FIRST: FrontrunnIIng Resilient Smart ConTracts

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Abstract—Owing to the meteoric rise in the usage of cryptocurrencies, there has been a widespread adaptation of traditional financial applications such as lending, borrowing, margin trading, and more, to the cryptocurrency realm. In some cases, the inherently transparent and unregulated nature of cryptocurrencies leads to attacks on users of these applications. One such attack is frontrunning, where a malicious entity leverages the knowledge of currently unprocessed financial transactions submitted by users and attempts to get its own transaction(s) executed ahead of the unprocessed ones. The consequences of this can be financial loss, inaccurate transactions, and even exposure to more attacks. We propose FIRST, a framework that prevents frontrunning attacks, and is built using cryptographic protocols including verifiable delay functions and aggregate signatures. In our design, we have a federated setup for generating the public parameters of the VDF, thus removing the need for a single trusted setup. We formally analyze FIRST, prove its security using the Universal Composability framework and experimentally demonstrate the effectiveness of FIRST.

Index Terms—DeFi, Frontrunning, Ethereum.

I. INTRODUCTION AND RELATED WORK

The decentralized, trustless, and censor-resistant nature of Ethereum, along with its support for smart contracts, has enabled a wide range of financial applications and has created the Decentralized Finance (DeFi) ecosystem, which is worth more than 81 Billion USD as of April 2022 [2]. With the recent developments, many real-world financial products such as money lending/borrowing, margin-trading, exchange platforms, derivatives and more, are being made available to the blockchain users via smart contracts [1], [3], [7], [11]–[13]. Unfortunately, the lack of regulations emboldens malicious actors to adapt and apply questionable practices, long-known in traditional finance, to the cryptocurrency ecosystem. In finance, frontrunning is an act of purchasing stock or other securities right before a large (whale) transaction owing to access to non-public information. By doing so, one can take advantage of the outcomes of large unprocessed transactions to be executed after a later time than one’s own. In today’s financial systems, frontrunning has been classified as illegal by monitoring entities, such as the U.S. Securities and Exchange Commission (SEC) and principally prevented by extensive regulations [38].

In Ethereum, every transaction is publicly visible in the pending pool (or mempool), before it is mined. Consequently, anyone watching the pending pool can identify a user transaction, $tx_A$, and try to frontrun it by submitting another transaction with more gas price than $tx_A$. We pictorially depict a frontrunning attack in Figure 1. The adversary, Mallory, watches the peer-to-peer (P2P) network for potential victim transactions. Once an honest user, Alice, submits a transaction $tx_A$ with gas price of $G_A$, Mallory creates a transaction $tx_M$ with gas price $G_M$ where $G_M > G_A$ to be included in the upcoming block. Examples of frontrunning attacks can be seen on various decentralized applications (dApps). The first and most prominent attack vector is on decentralized exchanges (DEX). DEX is an exchange platform built on smart contracts and enables users to exchange assets without the need for an intermediary [34]. Unlike centralized exchanges where users wait for their sell/buy orders to be complete, most DEX’s, e.g., Sushiswap and Uniswap [13], [14], use an automatic pricing mechanism known as Automated Market Maker (AMM) to perform instant trades.

A frontrunner can perform attacks with highly predictable results due to their deterministic pricing mechanism as well as the transparency of liquidity amounts. In this context, Qin et al. estimated a profit of 1.51 Million USD made by frontrunners [43]. Other domains that are affected by frontrunning attacks include (but are not limited to) gambling [26], bug bounty programs [20], smart contracts exploits [46], and clogging [43], which emphasizes the threat and the need for mitigation. In this work, we aim to mitigate frontrunning attacks on blockchains that support smart contracts such as Ethereum, but without modifying the blockchain’s underlying infrastructure.

Related Work and Motivation: Prior research in frontrunning prevention falls into four categories: (a) solutions that require direct interaction with miners to include the transaction $tx_A$ in the upcoming block [40], (b) solutions that are designed for DEX’s [21], [32], (c) solutions that prevent arbitrary re-ordering of transactions [24], [32], [33], [35], and (d) cryptography-based solutions [20], [34]. In the first category, Alice sends $tx_A$ directly to miners via
hidden endpoints (known as a private transaction) to prevent adversaries from noticing her transaction in the pending pool. Flashbots Auction framework [6] is one example, where entities called relayers bundle and forward transactions to miners through private channels. However, relayers could perform frontrunning attacks as they have complete access to the transaction details. The second category of solutions is built for AMM-based DEX’s to minimize the frontrunning attacks. It reduces the risks of frontrunning by computing the optimal threshold for the frontrunner’s transactions and routes the victim’s transaction (swap requests) to limit their profit. However, AMM is built for only decentralized exchanges and cannot be utilized by other dApps, such as auctions, naming services, games [26], [51].

The third category of solutions is built upon order-fairness property [35]; however, these solutions cannot be adopted directly and require drastic changes to the consensus layer, which is non-trivial, whereas our solution is compatible with most state-of-the-art DeFi EVM-based blockchains, with no consensus layer modifications. In the fourth category, Khalil et al. [34] proposed transaction ordering as a solution to frontrunning attacks; however, that approach uses timelock puzzles, which are not publicly verifiable. LibSubmarine uses a commit-and-reveal scheme to prevent frontrunning [29]. In LibSubmarine, the committer is required to create a new smart contract for every transaction that they submit to a dApp, which is inefficient. We do not require this in our design. Our solution falls into the fourth category; we propose a general-purpose solution to the frontrunning problem using cryptographic protocols such as verifiable delay functions (VDFs) and aggregate signatures [16], [18] and are publicly verifiable.

Although DeFi research has gained great attention in the past few years, the existing research on frontrunning prevention is limited. There have been works that present taxonomies of frontrunning attacks, and analyze the vulnerability of dApps: Eskandari et al. presented the taxonomy of frontrunning attacks and analyzed the attack surface of top dApps [26]. Qin et al. [43] extended the taxonomy and quantified the profit made by blockchain extractable value [43]. There have also been studies of Defi primitives and their economic aspects by Werner et al. [49]. Daian et al. [23] demonstrated the existence of bots that frontrun victim transactions and competitively participate in priority gas auctions and coined the term miner extractable value to show how miners maximize their profit by reordering the transactions.

The profits made by frontrunners have been quantified by Torres et al. [46] and Qin et al. [43]: the latter also brought to attention the presence of private transactions submitted to miners. Zhou et al. [52] formalized and quantified the profit made by sandwich attacks enabled by frontrunning on decentralized exchanges. Qin et al. [44] empirically analyzed the profit made by arbitragers using flash loans and proposed a method to maximize their profit. Baum et al. [15] presented the state-of-the-art frontrunning attacks and categorized mitigation mechanisms.

Overview: Our high-level idea is to eliminate frontrunning by requiring every user of a dApp, including frontrunner miner(s), to evaluate a VDF before submitting a transaction, while utilizing cryptographic means to obfuscate the transaction details. By doing so, our framework intercepts the attacker(s) from submitting a frontrunning transaction as soon as the victim transaction is seen on the pending pool. However, VDFs require a trusted party in the setup phase; to get around this, we employ a federated setup.

Contributions
- We propose FrontrunIng Resilient Smart ConTracts (FIRST), a framework that mitigates frontrunning attacks in a blockchain that supports smart contracts, without requiring any changes in the underlying blockchain infrastructure.
- Our framework is not application-specific, and hence can be easily adopted by any EVM based dApps.
- We discuss the effectiveness of our approach and experimentally evaluate it using the real-world Ethereum transaction data.
- We present a rigorous formal security analysis of FIRST using the Universal Composability (UC) framework.

Paper Organization:
In Section II we give a concise explanation of preliminary concepts relevant to the problem. In Section III we present the system model and threat model. In Section IV we describe FIRST’s construction and constituent protocols. In Section V we give the security analysis of FIRST. In Section VI we detail the implementation and evaluation, and discuss our design choices. We conclude the paper in Section VII.

II. Preliminaries

A. Ethereum and DeFi

The Bitcoin cryptocurrency has demonstrated the potential behind blockchain technology by allowing mutually untrusting parties to transact directly while eliminating the need for a central authority. Ethereum extended the blockchain technology by allowing parties to execute software programs called smart contracts. A smart contract is a program that resides on the Ethereum blockchain and gets executed automatically when some predetermined conditions are met. On Ethereum, smart contracts can be developed using programming languages like Solidity or Vyper. Their immutable and transparent nature created a new class of applications, called dApps.

