## DECLOAK: Enable Secure and Cheap Multi-Party Transactions on Legacy Blockchains by a Minimally Trusted TEE Network

Qian Reno, Yue Lio, Yingjun Wuo, Yuchen Wuo, Hong Leio, Lei Wango, and Bangdao Cheno

Abstract—As the confidentiality and scalability of smart contracts have become a crucial demand of blockchains, off-chain contract execution frameworks have been promising. Some have recently expanded off-chain contracts to Multi-Party Computation (MPC), which seek to transition the on-chain states by offchain MPC. The most general problem among these solutions is MPT, since its off-chain MPC takes on- and off-chain inputs, delivers on- and off-chain outputs, and can be publicly verified by the blockchain, thus capable of covering more scenarios. However, existing Multi-Party Transaction (MPT) solutions lack at least one of data availability, financial fairness, delivery fairness, and delivery atomicity. The data availability means entities can independently access the data required to rebuild new states and verify outputs; financial fairness implies at least one adversary will be punished monetarily; delivery fairness means parties can receive their outputs at almost the same time; delivery atomicity means that parties receive their outputs and new states are committed must both happen or neither. These properties are crucially valued by communities, e.g., the Ethereum community and users. Even worse, these solutions require high-cost interactions between the blockchain and offchain systems.

This paper proposes a novel MPT-enabled off-chain contract execution framework, DECLOAK. DECLOAK is the first to achieve data availability of MPT, and our method can apply to other fields that seek to persist user data on-chain. Moreover, DECLOAK solves all mentioned shortcomings with lower gas cost and weaker assumption. Specifically, DECLOAK tolerates all-but-one Byzantine party and TEE executors. Evaluating on 10 MPTs, DECLOAK reduces the gas cost of the SOTA, Cloak, by 65.6%. Consequently, we are the first to not only achieve such level secure MPT in practical assumption, but also demonstrate that evaluating MPT in the comparable average gas cost to Ethereum transactions is possible. And the cost superiority of DECLOAK increases as the number of MPT' parties grows.

#### Index Terms—Confidential Smart Contract, Multi-Party Com-

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putation, Trusted Execution Environment

#### I. INTRODUCTION

TITIE blockchains are rapidly developed and adopted in various domains, e.g., DeFi, NFT, IoT industries, contract privacy and scalability of blockchains have now become two of the top concerns. Unfortunately, in most existing blockchains [1], [2], blockchain data must be publicly accessible and verifiable so that miners can access the transaction data and re-execute transactions to verify all state transitions. Off-chain contract execution with MPC. The demand for both privacy and scalability motivates off-chain smart contract execution frameworks. Their common idea is to offload the smart contract execution from the blockchain to off-chain systems. The blockchain then functions only as a trust anchor to verify the execution and store states. Subsequently, some promising solutions extend the off-chain contract execution to multi-party scenarios, including auction [3], personal finance [4] and deal matching [5], [6]. This problem is generalized and defined in [7] as Multi-Party Transaction (MPT) [7], [8]. It means transitioning blockchain states by a publicly verifiable off-chain MPC, where the MPC takes on- and offchain inputs from, and delivers on- and off-chain outputs to multiple parties, without leaking their inputs/outputs to the public or each other. For example, in a second-price auction [3], multiple mutually distrustful parties jointly perform an auction on their confidential on-chain balance and off-chain bids. When the auction finishes, the party with the highest bid wins and pays the second-highest price on-chain. To enable MPT, two kinds of solutions exist. The first is cryptographybased solutions, which adopt MPC [9]–[11] or Homomorphic Encryption (HE) [12] to allow parties jointly and confidentially evaluate a program off-chain, then commit the evaluation status/outputs on-chain. The second, TEE-based solutions [4], [7], [8], [13], uses TEE to collect private data from parties, evaluates a program with the data inside enclaves, and finally commits the evaluation status/outputs on-chain.

**Limitations.** However, existing solutions of MPT suffer from at least one of the following flaws: (i) Do not achieve data availability, making them vulnerable to data lost when off-chain systems fail. For example, even with ZKP or TEE to prove the correct state transitions, users cannot know their balances if an off-chain operator withholds the states. This property is keenly required by the Ethereum community [14] and the community has designed a series of measures to

uphold it, e.g., calldata [15]-[17] and blob [18], which are keys of the coming Cancun upgrade [19]; (ii) Do not achieve financial fairness, so they can only assume a rate of honest nodes exists but cannot monetarily urge profit-driven nodes to behave honestly or punish the misbehaved nodes; (iii) Do not achieve delivery fairness, which requires delivering outputs to corresponding parties at almost the same time. Formally, we say a MPC protocol achieves  $\Delta$ -fairness if the time of different parties receiving their outputs distributes in a  $\Delta$ -bounded period. A large  $\Delta$  will lead to several attacks, e.g., a party prior to others knowing that the MPT buys an ERC20 token and change the trade rate can front-run an arbitrage transaction, so-called front-running attacks, e.g., MEV [20]. (iv) Do not achieve delivery atomicity, i.e., either both committing new states and delivering outputs are guaranteed, or none of them happens. The lack of atomicity either enables adversary knowing outputs before they are being committed on-chain to abort or rewind the MPT, or leads party to permanently lost their outputs when the outputs have been committed [21]; (v) Require high-cost interactions with the blockchain.

Our work. In this paper, we propose DECLOAK, a novel MPT-enabled off-chain contract execution framework. DE-CLOAK solves all above problems with lower gas cost and weaker assumption. Specifically, to enable MPTs on a legacy blockchain, e.g., Ethereum [2], we require multiple TEE executors to register their TEEs on a deployed DECLOAK contract. The contract thus be aware of all TEEs and will specify a specific TEE to serve all MPT. Then, multiple parties can interact with the specified TEE off-chain to send MPTs. To achieve data confidentiality and availability (cf., i), we propose a novel data structure of commitments. The structure allows each party and TEE to independently access the newest states from the blockchain, even though all other entities are unavailable. To achieve financial fairness (cf., ii) and low cost (cf., v), we propose a novel challenge-response subprotocol. With the subprotocol, all honest entities among parties and TEE executors will never lose money, and at least one misbehaved entity will be punished. Especially, it enables the DECLOAK contract to identify the misbehaviour of the specified TEE and replace it with another TEE. To achieve atomicity (cf., iv) and delivery fairness (cf., iii), we require all TEEs to release the keys of output ciphertext only when verifying that the output commitments have been accepted and confirmed by the blockchain. This way, we achieve the complete fairness of output delivery, where multiple parties obtain their corresponding outputs in almost the same time. Consequently, DECLOAK achieves the data availability, financial fairness, delivery fairness, and delivery atomicity of MPTs simultaneously with only 34.4% gas cost of the SOTA, Cloak [8], while assuming at least one parties and TEE executors are honest. Last, we demonstrate how to optimize or prune DECLOAK for simpler or less secure scenarios, including how to ignore some secure properties for lower gas costs further.

Contributions. Our main contributions are as follows.

 We design a novel off-chain contract execution framework, DECLOAK, which enables MPTs on legacy blockchains.

- We propose a DECLOAK protocol which handles the problem of how to maximize the security of MPTs by using a minimally trusted TEE network. Specifically, the protocol achieves confidentiality, data availability, financial fairness, delivery fairness, and delivery atomicity simultaneously, while requiring at least one party and at least one of TEE executors to be honest.
- We implement and evaluate DECLOAK on 10 MPTs with varying parties from 2 to 11.
- We demonstrate how to optimize further or fine-tune DE-CLOAK protocol to make trade-offs between security and cost for simpler scenarios.

Organization. We organize the paper as follows. Section II introduces MPT and how DECLOAK advances related work. Section III sketches DECLOAK. Section IV details the DECLOAK protocol. Section V illustrates the implementation of DECLOAK prototype. In Section VI, we conduct a security analysis of DECLOAK. In Section VIII, we discuss how to optimize the DECLOAK protocol and make trade-offs between the security and gas cost when degenerating MPT to simpler scenarios. Finally, we evaluate DECLOAK in Section VII and conclude in Section IX.

#### II. BACKGROUND AND RELATED WORK

#### A. Multi-Party Transaction

Informally, Multi-Party Transaction (MPT) refers to a transaction which transitions states on-chain by publicly verifiable off-chain MPC. The off-chain MPC in an MPT takes both on-/off-chain inputs and delivers both on-/off-chain outputs. Therefore, so far, MPT is the most general definition of off-chain contract execution in multi-party scenarios and can be easily applied to various domains. For example, recall the second-price auction in Section I. During the process, the bids should keep private to their corresponding parties, *i.e.*, *confidentiality* is held; The public (*e.g.*, the blockchain miners) ought to verify that the output is the correct output of a claimed joint auction, *i.e.*, the *correctness* and *public verifiability* hold. We demonstrate more MPT scenarios in Section VII.

Formally, MPT is modeled as below [7], [8].

$$c_{s_1}, \dots, c_{s_n} \stackrel{c_f, c_{x_1}, \dots, c_{x_n}}{\Longrightarrow} c_{s'_1}, \dots, c_{s'_n}, c_{r_1}, \dots, c_{r_n}, proof$$

$$| s_1, \dots, s_n \xrightarrow{f(x_1, \dots, x_n)} s'_1, \dots, s'_n, r_1, \dots, r_n$$

For a blockchain and an array of parties P where |P| = n  $(n \in \mathbb{Z}^* \land n > 1)$ , we denote a party P[i] as the party  $P_i$ . An MPT takes secret transaction parameter  $x_i$  and old state  $s_i$  from each  $P_i$ , confidentially evaluates f off-chain, then delivers the secret return value  $r_i$  and new state  $s_i'$  to  $P_i$ , while publishing their commitments  $c_{x_i}, c_{s_i}, c_f, c_{s_i'}, c_{r_i}$  and a *proof* on the blockchain. MPT should satisfy the following properties.

• Correctness: When each  $P_i$  providing  $x_i, s_i$  obtains  $s'_i, r_i$ , it must hold that

$$s_1,\ldots,s_n \stackrel{f(x_1,\ldots,x_n)}{\Longrightarrow} s'_1,\ldots,s'_n,r_1,\ldots,r_n$$

• Confidentiality: Each  $P_i$  cannot know  $\{x_j, s_j, s'_j, r_j | j \neq i\}$  except those that can be derived from public info and the secrets it provides.

#### Table I

COMPARING DECLOAK WITH RELATED WORK. THE SYMBOLS X, ○, ▶ AND ● REFER TO "NON-RELATED", "NOT-MATCHED", "PARTIALLY-MATCHED" AND "FULLY-MATCHED" RESPECTIVELY. "ADVERSARY MODEL" MEANS HOW MANY BYZANTINE ENTITIES CAN BE TOLERANT. "DATA AVAILABILITY" MEANS WHETHER PARTIES OR TEES HOLD MPT-SPECIFIC DATA. "FINANCIAL FAIRNESS" MEANS HONEST PARTIES NEVER LOST MONEY WHILE AT LEAST ONE MISBEHAVED NODE MUST BE PUNISHED. "DELIVERY FAIRNESS" MEANS EITHER THE MPT FAILS OR PARTIES OBTAIN THEIR OUTPUTS IN ALMOST THE SAME TIME. "DELIVERY ATOMICITY" MEANS WHETHER BOTH COMMITTING OF OUTPUTS AND THE DELIVERY OF OUTPUT OR NONE OF THEM ARE GUARANTEED.

Approach	Adversary Model		min(#TX)	Confidentiality	Data availability				Delivery
	Parties	TEE Executors	(" 111)		Parties	TEEs	Fairness	Fairness	Atomicity
Ekiden [21]	1*	$m^* - 1$	O(1)	•	0	0	×	×	•
Confide [22]	1*	$ (m^*-1)/2 $	O(1)	•	O	•	×	×	×
POSE [23]	$1^* - 1$	$m^*-1$	O(1)	•	•		×	×	0
Bhavani et al. [24]	$n^*$	$m^*\mid_{m=n}$	O(1)	•	×	×	×	•	×
Hawk [3]	$n^*$	×	O(n)	•	O	×	•	O	0
ZEXE [25]	$n^*$	1*	O(1)	•	O	×	×	×	0
Fastkitten [13]	(n	(* + 1*) - 1	O(n)	•	0	0	•	0	0
LucidiTEE [4]	$n^*$	$m^* - 1$	O(n)	•	0		×		•
Cloak [8]	(n	(* + 1*) - 1	O(1)	•	0	•	•	0	0
DECLOAK	$n^* - 1$	$m^* - 1$	O(1)	•	•	•	•	•	•

The \* denotes the total number of the specific type of entities, e.g.,  $1^*$  denotes the unique party/executor,  $n^*$  denotes all n parties, and  $m^*$  denotes all executors.

