties’ inputs are collected and matched, a $\mathcal{E}$ replaces the state of logic contract $\mathcal{F}$ with old state $s$, then execute $f(s)$ to get MPC outputs, i.e., return values $r$ and new states $s'$.

5.1.4 Distribution phase

This phase aims to adopt an fair distribution protocol $\text{Proc}_{\text{distribution}}$ to atomically confirm the MPC outputs’ commitments (i.e.,

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5Old state commitments has been stored as contract storage on-chain.

6Settlement condition of negotiation can be flexible, e.g., all inputs required have been provided or the number of parties exceeds a specific number.

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6The old states that the called $f$ read in execution. $\mathcal{E}$ reads $f$-needed old states commitments from $BC$ according to $f$’s read set $p_{f, p_{f'}}$. 

8
Figure 2: The TENET protocol $\pi_{\text{TENET}}$. The $E^{T\forall\forall}$ means a TENET Network holding TEE devices $E$ with deployed $T\forall\forall$. $BC^{TC,T\forall}$ means the TENET Blockchain with deployed TENET contract $TC$ and data contract $T\forall$. $\text{Proc}_{\text{anego}}$ refers to the anonymous negotiation protocol. $\text{Proc}_{\text{indis}}$ refers to the fair distribution protocol. Double dashed arrows refer to reading from the blockchain and double arrows refer to sending a transaction to the blockchain. Normal arrows mean off-chain communication in secure channels. All parties communicate with $E$ in $E$ in secure channels, i.e., messages broadcast by parties are signed and then encrypted by $pk_{E}$ of $E$, and all messages broadcast by $E$ are also signed by $sk_{E}$. Therefore, for simplicity, we omit to mark ciphertext in communications between $\bar{P}$ and $\bar{E}$, but will explicitly mark the ciphertext in each transaction sent to the blockchain.
$C_i$, $C_r$) on-chain and reveal the plaintext outputs (i.e., $s'_i, r_i$) to corresponding parties respectively, meanwhile, ensuring that parties receiving their plaintext outputs at the same time. The Pro onego also proceeds in three steps.

S1: Each $E$ generates symmetric keys $k'_i, k'_r$ to compute commitments of $s'_i, r_i$, thus getting $C'_i, C'_r$, and generates a proof $= \langle H_g, H_f, \hat{H}_C \rangle$ for proving the MPC-caused state transition. Here, the $\hat{H}_C$ refers to hash of the whole array of old state commitment, i.e., Hash([HC_s],[1,n]), similarly to $\hat{H}_C$. Then, $E$ sends $TX_{com} = BC.TC.commit(id_p, proof_f, C'_i, C'_r, E_k)$ to commit the outputs on-chain. We note that the published $C'_i, C'_r$ includes all elements of normal $C_i$, $C_r$ except the ciphertext of $k'_i, k'_r$ so that parties with only $C'_i, C'_r$ cannot decrypt them to get the $s'_i, r_i$. Instead, the generated $k'_i, k'_r$ varies from different $E$, we require each $E$ attach its keys’ ciphertext $Ek \leftarrow Enc_{pk_e}(k'_i, k'_r)$ to its $TX_{com}$ so that when the $TX_{com}$ is confirmed, other $E$ will decrypt the $Ek$ to use the same keys thus avoiding the inconsistency of these keys. Moreover, the proof $f$ in $TX_{com}$ proves the validity of state transition caused by the MPC program $f$ in following way: The signed $TX_{com}$ means that an verified enclave $E$ endorses that by enforcing a privacy policy $P$ (matching $H_g$), it evaluate the MPC program $\{ \text{logic contract } f \}$ (matching $H_f$) based on old state $s$ (matching $\hat{H}_C$). Therefore, by trusting the integrity and confidentiality of $E$, if the $\Psi$.verify($f$, proof,$\hat{H}_C$) called by $BC.TC.commit$ checks that $H_g, H_f$ in proof $f$ match recorded $H_g, H_f$ in $\Psi$ and the $\hat{H}_C$ in proof $f$ matches the current state commitments of $\Psi$, $\Psi$ then accepts the state transition and updates $\Psi$’s current state commitment with $C'_r$, which signals the COMMIT of the MPC outputs.