The finance-related dApps have enabled what is known as decentralized finance or DeFi. DeFi is an umbrella term that includes various financial products (such as flashloans, asset management services, decentralized derivatives, and insurance services) available to any user with an internet connection in a decentralized manner [5], [8–10]. It allows users to utilize financial products at any time while keeping their identities private. In addition, DeFi products enable end-users to employ them in a non-custodial fashion, giving users complete control over their money, as opposed to traditional financial services based on a custodial model. As of January 2022, the total
the message was to encrypt a message to the future. The only way to retrieve proposed time-lock puzzles \cite{45}, whose application was to modifications, users are required to pay a base fee of gas prices even during dynamic periods \cite{48}. With the Wesolowski \cite{42, 50}. Although both VDF schemes could be constructions were proposed independently by Pietrzak and nately, time-lock puzzles were not publicly verifiable, thus not be made faster even using parallel processors. Unfortu-

Verifiable Delay Function: A VDF is a deterministic function \( f: X \rightarrow Y \) that takes in a prescribed number of sequential steps, \( T \), to compute, allowing its correctness to be verified publicly and efficiently \cite{16}. The idea of slowing down function computation is indeed not new: Rivest et al. proposed time-lock puzzles \cite{45}, whose application was to encrypt a message to the future. The only way to retrieve the message was to perform \( T \) sequential steps, which cannot be made faster even using parallel processors. Unfortunately, time-lock puzzles were not publicly verifiable, thus limiting their applicability. Following \cite{16}, two novel VDF constructions were proposed independently by Pietrzak and Wesolowski \cite{42, 50}. Although both VDF schemes could be utilized in our framework, we prefer the VDF construction by Wesolowski \cite{50} due to its shorter proof size and faster proof verification compared to \cite{42}. We refer the reader to \cite{17} for detailed comparisons of both VDF schemes, and give the formal definition of a VDF below.

Definition 1 (Verifiable Delay Function \cite{16}): A verifiable delay function, \( \mathcal{V} \) is defined over three polynomial time algorithms.

1) \( \text{Setup}(k, T) \rightarrow pp = (ek, vk) \): This is is a randomized algorithm that takes a security parameter \( k \) and a desired puzzle difficulty \( T \) and produces public parameters \( pp \) that consists of an evaluation key \( ek \) and a verification key \( vk \). We require \( \text{Setup} \) to be polynomial-time in \( k \). By convention, the public parameters specify an input space \( X \) and an output space \( Y \). We assume that \( X \) is efficiently sampleable. \( \text{Setup} \) might need secret randomness, leading to a scheme requiring a trusted setup. For meaningful security, the puzzle difficulty \( T \) is restricted to be sub-exponentially sized in \( k \).

2) \( \text{Eval}(ek, x) \rightarrow (y, \pi) \): This algorithm takes an input \( x \in X \) and produces an output \( y \in Y \) and a (possibly empty) proof \( \pi \). \( \text{Eval} \) may use random bits to generate the proof \( \pi \) but not to compute \( y \). For all \( pp \) generated by \( \text{Setup}(k, T) \) and all \( x \in X \), \( \text{Eval}(ek, x) \) must run in parallel time \( T \) with \( \text{poly}(\log(t), k) \) processors.

3) \( \text{Verify}(vk, x, y, \pi) \rightarrow \{ \text{"accept"}, \text{"reject"} \} \): This is a deterministic algorithm that takes an input, output and proof and outputs accept or reject. The algorithm must run in total time polynomial in \( \log T \) and \( k \). Notice that \( \text{Verify} \) is much faster than \( \text{Eval} \).

Aggregate Signatures: An aggregate signature scheme allows the aggregation of \( n \) distinct signatures from \( n \) users, each on a distinct message of their choice, into a single signature \cite{18}. Moreover, it allows the aggregation to be done by any party among the \( n \) users, including a potentially malicious party. By verifying the aggregate signature, one can be convinced that \( n \) distinct users have signed \( n \) distinct messages, which have been collected into a single signature. FIRST utilizes this cryptographic primitive to aggregate the verification results of a VDF proof. We give the definition of an aggregate signature scheme below.

Definition 2 (Aggregate signature \cite{18}): An aggregate signature, \( \text{Agg} \), is defined over five polynomial time algorithms: (KeyGen, Sign, Verify, Aggregate, AggregateVerification). Let \( U \) be the universe of users. KeyGen(1\(^k\)) \rightarrow (x, v): Each user picks random \( x \leftarrow \mathbb{Z}_p \) and does \( v \leftarrow g_x^r \). The user’s public key is \( v \in \mathbb{G}_2 \) and secret key is \( x \in \mathbb{Z}_p \). Sign(\( x_i, M_i \)) \rightarrow \sigma_i: Each user \( i \in U \), given their secret key \( x_i \) and message of their choice \( M_i \) takes hash \( h \leftarrow H(M) \) and signs \( \sigma_i \leftarrow h_x^r \).

Verify(\( v_i, M_i, \sigma_i \)) \rightarrow \{ \text{true, false} \}: Given public key \( v \) of user \( i \), a message \( M_i \) and \( \sigma_i \), compute \( h \leftarrow H(M) \) and return true if \( e(\sigma, g_x) = e(h, v) \).

Aggregate(\( M_1, \ldots, M_n, \sigma_1, \ldots, \sigma_n \)) \rightarrow \sigma_{agg}: Each user \( i \in U \) gives signature \( \sigma_i \) on a message of their choice \( M_i \), \( C \) computes \( \sigma_{agg} \leftarrow \prod_{i=1}^{n} \sigma_i \) where \( n = |U| \).

AggregateVerification(\( \sigma_{agg}, M_1, \ldots, M_n, p_{k1}, \ldots, p_{kn} \)) \rightarrow \{ \text{true, false} \}: For each user \( i \in U \), given original messages \( M_i \).
along with their public keys \( v_i \), to verify aggregated signature \( \sigma_{agg} \), check if:

1) All messages \( M_i \) are distinct, and:
2) For each user \( i \in U \), \( e(\sigma, g_2) = \prod_{i=1}^{n} e(h_i, v_i) \) holds true where \( h_i \leftarrow H(M_i) \).

### III. System and Adversary Model

#### A. System Model

**Parties:** In our system, there exist four main entities as depicted in Figure 2: 1) A smart contract \( SC \), that is residing on the Ethereum Blockchain, 2) Alice, who is a legitimate user interacting with \( SC \) by creating a transaction \( tx_A \) that is potentially vulnerable to frontrunning attacks. Alice is equipped with a verification/signing keypair \((pk_A, sk_A)\). She evaluates a VDF instance, \( V \) given to her by a set of verifiers.

3) A set of verifiers \( \mathcal{V} \) who generate and send the public parameters of a VDF, \( \pi \), to Alice and verify the evaluated \( V \) and its proof of correctness that Alice submits to them. 4) Miners, whose goal is to mine a new block and distribute it to the P2P network.

![System Model for FIRST](image)

**Fig. 2. System Model for FIRST.**

A coordinator \( C \), is an entity picked from the members of \( \mathcal{V} \) to help aggregate their signatures into a single signature. \( C \) need not be trusted, and can either be elected by members of \( \mathcal{V} \) or can be chosen by Alice. We assume that the miners are greedy—they sort transactions in descending order of miner tip and pick them up in a way that maximizes their profit. The FIRST framework is built to be adopted by anyone who aims to prevent their dApp from being frontrun. We assume that the creator of the dApp will deploy \( SC \) and implement it correctly. The dApp creator, \( dAC \), is the smart contract owner, who implements applications such as auctions, exchanges, bug bounty programs, etc., which have traditionally been affected by frontrunning attacks. We assume communications between all parties takes place through secure and authenticated channels, with nonces/timestamps wherever needed.

**Verifiers:** We assume an honest majority among the set of verifiers, \( \mathcal{V} \). We take into account the case where a subset of malicious verifiers attempts to leak details about \( tx_A \) to Mallory.

Our framework assumes that the smart contract creator, \( dAC \) is not colluding with any other participant or with miners as it is in their best interest to protect their dApp against attackers. Moreover, the public nature of smart contracts will limit malicious attacks even in the case of collusion. Furthermore, as in other papers, we assume no miner can accumulate more than 33% of the total hashrate [28], [51]. However, we assume miners can re-order transactions to increase their profit and attempt to frontrun victim transactions. In FIRST, every participant, including miner(s), must evaluate a VDF before submitting a transaction to the smart contract, and transaction of participants who do not compute VDF will be rejected by smart contract. We do not discuss networking-related attacks such as DoS and DDoS as they are out of the scope of this work; we refer the reader to relevant research in this area [31], [37], [39]. We now state our security and efficiency goals.