• *Public verifiability*: With *proof*, all nodes can verify that the state transition from  $c_s \leftarrow [c_{s_i}|_{1..n}]$  to  $c_{s'} \leftarrow [c_{s'_i}|_{1..n}]$  is correctly caused by a unknown function f (committed by  $c_f$ ) taking unknown parameter  $x_i$  (committed by  $c_{x_i}$ ) and old state  $s_i$  (committed by  $c_{s_i}$ ), and obtains unknown new state  $s'_i$  (committed by  $c_{s'_i}$ ) and return value  $r_i$  (committed by  $c_{r_i}$ ).

#### B. Related Work

Here we highlights the difference and novelty of DECLOAK, as shown in Table I.

**TEE-based confidential smart contract.** Ekiden [21], [26], CCF [27], Confide [22], and POSE [23] are designed for confidential smart contracts where transaction inputs/outputs and contract states are confidential and all transactions are regarded as independent. These frameworks never consider properties specific in multi-party scenarios, *e.g.*, fairness.

Ekiden is a confidential smart contract framework which features appointing the consensus, execution, and key management functionality to different nodes. Specifically, besides consensus nodes, Ekiden sets up multiple TEE-enabled executors to serve users independently, where consensus nodes can obtain outputs as long as at least one executor is honest. Yet it requires executors' TEEs to fetch keys from a TEE-based key management committee to evaluate each transaction. This requirement additionally assumes the number of available TEE executors in the committee should be over a specific threshold, where the threshold depends on the threshold of the distributed key generation algorithms adopted by the committee. On atomicity, Ekiden proposes a two-phase protocol which delivers keys encrypting the outputs to users off-chain when the outputs have been committed on-chain, thus achieving atomicity. On data availability, users cannot access their states on-chain since the states are encrypted by TEEs. However, each executor also cannot decrypt on-chain states without requesting keys from the committee. Therefore, it is flawed in data availability.

Confide and CCF are permissioned network where TEEenabled executors maintain a consensus, e.g., RAFT, thereby can tolerate less than 1/2 unavailable executors. They store contract data (*e.g.*, code, states) by encrypting data with keys shared among TEEs, thereby achieving data availability of TEEs. However, like Ekiden, if TEE executors are unavailable, users will temporarily lose accessibility to and even permanently lose their private data and on-chain assets. The TEEs' data availability holds.

POSE propose an off-chain contract execution which features high availability and no interaction with blockchain in optimistic cases. It introduces a challenge-response mechanism, ensuring the system's availability even if all-but-one executors are Byzantine. The protocol additionally requires the transaction sender to be honest to initiate the challenge. Users of POSE cannot access their states independently. Each TEE need to synchronize with other TEEs to obtain state updates. On atomicity, while involving reading inputs from and writing blockchain, POSE does not consider the atomicity of the onchain writing and off-chain output delivery.

**TEE-based smart contracts enabling MPTs.** Choudhuri *et al.* [24] is the first to achieve complete fairness for general-purpose functions with the help of blockchain and TEEs. It requires each party to hold a TEE itself. Bhavani *et al.* does not consider executing contract relying on on-chain states, committing states on blockchains, or punishing misbehaved nodes, thus being non-related to delivery atomicity, data availability, or financial fairness.

Fastkitten [13] seeks to enable arbitrary contracts, especially including multi-round MPC, on Bitcoin. It lets parties execute a transaction with private inputs in TEEs, persists the outputs locally, and only submit new state commitments with TEE signatures on-chain. Therefore, the party must persist all its latest private contract states and corresponding keys to ensure its ability to transition the states next time, lacking data availability. In long-running systems, parties' persisted data keep growing, making it a disaster for parties to maintain. Moreover, it involves a challenge-response mechanism to achieve financial fairness but requires each party to send a deposit transaction before each MPT, leading to O(n) transactions.

LucidiTEE [4] loosely requires part of parties to hold TEEs to achieve delivery fairness. However, the time of parties receiving outputs distributes in a period the length of which equals the generation time of Proof of Publication  $(PoP)^1$  [13], [21], [28] for proving TEE that a key-releasing transaction has been finalized on-chain, which costs more than 50 block intervals on Ethereum <sup>2</sup>. Moreover, LucidiTEE requires each party to send a transaction to join an MPT or deposit, leading to O(n) transactions. On financial fairness, LucidiTEE lacks mechanisms to punish misbehaviours. With a similar state confidentiality mechanism as Ekiden and commitment as Fastkitten, LucidiTEE also lacks data availability.

Cloak [8] firstly propose a *one-deposit-multi-transaction* mechanism, where each honest party deposits coins once globally and then joins MPTs ultimately. The mechanism reduces it required on-chain transactions to O(1). Cloak only commits the hash of transaction data on-chain, e.g., inputs, outputs, keys, and policies. Thereby their parties also cannot access their states without TEE executors, i.e., lacking data availability.

DECLOAK propose a novel commitment structure to confidentially persist states on the blockchain with low cost. Each party can access their MPT-specific data from the blockchain with only its own account private key. Each TEE can read MPT-specific data from the blockchain without the help of either parties or other TEEs. Consequently, even if the whole off-chain system is unavailable, the data availability of the newest states is still guaranteed. As DECLOAK adopt the same one-deposit-multi-transaction and a novel challenge-response protocol, it only requires O(1) transactions in optimistic cases. Finally, while achieving complete delivery fairness, DECLOAK frees parties from maintaining TEEs

Cryptography-based smart contracts enabling MPTs. Cryptography-based schemes usually combine MPC/HE with ZKP to enable MPTs. Before the combination, MPC/HEbased works like [29]–[31] achieve great confidentiality but not targets public verifiability. ZKP-based solutions achieve public verifiability but lack confidentiality. For example, Hawk [3] requires a tight-lipped manager to collect parties' secrets, execute a contract, and generate the ZKP proof, thus the confidentiality of Hawk is limited. ZEXE [25] proves the satisfaction of predicates by ZKP proof without revealing party secrets to the public. However, generating the proof requires a party to know all predicate's secrets, thereby violating inter-party confidentiality. Combining MPC with ZKP, public auditable MPC (PA-MPC) [9] achieves the publicly verifiable MPC, allowing multiple parties jointly evaluate a program and prove it. Nevertheless, existing PA-MPC primitives are not designed for committing data or proving state transitions, e.g., MPCs expressed in Solidity that operate both on- and offchain inputs/outputs. Moreover, they have flaws at inefficiency and weaker adversary model, and still fail in practically supporting nondeterministic negotiation or achieving financial fairness. Specifically, [9] requires trusted setup or un-corrupted parties. [32] is function-limited. [33] very recently achieves general-purpose PA-MPC but only support circuit-compatible operations. None of the above solutions are for confidential smart contracts or can punish adversaries. Instead, using the same proof structure with Cloak, DECLOAK conforms to both confidentiality and public verifiability. For security, while the underlining MPC of [24], [29]–[31] requires honest-majority parties, DECLOAK secure the system under an Byzantine adversary corrupting all parties and all-but-one TEE executors.

#### III. DECLOAK DESIGN

In this section, we first overview the system model, adversary model, and system goals of DECLOAK. Then, we overview DECLOAK protocol and highlight the challenges we handled and corresponding countermeasures.

#### A. System model

Figure 1 shows the framework of DECLOAK, *i.e.*, a TEE-Blockchain system consisting of three components.

**Blockchain** (*BC*). A blockchain, *e.g.*, Ethereum [2], that can deploy and evaluate Turing-complete smart contracts.

**Parties** (*P*). an array of parties who participate a specific MPT. **DECLOAK network** (*DN*). A DECLOAK Network consists of multiple TEE executors and TEEs, where each executor E is a server hosting a TEE  $\mathscr{E}$ . We denote the set of all executors as E and all TEEs as E.

#### B. Adversary model

We assume that a Byzantine adversary presents in a DE-CLOAK system. The assumptions and threats are as follows. **Blockchain.** We assume that *BC* satisfies the common prefix, chain quality and chain growth, so it can continuously handle and reach consistency on new transactions. Moreover, there is a Proof of Publication (PoP) scheme to prove to TEEs that a transaction has been finalized on *BC*, which is for against eclipse attack and also adopted by [8], [13], [21], [28]. The PoP of a transaction is a block sequence that contains the transaction and is provided to TEEs in the expected time.

**Parities.** An honest party can access the latest view of the blockchain and trust the data it reads from the blockchain. It trusts its platform and running code but not others. An honest party also trusts the integrity and confidentiality of all TEEs it attested. An honest party never reveal its secrets to others except attested TEEs.

**DECLOAK network.** An honest TEE executor can access the latest blockchain view and trust the data it reads from the blockchain. An honest executor also trusts its platform and running code but not others. An honest executor also trusts the integrity and confidentiality of attested TEEs.

**Threat model.** A Byzantine adversary can corrupt all parties and all-but-one TEE executors. A corrupted party or executor can behave arbitrarily, *e.g.*, mutating, delaying and dropping messages, but never break the integrity/confidentiality of TEE. Moreover, the adversary cannot interfere with the communications among honest entities, *e.g.*, the communications among honest parties or between honest parties and honest executors.

<sup>&</sup>lt;sup>1</sup>Recall that PoP is a proof constructed for proving that a transaction has been confirmed on a blockchain

 $<sup>^2</sup>For$  achieving  $\leq 0.001$  false negative and false positive under an adversary with  $\leq 1/3$  computing power of Ethereum

#### C. System goals

Informally, we seek to achieve following properties.

**Correctness.** If an MPT succeeds, the outputs must be the correct results of the MPT applied to the inputs committed. **Confidentiality.** The inputs and outputs of MPT are always confidential to their corresponding parties.

**Public verifiability.** The public, including the blockchain, can verify the correctness of the state transition caused by a MPT. Particularly, to accept a state transition, the blockchain will verify that the old states from which the new state is transitioning match its current states.

**Data availability.** If an MPT successfully completes, it holds that (i) each honest party can access the plaintext of its newest states independently, and (ii) each honest executor's TEE can access the plaintext of the newest states independently to restore the newest states. This means honest parties will never lose their newest states, no matter how TEE executors behave. **Financial fairness.** If at least one party is honest, then either (i) the protocol correctly completes the MPT or (ii) all honest parties know that negotiation of the MPT failed and stay financially neutral or (iii) all honest parties know the protocol aborted, stay financially neutral, and at least one of malicious entities must have been financially punished.

**Delivery fairness.** If at least one TEE executor is honest, then either (i) all parties know the plaintext return values and new states in a  $\Delta$ -bounded period, or (ii) the new states and return values are not committed on-chain, and none of the parties or executors can know the plaintext of new states and return values.

**Delivery atomicity.** If at least one TEE executor is honest, then either (i) some parties know the plaintext new states or return values, and the new states must have been committed on-chain, or (ii) new states are not committed on-chain, and none of the parties obtains its plaintext new states or return values.

#### D. Protocol workflow

Figure 1 shows the workflow of  $\pi_{\text{DECLOAK}}$ . We assume all TEEs have been registered on-chain as a TEE list  $\mathcal{E}$  before the protocol started. Then,  $\pi_{\text{DECLOAK}}$  starts to serve an MPT in four phases, *i.e.*, *global setup*, *negotiation*, *execution*, and *delivery* phases. The *global setup* phase happens only once for any party. Other three phases of  $\pi_{\text{DECLOAK}}$  happen in evaluating each MPT.

- (0) Global setup phase: All parties and TEEs deposit some coins to the network account  $ad_{\mathcal{E}}$  on BC.
- (1) Negotiation phase: A party sends an MPT proposal p to the first executor  $\mathcal{E}^*$  in the registered TEE executor list to initiate an MPT. Upon receiving the proposal, the TEE  $\mathcal{E}^*$  starts a nondeterministic negotiation subprotocol Proc<sub>nneg</sub>. Specifically, the  $\mathcal{E}^*$  signs and broadcasts the proposal to all parties. If any party want to join or is required by the proposal, it responds with an acknowledgement to  $\mathcal{E}^*$ . The  $\mathcal{E}^*$  keeps collecting parties' acknowledgements. When the collected acknowledgements match the settlement condition of the negotiation phase  $(e.g., The number of parties exceeds the number specified in the policy), <math>\mathcal{E}^*$  settles the proposal,

- deducts parties' collaterals from their coins cached in  $\mathcal{E}^*$ , and broadcasts the settled MPT proposal p' to all parties.
- (2) Execution phase: Upon receiving p', each party involved in the proposal submits its signed plaintext inputs (i.e., parameters) to  $\mathcal{E}^*$ .  $\mathcal{E}^*$  first read old states on the blockchain with their PoP<sup>3</sup>. Then,  $\mathcal{E}^*$  evaluates the MPT to obtain the outputs (i.e., return values and new states) inside.
- (3.1-3.2) **Delivery phase**: When the  $\mathscr{E}^*$  gets the MPT outputs, it starts a  $\Delta$ -fair delivery subprotocol  $Proc_{\text{fdel}}$ . First, it generates one-time symmetric keys to compute the commitments of the outputs and sends a  $Commit\ TX_{cmt}$  to publish output commitments on BC with the ciphertext of the symmetric keys (encrypted by the network key  $k_{\mathcal{E}}$ ). Upon  $TX_{cmt}$  being confirmed on the blockchain, each  $\mathscr{E} \in \mathcal{E}$  independently verifies the PoP of  $TX_{cmt}$ , obtains the symmetric keys from  $TX_{cmt}$ , then sends a  $TX_{com}$  to reveal the committed outputs to each party respectively. Consequently, both parties and executors do not need to persist any MPT-specific commitments or keys.