S2: When $TX_{com}$ has been confirmed on-chain, each $E$ checks the PoP of $TX_{com}$ and read keys $k'_i, k'_r$ from the $TX_{com}$, then, sends an transaction $TX_k = BC.TC.complete(id_p, Enc_{pk_e}(k'_i), Enc_{pk_e}(k'_r))$ to complete the $k'_i, k'_r$ to confirm $C'_i, C'_r$. The $TX_k$ also refunds deducted collaterals to each party and finish this MPC proposal. Here, the atomicity and standard fairness of output distribution are achieved as follows: In S1, each party $P_i$ has received the incomplete outputs’ commitments but cannot decrypt them without corresponding $k'_i, k'_r$. In S2, each $E$ first verifies PoP to ensure that MPC outputs have been committed on BC. Then, each $E$ independently sends $TX_k$ to finish the protocol with COMPETE. Since the time of sending $TX_k$ to BC’s transaction pool and the communication between parties and honest Executors can be ignored, parties will get the $k'_i, k'_r$ from $TX_k$ at the same time, which finally achieves standard fairness as long as at least one $E$ honestly sends $TX_k$. Otherwise, if $TX_{com}$ is not successfully confirmed on the blockchain, $TX_k$ will consequently cannot be released to complete the protocol before the block height $\tau_{com}$. Then, parties of the MPC go to

\[ S3: \text{If there is no } E \text{ in } \bar{E} \text{ successfully stops (by } TX_{term}) \text{ or completes (by } TX_s) \text{ the MPC proposal before the block height } \tau_{com}, \text{ any } P_i \text{ can send a } TX_{out} \text{ to refunds their collaterals. } TX_{out} \text{ also finishes the MPC with TIMEOUT. We note that this scenario only happens when the } TX_{com} \text{ is not accepted by } \Psi \text{ due to the mismatching of old state commitments’ hash so that the subsequent } TX_k \text{ cannot be released.} \]

6 Enclave Facilities

6.1 Enable TENET on Existing Blockchain

To be interoperable with existing blockchains, TENET is designed to depend on contract-based infrastructure to support MPC-enabled confidential smart contract. A service provider of TENET should perform a one-time global initialization of the target blockchain first, then anyone can interact with the blockchain and TENET Network to evaluate the MPC program.

6.1.1 Initialize TENET blockchain

A service provider of TENET deploys a TENET contract $TC$ on the blockchain to get the TENET Blockchain, marked as $BC$. $TC$ is constructed by the config of $E$, e.g., $pk_E$ and $adr_E$, so that users can authenticate each $E$ and build secure channel with all $E$ of $\bar{E}$. Moreover, $TC$ also allows users to call $TC.register$ to register their public key, so that each $E$ can get parties’ registered encryption keys $pk_i$ on BC to encrypt private data by their corresponding parties’ public keys respectively. Moreover, $TC$ provides several functions to manage the lifecycle of each MPC proposal, e.g., $TC.complete$, which is called by $TX_{com}$ to verify the validity of state transition by calling $\Psi$.verify. The pseudocode of $TC$ is shown in Algorithm 1 and how $TC$ interacts with $\bar{E}$ and parties has been illustrated in Figure 2.