**Security goal:** Every transaction that utilizes FIRST should be protected against frontrunners, including miners (miners can also attempt frontrunning), with very high likelihood, even in the case where any malicious \( V_i \in \mathcal{V}; i \in [1 \ldots n], n = |\mathcal{V}| \) leaks any information they are privy to.

**Efficiency goal:** Frontrunning should be prevented with least overhead on the system and minimal increase in transaction confirmation duration. We give our table of notations in Table 1.

#### B. Adversary Model and Assumptions

**Mallory:** We assume Mallory is an adversary who is computationally bounded and economically rational. Mallory is observing the pending transaction pool for Alice’s transaction, \( tx_A \) on the Ethereum network. Mallory will attempt a frontrunning attack as soon as she observes \( tx_A \) on the pending pool by paying a higher miner tip. We also take into account the case where more than one adversaries attempts to frontrun \( tx_A \). For ease of exposition, we use Mallory to represent a group of adversaries.

### IV. The FIRST Framework

#### A. Design Overview/Conceptualization of FIRST

The conceptual idea behind FIRST is that Alice’s transaction cannot be frontrun by an attacker Mallory with her attack transaction if the system does not allow Mallory’s transaction to hit the mempool until Alice’s has been confirmed. We can achieve this by making Mallory’s transaction wait until Alice’s transaction has been confirmed. Hence, our FIRST framework requires each user to wait for a predetermined time before entering the mempool \( (t_1) \). The goal is to choose \( t_1 \) for a
The minpool with high probability. The time $t_2$ is the expected wait time of the transaction of any Alice in the mempool before getting confirmed on the Blockchain. This ensures that Mallory cannot frontrun Alice’s transaction that she sees in the mempool with high probability. The time $t_2$ depends on several dynamic factors, namely transaction gas price, miner tip, miner extractable value (MEV), and network congestion at the time of submission, which makes an exact assessment of $t_2$ difficult. Since we can only use the expected value of $t_2$, hence there is a chance of $t_1$ being less than the actual waiting time for Alice’s transactions. However, as we detail in Section VI, we noticed that the miner tip has a significant bearing on $t_2$ for a transaction.

### Protocol 1: System Setup

| Inputs | Security parameter $k$. |
| Output: | SC, $(pk, sk)$ keypair for each member of $V$. |
| Parties: | $dAC$, $V$. |

1. dApp creator $dAC$ implements the SC and deploys it on Ethereum.
2. Each $V_i; i \in [1 \ldots n]$ generates $(pk_i, sk_i) \leftarrow$ Agg.KeyGen($1^k$).

Given that $t_2$ is difficult to predict, and a high $t_1$ is detrimental to the transaction throughput, what we do is empirically arrive at a “reasonable” value for $t_1$. By continuously monitoring the blockchain data, we identify the minimum miner tip value that would result in a high likelihood of all FIRST transactions waiting approximately $t_2$ time in the mempool. The $t_1$ wait time is then fixed for a given epoch higher than $t_2$, ensuring that a potential attack transaction will not be able to frontrun valid FIRST transactions. The $dAC$ obtains the value of $t_1$ via statistical analysis of the relation between the miner tip value of the transaction and transaction confirmation time by monitoring the Ethereum network continuously. Consequently, FIRST recommends an optimal miner tip value that decreases the likelihood of transactions getting frontrun. We detail how we performed such a statistical analysis in Section VI.

### Protocol 2: Parameter Generation

| Inputs | Security parameter $k$. |
| Output: | $pp$. |
| Parties: | $dAC$, $V$. |

1. Each $V_i \in V$, initializes lists $D_i, U_i = \emptyset$.
2. $dAC$ picks a $T \in \mathbb{Z}^+$. 
3. Each $V_i \in V$, selects $s_i \leftarrow \mathbb{P}$, and sends $s_i$ to all other $V_i$.
4. On receiving $s_1 \cdots s_n$, each verifier first checks $s_i$, if $s_i \notin \mathbb{P}$, $i \in [1 \ldots n]$, all verifiers restart from Step 1. Else, $V_i$ computes $N = \sum_{i=1}^{n} s_i$.
5. The members of $V$ do $G \leftarrow V$.Setup($k, T$), s.t., $N = |G|$. 
6. All $V_i \in V$ output $pp = (G, T)$, $\sigma_{pp} \leftarrow \text{Sign}(sk_{V_i}, pp)$.

### Protocol 3: Transaction Detail Generation

| Inputs | $addr_A, f_{name}, addr_{SC}$. |
| Output: | Secret message $M_A$, $h$, Signature $\sigma_A$. |
| Parties: | $V, Alice$. |

1. Alice generates message $M_A = (addr_A, f_{name}, addr_{SC})$.
2. Alice generates hash of $M_A$, $h = H(M_A)$, and signs it: $\sigma_A \leftarrow \text{Sign}(sk_A, h)$.
3. Alice sends $(h, \sigma_A)$ to each $V_i; i \in [1 \ldots n]$, $n = |V|$, including $V_i$ picked as $C$.

The fifth part is the verification of the delay function and the user’s signature being submitted to the BC (Protocol 5). Finally, the verification of signatures on the VDF evaluation and contract execution (Protocol 6). Now, we explain each protocol in detail. We use Sign and Verify with no pre-pended string to denote regular digital signature functions, whereas Agg.function() denotes functions specific to the aggregate signature scheme. We use Verify for both, signature and VDF verification, which will be clear from context.

### Protocol 1

This is the bootstrap Protocol of FIRST, and is executed only once. It takes in as input a security parameter and outputs the smart contract $SC$ and verification/signing keypairs for each member of $V$. First, the $dAC$ implements and deploys the dApp on Ethereum. Entities sign up with the $dAC$ to become verifiers. Following deployment, each member of $V$ generates their key pairs independently.

### Protocol 2

The protocol is used to generate the system parameters of FIRST. It takes in security parameter and outputs the public parameters of $V$. In Line 1, each $V_i \in V$ initializes its list $D_i$ and $U_i$, used to keep track of values used in the VDF $V$’s evaluation and verification, respectively. We note that both lists will get reset along with $V$’s public parameters (specifically $N$ and $T$) at the end of each epoch. This step is crucial to prevent and detect situations where a malicious coordinator, $C$, attempts to speed up $V$’s evaluation for Mallory. In Line 2, the dApp creator initializes the number of steps $T$ that will be used in the evaluation of $V$.

We discuss possible ways to pick $T$ in Section VI. For setting up the public parameters of the VDF instance $V$, the members of $V$ need to generate a group of order $N$, such that factoring $N$ is hard. In Line 3, each verifier picks a large
prime \( s_i \) as their share of \( N \) from a set of large primes \( \mathbb{P} \) and shares it with the rest of the verifiers. On receiving all the shares \( s_1, \ldots, s_n \), the verifiers compute \( N \) as a sum of all the individual shares (Line 4). We note that FIRST requires an odd number of verifiers in the system for the final \( N \) to be an odd number.

**Protocol 4: User-Verifiers Interaction**

*Inputs*: \( \sigma_A, h, pp, \sigma_{pp1}, \ldots, \sigma_{ppn} \).

*Output*: VDF output \( y \), VDF proof \( \pi \).

*Parties*: Alice, \( \mathcal{V} \).

Upon receipt of \( (\sigma_A, h) \) from Alice, \( \mathcal{V} \in \mathcal{V} \) picks prime \( l \leftarrow \mathbb{P} \) and sends \( (h, l) \) to \( \mathcal{V} \).

/* Upon receipt of \( (h, l) \), each verifier independently does the following steps */

1. **for each** \( V_i \in \mathcal{V} \) **do**
2.   | **if** \( l \notin D_i \) and \( l \notin U_i \) **then**
3.     |   | \( M_i = (h, V_i, block_{curr}) \).
4.     |   | \( \sigma_{V_i} \leftarrow \text{Agg.Sign}(sk_{V_i}, M_i) \).
5.     |   | Add \( (l) \) to \( D_i \).
6.     |   | Send \( (M_i, \sigma_{V_i}) \) to \( C \).
7.   | **else**
8.     |   | return \( \perp \)
9.   | **end**
10. **end**
11. **end**

/* Signature aggregation and \( \mathcal{V} \) evaluation. */

12. \( C \) checks if each \( \text{Agg.Verify}(pk_i, M_i, \sigma_{V_i}) \) \( \equiv \) true. If majority of members of \( \mathcal{V} \) return \( \perp \), \( C \) returns \( \perp \) to Alice. Else \( C \) does \( \sigma_{agg} \leftarrow \text{Agg.Aggregate}(M_1, \ldots, M_j, \sigma_{V_1}, \ldots, \sigma_{V_j}) \), where \( j > |\mathcal{V}|/2 \).