If any misbehaviour appears during the negotiation, execution, or delivery phase, we adopt a novel challenge-response mechanism to identify the misbehaved entities in parties and TEE executors.

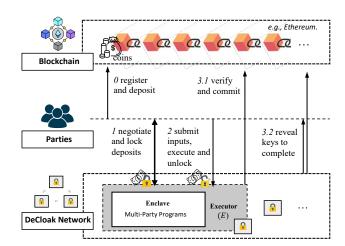


Figure 1. The framework and workflow of DECLOAK.

#### E. Design challenges and highlights

#### 1) Achieve data availability of both TEEs and parties

The challenge here is (i) how to achieve the data availability of both parties and TEEs and (ii) ensuring confidentiality and living in harmony with the protocol for delivery atomicity and fairness. To achieve these, we introduce a novel data commitment subprotocol. Specifically, say each party  $P_i$  has its account  $(sk_i, pk_i, ad_i)$ , where  $sk_i, pk_i, ad_i$  refer to the private key, public key and address of the account. As each party  $P_i$  is identified by its address, we refer  $P_i$  to  $ad_i$  indiscriminately. We assume a common TEE network account  $(sk_{\mathcal{E}}, pk_{\mathcal{E}}, ad_{\mathcal{E}})$  has been synchronized among all TEEs. Then, we require all entities commit private data  $d_i$  on blockchain in the following structure  $c_{d_i}$ .  $k_{d_i}$  denotes a one-time symmetric key

<sup>&</sup>lt;sup>3</sup>We use the same PoP as [8], [13], [28]

for encrypting  $d_i$ .  $k_{ie}$  denotes the symmetric key generated by ECDH, i.e.,  $k_{ie} \leftarrow \text{ECDH}(sk_i, pk_{\mathcal{E}})$  and  $k_{ie} \leftarrow \text{ECDH}(sk_{\mathcal{E}}, pk_i)$ . Consequently, on the one hand, either  $P_i$  or TEEs can independently obtain  $k_{ie}$  without interacting with the other. And a party needs only to hold the account private key  $sk_i$  to access and operate its all commitments on-chain. On the other hand, when DECLOAK release  $c_{d_i}^*$  ( $c_{d_i}$  without  $\text{Enc}_{k_{ie}}(k_{d_i})$ ) to commit and verify the state transition on-chain first for atomicity and fairness, any adversary cannot obtain  $k_{d_i}$  to decrypt  $\text{Enc}_{k_{d_i}}(d_i)$ .

$$c_{d_i} := [\mathtt{Enc}_{k_{d_i}}(d_i), \mathtt{Enc}_{k_{ie}}(k_{d_i}), P_i]$$

#### 2) Achieve complete delivery fairness

In DECLOAK, when a TEE executor evaluated the MPT inside its TEE, the TEE cannot release the output immediately. Instead, the TEE first generates one-time symmetric keys to encrypt the outputs, then sends a  $TX_{cmt}$  to publish the output ciphertext and the ciphertext of the keys on-chain. The keys' ciphertext can be decrypted by all TEEs independently but each TEE only releases the decrypted keys after  $TX_{cmt}$  has been finalized on-chain. Since we assume the blockchain is ideally available, all honest TEE executors can feed the PoP of  $TX_{cmt}$  to their TEE. Therefore, if at least one honest executor exists, parties communicating with all executors can obtain the keys to decrypt the output ciphertext at almost the same time.

### 3) Resist Byzantine adversary with minimal transactions In this paper, we propose a novel challenge response subprotocol Proc<sub>rcha</sub>. At a high level, Proc<sub>rcha</sub> is designed with the following idea: when an honest party does not receive protocol messages off-chain from the specified TEE, it can publicly challenge the TEE with the proposal on-chain. The TEE can only avoid being punished if it can respond with expected outputs or prove that the problem is caused by some misbehaved parties rather than itself. Specifically, an MPT proposal only has three possible results: (i) NEGOFAILED, which means the negotiation of the proposal failed; (ii) COMPLETED, which means the completion of the MPT, i.e., an $TX_{com}$ is sent and accepted by the blockchain (iii) ABORTED, i.e., some entities misbehaved, making the MPT aborted. Therefore, the challenged TEE needs to respond with one of the following three results to prove its honesty: (i) sending a transaction $TX_{fneg}$ to prove that the negotiation of the MPT failed; (ii) sending a transaction $TX_{com}$ to complete the MPT and release its outputs; (iii) sending a transaction $TX_{pnsP}$ to prove that it cannot complete the MPT as expected because some parties misbehaved after the negotiation succeeded rather than itself. If none of the above transactions can be sent, the TEE will be punished. However, while (ii) is inherited by the success of MPT, how to achieve (i) and (iii) becomes challenging. To achieve (i), we require each MPT proposal should specify a block height $h_{neg}$ to notify when the negotiation phase is expected to finish. Then, a TEE can send a $TX_{fneg}$ to fail the proposal on-chain if it verifies that the collected acknowledgements from both off-chain ack and on-chain $TX_{ack}$ before $h_{neg}$ -th block still cannot satisfy the settlement condition of the proposal. To achieve (iii), when a TEE cannot complete the MPT, the TEE needs to challenge those misbehaved parties to prove that the reason is some parties did not submit their

inputs rather than itself.

#### IV. DECLOAK PROTOCOL

In this section, we present the DECLOAK protocol  $\pi_{\text{DECLOAK}}$  in detail. Given a blockchain BC, a DECLOAK Network DN having an array of executors E and TEEs  $\mathcal{E}$ , we assume a common network account  $(sk_{\mathcal{E}}, pk_{\mathcal{E}}, ad_{\mathcal{E}})$  has been synchronized among all TEEs  $\mathcal{E}$ . For an MPT  $\mathscr{F}$  with its party set P, we assume  $|E| = |\mathcal{E}| = m$  and |P| = n. Since  $\pi_{\text{DECLOAK}}$  involves data from different parties, we use  $d_i$  to denote the private data of  $P_i$   $(e.g., x_i, s_i, k_{s_i})$ , d to denote an array  $[d_i|_{1..n}]$  including all  $d_i$  from n parties  $(e.g., x, s, k_s)$ . We let  $H_{d_i}$  denote hash  $(d_i)$  and  $H_d$  denote  $[\text{hash}(d_i)|_{1..n}]$   $(e.g., H_{c_x}$  denotes the hash of the array of transaction parameters  $[\text{hash}(c_{x_i})|_{1..n}]$ . The main symbols we will use are summarized in Table II. Next, we picture the whole protocol in Figure 2.

#### A. Global setup phase

Before evaluating any MPT, each party  $P_i$  is supposed to register their account public key  $pk_i$  and deposit some coins with amount  $Q_i$  to the DECLOAK contract  $\mathcal{V}$  (Algorithm 1). We stress that each party only needs to do it once.

#### B. Negotiation phase

An MPT is started from its negotiation phase, where DECLOAK uses the *nondeterministic negotiation subprotocol* (*Proc*<sub>nneg</sub>) to guide parties to reach a agreement on an MPT proposal. In detail, *Proc*<sub>nneg</sub> proceeds in two steps.

1.1: A party who wants to call an MPT  $\mathscr{F}$  sends an MPT proposal  $p = (\mathscr{F}, \mathscr{P}, q, h_{neg})$  to the first executor  $E^*$  in the registered TEE executor list, i.e.,  $E^* = E[0]$ , to initiate an MPT. Sending proposals to other TEEs will be rejected by the TEEs.  $\mathscr{P}$  denotes a privacy policy of  $\mathscr{F}$ . Briefly,  $\mathscr{P}$  captures what data are needed by the MPT  $\mathscr{F}$  and how to confide these data. We detail and formalize the  $\mathscr{P}$  in Appendix IX-A. q denotes the collateral required for joining or executing the proposed MPT.  $h_{neg}$  denotes that the proposal is expected to be negotiated before the block height  $h_{neg}$ . Then, the specified executor's TEE  $\mathscr{E}^*$  computes hash p to be the proposal id  $id_p$  and broadcasts a signed  $(id_p, p)$  to parties.

1.2: Upon receiving  $(id_p, p)$ , each  $P_i$  interested in the MPT autonomously responds with a signed acknowledgement  $ack_i$  to  $E^*$ . The  $\mathscr{E}^*$  receiving  $ack_i$  knows  $P_i$ 's intent of joining the proposal  $id_p$ .  $\mathscr{E}^*$  keeps collecting  $ack_i$  until the acknowledgements match the settlement condition<sup>4</sup> in  $\mathscr{P}$ . Then,  $\mathscr{E}^*$  constructs a settled proposal p' that expands p with the settled parties' addresses P. Meanwhile,  $\mathscr{E}^*$  caches its and parties' coin balances and deducts q collateral from their balance, respectively, ensuring that any involved entity has enough collateral to be punished when it misbehaves. Then,  $\mathscr{E}^*$  broadcasts p' to notify the involved parties of the settled proposal.

Otherwise, if  $\mathcal{E}^*$  does not collect satisfied acknowledgements, a *challenge-response subprotocol Proc*<sub>rcha</sub> in section IV-E will be triggered to identify misbehaviour. We defer the detail in section IV-E.

<sup>&</sup>lt;sup>4</sup>Settlement condition of negotiation is flexible, *e.g.*, the number of parties exceeds a specified threshold.

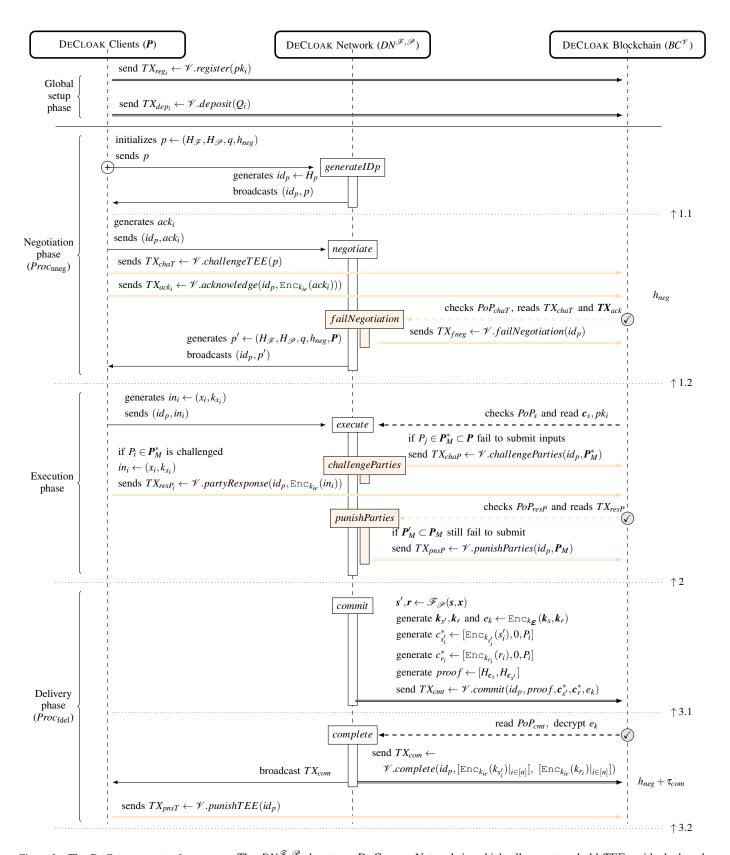


Figure 2. The DECLOAK protocol  $\pi_{\text{DECLOAK}}$ . The  $DN^{\mathcal{F},\mathcal{P}}$  denotes a DECLOAK Network in which all executors hold TEEs with deployed  $\mathcal{F},\mathcal{P}.BC^{\mathcal{V},\mathcal{V}}$  denotes a blockchain with deployed DECLOAK contract  $\mathcal{V}.Proc_{\text{nneg}}$  and  $Proc_{\text{fdel}}$  denote the nondeterministic negotiation, and  $\Delta$ -fair delivery subprotocols, respectively. Double dashed arrows denote reading BC and double arrows denote writing BC. Orange arrows denote the messages of challenge-response. Other arrows denote off-chain communications in secure channels. Specifically, messages sent by parties are signed by parties and encrypted by  $k_{ie}$  of DN, where  $k_{ie} \leftarrow \text{ECDH}(sk_i, pk_{\mathcal{E}})$ . All messages broadcast by DN are plaintext in default and signed by  $sk_{\mathcal{E}}$ . For simplicity, we omit marking ciphertext of messages that parties are sending to DN, but mark the ciphertext explicitly in each transaction sent to BC.