6.1.2 Initialize TENET network

Anyone with a TEE device can instantiate an TEE device with the TENET enclave program (as is shown in Algorithm 2) to get an $E$ and the one itself becomes a TENET Executor $E$. Given that one becomes the first $E$, the $E$ of this first $E$ generates the config (i.e., $pk_E, adr_E$) of the TENET Network $\bar{E}$. Then, the enclaves of other $E$ must be attested by one of $E$ in a specific $E$ to get the network $\bar{E}$’s config ($pk_E, sk_E$) and $(adr_E, key_E)$, and join the $\bar{E}$. Therefore, any $E$ can join the $\bar{E}$ and contribute to the liveliness and scalability of $\bar{E}$. We stress that it’s easy to expand our key synchronization to a more secure method, e.g., distributed key generation protocol, which is out of scope of this paper.
## Algorithm 1: TENET contract (TC)

// Can be deployed to existing blockchains

1 Function constructor(pk_s, addr_g)
   // called by TENET service provider
   pk_s, addr_g ← pk_s, addr_g // for secure channel
   Prpls ← []

2 Function register(pk_h)
   // called by TXhk
   ParPKs[msg.sender] ← pk_h

3 Function deposit(Q)
   // called by TXc
   Coins[msg.sender] ← Coins[msg.sender] + Q

4 Function propose(id_p, p', s_c, t_c, t_coon)
   // called by TXkp from TEE
   require(Prpls[id_p] = 0)
   Prpls[id_p], [q', f, P, C, q, s_t, s_coon, h_c] ← p', [s_c, p', f, P, C, q], s_coon, BC getHeight() // deduct collaterals before execution
   for i ∈ P do
     Coins[i] ← Coins[i] + Prpls[id_p].q
     require(Coins[i] ≥ 0)
   Prpls[id_p].status ← SETTLE

5 Function challenge(id_p, P_q)
   // called by TXcha from TEE
   for i ∈ P do
     Prpls[id_p].P[i].cha ← true

6 Function response(Encpk_e, in)
   // called by TXres from parties
   Prpls[id_p].Msgs_sender[res] ← Encpk_e(in)

7 Function punish(id_p, P_q)
   // called by TXpm from TEE
   require(BC getHeight() > Prpls[id_p].h_p + t_coon)
   require(Prpls[id_p].status = SETTLE)
   rfc = Prpls[id_p].q * (1 + P_q.id_p / [P_q.id_p - P_M.id_p])
   for i ∈ (Prpls[id_p].P - P_q) do
     Coins[i] ← Coins[i] - rfc
   Prpls[id_p].status ← ABORT

8 Function commit(id_p, proof, C_y, C_y)
   // called by TXcom from TEE
   require(Prpls[id_p].status = SETTLE)
   if verify(Prpls[id_p].f, proof, HC_e) then
     Prpls[id_p], [C_y, Encpk_e(k_y)] ← C_y
     Prpls[id_p].status ← COMMIT
   Prpls[id_p].status ← COMPLETE

9 Function complete(id_p, Encpk_e(k_y'), Encpk_e(k_y'))
   // called by TXcp from TEE
   require(Prpls[id_p].status = COMMIT)
   for i ∈ Prpls[id_p].P do
     Prpls[id_p], [q', Encpk_e(k_y'), C_y, Encpk_e(k_y')] ← Encpk_e(k_y'), Encpk_e(k_y')
     Coins[i] ← Coins[i] + Prpls[id_p].q
   Prpls[id_p].status ← COMPLETE

10 Function timeout(id_p)
   // called by TXout from parties
   require(BC getHeight() > Prpls[id_p].h_p + t_coon)
   require(Prpls[id_p].status ̸= COMPLETE)
   for i ∈ Prpls[id_p].P do
     Coins[i] ← Coins[i] + Prpls[id_p].q
   Prpls[id_p].status ← TIMEOUT

## Algorithm 2: TENET enclave program (E)

A E can be initialized in two ways: (i) initialized with a security parameter k to create a new TENET Network E, or (ii) being attested by other E to synchronize the config of an existing E. In both ways, the new E finally get a config pkek, skkek, adrek, keye, s_t, t_coon, where s_t, t_coon are timeout parameters of πTENET // For deploying of F, P. We ignore the id_p management