13. \( C \) creates \( M_{agg} = (\sigma_{agg}, M_1, \ldots, M_j, pk_1 \ldots pk_j) \) and sends \( M_{agg} \) to Alice.

14. Alice checks if \( \text{Agg.AggregateVerification}(\sigma_{agg}, M_1, \ldots, M_j, pk_1 \ldots pk_j) \) \( \equiv \) true, and if \( \text{Verify}(pk_i, pp, \sigma_{pp_i}) \) \( \equiv \) true where \( i \in \{1 \ldots j\} \), and \( j > |\mathcal{V}|/2 \). If both return yes, Alice computes \( (\pi, y) \leftarrow \mathcal{V}.\text{Eval}(pp, l) \). Else returns \( \perp \) and retry.

15. Alice sends \( (\pi, y) \) to all members of \( \mathcal{V} \).

We require this to prevent potential problems, e.g., \( N \) being factored and rendered unusable.

We note that at an epoch change over, if the value of \( T \) is being decreased for the next epoch, FIRST requires that there are no current transactions in the pending pool related to the current dApp. This is done to reduce the chances of front-running because of reduced VDF computation time in the current epoch.

**Protocol 5: VDF Proof Verification and Transaction Submission**

*Inputs*: \( \pi, y \).

*Output*: Aggregate signature \( \sigma'_{agg} \), transaction \( tx_A \).

*Parties*: Alice, \( \mathcal{V} \).

/* Proof verification run independently by each verifier */

1. **for each** \( V_i \in \mathcal{V} \) **do**
2.   | **if** \( l \notin U_i \) and \( l \notin D_i \) **then**
3.     |   | Add \( l \) to \( U_i \).
4.     |   | if “accept” \( \leftarrow \mathcal{V}.\text{Verify}(pp, l, y, \pi) \) **then**
5.     |     | \( M'_i = (\text{“accept”}, V_i, l) \).
6.     |     | \( \sigma'_{V_i} \leftarrow \text{Agg.Sign}(sk_{V_i}, M'_i) \).
7.     |     | Send \( (M'_i, \sigma'_{V_i}) \) to \( C \).
8.     | **end**
9.     | **else**
10.       | **if** \( \text{return} \perp \) **then**
11.       |   | **end**
12.     | **else**
13.       | **if** \( \text{return} \perp \) **then**
14.       |   | **end**
15. **end**
16. **end**

/* Signature aggregation and transaction submission */

17. \( C \) checks if each \( \text{Agg.Verify}(pk_i, M'_i, \sigma'_{V_i}) \) \( \equiv \) true. If majority of members of \( \mathcal{V} \) return \( \perp \), \( C \) returns \( \perp \) to Alice. Else \( C \) does \( \sigma'_{agg} \leftarrow \text{Agg.Aggregate}(M'_1, \ldots, M'_j, \sigma'_{V_1}, \ldots, \sigma'_{V_j}) \), where \( j > |\mathcal{V}|/2 \).

18. \( C \) creates \( M'_{agg} = (\sigma'_{agg}, M'_1, \ldots, M'_j, pk_1 \ldots pk_j) \) and sends to Alice.

19. Alice checks if \( \text{Agg.AggregateVerification}(\sigma'_{agg}, M'_1, \ldots, M'_j, \sigma'_{V_1}, \ldots, \sigma'_{V_j}) \) \( \equiv \) true and \( j > |\mathcal{V}|/2 \). If yes, Alice creates \( M' = (M_A, M'_{agg}, M'_{agg}) \) and signs it, \( \sigma'_A \leftarrow \text{Sign}(sk_A, M') \). Else returns \( \perp \) and retry.

20. Alice creates and submits transaction \( tx_A = (\sigma'_A, M', pk_A) \).

**Protocol 3** This protocol is used to generate transaction details of FIRST’s users. It takes as input Alice’s transaction details and outputs a message, its digest and a signature over the digest; the latter two are meant to be given to \( \mathcal{V} \). In Line 1, user Alice constructs a tuple, \( M_A \), with the transaction details, including her Ethereum address \( addr_A \), the dApp smart contract address that she intends to submit.
a transaction to, $addr_{SC}$ (that $DAC$ created), and the name of the function that she intends to invoke to trigger the smart contract $SC$, $f_{name}$. We assume she has a verification/signing keypair $(pk_A, sk_A)$, using which, in Line 2, she creates and signs a digest of $M_A$. Using the cryptographic hash of the transaction details prevents the leakage of any detail that may help a potential frontrunner. Alice sends the digest of $M_A$ (h) and her signature over it $(\sigma_A)$ to each $V_i$; $i \in [1 \ldots n]$.

**Protocol 5** This protocol must be executed between Alice and members of $V$. It takes as input the output of Protocol 3 and Protocol 2, i.e., the digest and signature over Alice’s message, and public parameters of $V$ and verifiers signature on it, outputs the evaluation of the VDF instance, $\mathcal{V}$, and its corresponding proof. In Line 1, the coordinator $C$ samples a unique (per user) prime $l$ from a set of primes $P$ that contains the first $2^{2k}$ primes, where $k$ is the security parameter. We note that $C \in V$ and need not be trusted. We require each $V_i$ to check the newly sampled $l$ and verify that it was not generated before (Lines 2, 3). Upon checking the validity of $l$ and Alice’s signature, each $V_i$ creates a message $M_i$ by concatenating $l$, block$_{curr}$, and $h$ from Protocol 3 to its id and signs $M_i$ (Lines 5, 6). $V$’s freshness block$_{curr}$, which represents the block height at the time of request is included in $M_i$ to prevent off-line attacks on $V$. For an off-line attack, Mallory requests $l$ and pre-evaluates the $V$ to submit the frontrunning transaction when the victim transaction is seen on the network. However, the smart contract eliminates this attack by verifying the freshness of $V$. In Line 7 and 8, each $V_i \in V$ updates their $D_i$ to keep track of used $l$ values and sends their $\sigma_i$ to $C$. In Lines 18 and 19, $C$ verifies the signatures of verifiers, aggregates them, and sends the aggregate signature to Alice for verification.

The goal of the aggregate signature scheme in FIRST is to cut down the cost of verifying each $V_i$’s signature individually. Moreover, we can aggregate signatures from all members of $V$ without requiring any trust assumption on them. We refer interested readers to [18] for further details on the aggregate signature scheme. Alice checks the validity of $\sigma_{agg}$ and the number of received messages $j$, where $j > |V|/2$. If both return true, Alice retrieves and verifies the public parameters of $V$, $pp$, and starts the evaluation of $\mathcal{V}$ (we recollect that per our system model, user Alice evaluates $\mathcal{V}$). During the evaluation, Alice generates its output and proof of correctness $\pi$, which she sends to all members of $V$ (Lines 20, 21).

**Protocol 6** Protocol 5 is required to be executed between Alice and $V$. It takes as input the VDF evaluation result and its proof (given as output by Protocol 4), and outputs Alice’s transaction $tx_A$ to be submitted to $SC$. In Line 2, every $V_i \in V$ first checks if $l \not\in U_i$. This check ensures that Mallory is not reusing the $l$ to evaluate $\mathcal{V}$. Each $V_i$ also checks if $l \in D_i$, to check if $l$ has indeed been assigned to a user.

If the check returns true, every $V_i \in V$ adds $l$ to $U_i$. In Line 4, every $V_i \in V$ verifies the VDF proof $\pi$ sent by Alice. Depending on the outcome of the verification, each $V_i$ creates $M_i’$ and signs it (Lines 5, 6). Upon completion of the verification phase, in Line 17, $C$ first verifies each $\sigma_i’$.
and aggregates the signatures into a unique signature $\sigma'_{\text{agg}}$. In Line 18, $C$ creates a tuple $M'_{\text{agg}}$, containing the $\sigma'_{\text{agg}}$, distinct messages of members of $V$, their public keys, and sends it to Alice. Alice checks the validity of $\sigma_{\text{agg}}$ and the number of received messages $j$, where $j > |V|/2$, for a majority of verifiers from $V$. If both return true, Alice creates $M'$ consisting of her message, $M_A$ from Protocol 3, $M'_{\text{agg}}$ from Protocol 4 and the aggregate message, $M'_{\text{agg}}$ received from $C$, and signs it before creating and submitting transaction $tx_A$ (Lines 19 and 20).