Table II
A SUMMARY OF MAIN SYMBOLS

Topic	Symbol	Name	Description	
Framework	$BC$ $P$ $DN (E, \mathcal{E})$ $E^*$ $\mathscr{E}^*$	Blockchain Parties DECLOAK network TEE executor TEE	A $BC$ enables Turing-complete smart contracts An array of an MPT's participants A network $DN$ consisting of an array of executors $E$ and TEEs $E$ The server hosting the specified TEE $E^*$ The specified TEE running the enclave program $E$ .	
Protocol	adɛ,skɛ Proc <sub>nneg</sub> Proc <sub>rcha</sub> Proc <sub>fdel</sub>	Enclave account	The address and private key of the common network account controlled by $\mathcal{E}$ Nondeterministic negotiation subprotocol challenge-response subprotocol $\Delta$ -fair delivery subprotocol	
МРТ	TX <sub>chaT</sub> TX <sub>ack<sub>i</sub></sub> TX <sub>fneg</sub> TX <sub>chaP</sub> TX <sub>crsF<sub>i</sub></sub> TX <sub>cmt</sub> TX <sub>com</sub> TX <sub>pnsP</sub> TX <sub>pnsT</sub>	challengeTEE acknowledge failNegotiation challengeParties partyResponse commit complete punishParties	A transaction from the specified TEE $\mathcal{E}[0]$ to publicly challenge the malicious parties A transaction from the party $P_i$ to publicly join the MPT proposal A public response from the specified TEE $\mathcal{E}[0]$ to $TX_{chaT}$ to signal the negotiation failure A transaction from the specified TEE $\mathcal{E}[0]$ to publicly challenge the malicious parties A public response from the party $P_i$ to $TX_{chaP}$ A transaction from the specified TEE $\mathcal{E}[0]$ to commit and lock the MPT outputs A public response from the specified TEE $\mathcal{E}[0]$ to $TX_{chaT}$ to complete the MPT A public response from the specified TEE $\mathcal{E}[0]$ to $TX_{chaT}$ to punish malicious parties A transaction from anyone to punish the misbehaved TEE	

#### C. Execution phase

In this phase,  $\mathcal{E}^*$  collects plaintext inputs from parties and executes  $\mathscr{F}$  to obtain outputs inside TEE.

2: Upon receiving  $(id_p, p')$ , each party  $P_i$  knowing they are involved in the settled proposal p' feeds their inputs  $(i.e., parameters x_i$  and old states  $s_i$ ) to  $\mathcal{E}^*$ . The  $\mathcal{E}^*$  keeps collecting parties' inputs and, especially, reads  $\mathcal{F}$ -needed old state s from BC according to the policy  $\mathcal{P}$ . If all involved parties' inputs are collected and matched,  $\mathcal{E}^*$  executes  $\mathcal{F}(s,x)$  to obtain the MPT outputs, i.e., return values r and new states s' inside. Then,  $\mathcal{E}^*$  goes to the step 3.1.

Otherwise, if some parties do not submit their inputs as expected, the  $Proc_{rcha}$  will identify them and punish them. We defer the detail in section IV-E.

#### D. Delivery phase

This phase adopts an  $\Delta$ -fair delivery subprotocol ( $Proc_{fdel}$ ) to reveal the plaintext outputs (i.e.,  $s'_i, r_i$ ) to corresponding parties in a  $\Delta$ -bounded period. The  $Proc_{fdel}$  proceeds in two steps

3.1  $\mathcal{E}^*$  generates two arrays of symmetric keys  $k_{\mathcal{E}}, k_r$  to computes the commitments of old state and return values  $s_i', r_i, i.e., c_{s_i'}, c_{r_i}, \text{ and generates a } proof \leftarrow [H_{c_s}, H_{c_{s'}}].$  The transaction with proof signed by  $\mathscr{E}^*$  can prove the MPTcaused state transition. Then,  $\mathscr{E}^*$  sends a Commit transaction  $TX_{cmt} \leftarrow \mathcal{V}.commit(id_p, proof, \boldsymbol{c}_{cl}^*, \boldsymbol{c}_r^*, e_k)$  to commit the outputs on-chain. We note that the published  $c_{s'}^*, c_r^*$  do not include the ciphertext of  $k_s, k_r$  so that parties cannot reveal the commitments of s', r. Instead, we require  $\mathscr{E}^*$  encrypts the keys with the network key  $k_{\mathcal{E}}$ , where  $k_{\mathcal{E}} \leftarrow \text{ECDH}(sk_{\mathcal{E}}, pk_{\mathcal{E}})$ , and attaches the obtained ciphertext  $e_k \leftarrow \text{Enc}_{k_{\mathcal{E}}}(k_{s'}, k_r)$  in  $TX_{cmt}$ . So when  $TX_{cmt}$  is confirmed, all  $\mathscr{E} \in \mathcal{E}$  can read  $k_{\mathscr{E}}, k_r$ on-chain without interacting with each other. Moreover, the proof in  $TX_{cmt}$  proves the validity of state transition caused by the MPT  $\mathscr{F}$ .  $\mathscr{V}$  will validate the *proof* and lock the on-chain states corresponding to old and new states, which signals the acceptance of the state transition and prevents its corresponding on-chain states from being updated by other concurrent MPTs before this MPT completes.

3.2: When  $TX_{cmt}$  becomes confirmed on-chain, each  $E \in E$  feeds the  $PoP_{cmt}$  (The PoP of the transaction  $TX_{cmt}$  which is an enough long and timely block sequence that contains  $TX_{cmt}$  to prove  $TX_{cmt}$  has been finalized) of  $TX_{cmt}$  to its  $\mathscr{E}$ . Each  $\mathscr{E}$  reads key array  $k_{s'}, k_r$  from the  $TX_{cmt}$ , then sends an transaction  $TX_{com} = \mathscr{V}.complete(id_p, [\operatorname{Enc}_{k_{le}}(k_{s_l'})], [\operatorname{Enc}_{k_{le}}(k_{r_l})])$  to add the ciphertext of  $k_{s'}, k_r$  to  $c_{s'}^*, c_r^*$ . The  $TX_{com}$  signals the COMPLETED of this MPT.

Here, the delivery fairness is achieved as follows: In 3.1, each party  $P_i$  has received the incomplete output commitments  $c_{s'}^*$ ,  $c_r^*$  but cannot decrypt them without corresponding  $k_{s'_i}$ ,  $k_{r_i}$ . In 3.2, each  $\mathscr E$  first verifies  $PoP_{cmt}$  to ensure that MPT outputs have been committed on BC. Then, each  $\mathscr E$  can send a  $TX_{com}$  to complete the protocol with COMPETED. Since parties can directly communicate with all executors to obtain  $TX_{com}$ , they can obtain the  $k_s$ ,  $k_r$  within the network latency  $\Delta$ , as long as at least one E honestly respond parties with  $TX_{com}$ . Otherwise, if  $TX_{cmt}$  is rejected by  $\mathscr V$ , any E cannot feed valid  $PoP_{cmt}$  to its TEE  $\mathscr E$ . Therefore, no TEE can release  $TX_{com}$  to reveal the plaintext outputs or complete the MPT before  $h_{neg} + \tau_{com}$ -th block. Therefore, DECLOAK guarantees the  $\Delta$ -fairness of delivery, where  $\Delta$  is the network latency of the blockchain.

#### E. Challenge-response subprotocol

When in any phase one of the honest parties did not receive TEE's protocol messages as expected, the party can initiate an *challenge-response subprotocol Proc*<sub>rcha</sub>. Specifically, it can send a *challengeTEE* transaction  $TX_{chaT}$  to challenge the TEE on-chain publicly. The TEE being challenged can only avoid being punished by successfully responding with one of the following transactions:

• (i)  $TX_{fneg}$ : If the  $h_{neg}$ -th block has not been produced, the TEE  $\mathscr{E}^*$  should keep collecting ack, which are sent by parties from off-chain channels, and  $TX_{ack}$ , which are sent by parties to the blockchain and accepted before the  $h_{neg}$ -th

block. Only if all collected acknowledgement cannot satisfy the settlement condition of MPT policy  $\mathscr{P}$  (If a party  $P_i$  send different  $ack_i$  by the off-chain channel and the on-chain transaction  $TX_{ack_i}$ , respectively, the off-chain  $ack_i$  will be chosen),  $\mathscr{E}^*$  then is allowed to send a  $TX_{fneg}$  to fail the proposal on-chain. In all other cases where the  $h_{neg}$ -th has not been confirmed, or the  $\mathscr{E}^*$  has successfully settled the proposal, it's impossible for a TEE to release a  $TX_{fneg}$ .  $TX_{fneg}$  will finish the MPT as NEGOFAILED.

- (ii)  $TX_{com}$ : If the negotiation phase succeeds and the MPT completes, a  $TX_{com}$  will be sent to the blockchain inherently.  $TX_{com}$  will finish the MPT as COMPLETED.
- (iii)  $TX_{pnsP}$ : If the negotiation phase succeeds, but the  $\mathscr{E}^*$ cannot complete the MPT as expected, both parties and the specified TEE's executor  $E^*$  can be misbehaved entities. Therefore, to avoid being punished in default,  $E^*$  should call its  $\mathscr{E}^*$  to challenge parties publicly. Specifically, if  $\mathscr{E}^*$ does not receive some parties' inputs or match some parties' inputs with their on-chain commitments,  $\mathcal{E}^*$  marks these parties as suspicious parties  $P_M^*$  and returns  $P_M^*$  to its host  $E^*$ . The  $E^*$  calls  $\mathcal{E}^*$ .challengeParties to send a  $TX_{chaP}$ to challenge all parties in  $P_M^*$  on-chain. When  $TX_{chaP}$  is confirmed on-chain, honest parties in  $P_M^*$  are supposed to send a  $TX_{resP}$  to publish the ciphertext of their inputs  $x_i, s_i$ . All published  $TX_{resP}$  are required to be confirmed before block height  $h_{neg} + \tau_{resP}$ . Otherwise, the late  $TX_{resP}$  will be regarded as invalid by  $\mathscr{E}^*$ . Upon the confirmation of the  $h_{neg} + \tau_{resP}$ -th block,  $\mathscr{E}^*$  reads the  $PoP_{resP}$  of all  $TX_{resP}$ . If  $\mathscr{E}^*$  successfully reads matched inputs of a party  $P_i \in P_M^*$ from its  $TX_{resP_i}$ , it removes  $P_i$  from  $P_M^*$ . Otherwise, if  $PoP_{resP}$ shows that no  $TX_{resP_i}$  is published on-chain or the inputs in  $TX_{resP_i}$  are still mismatched,  $\mathscr{E}^*$  retains  $P_i$  in  $P_M^*$ . After that, if  $P_M^*$  becomes empty, which means all inputs are collected,  $\mathscr{E}^*$  goes to the step 2. Otherwise, if  $P_M^*$  is not empty, which means the misbehaviour of parties left is confirmed,  $\mathscr{E}^*$  marks these parties as  $P_M$ . Then,  $\mathscr{E}^*$  sends a  $TX_{pnsP}$ .  $TX_{pnsP}$  calls *punishParties* to punish the misbehaved parties in finance and signal the MPT with ABORTED.

If the  $\mathscr{E}^*$  being challenged by a party either fails (by  $TX_{fneg}$ ), stops (by  $TX_{pnsP}$ ), or completes (by  $TX_{com}$ ) the MPT, anyone can send a  $TX_{pnsT}$  after the  $h_{neg} + \tau_{com}$ -th block to punish  $\mathscr{E}^*$  and signal the MPT with ABORTED.

#### V. IMPLEMENTATION

DECLOAK is designed to depend on contract-based infrastructure. A service provider of DECLOAK can deploy a contract  $\mathcal{V}$  on a legacy BC. Then, anyone can interact with the BC and TEEs in DN to transition the states of BC by MPTs.