1 Function deploy(F, P, addr_g)
   // called by TXfk
   bind(F, P, addr_g)
   return addr_g

2 Function generateIDp(p)
   // for enforcing MPC programs
   p.id_p, status ← p, hash(p), GENERATEIDP
   return (id_p, p)

3 Function propose(ACK, TXpk)
   if status ̸= GENERATEIDP or current Time > p.t_p or
     MeetPolicy(ACK, F, P, P, ACK, C, p.q), SETTLE
   return TXpk(id_p, p', s_coon, t_coon)

4 Function execute(in, TXkp, PoP, C)
   if status ̸= SETTLE or verifyPoP(h_c, TXkp, PoP) ̸= 1 then abort
   PoP ← 0
   for i ∈ in do
     x_i, k_i, s_i, k_i in \{x, k, s, k\}
   newC_i = Encg(a_i), Encg(pk_e, k_i), P_i
   newC_i = Encg(a_i), Encg(pk_e, k_i), P_i
   if newC_i ̸= TXkp.C_i or newC_i ̸= C_i then
     PoP ← PoP + P_i
   if PoP > 0 then
     return PoP
   s, r ← evaluate F, (x, s) based on s
   k_i, k_i ← Gen(1^s)
   C_i, C_i ← Encg(k_i), 0, P_i, Encg(r_i), 0, P_i
   goto commit()

5 Function challenge(P_q)
   if status ̸= SETTLE then abort
   if PoP > 0 then
     return TXcha(id_p, PoP)

6 Function punish(TXcha, TXcom, PoP)
   if status ̸= SETTLE or verifyPoP(h_c, TXcha, PoP) ̸= 1
     then abort
     PoP ← 0
   for i ∈ P do
     x_i, k_i, s_i, k_i ← TXcha \{x_i, k_i, s_i, k_i\}
   newC_i = Encg(a_i), Encg(pk_e, k_i), P_i
   newC_i = Encg(a_i), Encg(pk_e, k_i), P_i
   if verifyPoP(h_c, TXcha, PoP) ̸= 1
     or newC_i ̸= TXcha.C_i or newC_i ̸= C_i then
     PoP ← PoP + P_i
   if PoP > 0 then
     return TXcha(id_p, PoP)

7 Function commit()
   if status ̸= EXECUTE then abort
   proof, status ← (H_g, PoP, HC_e, COMMIT
   return TXcom(id_p, proof, C, C)

8 Function complete(TXcom, PoP)
   if status ̸= COMMIT or verifyPoP(h_c, TXcom, PoP) ̸= 1
     then abort
     status ← COMPLETE
   return TXc(id_p, Encpk_e(k_i)[1..L], Encpk_e(k_i)[1..L])
7 System Security

In this section we present the underlying security considerations of TENET.

7.1 Protocol Security

To guarantee security for $\pi_{\text{TENET}}$, we achieve four security properties. Intuitively, they can be explained as the following: Confidentiality. The private parameters, return values and contract states are always kept private to their corresponding parties during the whole protocol.

Anonymity. During the negotiation protocol, a set of apriori-unknown parties will finally reach a consensus about an MPC proposal without knowing each other’s identities.

Financial Fairness. At least one TENET Executor is honest, then either (i) the protocol correctly completes execution of MPC program or (ii) all honest parties knows that setup failed and stay financially neutral or (iii) all honest parties know the protocol abort, stay financially neutral, and malicious parties must have been financially punished or (iv) all honest parties know the protocol timeout and stay financially neutral.

Standard Output Fairness. At least one TENET Executor is honest, then either (i) the new states and return values have been committed on-chain and all parties know the plaintext of new states and return values. or (ii) the new states and return values can not be committed on-chain and none of parties or TENET Executors can know the plaintext of new states and return values.

Theorem 1 (Informal statement). The protocol $\pi_{\text{TENET}}$ satisfies confidentiality, anonymity, fairness, and standard output fairness.