Protocol 6: This protocol is used to validate the transaction $tx_A$, V’s verification details, and the signature aggregation. Alice creates and submits $tx_A$ with recommended gas price and miner tip. SC parses $tx_A$ to access necessary fields. SC verifies transaction details committed to in Protocol 3 verifies the messages of verifiers and checks if the number of participants in the verification phase is more than $|V|/2$. Finally, SC will check the given V’s freshness by checking if the difference between the block height at the time of request and the current lies within a pre-defined time threshold. The threshold value is a system parameter and should be adjusted by $dAC$. This check ensures that the attacker did not pre-compute V to submit as soon as the victim transaction is seen on the network. SC will abort the function execution if any check fails.

C. Design Choices

In this section, we discuss the alternative solutions and their disadvantages.

Intel SGX: The trusted Execution Environment (TEE) is an isolated environment on the main processor and runs parallel to the OS [29]. Intel’s Software Guard Extensions (SGX) is a feature of Intel architecture that aims to protect the integrity and confidentiality of the program and its code through TEE technology. Our initial design anticipated adopting Intel SGX to protect the confidentiality of the transaction details from other entities and implement the delay within enclaves. However, its black-box nature, challenges towards scalability, and the recent attacks pushed us to discover new solutions [22], [29], [30], [41], [47].

Transaction Ordering: An alternative solution to prevent frontrunning could be enforcing an ordering on transactions, i.e., timestamps. However, challenges such as synchronization, delay on the peer-to-peer network, unwillingness to create a centralized timestamp server, or depend on off-chain services to produce timestamps discouraged us from going this route [19], [27].

Verifiers: One might question the need for VDF in the existence of an honest-majority committee rather than relying on the verifiers waiting for a certain amount of time. However, the latter approach mandates verifiers to keep track of perhaps, a vast number of timers per request, to track waiting time and is not publicly verifiable. On the other hand, VDF provides easy verification and is publicly available. The trust assumption on verifiers is required to maintain the flow of the protocol, not to maintain the security or privacy of FIRST.

V. SECURITY ANALYSIS OF FIRST

A. Informal Security Analysis

In this section, we analyze the security of FIRST informally by considering potential attack scenarios and describe how FIRST eliminates them.

Malicious Verifier: In this attack, an adversary might try to corrupt some members of $V$, and try to glean information about Alice’s transaction $tx_A$ while she computes the VDF. FIRST accounts for this by having Alice obfuscate all transaction details by hashing them and sharing only the digest with the verifiers (Protocol 5 Steps 2-3), thus preventing any possibility for leakage of sensitive information. We note that the same security guarantees remain for the case where a malicious verifier attempts to frontrun Alice.

Proactive Attacker: Consider a scenario where Mallory or a bot she created are monitoring the pending transaction pool to identify a transaction $tx_A$ submitted by a user Alice. Let $t_M$ represent the time Mallory first sees $tx_A$, with a gas price $G_A$, on the pending pool. Mallory creates a transaction $tx_M$ with gas price $G_M$ where $G_M > G_A$. We note that, in order for this attack to succeed, $tx_M$ is required to be included in the previous or in the same block but before $tx_A$. To address this, FIRST assigns V related parameters and updates them regularly using the empirical analysis we describe in Section VI. Since all valid transactions need to wait for FIRST stipulated time delay (V delay), $tx_M$ will need to wait to generate valid V proof. If Alice paid the FIRST recommended miner tip, $tx_A$ will wait for at most $t_2$ time in the pending pool, and since $t_2$ is less than the V delay set by FIRST with high probability, Alice’s transaction will not get frontrun by Mallory.

B. Formal Security Analysis

We analyze the security of FIRST in the Universal Composability (UC) framework [21]. The notion of UC security and indistinguishability is captured by the following two theorems from [21].

Definition 3: (UC-emulation [21]) Let $\pi$ and $\phi$ be probabilistic polynomial-time (PPT) protocols. We say that $\pi$ UC-emulates $\phi$ if for any PPT adversary $A$ there exists a PPT adversary $S$ such that for any balanced PPT environment $Z$ we have

$$\text{EXEC}_{\phi,S,Z} \approx \text{EXEC}_{\pi,A,Z}$$

Definition 4: (UC-realization [21]) Let $F$ be an ideal functionality and let $\pi$ be a protocol. We say that $\pi$ UC-realizes $F$ if $\pi$ UC-emulates the ideal protocol for $F$.

We define an ideal functionality, $F_{\text{FIRST}}$, consisting of three independent functionalities, $F_{\text{setup}}$, $F_{\text{bc}}$, and $F_{\text{construct}}$. In addition, we use two helper functionalities $F_{\text{agg}}$ [21] and $F_{\text{vdf}}$ [36]. We assume the existence of eight tables: $a$Table, $u$Table, $c$Table, $s$Table, $id$Table, $sc$Table, $bc$Table and $txpoolTable$.
that store the internal state of $F_{\text{FIRST}}$ and are accessible at any time by $F_{\text{setup}}$, $F_{\text{bc}}$, and $F_{\text{construct}}$. The uTable is used to store transaction specific information for users, aTable stores the aggregated signatures of verifiers, and idTable stores identifiers and keys of users. The scTable stores the deployed smart contract address and code, bcTable stores the generated transactions, and txpoolTable stores the current transaction pool.

We need to prove that any attack on the real-world protocols–Protocols 1-6–can be simulated by the ideal world functionality $F_{\text{FIRST}}$ as well. We describe our ideal functionalities in Figures 3, 5. We now prove the following theorem.

**Theorem 1:** Let $F_{\text{FIRST}}$ be an ideal functionality for FIRST. Let $\mathcal{A}$ be a probabilistic polynomial-time (PPT) adversary for FIRST, and let $\mathcal{S}$ be an ideal-world PPT simulator for $F_{\text{FIRST}}$. FIRST UC-realizes $F_{\text{FIRST}}$ for any PPT distinguishing environment $\mathcal{Z}$.

To this end, we need to prove that no balanced PPT environment $\mathcal{Z}$ (which is malicious and models anything external to the protocol execution) can distinguish between the execution of the real-world protocols in FIRST, and the execution of the ideal-world protocols in $F_{\text{FIRST}}$. Let us assume the real-world adversary is denoted by $\mathcal{A}$, and the ideal-world adversary is denoted by $\mathcal{S}$. We need to show that $\mathcal{S}$, by interacting with $F_{\text{FIRST}}$ can simulate the actions of the real-world protocol, in sequence, including being able to produce the exact same outputs and same messages being posted on the blockchain. Let us assume that all communication between all parties takes place via secure and authenticated channels (see [25] for a formal description of such channels).

We first note that if a party is corrupted, it comes under the control of $\mathcal{Z}$ and need not be simulated. Hence, $\mathcal{S}$ only needs to accurately simulate the actions of honest parties in the ideal world. For a complete run of the protocol, we analyze the various corruption cases, and discuss how $\mathcal{S}$ can simulate the actions of the honest parties. $\mathcal{A}$ can corrupt any user at any point in time by sending a message “corrupt” to them. Once an entity is corrupted, all their information is sent to $\mathcal{A}$ and all further communication to and from the corrupted party is routed through $\mathcal{A}$. We present Parts 1 and 2 of the proof here and provide Part 3 in Appendix A.

**Proof 1:** To make the presentation clear, for each corruption case, through a complete run of the protocol, we discuss the two worlds separately, and show that $\mathcal{Z}$’s view will be the same.