#### A. DECLOAK contract

We implement the DECLOAK contract in Solidity 0.8.10 [34]. As shown in Algorithm 1,  $\mathscr V$  is constructed by the config of DN, e.g.,  $ad_{\mathcal E}$ , so that parties can authenticate and build secure channels with all  $\mathscr E \in \mathcal E$ . Moreover,  $\mathscr V$  provides functions to manage the life cycle of each MPT. Specifically, a party calls  $\mathscr V$ .challengeTEE by  $TX_{chaT}$  to challenge the

specified TEE. and signal the negotiation as NEGOTIATED. When an MPT was evaluated, a  $\mathscr E$  calls  $\mathscr V.commit$  by  $TX_{cmt}$  to validate the state transition and commit the outputs. Finally, a  $\mathscr E$  calls  $\mathscr V.complete$  by  $TX_{com}$  to release keys' ciphertext and signal the MPT as COMPLETED.

#### **Algorithm 1:** DECLOAK contract $\mathscr{V}$

```
// This contract is constructed by the network
        config ad_{m{\mathcal{E}}} and a TEE list m{\mathcal{E}}. ad_{m{\mathcal{E}}} is the
        network account for managing coins deposited
        by parties. For simplicity, we ignore the
        register and deposit functions here.
 1 Function challengeTEE(p)
         // called by TX_{chaT} from one of parties
        id_p \leftarrow \text{hash}(p)
         require(prsls[id_p] = \emptyset)
        prsls[id_p].\{q, h_{neg}, \tau_{com}, \mathcal{E}\} \leftarrow p.\{q, h_{neg}\}, \tau_{com}, \mathcal{E}[0]
        prsls[id_p].sta \leftarrow \texttt{PROPOSED}
 6 Function acknowledge(id_p, Enc_{k_{\mathcal{E}}}(ack_i))
        // called by TX_{ack} from parties
        require(BC.getHeight() < h_{neg})
 8 Function failNegotiation(id_p)
         // called by TX_{fneg} from the specified TEE
        require(msg.sender = prsls[id_p].\mathcal{E})
        prsls[id_p].sta \leftarrow \texttt{NEGOFAILED}
11 Function challengeParties (id_p, P_M^*)
     // called by TX_{chaP} from the specified TEE
12 Function partyResponse (id_p, Enc_{k_F}(in))
        // called by TX_{resP} from parties
        require(BC.getHeight() < h_{neg} + \tau_{resP})
14 Function punishParties (id_p, P_M)
         // called by TX_{pnsP} from the specified TEE
        require(msg.sender = prsls[id_p].\mathcal{E})
         // update coins for punishment
        for P_i \in P_M do
16
              coins[P_i] \leftarrow coins[P_i] - q
17
18
        prsls[id_p].sta \leftarrow ABORTED
Function commit (id_p, proof, c_{s'}^*, c_r^*, e_k)
         // called by TX_{cmt} from the specified TEE
        require(msg.sender = prsls[id_p].\mathscr{E})
        require(verify(proof, H_{c_s})) // match old states
22 Function complete (id_p, [\operatorname{Enc}_{k_{ie}}(k_{s'_i})|_{1..n}], [\operatorname{Enc}_{k_{ie}}(k_{r_i})|_{1..n}])
         // called by TX_{com} from \dot{} any registered TEE
23
        require(msg.sender \in \mathcal{E})
        \textit{H}_{\textit{c}_{\textit{s}}} \leftarrow \textit{proof}.\textit{H}_{\textit{c}_{\textit{s}'}} // set new states
24
        prsls[id_p].sta \leftarrow \texttt{COMPLETED}
25
26 Function punishTEE(id_p)
         // called by T\hat{X_{pnsT}} from anyone
        require(prsls[id_p] \neq \emptyset \text{ and } BC.getHeight() > h_{neg} + \tau_{com})
27
28
         require(prsls[id_p].sta \notin
          {NEGOFAILED, ABORTED, COMPLETED})
        coins[prsls[id_p].\mathscr{E}] \leftarrow coins[prsls[id_p].\mathscr{E}] - q
29
        prsls[id_p].sta \leftarrow \texttt{ABORTED}
```

#### B. DECLOAK network

To construct the DN, we instantiate each TEE  $\mathscr{E}$  (Algorithm 2) based on SGX [35]. Anyone with a TEE device can instantiate a  $\mathscr{E}$  (Algorithm 2) to become a executor E. The first  $\mathscr{E}$  generates the network account  $(sk_{\mathcal{E}}, pk_{\mathcal{E}}, ad_{\mathcal{E}})$  to initialize a network DN. Then, other  $\mathscr{E}$  must be attested by one of  $\mathscr{E}$  in the DN to join the DN and obtain the network key and account.

To evaluate MPT, we express  $\mathscr{F}$  in Solidity 0.8.10 [34] and port EVM [36] into SGX.  $\mathscr{P}$  is expressed in JSON.  $\mathscr{P}$ 

#### **Algorithm 2:** DECLOAK enclave program $(\mathscr{E})$

```
// For simplicity, we assume each \mathscr E has
          obtained the network config and cached the
          balances of parties' coins by
          synchronization. The config includes a
          secure parameter \kappa, a checkpoint b_{cp} of BC,
          and the network account (sk_{\mathcal{E}}, pk_{\mathcal{E}}, ad_{\mathcal{E}}).
 1 Procedure generateIDp(p)
           // check this is the specified TEE
          if sel f \neq BC.\mathcal{E}[0] then abort
 2
          id_p \leftarrow \mathtt{hash}(p)
 3
          return (id_p, p)
 5 Procedure negotiate(id_p,ack)
          if status = NEGOTIATED then return (id_p, p')
          if status \neq \emptyset or conform(ack, \mathscr{P}) \neq 1
              or cacheCoins[self] - q < 0
 8
              or \exists P_i \in P, cacheCoins[P_i] - q < 0 then abort
          p', status \leftarrow (p.\{H_{\mathscr{F}}, H_{\mathscr{P}}, q, h_{neg}\}), NEGOTIATED
10
          return (id_p, p')
12 Procedure failNegotiation(id_p, TX_{chaT}, PoP_{chaT})
          if status \neq \emptyset or veriPoP(b_{cp},PoP_{chaT},TX_{chaT}) \neq 1 then abort
13
          if PoP_{chaT}.getComfHeight() > p.h_{neg} then
14
                 TX_{ack} \leftarrow \text{all } PoP_{chaT}.TX_{ack_i} \text{ before } p.h_{neg}
15
                 ack \leftarrow ack \cup TX_{ack}.ack
16
          if conform(ack, \mathcal{P}) = 1 then abort
17
18
          return TX_{fneg}(id_p)
19
    Procedure execute (id_p, in, PoP_s)
          if status \neq \texttt{NEGOTIATED} then abort
20
          P_M^* \leftarrow P
21
22
          for x_i, k_{x_i} in in.\{x, k_x\}
                P_M^* \leftarrow P_M^* \setminus \{P_i\}
23
          if |P_M^*| > 0 then return (id_p, P_M^*)
24
           // evaluates \mathscr{F}(x) on states s
25
          s', r \leftarrow \mathscr{F}(PoP_s.s, x)
          b_{cp} \leftarrow PoP_s. \texttt{getLastComfBlock()}
26
27
          \hat{status} \leftarrow \texttt{EXECUTED}
28 Procedure commit (id_n)
          if status \neq \texttt{EXECUTED} then abort
29
          \mathbf{k}_{s'}, \mathbf{k}_r \leftarrow Gen(1^{\kappa})
30
          c_{s'_i} \leftarrow [\text{Enc}_{k_{s'_i}}(s'_i), \text{Enc}_{k_{ie}}(k_{s'_i}), P_i]
31
32
          proof \leftarrow [PoP_s.H_{c_s},H_{c_{s'}}]
          c_{s_i'}^*, c_{r_i}^* \leftarrow [\texttt{Enc}_{k_{s_i'}}(s_i'), 0, P_i], \ [\texttt{Enc}_{k_{r_i}}(r_i), 0, P_i]
33
          return TX_{cmt}(i\dot{d}_p, proof, \boldsymbol{c}_{s'}^*, \boldsymbol{c}_r^*, e_k)
34
   Procedure challengeParties (P_M^*)
35
          if status \neq NEGOTIATED then abort
36
          if |P_M^*| > 0 then
37
                 return TX_{chaP}(id_p, P_M^*)
38
    \textbf{Procedure} \ \textit{punishParties} \ (\textbf{\textit{TX}}\textit{chaP}, \textbf{\textit{TX}}\textit{resP}, PoP\textit{resP}) 
39
          if status \neq \texttt{NEGOTIATED} or
            veriPoP(b_{cp}, TX_{chaP}, PoP_{resP}) \neq 1 then abort
41
          P_M \leftarrow P_M^*
          for P_i \in P_M^* do
42
                 if x_i, k_{x_i} \leftarrow TX_{resP_i}.\{x_i, k_{x_i}\} then
43
44
                       P_M \leftarrow P_M \setminus \{P_i\}
          if |P_M| > 0 then
45
                 return TX_{pnsP}(id_p, P_M)
46
47
   Procedure complete (TX_{cmt}, PoP_{cmt})
          if status \neq \texttt{NEGOTIATED} or \texttt{veriPoP}(b_{cp}, TX_{cmt}, PoP_{cmt}) \neq 1
48
          status \leftarrow \texttt{COMPLETED}
49
          return TX_{com}(id_p, [\text{Enc}_{k_{ie}}(k_{s'_i})|_{i \in [n]}], [\text{Enc}_{k_{ie}}(k_{r_i})|_{i \in [n]}])
```

is introduced to specify the parameters, states to read and write, and return values of  $\mathscr{F}$ , which is for TEE to know the I/O of the MPT. The hash of both  $\mathscr{F}$  and  $\mathscr{P}$  are registered and updated on BC, while their codes are provided by the MPT' developers/initiators and cached by  $\mathscr{E}$ . Admittedly,  $\mathscr{P}$  is now pre-specified thus restricting that the I/O of  $\mathscr{F}$  should

be statically identified. However, this problem could solved by hooking EVM's sstore and sload instructions [26], and we leave it for future work.

#### VI. SECURITY ANALYSIS

#### A. Assumption reliability

Our assumption that TEE's confidentiality and attestable integrity hold is still practical now. While attacks against SGX, *e.g.*, memory-corruption attacks and side-channel attacks, keep coming out, the community has developed efficient software-based [37]–[39] and hardware-based countermeasures [40], [41]. So far, most of existing attacks against SGX are either function-limited [42], [43], solved, or patched [44], [45]. For some very recent and considerable attacks like xAPIC and MMIO, they are also mitigated in Dec. 22 and will be solved in Jan. 23 [46].

#### B. Protocol security

Informally, we claim that the following theorem holds. We leave the formal security property definition and corresponding game theory-based proof in Appendix IX-C. Limited by space, here we will briefly outline the idea of how we prove *financial fairness*, and *delivery fairness*.

**Theorem 1** (Informal statement). The protocol  $\pi_{DECLOAK}$  satisfies correctness, confidentiality, public verifiability, data availability, financial fairness, delivery fairness, and delivery atomicity

To prove DECLOAK holds *financial fairness*, we prove that there are only three possible statuses of an MPT, *i.e.*,  $\emptyset$  (negotiation not started or gets failed), ABORTED (negotiation succeeded, but the MPT did not complete as expected) and COMPLETED (the MPT complete as expected). Then, we exhaustively prove that parties' balance will stay fair in any of the three statuses: i) if the status of an MPT stays at  $\emptyset$ , all entities' balances would have no change; ii) if an MPT's status is ABORTED, then either some parties misbehaved and were punished, or the specified TEE executor misbehaved and were punished; iii) if an MPT's status becomes COMPLETED, the MPT succeeds, and all entities' balances would have no change.

To prove the *delivery fairness* being held, we utilize the ideal availability of blockchain and the assumption that all-but-one TEE executors are Byzantine. Specifically, to release outputs, the  $TX_{cmt}$ , which contains data ciphertext and the ciphertext of their corresponding keys, must have been published on the blockchain. Therefore, if each party communicate with all TEE executors directly and at least one TEE node is honest, all parties can obtain their corresponding outputs in the  $\Delta$ -bounded period. The  $\Delta$  equals to the message delivery upper bound of the (semi-)synchronous network among parties and TEE nodes.

#### VII. EVALUATION

**Methodology and setup.** To evaluate the effectiveness of DECLOAK, we propose 3 research questions.

- Q1: Can DECLOAK capably serve real-world MPTs?
- Q2: What is the cost of enabling MPTs on a blockchain?
- Q3: What is the cost of evaluating MPTs using DECLOAK?

The experiment is based on a server with Ubuntu 18.04, 32G memory, and 2.2GHz Intel(R) Xeon(R) Silver 4114 CPU. The memory used by TEE is set up to 200M.

**Answering Q1.** We evaluate DECLOAK on 5 contracts which involve 10 MPTs in different scenarios. All them are in Solidity and the number of parties they involved varies from 2-11.