7.2 Architecture Security

TENET aims to enable confidential smart contract with MPC on any contract-enabled blockchain. Here, we analyse architecture security of TENET by considering its implementation. An adversary can corrupt malicious parties of MPC, malicious Executors, or a combination of both. We note that parties of MPC are only required to send and receive transactions from the blockchain and exchange protocol messages with multiple TENET Executors in TENET Network. Parties can implement the client by themselves using diverse set of entirely different code bases in practice, possibly using memory-safe languages such as Go and Rust. Hence, we focus on the TENET Executors in the following.

To prevent malicious TENET Executors from departing the protocol, related works [11] assume a unique Executor incentivized by money to adhere the protocol. These solutions suffer low availability a lot because the system is fragile to unexpected crash of the unique Executor. TENET involves multiples TENET Executors to avoid single point failure and furthermore achieves the consistency among these multiples TENET Executors in TENET protocol. Thus, we assume that the goal of a malicious TENET Executor is to exploit the enclave program at runtime. Enclaves have a well-defined interface and any attack has to be launched using this interface. A malicious TENET Executor can provide fake data through these interfaces to try to exploit a memory-corruption vulnerability in the low-level enclave code to launch (a) a code-reuse attack, e.g., by manipulating enclave stack memory, or (b) a data-only attack, e.g., to leak information about private data of an MPC. For (a) we assume a standard code-reuse defense such as control-flow integrity or fine-grained code randomization. For (b), since parties communicate with TEE devices in secure channels, and all private data are sent to blockchain in ciphertext, TEE devices will resist data leakage. Although we prototype TENET Executor in C++, we note that it’s easy to tackle both attack vectors by using memory-safety languages, such as Python and Rust.

8 Evaluation

System implementations. We express the $P$ in JSON and $\mathcal{F}$, $\mathcal{F}$ in Solidity smart contracts in version 0.8.10 [13]. We use Ganache [29] as BC and the SGX [9] with TENET enclave program as $E$.

Methodology and setup. To evaluate the effectiveness of TENET, we propose 2 research questions.

• Q1: What’s the cost of setup and deployment for enabling MPC on the blockchain by using TENET?

• Q2: What’s the cost of evaluating an MPC program by using TENET?

The experiment is based on Ubuntu 18.04 with 32G memory and 2.2GHz Intel(R) Xeon(R) Silver 4114 CPU. We apply TENET to 6 contracts with 14 MPC programs. As is shown in Table 2, the LOC of these contracts varies from tens to hundreds. The involved parties of these 14 MPC programs varies from 2 to 11. Although the gas cost of a specific transaction is deterministic, it also varies from transaction arguments. Therefore, we send each transaction 5 times with different arguments to get the average.

Table 2: The LOC of contracts. #MPC refers to the number of MPC programs; The #F, #F, and #P refer to LOC of the private contract, data contract, and privacy policy respectively.

| Name         | #MPC | #F  | #F | #P  |
|--------------|------|-----|----|-----|
| SupplyChain  | 1    | 39  | 37 | 120 |
| Scores       | 1    | 95  | 118| 213 |
| ERC20Token   | 3    | 55  | 37 | 240 |
| Yunbdou      | 3    | 105 | 58 | 433 |
| Oracle       | 2    | 60  | 48 | 307 |
| HTLC         | 4    | 200 | 90 | 526 |
8.1 Initialization and Setup Cost

To answer Q1, we discuss the gas cost of deploying the $T_C$ contract and each contract in Table 2. The result is shown in Figure 3.

**Gas cost of initialization.** In global initialization phase, TENET costs 4.5M gas to deploy the $T_C$ contract to enable MPC programs in existing blockchains. This cost is only paid by TENET service provider for once, thus is mostly irrelevant.

**Gas cost of global setup.** Each party pays 12.7k gas to register($reg.$) its public key and 4.2k gas to deposit($dep.$) its coins. Moreover, since each party only pays and does it once, the gas cost of global setup phase is acceptable.