**Part 1:** Let us first consider the system and parameter setup described in Protocols 1 and 2.

1) **Case 0: All verifiers are honest:**

a) **Real-world:** In the real-world (Protocols 1, 2), the $DAC$ generates a smart contract and deploys it on the BC. The $n$ verifiers will generate their key-pairs, $(pk_i, sk_i)$, $i \in [1..n]$. $\mathcal{Z}$ sees the SC and each verifier’s $pk$. $DAC$ will pick a $T$, and all verifiers will individually compute $N$. All verifiers will then generate the group $\mathcal{G}$. Note that since all verifiers are honest, $\mathcal{Z}$ does not get to see their internal state, and secret keys. The view of $\mathcal{Z}$ will be $(SC, pp = (\mathcal{G}, T), pk_1, \ldots, pk_n, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, k)$, where $k$ is the security parameter.

b) **Ideal-world:** $\mathcal{S}$ picks a security parameter $k$, $T \leftarrow \{0, 1\}^k$, and sends $(txid, T)$, $(\text{compute}, s_i, \text{vid})$ to $F_{\text{setup}}$, where $s_i \leftarrow \mathbb{P}$, and vid is a randomly generated identifier. $\mathcal{S}$ will send the latter tuple $n$ times to $F_{\text{setup}}$ (each being unique) to simulate the $n$ verifiers. In response, $\mathcal{S}$ will receive $(\text{Init}, T, s_i)$ from $F_{\text{setup}}$. $\mathcal{S}$ calls $F_{\text{bc}}$ with (deploy, $SC.id$, code). $\mathcal{Z}$ sends $getData()$
Functionality $F_{bc}$

Smart contract deployment: $F_{bc}$ on receiving (deploy, $SC.id$, code) from any node stores the tuple $(SC.id$, code) in an $scTable$. $scTable$ stores the smart contract ID and its corresponding code for later retrieval and execution.

Transaction request handling: $F_{bc}$ on receiving (invoke, $tx$) from a user $u$ stores the $tx$ in $bcTable$. If the $tx$ is invoking a smart contract $SC.id$, then $F_{bc}$ retrieves the tuple $(SC.id$, code) from $scTable$. $F_{bc}$ executes code with the given $tx$ and the output transaction $tx'$ is generated and added to $txpoolTable$, and also sent back to user $u$ and $S$. After $t_{BC}$ time, which is a system parameter, parameter, the $tx$ and $tx'$ are moved from $txpoolTable$ to $bcTable$.

BC data request handling: $F_{bc}$ on receiving request get_data() from a user $u$ retrieves all data tuples from $bcTable$, $txpoolTable$, and $scTable$, and send to $u$ and $S$.

BC block num request handling: $F_{bc}$ on receiving request get_block_num() from a user $u$ calculates the total number of data tuples in $bcTable$ and $scTable$ as $num_{tx}$. Then $[num_{tx}/block_{qty}]$ is returned to $u$ and $S$. $block_{qty}$ is a system parameter and signifies the number of transactions in a given block.

Fig. 5. Ideal functionality for blockchain.

$F_{bc}$ to $F_{bc}$ to get a copy of $SC$ (also including all contents of the blockchain). $S$ makes $n$ calls to $F_{setup}$, (KeyGen, $vid_i$), $i \in [1..n]$. $F_{setup}$ returns (VerificationKey, $vid_i$, $pk_i$) to $S$. $S$ generates a random $G$, and sets $pp = (G,T)$. Next, $S$ needs to simulate the signatures. It calls $F_{setup}$ with (Sign, $vid_i$, $pp$), who returns ($Signature, vid_i, pp, \sigma_i$), $i \in [1..n]$. $S$ outputs $(pp = (G,T), pk_1, \ldots, pk_n, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, k)$. Thus the view of $Z$ will be the same as the real-world.

The view of $Z$ will be $(SC, pp = (G,T), pk_1, \ldots, pk_n, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, k)$, where $k$ is the security parameter.

2) Case 1: Some verifiers are corrupted:

a) Real-world: Per our adversary model, less than half of the verifiers can be corrupted. $dAC$ deploys the SC on the blockchain, all verifiers will generate their keypairs. In this case, $Z$ will have access to both $pk$ and $sk$ of a corrupted validator. $Z$ will also have access to the corrupted validators’ $D_i = U_i = \emptyset$, and all other validators’ $s_i$, since the corrupted validator(s) will receive all other validators’ shares. If the corrupted validators send an $s_i \notin P$, the honest validators will abort and retry. Eventually, the honest validators will output $N$, and generate the $pp$, and signatures on the $pp$. $dAC$ will deploy the SC on the blockchain as before, and will generate $T$. Let the set of corrupted validators be $\Psi'$, such that $\Psi' \subset \Psi$, and $|\Psi'| < |\Psi|/2$. The view of $Z$ will be $(SC, pp = (G,T), \{pk_i, sk_i, D_i, U_i, s_i\}_{i \in \Psi'}, \{pk_j, s_j\}_{j \in (\Psi \setminus \Psi')}, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, N, k)$.

b) Ideal-world: As in Case 0, $S$ simulates $dAC$’s role and receives from $F_{setup}$ (Init, $T$, $s_i$). $S$ calls $F_{bc}$ with (deploy, $SC.id$, code). $Z$ sends getData() to $F_{bc}$ to get a copy of $SC$ (also including all contents of the blockchain). For the honest verifiers, $\Psi' \subset \Psi$, $S$ creates $pk \leftarrow \{0,1\}^k$. Corrupt verifiers in $\Psi' \subset \Psi$ are handled by $Z$. When $S$ receives an $s_i \notin P$ from a member of $\Psi'$, $S$ uses it in the computation of $N$. If the corrupt verifier sends an $s_i \notin P$, $S$ aborts and restarts the simulation again, forcing $\Psi'$ to restart the protocol. Following the same procedure as in Case 0’s ideal world, $S$ generates a random $G$ s.t., $N = |G|$ and outputs $(SC, pp = (G,T), pk_1, \ldots, pk_n, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, k)$. The view of $Z$, taking into account the additional information $Z$ has from corrupted validators will be $(SC, pp = (G,T), N, \{pk_i, sk_i, D_i, U_i, s_i\}_{i \in \Psi'}, \{pk_j, s_j\}_{j \in (\Psi \setminus \Psi')}, \sigma_{pp_1}, \ldots, \sigma_{pp_n}, N, k)$, which is the same as the real-world.

Part 2: Now, let us consider Alice’s setup as given in Protocol 3.

1) Case 0: Alice and all verifiers are both honest:

a) Real-world: Alice generates $M_A$, hashes it, signs the digest, $h$: $\sigma_A \leftarrow \text{Sign}(h, sk_A)$, and sends $(h, \sigma_A)$ to all members of $\Psi$. $Z$’s view will be $\emptyset$ (since all verifiers are honest, it does not have access to their inputs).

b) Ideal-world: $S$ simulates Alice and will receive (req, aliceID, $h, \sigma_A$) from $F_{construct}$. $S$ does not take any further actions.

2) Case 1: Alice is honest, some verifiers are corrupt:

a) Real-world: Alice generates the $(M_A, h, \sigma_A)$ as in Case 0, and sends $(h, \sigma_A)$ to $\Psi$. If $\Psi'$ is the set of corrupted verifiers, $Z$ will have access to $\Psi'$’s inputs, i.e., $(\{sk_i\}_{i \in \Psi'}, h, \sigma_A)$.

b) Ideal-world: $S$ generates an $h \leftarrow \{0,1\}^k$ (note that verifiers do not know the preimage). $S$ then calls $F_{setup}$ with (Sign, $aid, h$), where $aid$ is chosen at random. $F_{setup}$ returns ($Signature, aid, h, \sigma_{aid}$). $S$ outputs $(h, \sigma_{aid})$.

3) Case 2: Alice is corrupt and all verifiers are honest:

a) Real-world: Alice generates $M_A$ and $\sigma_A$ over $M_A$’s digest. If the signature does not verify, verifiers will eventually return $\bot$. If Alice does not send anything, verifiers will do nothing. In any case, $Z$’s view will be $(M_A = (\text{addr}_A, \text{fname}, \text{addr}_{SC}), h, \sigma_A)$.

b) Ideal-world: $S$ gets $(h, \sigma_A)$ from $Z$. $S$ does not take any further actions.

4) Case 3: Both, Alice and some verifiers are corrupt: Note that this cannot be locally handled by $Z$, as one might expect, since some verifiers are still honest.

a) Real-world: Alice’s actions will be the same as in Case 2’s real world. $Z$’s view will be
**Functionality $F_{vdf}^\eta$**

The functionality is parametrized by a computation rate $\gamma > 0$. Let $VDF: \{0, 1\}^\times N \rightarrow \{0, 1\}^\nu$ be a global random oracle each oracle instance has access to. The oracle also has access to the global clock clock. Let $Q := \emptyset$ be the (initially empty) query log. All the returned values are also forwarded to $S$.

On input $(\text{start}, t)$:
- Update $Q \leftarrow Q \cup (x, \text{clock}())$

On input $(\text{output}, t)$ at time $t_o = \text{clock}()$:
- Let $t_s := \min(t, t) \in Q$, return 𝒩 if there is no such $t_s$;
- Let $s := (t_o - t_s) \cdot \gamma$; /* the strength of the resulting proof */
- Let $p := VDF(x, s)$;
- Return $(s, p)$.