SupplyChain is a contract allowing suppliers to negotiate and privacy-preservedly bids off-chain, and commit the evaluation with their new balances on-chain. It has 39 LOC and contains one MPT.

*Scores* is a contract allowing students to join and get mean scores off-chain and commit the evaluation on-chain. It has 95 LOC and contains one MPT.

*ERC20Token* is a contract allowing accounts to pair and transfer without revealing balances off-chain, and commit the evaluation with new balances on-chain. It has 55 LOC and contains three MPTs.

YunDou is a fine-tuned ERC20 token contract with comanaged accounts where account managers self-selectly vote to transfer tokens without revealing the votes. It has 105 LOC and contains three MPTs.

*Oracle* is a Oracle contract that allows parties to negotiate to join then jointly and verifiably generate random numbers. It has 60 LOC and contains three MPTs.

**Answering Q2.** Table III shows the gas cost of all methods of  $\mathcal{V}$  in different phases. To answer Q2, here we focus on the initialization and global setup phase.

Table III

On-chain cost of challenge-response submission phase. For each MPT, we assume all partied involved are challenged

Phase	TX	Gas cost
Clobal satur	register $(TX_{reg_i})$	127068
Global setup	deposit $(TX_{dep_i})$	42325
MPT	commit $(TX_{cmt})$	104568
MP1	complete $(TX_{com})$	110570
	challengeTEE $(TX_{chaT})$	131762
	$acknowledge\ (TX_{ack_i})$	26999
	failNegotiation $(TX_{fneg})$	30563
$Proc_{rcha}$	challengeParties $(TX_{chaP})$	33786
	$partyResponse (TX_{resP_i})$	34313
	punishParties $(TX_{pnsP})$	45518
	$punishTEE (TX_{pnsT})$	53254
	DeFi: ERC20: Transfer	65000
	DeFi: Uniswap V3: Swap	184523
	DeFi: Balancer: Swap	196625
	NFT: OpenSea: Sale	71645
	NFT: LooksRare: Sale	326897

Gas cost of initialization. It costs 4.9M gas to deploy  $\mathscr V$  to enable DECLOAK on a blockchain. This cost is only once paid by DECLOAK service provider, thereby is irrelevant.

Gas cost of global setup. A party pays 12.7k to register its public key and 4.2k gas to deposit coins. This setup happens once for each party, thus being acceptable.

Answering Q3. We analyze the gas and off-chain cost for evaluating each MPT, respectively. Especially, we compare the gas cost of DECLOAK with the most related MPT-oriented work, Fastkitten [13] and Cloak [8].

On-chain cost of MPTs. Figure 3 shows the gas cost of each MPT. Overall, DECLOAK reduces gas by 72.5% against Fastkitten. Specifically, for six 2-party MPTs, DECLOAK costs 0.27-0.46X gas. For two 3-party and two 10/11-party MPTs, the gas significantly reduces to 0.22-0.25X and 0.09-0.11X, respectively. For Cloak, the cost of DECLOAK decreases by 65.6% in average. Specifically, DECLOAK costs 0.27-0.56X gas against Cloak in 2/3-party MPTs, while just 0.17-0.22X gas in 10/11-party MPTs. Therefore, DECLOAK enables a more secure MPTs with lower on-chain cost. The on-chain cost not only surpasses Cloak, but is comparable to typical single-party transactions, e.g., NFT sale and ERC20 swap, on Ethereum. Moreover, as the number of parties growing, the cost superiority of DECLOAK improves.

Off-chain cost of MPTs. All 10 MPTs complete in constant 2 transactions. Specifically, the negotiation, execution, and delivery phases cost 0.21-0.58s, 0.39-1.15s, and 0.30-0.77s, respectively, which can be ignored.

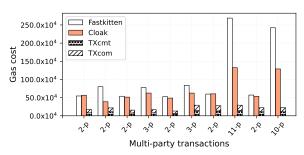


Figure 3. The gas cost of DECLOAK. "Fastkitten" refers to the gas cost sum of n+1 transactions for each MPT. Here we adapt the protocol of Faskkitten to Ethereum. "Cloak" refers to the gas cost sum of its 2 transactions for each MPT. "TXcmt" and "TXcom" refers to gas cost of  $TX_{cmt}$ ,  $TX_{com}$  in  $\pi_{DECLOAK}$ , respectively.

#### VIII. OPTIMIZATION AND FINE-TUNING

#### A. Improve the scalability of DECLOAK

#### 1) Reduce gas cost in optimistic cases

Recall that serving an MPT in optimistic scenarios only involves 2 transactions,  $TX_{cmt}$  and  $TX_{com}$ . Therefore, to serve a n-party MPT without adversary, DECLOAK needs to send O(1) transactions. We note that we can adopt the following measures to furthermore reduce the optimistic cost of DECLOAK.

**batch processing.** According to the height of the blockchain, we can split the execution of MPT to different slots. In each slot, DECLOAK handles  $\lambda$  MPTs ( $\lambda \geq 1$ ) and sends only two transactions, *i.e.*  $TX_{cmt}$ ,  $TX_{com}$ , to finish all MPTs in the slot in a batch. This way, it can reduce the complexity to  $O(1/\lambda)$  without sacrificing the security or changing the adversary model.

making trade-off. We note that by intentionally sacrificing some of our system goals, DECLOAK can furthermore reduce its on-chain cost. First, we can drop data availability to delete the last transaction  $TX_{com}$ . Specifically, in the delivery phase, TEEs will first send  $TX_{cmt}$  to commit outputs on-chain. If the proof in  $TX_{cmt}$  passes,  $\mathscr V$  will accept the state transition immediately. Then, upon  $TX_{cmt}$  being accepted and confirmed, TEEs will release the keys of the output ciphertext in  $TX_{cmt}$ to parties by off-chain channels, rather than sending a  $TX_{com}$ . Consequently, the required transactions of DECLOAK reduce to only 1, i.e.,  $TX_{cmt}$ . However, in this variant, parties need to keep all received keys to access their plaintext states. Second, we can furthermore drop delivery atomicity and delivery fairness to delete  $TX_{cmt}$ , meaning that no transactions are required in the optimistic case. Specifically, MPT involves reading on-chain inputs. If we delete  $TX_{cmt}$ , when the specified TEE obtains outputs, the blockchain has no change to ensure that old states that MPT read have not been mutated. This way, the MPT outputs that TEE regard as valid cannot be accepted by the blockchain, breaking the atomicity. Moreover, as we cannot utilize the  $TX_{cmt}$  to ensure that output ciphertext can be ideally delivered to all TEEs, delivery fairness is broken.

#### 2) Reduce gas cost in pessimistic cases

In the pessimistic scenarios, the *challenge-response protocol* ( $Proc_{rcha}$ ) will be triggered. In the protocol, each party being challenged on-chain has to respond with their acknowledgements or inputs independently. We can introduce an off-chain third-party service to collect parties' responses and publish an aggregated  $TX_{resP}$  to the blockchain. In this, way, even though a  $Proc_{rcha}$  is being triggered, the on-chain transaction complexity is still O(1). And combining with the batch processing technique of MPT, the complexity of  $Proc_{rcha}$  can furthermore reduce to O(1/m), where m is the number of MPTs in a batch.

#### 3) Reduce storage cost

To minimize the trust of off-chain TEE network, DECLOAK stores parties' privacy-preserved data on blockchain and ensure the plaintext of the stored data are still accessible to parties even without DECLOAK. This sounds indicating a heavy storage cost. However, as we demonstrated in Section VII, the storage cost is acceptable. Actually, storing off-chain states onchain as calldata has been well-adopted in Ethereum Rollup projects [16], [17]. Moreover, reducing the storage cost is also a main issue of Ethereum 2.0. Specifically, Ethereum propose to reduce the gas cost of calldata from 16 to 3, which means a 81% decrease [15]. Furthermore, Ethereum 2.0 will introduce blob [18], a new storage mechanism which allows different Ethereum Layer-2 projects to cheaply store all their transactions and states on the Beacon chain. Therefore, the design of DECLOAK strongly match the need and tendency of Ethereum.

#### B. Improve the availability of DECLOAK

An industry *tee* service usually has a robust error-handling mechanism and is DDoS-resistant. Therefore, we practically assume that the service provided by the specified honest TEE executor is highly available. However, it does mean we cannot further improve the availability of DECLOAK. For example,

DECLOAK can adopt a similar availability enhancement mechanism as in POSE [23]. Specifically, every time the specified TEE executor changes its local state, it should synchronize the state updates to all other registered TEEs and collect their signatures in off-chain channels to carry on the next state transfer. If the specified TEE is not available off-chain, parties can publicly change it on-chain. If the unavailability of the specified TEE is because that other TEE executors do not respond with signatures as expected, the specified TEE can publicly challenge other unavailable TEEs on the blockchain. Finally, if the on-chain challenge-response mechanism finally punishes the specified TEE, it will be kicked out, and the next TEE in the registered list will be specified to serve MPTs. As a result, in an optimistic scenario, i.e., all other TEEs honestly respond with their signatures, DECLOAK will not lose its offchain states if at least one TEE is available. In a word, we stress that improving the availability of TEE network is an orthogonal field with DECLOAK, and DECLOAK can combine with the related work [23] to further improve its availability.

#### IX. CONCLUSION

In this paper, we develop a novel framework, DECLOAK, which can support MPT-enabled off-chain contract execution on legacy blockchains by using a TEE network. DECLOAK features maximising the security of MPT and minimising the gas cost and the network's trust. Comparing with the SOTA, Cloak [8], DECLOAK not only realizes all security properties the SOTA claimed but also additionally achieves data availability, delivery fairness, and delivery atomicity. To our knowledge, DECLOAK achieves the most general and secure MPT. Meanwhile, it assumes at least one party and executor are honest, which is also one of the weakest assumptions compared to related work. Moreover, according to our evaluation, DECLOAK reduces the gas cost of the SOTA by 65.6%, and the superiority of DECLOAK increases as the number of parties grows.

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# Supplementary Material for "DECLOAK: Enable Secure and Cheap Multi-Party Transactions on Legacy Blockchains by a Minimally Trusted TEE Network"

#### A. MPT-enabled contracts

We have introduced the program  $\mathscr{F}$ , verifier  $\mathscr{V}$ , and enclave for achieving an MPT. Here we model the privacy policy  $\mathscr{P}$  we used for better managing parties' private data on-chain and specify the privacy demand of the MPT.

Since each  $\mathscr{E}$  need to encrypt/decrypt states before evaluating  $\mathscr{F}$ ,  $\mathscr{E}$  must aware about the states sets to read and write sets of  $\mathscr{F}$ . Therefore, we bind a privacy policy  $\mathscr{P}$  to each  $\mathscr{F}$ .

$$\begin{array}{rcl} adr_{\mathscr{V}} &:=& \{0,1\}^* \\ v &:=& [a-zA-z0-9]+ \\ P &:=& \{0,1\}^* \\ \mathscr{P}_v &:=& \emptyset \mid (v:P) \mid (v:P^?) \\ \mathscr{P}_{\mathscr{F}} &:=& \{ \\ \mathscr{P}_x := \{\mathscr{P}_v\}^* \\ \mathscr{P}_s := \{\mathscr{P}_v\}^* \\ \mathscr{P}_{s'} := \{\mathscr{P}_v\}^* \\ \mathscr{P}_r := \{\mathscr{P}_v\}^* \\ \end{array}$$

A privacy policy  $\mathscr{P}$  is modeled as the above.  $adr_{\mathscr{V}}, adr_{\mathscr{V}}$  denote the address of its corresponding deployed  $\mathscr{V}$  and verifier contract  $\mathscr{V}$  on BC, respectively. v refers to the identifiers of variables. The P refers to parties' addresses.  $(\mathscr{P}_x)$  refers to transaction parameters of  $\mathscr{F}$ .  $\mathscr{P}_s$  refers to states variables to be read to evaluate  $\mathscr{F}$ .  $\mathscr{P}_{s'}$  refers to states variables to update by the  $\mathscr{F}$ .  $\mathscr{P}_r$  refers to return variables of  $\mathscr{F}$ . Each variable is denoted by the tuple (v:P), containing its identifier v and the address of of its owner P (i.e., the party that the variable private to). v is owned by P meaning that v is confidential to P. Consequently,  $\mathscr{E}$  expect to receive the v from P and commit v with P's public key. If the owner of an variable is unknown before MPT, we write  $(n:P^2)$ . The unknown party will be settled after the *negotiation phase* in Section III.

#### B. Notations and Definitions

In this section, we fine-tuned the notation system of [8], [13] to denote variables involved in DECLOAK.