8.2 Transaction Cost

**Gas cost of evaluating MPC programs.** The right part of Figure 3 shows the transaction costs of all 14 MPC programs in 6 contracts. In general, TENET reduces gas by 9.4% against Fastkitten that requires $n+1$ transactions to secure an MPC program. Specifically, for 6 MPC programs with only 2 parties, TENET costs 1.0-1.11X gas to Fastkitten. However, for other 8 MPC programs (including all 5 MPC programs with more than 2 parties), TENET costs only 0.55-0.98X gas against Fastkitten. When the number of parties increases to 10 and 11, the cost of TENET significantly decreases to 0.55X and 0.58X respectively. Overall, we conclude that TENET evaluates MPC programs in not only an secure adversary model but also lower cost.

**Off-chain cost of evaluating MPC programs.** Normally, all 14 MPC programs complete in 3 blockchains interactions, where the negotiation phase costs 0.21-0.58s, the execution phase costs 0.39-1.15s, and the distribution phase costs 0.30-0.77s. Most time 3-5s is spent on verifying the confirmed $TX_p$ and $TX_{com}$ respectively.

![Gas Cost](image)

**Figure 3:** The gas cost of TENET. "Fastkitten" refers to the gas cost sum of $n+1$ transactions required by evaluating an MPC program by Fastkitten. Here we implement the protocol of Fastkitten on Ethereum. "$TX_p$", "$TX_{com}$" and "$TX_k$" refers to gas cost of $TX_p, TX_{com}, TX_k$ in $\pi_{TENET}$ respectively.

9 Discussion

**Expanding policy to meet general-purpose need.** In current syntax, the owner of private data is specified to a single party’s address, limiting the owner to a specific account. However, in the real-world, the owner could be a group or committee. We can definitely expand the party in policy to an predicates which corresponds to an complex access control system. Finally, It’s also possible to allow a owner to transfer his ownership to others, for which the TENET can match the plaintext secret with on-chain ciphertext, encrypt the secret with transferee’s public key and record the ownership transfer event on-chain.

**Expanding to multi-party privacy-preserved computation.** Currently, the data is bound to the encryption commitments stored in a on-chain data contract, which indicate small size and simple structure of private data. However, the private data in some promising scenarios (e.g., joint AI training) with large volume or complex data structures are not suitable to be stored on-chain. We note that TENET can replace the encryption commitments in policy to hash commitments, so that no matter what’s the data structure or where the data is stored, it can be identified and used as inputs to the MPC program. As for more complex computation, developer could just bind the code commitment (e.g., code hash) on-chain, so that the code expressing complex computation logic (e.g., AI training) by any language can be identified by the commitment and executed in TEEs. Moreover, the 2nd generation (e.g., 2rd version SGX) breaks the memory limitation of enclaves, which also contributes to this tendency. In this way, although parties have to persist the preimage data corresponding to commitments of each transaction thus sacrifice some stateless, the anonymous negotiation and fair distribution protocol can be easily adapted to off-chain big data scenarios.

10 Conclusion

In this paper, we have developed a novel framework, TENET, to support off-chain MPC-enabled confidential smart contract. Comparing with current solutions, while parties and enclaves in TENET system have no need to persist states or transaction-specific data, TENET furthermore supports apriori-unknown parties anonymously negotiate with others to join an MPC and delivers the MPC outputs in a standard fair manner. Moreover, by introducing an improved challenge-response mechanism, TENET guarantee the availability and security of each MPC program in presence of byzantine adversary, which is able to corrupt all parties and all-but-one TEE executors. TENET not only secures an MPC program by only 3 transactions in adversary model. During our evaluation of TENET in both examples and real-world smart contracts, for all MPC programs that involving 2 to 11 parties, TENET only cost 0.55-0.98 gas (0.91 on average) against the state-of-the-art.
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