On input $(\text{verify}, x, p)$:
- If $VDF(x, s) = p$ then return accept, else return reject.

On input $(\text{extend}, x, p, s)$:
- If $VDF(x, s) \neq p$ return 𝒩;
- Else update $Q \leftarrow Q \cup (x, \text{clock}() - s \gamma)$.

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$(M_A, h, \sigma_A, \{sk_i\}_{i \in V'})$, where $V'$ is the set of corrupted verifiers.

b) **Ideal world**: $S$ gets $(h, \sigma_A)$ from $E$. $S$ does not take any further actions.

For Part 3 of the proof, please refer to Appendix A

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VI. Evaluation

We evaluate FIRST by analyzing the relationship between miner tips paid and corresponding wait times for the transactions in the mempool. We show the recommended miner tip as a percentage of the corresponding base block fee for different values of $V$ delays. The recommended miner tip is calculated to ensure that the transactions submitted during a given time period are confirmed on the blockchain within $t_2$ time with a high likelihood. All the experiments were carried out on a machine with an Apple M1 Max chip, 32 GB RAM, 1 TB HDD, running macOS Monterey version 12.1.

In the real-world application of FIRST to get the most accurate current transaction wait times in the mempool ($t_2$), we need to run multiple Ethereum nodes distributed geographically across the world and connect them to the majority of peers in the Ethereum network. This would ensure that the application gets the most updated information on the current mempool, which is needed to calculate accurate timestamps of transactions as soon as they hit the mempool. Then FIRST calculates $t_2$ for the corresponding transactions as soon as they are confirmed on the $BC$.

Given the difficulty of requisitioning several Ethereum nodes, we created a tool that uses the Web3.py library to interact with a full Ethereum node provided by Infura [4]. First, we gathered information about transactions such as block base fees, paid miners tips, and gas prices between blocks 13163075 and 13163571, a total of 37672 Type-2 (EIP-1559) transactions. Then, we use Etherscan [5] block explorer to collect confirmation times of the previous transactions.

**Fig. 6.** Ideal functionality for verifiable delay function [36].

**Fig. 7.** Number of transactions between blocks 13163075 and 13163571 that waited longer than the VDF delay time (Y-axis) while paying the corresponding miner tip (X-axis). Miner tip values are represented as a percentage of the base block fee (X-axis). Markers represent the corresponding VDF evaluation times in seconds.

Figure 7 shows the influence of miner tip on the transaction wait time ($t_2$) and depicts the number of transactions during our observation period that would have been frontrun for different delay values for VDF $V$. For example, if $V$ in FIRST was set to 2000 seconds (represented in orange in Figure 7), only 205 out of 37672 transactions that paid at least 20% of base block fee as miner tip, would have been vulnerable to frontrunning attack during the given time period, making the probability of those transactions getting frontrun $\approx 0.0054$. Whereas, if the users paid 10% of base block fee as miner tip, the probability of getting frontrun would be $\approx 0.0057$.

However, interestingly, the effect of miner tip on the probability of frontrunning decreases for values of miner tips greater than 20% of base block fee—all the curves in Figure 7 flatline after 20%. For the given observation period, FIRST would recommend the miner tip value to be at least 20% of the base block fee and the value of $V$ would be set according to the desired probability and the appetite for the transaction delays in the system. As the value $V$ is increased, the probability to get frontrun decreases, but the increase in $V$ also increases the waiting time (delay corresponding to $V$) for valid users after which they can submit transactions to the mempool.

Let $i$ be the index of transactions ($tx_i$) within the given epoch ($\epsilon$) where $\epsilon_{tip}$ and $\epsilon_{contin}$ represents the miner tip and confirmation time of $tx_i$, respectively. Then, FIRST computes the probability of a transaction getting frontrun using Equation 1.

$$\Pr(t_x \in \epsilon_{run}) = \sum_{i=0}^{T_x} \left[ \epsilon_{tip} \geq t_x \epsilon_{contin} \geq V_x \right] / N$$ (1)
where \( tip_e \) is FIRST recommended tip; \( V_e \) is the \( t_1 \) value for epoch; \( T_{xe} \) is the number of transactions within the given epoch; \( \llbracket \cdot \rrbracket \) indicates Iverson brackets such that \( \llbracket i_{tip} \geq tip_e \rrbracket \) is true if \( t_{tip} \geq tip_e \); and \( N \) is the total number of transactions in epoch \( e \).

The naïve way to prevent frontrunning using FIRST is by assigning a moderately large value for the VDF delay. However, setting a large VDF delay is impractical for most applications as it can lead to scalability and efficiency concerns of the dApp. To demonstrate how much the time taken to evaluate \( V \) can affect the probability of a transaction getting frontrun, we plot \( 8(a) \) and \( 8(b) \).

The X-axis on both figures represents the paid miner tip in percent of the block base fee ranging from 0% to 25%. In figure \( 8(a) \), the Y-axis represents the evaluation time of \( V \) in seconds for a transaction from 0 to 300 seconds. The Y-axis in figure \( 8(b) \) represents the \( V \) evaluation time in seconds for a transaction from 300 to 1000 seconds. Finally, the Z-axis on both figures represents the percentage of transactions that could still be waiting in the pending pool after a delay of \( V \). Reducing the value of \( V \) comes with its own risk. Figure \( 8(a) \) represents \( V \) that is less compared to Figure \( 8(b) \) therefore the corresponding transactions have a much greater chance of getting frontrun. For example, if the \( V \) in FIRST were set to 100 seconds while requiring users to pay 20% of the block base fee as miner tip, transactions would have a 19% chance of getting frontrun (see Figure \( 8(a) \)) meanwhile the chances reduce to 1.8% for 500 seconds \( V \) (see Figure \( 8(b) \)).

From this we conclude that a VDF delay of \( \approx 500 \) seconds is a reasonable delay to set for transactions to join the mempool and significantly reduces the chances of frontrunning. For applications where frontrunning is even more deleterious, the VDF delay could be increased even further. Of course, this is a function of the data obtained for the epoch window, and any system that uses FIRST will use data of the current epoch to make stipulations on miner tip and \( V \) delay.

VII. Conclusion

In this paper, we proposed a decentralized framework, FIRST for mitigating frontrunning attacks on EVM-based smart contracts without modifying the consensus layer of blockchain. Our framework does not require a trusted setup and can be adopted seamlessly. FIRST is not an application-specific solution and hence is more accessible for implementation in various dApps. We experimentally show that with FIRST the probability of preventing frontrunning attacks is very high. We also proved FIRST’s security using the UC framework.

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Fig. 8. Representation of the percentage of transactions between blocks 13163075 and 13163571 that waited longer than the VDF delay time while paying the corresponding miner tip. Miner tip values are represented as a percentage of the base block fee.

| VDF delay (s) | Miner tip as % of base fee | % chance of being frontrunnable |
|--------------|---------------------------|-------------------------------|
| 300          | 0.00                      | 0.00                          |
| 400          | 0.05                      | 0.05                          |
| 500          | 0.10                      | 0.10                          |
| 600          | 0.15                      | 0.15                          |
| 700          | 0.20                      | 0.20                          |
| 800          | 0.25                      | 0.25                          |
| 900          | 0.30                      | 0.30                          |
| 1000         | 0.35                      | 0.35                          |

(a) VDF from 0s to 300s

(b) VDF from 300s to 1000s

APPENDIX

A. Proof of Theorem 1 (contd.)

Part 3: Now let us consider Alice, C, and verifiers’ interaction as given in Protocol 4. In the following cases, whenever some verifiers ($V'$) are corrupt, $|V'| < |V|/2$, hence, a majority of verifiers are still honest.