#### 1) Common notations

Generally, we denote a domain as  $\mathbb{S}$  and its n-ary Cartesian power  $\mathbb{S} \times \mathbb{S} \times \cdots \times \mathbb{S}$  as  $\mathbb{S}^n$ . Therefore, each  $s \in \mathbb{S}^n$  is a array  $[s_1, \cdots, s_n]$  and we refer s[i] or  $s_i$  to the i-th element of s. Moreover,  $\mathbb{S}^{n \times m}$  denotes the set of all n-ny-m matrices consisting of elements from  $\mathbb{S}$ . Similarly, we denote  $\mathbf{S}[i][j]$  as the element in i-th row and j-th column of  $\mathbf{S}$ ,  $\mathbf{S}[i][\cdot]$  as the i-th row, and  $\mathbf{S}[\cdot][j]$  as the j-th column.

#### 2) Coins

We define a set  $\mathbb{D}_{coin}$  as a *coin domain*, which includes all possible balance of parties' global coins and is a subset of non-negative rational numbers  $\mathbb{Q} \geq 0$ . Therefore, we define a *coin array*  $\mathbf{q} \in \mathbb{D}_{coin}^n$  where  $Q_i$  denotes the balance of party  $P_i$ 's global coins. Then, we define the set  $\mathbb{D}_{dep} \leftarrow \mathbb{D}_{coin} \setminus \{0\}$  as a

deposit domain, and define a deposit array  $d \in \mathbb{D}_{dep}^n$  where d[i] denotes the deposit of party  $P_i$  for joining an MPT.

#### 3) Multi-Party Transactions

We define a set  $\mathbb{D}_{pa}$  as a *plaintext domain* which is application-specific. Therefore, for each MPT, we have its plaintext *parameter array* x, *old state array* s, *new state array* s', and *return array array* r, where r, where r, where r, r is r in r correspondingly, we define a set r is a a *cryptography commitment domain* which is specific to the cryptography commitment algorithm we adopted in Section III. Then, for each MPT, we denote its *parameter commitment array*, *old state commitment array*, *new state commitment array*, and *return value commitment array* as r is r, r is pectively, where r is r in r in r in r is r in r

We define a *party domain*  $\mathbb{D}_{addr}$ .  $\mathbb{D}_{addr}$  is the set of all possible addresses of parties, thus depends on the address generation algorithm the *BC* adopted. Then, the parties of an MPT are modeled as a *party array* P where  $P_i$  denotes the i-th party of P and  $P_i \in \mathbb{D}_{addr}$ . We define the *target function* of an MPT which multiple parties jointly evaluate as  $\mathscr{F}$ , and the *privacy policy* of an MPT as  $\mathscr{P}$  which specifies the meta data of  $\mathscr{F}$ , e.g., expected x, s, s', r. Then, we denote  $\mathscr{F}_{\mathscr{P}}$  as a  $\mathscr{P}$ -conformed  $\mathscr{F}$ .

#### **Algorithm 3:** Evaluation function

**Input:** An *n*-party MPT  $\mathscr{F}$  and its policy  $\mathscr{P}$ , a parameter array x, a parameter key array  $k_x$ , a old state array s, a old state key array  $k_s$ , a old state commitment array  $c_s$ , and a party array P.

**Output:** A new state array s', new state key array  $k_{s'}$ , return value array r, return value key array  $k_r$ , new state commitment array  $c_{s'}$ , return value commitment array  $c_x$ , and a proof.

```
1 Function eval (\mathscr{F},\mathscr{P},x,k_x,c_s,P)

2 | foreach c_{s_i} in c_s

3 | assert c_{s_i} = [\operatorname{Enc}_{k_{s_i}}(s_i), \operatorname{Enc}_{k_{ie}}(k_{s_i}), P_i]

4 | s',r \leftarrow \mathscr{F}_{\mathscr{P}}(s,x)

5 | k_{s'},k_r \leftarrow Gen(1^K)

6 | c_{s'_i} \leftarrow [\operatorname{Enc}_{k_{s'_i}}(s'_i), \operatorname{Enc}_{k_{ie}}(k_{s'_i}), P_i]

7 | c_{r_i} \leftarrow [\operatorname{Enc}_{k_{r_i}}(r_i), \operatorname{Enc}_{k_{ie}}(k_{r_i}), P_i]

8 | c_{x_i} \leftarrow [\operatorname{Enc}_{k_{x_i}}(x_i), \operatorname{Enc}_{k_{ie}}(k_{x_i}), P_i]

9 | proof \leftarrow [H_{\mathscr{P}}, H_{\mathscr{F}}, H_{c_s}]

10 | return (s', k_{s'}, r, k_r, c_{s'}, c_r, c_x, proof)
```

#### 4) Protocol execution

While P, E, and  $\mathcal{E}$  denote the party array, executor array and TEE array of an MPT, respectively, we define  $P_H$  and  $E_H$  as the honest parties in P and E respectively.  $P_M$  and  $E_M$  denote the malicious parties in P and malicious executors of TEEs, i.e.,  $P_M \leftarrow P \setminus P_H$ ,  $E_M \leftarrow E \setminus E_H$ . For convenience, we also define  $P^+ \leftarrow P \cup E$  and  $P_M^+ \leftarrow P_M \cup E_M$ .

According to our adversary model in Section III, DECLOAK protocol  $\pi_{\text{DECLOAK}}$ , or simply  $\pi$ , proceeds in presence of an

byzantine adversary  $\mathscr{A}$  who can corrupts all-but-one  $P_i \in \mathbf{P}^+$ . And we define a *coin balance array*  $\mathbf{Q} \in \mathbb{D}^{n+m}_{coin}$ .  $Q_i|_{i < n}$  denotes the coin balance of  $P_i \in \mathbf{P}$  pre-deposited to  $k_{\mathcal{E}}$ .  $Q_{n+i}|_{i < m}$  denotes the coin pre-deposited balance of  $\mathscr{E}_i \in \mathcal{E}$ .

Classically, we define any protocol execution of  $\pi$  under the adversary  $\mathscr A$  as  $REAL_{\pi,\mathscr A}$ . The inputs of an execution include an n-party MPT  $\mathscr F$  and its policy  $\mathscr P$ , a parameter array x, a parameter key array  $k_x$ , a old state array s, a old state key array s, a old state commitment array s, a party array s, a deposit array s and a account coin balance array s. Therefore, we formalize a protocol execution as follows.

$$Q', s', k_{s'}, r, k_r, c_{s'}, c_r, c_x, proof, sta$$

$$\leftarrow REAL_{\pi, \mathcal{A}}(Q, \mathcal{F}, \mathcal{P}, x, k_x, c_s, P, q)$$

The outputs of  $\pi$  include a new coin balance array Q' after the execution, new state array s', new state key array  $k_{s'}$ , return value array r, return value key array  $k_r$ , and the commitment array of new states, return values, and parameters, i.e.,  $c_{s'}$ ,  $c_r$ ,  $c_x$ , respectively, and proof of the MPT-caused state transition.

#### 5) Security goals

We first define the basic *correctness* property. Intuitively, *correctness* states that if all entities in  $P^+$  behave honestly,  $\forall P_i \in P$  obtain their correct MPT outputs correspondingly and collateral back.

**Definition 1** (Correctness). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ ,  $q \in \mathbb{D}^n_{dep}$ ,  $s \in \mathbb{D}^n_{pa}$ ,  $x \in \mathbb{D}^n_{pa}$  and  $Q \in \mathbb{D}^n_{coin}$ , there is a negligible function  $\varepsilon$  that for the output of the protocol  $REAL_{\pi}(Q, \mathscr{F}, \mathscr{P}, x, k_x, c_s, P, q)$  and  $\forall P_i \in P$ 

$$\left| Pr \left[ \begin{array}{c} (s', k_{s'}, r, k_r, c_{s'}, c_r, c_x, proof) \\ = \text{eval}(\mathscr{F}, \mathscr{P}, x, k_x, c_s, P) \\ Q'_i \geq Q_i \\ sta = \text{COMPLETED} \end{array} \right] - 1 \right| \leq \varepsilon$$

**Definition 2** (Confidentiality). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ , any adversary  $\mathscr{A}$  corrupting parties from  $P_M^+$  in which  $P_M \subsetneq P$ , any  $q \in \mathbb{D}_{dep}^n$ ,  $s \in \mathbb{D}_{pa}^n$ ,  $x \in \mathbb{D}_{pa}^n$  and  $Q \in \mathbb{D}_{coin}^n$ , the protocol  $REAL_{\pi,\mathscr{A}}(Q,\mathscr{F},\mathscr{P},x,k_x,c_s,P,q)$  is such that: There is a negligible function  $\varepsilon$  ensuring that  $\forall x_1^*,s_1^*,s_1^{'*},r_1^*,x_2^*,s_2^*,s_2^{'*},r_2^*,\in \mathbb{D}_{pa}$  and  $\forall P_i \in P_H$ :

$$|Pr[x_{i}, s_{i} = x_{1}^{*}, s_{1}^{*}] - Pr[x_{i}, s_{i} = x_{2}^{*}, s_{2}^{*}]| \leq \varepsilon$$

$$and$$

$$|Pr[s'_{i}, r_{i} = s'_{1}^{*}, r_{1}^{*}] - Pr[s'_{i}, r_{i} = s'_{2}^{*}, r_{2}^{*}]| \leq \varepsilon$$

**Definition 3** (Data availability). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ , any adversary  $\mathscr{A}$  corrupting parties from  $P^+$ , any  $q \in \mathbb{D}^n_{dep}$ ,  $s \in \mathbb{D}^n_{pa}$ ,  $x \in \mathbb{D}^n_{pa}$  and  $Q \in \mathbb{D}^n_{coin}$ , the protocol  $REAL_{\pi,\mathscr{A}}(Q,\mathscr{F},\mathscr{P},x,k_x,c_s,P,q)$  is such that: There is a negligible function  $\varepsilon$  satisfies that if sta = COMPLETED, one of the following statements must be true.

- (i)  $E_M \subsetneq E : \forall E_i \in E_H$ , there is a polynomial function  $f_{\mathcal{E}_i}$  that  $s_i' = f_{\mathcal{E}_i}(sk_{\mathcal{E}}, P_i, c_{s_i'})$
- (ii)  $E_M = E \& P_M \subsetneq P : \forall P_i \in P_H$ , there is a polynomial function  $f_{\mathscr{P}_i}$  that  $s'_i = f_{\mathscr{E}_i}(sk_{P_i}, ad_{\mathcal{E}}, c_{s'})$

**Definition 4** (Financial fairness). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ , any adversary  $\mathscr{A}$  corrupting parties from  $P_M^+ \subsetneq P^+$ , any  $q \in \mathbb{D}_{dep}^n$ ,  $s \in \mathbb{D}_{pa}^n$ ,  $r \in \mathbb{D}_{pa}^n$  and  $Q \in \mathbb{D}_{coin}^n$ , the output of the protocol  $REAL_{\pi,\mathscr{A}}(Q,\mathscr{F},\mathscr{P},x,k_x,c_s,P,q)$  is such that one of the following statements must be true:

- (i)  $sta \in \{$  negofailed, completed $\}, \ \forall P_i \in P^+: Q_i' \geq Q_i$
- (ii)  $sta = ext{ABORTED}, \ \forall P_i \in P_H^+: \ Q_i' \geq Q_i \ and$

$$\sum_{j\in P_M^+} Q_j' < \sum_{j\in P_M^+} Q_j$$

**Definition 5** (Delivery fairness). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ , any adversary  $\mathscr{A}$  corrupting parties from  $P_M^+$  in which  $E_M \subsetneq E$ , any  $q \in \mathbb{D}^n_{dep}$ ,  $s \in \mathbb{D}^n_{pa}$ ,  $r \in \mathbb{D}^n_{pa}$  and  $Q \in \mathbb{D}^n_{coin}$ , there is a negligible function  $\varepsilon$  that for the output of the protocol  $REAL_{\pi,\mathscr{A}}(Q,\mathscr{F},\mathscr{P},x,k_x,c_s,P,q)$ , one of the following statements must be true:

- (i)  $s', r = \emptyset, \emptyset$
- (ii)  $\mathbf{s}', \mathbf{r}, \neq \emptyset, \emptyset$ , and the following two hold simultaneously:
  - (a)  $\forall P_i \in \mathbf{P}_H : |t_{s_i} t_{r_i}| \leq \Delta$
  - (b)  $\forall P_i, P_i \in \mathbf{P}_H : |t_{s_i} t_{s_i}| \leq \Delta$  and  $|t_{r_i} t_{r_i}| \leq \Delta$

**Definition 6** (Delivery atomicity). For any n-party MPT  $\mathscr{F}_{\mathscr{P}}$ , any adversary  $\mathscr{A}$  corrupting parties from  $P_M^+$  in which  $E_M \subseteq E$ , any  $q \in \mathbb{D}^n_{dep}$ ,  $s \in \mathbb{D}^n_{pa}$ ,  $r \in \mathbb{D}^n_{pa}$  and  $Q \in \mathbb{D}^n_{coin}$ , there is a negligible function  $\varepsilon$  that for the output of the protocol  $REAL_{\pi,\mathscr{A}}(Q,\mathscr{F},\mathscr{P},x,k_x,c_s,P,q)$ , one of the following statements must be true:

- (i)  $sta \in \{\emptyset, NEGOFAILED, ABORTED\}, and s', r = \emptyset, \emptyset$
- (ii) sta = COMPLETED, and  $s', r, \neq \emptyset$

#### C. Security Proof

In this section, we claim that the following theorem holds in the DECLOAK protocol  $\pi_{DECLOAK}$ .

**Theorem 1** (Formal statement). Assume a EUF-CMA secure signature scheme, a IND-CCA2 encryption scheme, a hash function that is collision-resistant, preimage and second-preimage resistant. a TEE emulating the TEE ideal functionality and a BC emulating the BC ideal functionality,  $\pi_{DECLOAK}$  holds correctness, confidentiality, public verifiability, data availability, financial fairness, delivery fairness, and delivery atomicity.

#### 1) Proof of correctness

Consider adversaries absent in  $\pi_{DECLOAK}$ . The evaluation of an MPT starts by the specified  $\mathscr{E}^*$  receiving an MPT proposal  $p \leftarrow (H_{\mathscr{F}}, H_{\mathscr{P}}, q, h_{neg})$  and starting the *negotiation phase*.  $\mathscr{E}^*$  first deterministically generates an id  $id_p$  of the proposal and broadcast the  $id_p$  with the proposal to  $P_i \in P$ . When  $\mathscr{E}^*$ s collects satisfied acknowledgement from P, it broadcasts the settled p'. In the *execution phase*,  $\mathscr{E}^*$  collects the plaintext inputs in from P and read  $s_i$  from  $BC.c_s$ . Then,  $\mathscr{E}^*$  obtains the MPT's outputs by

$$s', k_{s'}, r, k_r, c_{s'}, c_r, c_x, proof \leftarrow \text{eval}(\mathscr{F}, \mathscr{P}, x, k_x, c_s, P)$$

Then it moves to the *delivery phase*.  $\mathscr{E}^*$  releases a  $TX_{cmt}$  to commit the outputs without publishing the symmetric key ciphertext. Upon the only one  $TX_{cmt}$  is confirmed on BC, each  $\mathscr{E}$  reads the  $TX_{cmt}$  to obtain the shared symmetric keys  $k_{s_i'}, k_{r_i}$ . Then, each  $\mathscr{E}$  encrypts the keys  $k_{s_i'}, k_{r_i}$  with the  $k_{ie}$  and broadcasts a  $TX_{com}$  to both P and BC immediately. As no  $P_i \in P^+$  is punished, we have  $Q_i' \leftarrow Q_i \geq Q_i$ .

Since all protocol messages are sent in secure channels between P and  $\mathscr{E}$ s and we ignore the leakage caused by  $\mathscr{F}$  and parties' voluntarily revealing, the *confidentiality* is axiomatic. Therefore, we proves *data availability*, *financial fairness*, and *delivery*  $(\Delta -)$  *fairness* in the following.

#### 2) Proof of data availability

According to the Algorithm 1, when sta = completed, there must be  $c_s$  published on BC. Recall the data structure of  $c_{s_i'} \leftarrow [\text{Enc}_{k_{s_i'}}(s_i'), \text{Enc}_{k_{ie}}(k_{s_i'}), P_i]$ , we construct a polynomial function in Algorithm 4. With the function, any  $\mathscr{E} \in \mathcal{E}$  or  $P_i \in P$  can construct the newest states of all completed MPT independently. Therefore, the data availability holds.

#### Algorithm 4: States construction function

```
Function constructStates (sk, pk, c_{s_i'})
\begin{vmatrix} k_i e \leftarrow \texttt{ECDH}(sk, pk) \\ k_{s_i'} \leftarrow \texttt{Dec}_{k_i e}(c_{s_i'}[1]) \\ s_i' \leftarrow \texttt{Dec}_{k_{s_i'}}(c_{s_i'}[0]) \end{vmatrix}
return s_i'
```

#### 3) Proof of financial fairness

Here we prove that in all possible sta, the financial fairness of  $\pi_{\text{DECLOAK}}$  holds. First, we consider the *Negotiation phase*. Briefly, we prove that if the phase does not complete successfully then the proposal will have sta = NEGOFAILED and  $\forall P_i \in P_H$  stays financially neutral.

**Lemma 2.** If there  $\exists P_i \in P_H$  stays at sta = NEGOFAILED, then the statement (i) of the financial fairness property holds.

*Proof*: There is only one cases when an  $P_i \in P_H$  has sta = NEGOFAILED:

• (i)  $TX_{fneg}$  is confirmed on BC after  $Proc_{nneg}$ .

Specifically, this scenario happens when the collected *ack* from both on-chain and off-chain channels cannot satisfy the settlement condition of MPT proposal or  $\exists P_i \in P$  holds that  $Q_i \leq q$ . No matter what reasons cause the failure, we require  $\forall P_i \in P_H$  identifying the *sta* of an MPT by reading it from the *BC*. As we assume that the *BC* emulates the ideal blockchain functionality which achieves ideal consistency and availability,  $\forall P_i \in P$  can access the consistent *BC* view. Therefore, if a  $TX_{fneg}$  is successfully confirmed on-chain. The result will be the unique result of the proposal ensured by DECLOAK contract  $\mathscr{V}$ , and  $\forall P_i \in P_H$  will immediately identify that sta = NEGOFAILED. Then  $Q_i' = Q_i$ , *i.e.*,  $Q_i' \geq Q_i$  holds.

**Lemma 3.** If  $\exists P_i \in P_H$  such that sta = COMPLETED, then the statement (i) of the financial fairness property holds.

*Proof:* According to Algorithm 1 , the protocol outputs sta = COMPLETED iff a transaction  $TX_{com}$  is contained on BC before the  $h_{cp} + \tau_{com}$ -th block. Therefore,  $\forall P_i \in \textbf{\textit{P}}^+$  the  $Q_i' = Q_i \geq Q_i$  holds.

Next, we show that the financial fairness also holds even if an MPT fails by ABORTED after an successful *Negotiation phase*.

**Lemma 4.** If  $\exists P_i \in P_H$  is such that sta = ABORTED, then the statement (ii) of the financial fairness property holds.

*Proof:* There are two cases when  $\exists P_i \in P_H$  outputs ABORTED:

- (i) Before the  $h_{cp} + \tau_{com}$ -th block,  $TX_{pnsP}(id_p, P_M')$  is published on BC.
- (ii) After the  $h_{cp} + \tau_{com}$ -th block,  $TX_{pnsT}(id_p)$  is published on BC

We first consider the case (i) where  $\exists P_j \in P_M'$  does not provide inputs  $in_j$  after the negotiation succeeded. According to Algorithm 2, the  $\mathscr{E}^*$  releases a transaction  $TX_{pnsP}(id_p, P_M)$  iff  $E^*$  calls the  $\mathscr{E}^*$  punishParties with a  $PoP_{resP}$  which proves that  $P_j \in P_M|_{P_M \neq \emptyset}$  did not provide their inputs even though they were challenged by a  $TX_{chaP}$ . The  $TX_{pnsP}$  will deduct coins of  $\forall P_i \in P_M$  by the MPT-specific collaterals q. In other word, for  $\forall P_i \in P_M$ , it holds that  $Q_i' = Q_i - q_i$ . Since  $Q_i > q_i$ , which has been ensured by  $Proc_{nneg}$ , and  $P_M \neq \emptyset$ , it holds that  $\sum_{j \in P_M} Q_j' < \sum_{j \in P_M} Q_j$ . Notably, no malicious party earned coins in this case.

Second, we consider the case (ii) which indicates that  $TX_{com}$  fails to be contained before the  $h_{cp} + \tau_{com}$ -th block. Since the case (i) not happens, then either  $\mathscr{E}^*$  have collected correct inputs from all parties, which means that  $P_M = \emptyset$ , or  $E^*$  detains the  $TX_{pnsT}$  or  $TX_{cmt}$ , or  $TX_{cmt}$  fails on validation, e.g., the old state commitments  $c_s$  that  $\mathscr{E}^*$  read from and executed MPT on has been changed, which fails the  $verify(proof, H_{\mathscr{F}}, H_{\mathscr{D}}, H_{c_s})$  in  $TX_{cmt}$ . In any case, when the timeout transaction  $TX_{pnsT}$  is posted by an honest party on the BC, it p' will be marked as ABORTED and  $\forall P_i \in P$  gets i.e.,  $Q'_i = Q_i$ . The  $Q'_i \geq Q_i$  holds.

**Lemma 5.** When  $\pi_{DECLOAK}$  terminates, it must hold  $sta \in \{NEGOFAILED, NEGOFAILED, COMPLETED\}.$ 

*Proof:* As we stressed,  $\forall P_i \in P_H$  and  $\forall E \in E_H, \mathscr{E} \in \mathcal{E}$  identify current sta from the  $\mathscr{V}$  on BC. If an MPT succeeds, a  $TX_{com}$  must be sent, which leads to  $std \leftarrow \texttt{COMPLETED}$ . Otherwise, we claim that there must be  $std \leftarrow \texttt{NEGOFAILED}/\texttt{NEGOFAILED}$ . According to the Algorithm 1, there are additionally one temporary status. When  $TX_{cmt}$  is accepted, it indicates that the MPT outputs are successfully validated. Recall that BC can continuously serve new transactions,  $TX_{com}$  has no output validation logic, and at least one executor is honest. There must be a executor who can send  $TX_{com}$  to set  $sta \leftarrow \texttt{COMPLETED}$ .

#### 4) Delivery ( $\Delta$ -)fairness

Recall that the Lemma 5 holds. In the following, we prove that the *delivery* ( $\Delta$ -)*fairness* holds in all three values of *sta* that  $\pi_{\text{DECLOAK}}$  terminates at. We first consider the *negotiation phase*. Intuitively, if no sufficient acknowledgement is

collected,  $\mathscr{E}^*$  cannot move to the *Execution phase*, therefore no outputs are obtained or delivered.

**Lemma 6.** If there exist an honest party  $P_i$  staying at sta = NEGOFAILED, then the statement (i) of the delivery  $(\Delta -)$  fairness holds.

*Proof:* As proved in Lemma 2, an honest party  $P_i$  stays at sta = NEGOFAILED only when there is a  $TX_{fneg}$  being successfully confirmed on the BC. Consequently, the  $\mathscr{E}^*$  with the *Execution phase*. Therefore, parties in P obtain no outputs, i.e.,  $s', r = \emptyset, \emptyset$ .

**Lemma 7.** If there exist an honest party  $P_i$  such that sta = ABORTED, then the statement (i) of the delivery  $(\Delta -)$  fairness holds.

*Proof:* One of  $\mathscr E$  releases the  $TX_{com}$  only when it validates that the predecessor  $TX_{cmt}$  has been confirmed on BC. When sta = ABORTED, it means that, according to Algorithm 1, the protocol terminates and there is no possibility for sta = COMMITTED, so as to releasing  $TX_{com}$ . Therefore, it holds that  $s', r = \emptyset, \emptyset$ .

**Lemma 8.** If there exist an honest party  $P_i$  such that sta = COMPLETED, then the statement (ii) of the delivery  $(\Delta-)$  fairness holds.

*Proof:* According to Algorithm 1, sta = COMPLETED only when  $TX_{com}$  is accepted and confirmed by BC, which means that  $TX_{com}$  is released by at least one  $\mathscr{E}$ s. In fact, if  $TX_{cmt}$  has been confirmed on BC, any  $\mathscr{E} \in \mathcal{E}$  can validate the  $PoP_{cmt}$  of  $TX_{cmt}$  and read the  $k_{s'}, k_r$  from  $TX_{cmt}$  to constructs and releases a  $TK_{com}$ . As we assume that BC is ideally accessible to any honest entity. Therefore, say  $TX_{cmt}$  is confirmed on BC in a wall-time  $t_{com}$ , then the time of all honest entities in  $P^+$  knowing that  $TX_{cmt}$  has been confirmed is also  $t_{com}$ , i.e.,  $t_i \leftarrow t_{com}|_{t_i \in t^+_{com}}$ . Moreover, as  $P_i \in P_H$  undisturbedly obtain  $TX_{com}$  from honest Es within the network latency  $\Delta$ , then we conclude that  $t_s = t_r$ , i.e., the (a) and (b) of (ii) are satisfied, if at least one honest E exists.