1) Case 0: Alice, C and all verifiers are honest:

a) Real-world: On receiving a new VDF request from Alice, C picks an $l \leftarrow \mathbb{P}$, all verifiers send $(M_i, \sigma_{V_i})$ to C. C will verify the signatures, and will return the aggregate signature $\sigma_{agg}$ to Alice, who will then compute the VDF proof ($\pi, y$). This proof is sent to the V who will verify it before submitting their signatures to the C for aggregation. The aggregated signature is sent to Alice by the C who verifies it, and eventually submits $tx_A$ to the SC. Z’s view will only be $\{pk_i\}_{i \in V}$ initially, and it will see $tx_A$ only when it hits the transaction pool.

b) Ideal-world: S creates $M_A$, creates hash $h_A = H(M_A)$ and calls $F_{setup}$ and gets $\sigma_A$. It then forwards $(req, h_A, \sigma_A)$ to $F_{construct}$’s User request function and
receives “success” and (req, aliceID, h_A, σ_A). S generates l on behalf of the C and sends (l, aliceID) to $\mathcal{F}_{\text{construct}}$ using Coordinator request function and it receives (valid, l, h_A, σ_A, pk_A). For each $V_i$, S signs the $M_i = (l, h_A, V_i, \text{block}_\text{curr})$ using $\mathcal{F}_{\text{setup}}$ and $\text{block}_\text{curr}$ is retrieved by calling $\mathcal{F}_{\text{bc}}$. S sends $(V_i, M_i, \sigma_M)$ to $\mathcal{F}_{\text{construct}}$ using Coordinator response function call. S then simulates the aggregation step of C by calling $\mathcal{F}_{\text{setup}}$ and receives $\sigma_{agg}$. S calls $\mathcal{F}_{\text{construct}}$ User response to send $\sigma_{agg}$ to Alice. S calls $\mathcal{F}_{\text{vdf}}$ (start, l) function to start V delay. After V delay time, S calls (output, l) function in $\mathcal{F}_{\text{vdf}}$ to generate the V proof which returns $(s, p)$. S then verifies the proof calling (verify, l, p, s) on behalf of each $V_i$ and generates $M'_i$ and $\sigma'_V$ in a straightforward way. S aggregates all the signatures from V using $\mathcal{F}_{\text{setup}}$ and generates $\sigma'_\text{agg}$ and forwarded to Alice using $\mathcal{F}_{\text{construct}}$’s User response function. S creates $tx_A = (\sigma_A, M'_i, pk_A)$, where $M'_i = (M_A, M_{agg}, M'_{agg})$, $M_{agg} = (\sigma_{agg}, M_1, \ldots, M_n, pk_V, \ldots, pk_V)$ and $M'_{agg} = (\sigma'_{agg}, M'_1, \ldots, M'_n, pk_V, \ldots, pk_V)$. S sends $tx_A$ to $\mathcal{F}_{\text{bc}}$ calling smart contract with SC.id. The code associated with SC.id checks that the $\sigma_{agg}$ and $\sigma'_\text{agg}$ are signed by majority V, $\text{block}_\text{curr}$ signed in $\sigma_{agg}$ is valid, and that the $h_A = H(M_A)$. If any of the checks fail, the smart contract returns $\perp$, else outputs a valid transaction $tx'$.  

2) Case 1: Alice and the C are honest, and some verifiers are corrupt: 

a) Real-world: Honest C generates $l \leftarrow S \mathbb{P}$. Corrupted verifiers can either: 1) deliberately fail Alice’s signature verification (Step 4 of Protocol 4), or 2) create a bogus signature over a possibly incorrect message (Steps 5, 6 of Protocol 4). In both cases, the corrupt verifiers in V’ will not contribute towards $\sigma_{agg}$, since the C needs a majority to abort the process and return $\perp$ (Step 18 of Protocol 4). As long as we have a honest majority in V, honest C will create and return $\sigma_{agg}$ to Alice, who will then evaluate the VDF and generate $(\pi, y)$, and send $(\pi, y)$ to all members of V. Similarly, during the generation of $\sigma'_{agg}$, C can ignore the inputs from V’. C sends $(M_{agg}, \text{block}_\text{curr})$ to Alice. Honest Alice eventually outputs $tx_A$. Z’s view will be $(l, \sigma_A, h, pk_A, \pi, y, tx_A, \text{block}_\text{curr}, pp)$. 

b) Ideal-world: S needs to simulate the actions of C and Alice to Z. S creates $M_A$, creates hash $h_A = H(M_A)$ and calls $\mathcal{F}_{\text{setup}}$ and gets $\sigma_A$. It then forwards (req, h_A, σ_A) to $\mathcal{F}_{\text{construct}}$ and receives “success” and (req, aliceID, h_A, σ_A). S picks an l $\leftarrow S \mathbb{P}$, calls Coordinator request function in $\mathcal{F}_{\text{construct}}$, and sends l to Z. If members of V’ return $\perp$ for Alice’s signature verification or return bogus signatures from V’ (S can check these using Verify function call in $\mathcal{F}_{\text{setup}}$). S ignores them, since $|V'| < |V|/2$. S then calls $\mathcal{F}_{\text{setup}}$’s Aggregate Signature function with (Aggregate, $M_1, \ldots, M_n, pk_1, \ldots, pk_n, \sigma_{V_1}, \ldots, \sigma_{V_n}$) to aggregate all honest majority V’s signatures. $\mathcal{F}_{\text{setup}}$ returns $\sigma_{agg}$ to S. S then calls $\mathcal{F}_{\text{vdf}}$ to generate V proof $(s, p)$. S sends $(l, p, s)$ to Z. Members of V’ will send $(\sigma'_{agg})_{i \in V'}$ to S. S will simulate signatures for members of (V – V’) in a straightforward way and calls $\mathcal{F}_{\text{bc}}$’s getBlockNum() function to get the $\text{block}_\text{curr}$ value. S generates the $\sigma'_{agg}$ similar to the previous $\sigma_{agg}$, by taking the majority signatures. Since members of V’ will be in a minority, even if they return $\perp$, it will not affect the creation of $\sigma'_{agg}$. Finally S generates Alice’s signature over $M'$, creates $tx_A$ and submits it to $\mathcal{F}_{\text{bc}}$. The view of Z, who controls V’ will be $(l, \sigma_A, h_A, pk_A, p, s, tx_A, \text{block}_\text{curr}, pp)$. 

3) Case 2: Alice and all verifiers are honest, and the C is corrupt: 

a) Real-world: On receiving VDF request from Alice, corrupt C could either pick l $\leftarrow S \mathbb{P}$ which has already been assigned to another user or an l $\notin \mathbb{P}$, in this case the honest members of V identifying the C as corrupt, will not generate an accept message which can be aggregated by the C and the C cannot proceed. If the C had picked l $\leftarrow S \mathbb{P}$ correctly, on receiving the accept messages and signatures from V, C can still choose to create $\sigma_{agg}$ that would fail verification, in this case Alice’s checks would fail, identifying the C as corrupt and she would not proceed further with the protocol. If the C had created $\sigma_{agg}$ correctly, Alice would generate the V proof and send it for verification to all V. Upon verification, V send their replies to C for aggregation. Like the previous aggregation step, if the C creates a corrupt message in this step, Alice would be able to identify the C as malicious. If the C sends Alice a valid $\sigma'_{agg}$. Alice eventually outputs $tx_A$. Z’s view will be $(l, \sigma_A, h, pk_A, \pi, y, tx_A, \text{block}_\text{curr}, pp, \sigma_{V_i}, M_i, \sigma'_{V_i}, M'_i)$ for i $\in [1, \ldots, |V|]$. 

b) Ideal-world: S needs to simulate the actions of V and Alice to Z. Z picks an l $\leftarrow S \mathbb{P}$, and sends to S. S sends (l, aliceID) to $\mathcal{F}_{\text{construct}}$ and if it received (used, l) then l has been used before and S would return $\perp$ stopping the protocol. If Z picked a valid l, S simulates the operations of the honest V. S sends each V’s accept message to Z who creates an $\sigma_{agg}$ by calling $\mathcal{F}_{\text{setup}}$’s Aggregate Signature function call. S verifies $\sigma_{agg}$ before proceeding, else return $\perp$. This is sent to S who simulates Alice’s operation of computing the VDF, before simulating the members of V’s response accepting Alice’s VDF proof computation, and forwarding $(M'_1, \ldots, M'_n, pk_V, \ldots, pk_V, \sigma_{V_1}, \ldots, \sigma_{V_n})$ to Z. If Z does not aggregate the signatures from

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2We note that Z always has access to all the BC data: In the real world Z can query a full node, run a light node, etc. In the ideal world, Z can send a getData() request to $\mathcal{F}_{bc}$. Without loss of generality, we say the Z’s view includes blockcurr because a given blockcurr is only tied to the current request and signifies the current block number on the BC when the VDF request was received by the verifiers.
\( V \) correctly, and sends corrupted/malformed \( \sigma'_{agg} \) to \( S \), the signature verification by \( S \) would fail. Finally \( S \) simulates Alice’s signature over \( tx_A \) and submits to \( F_{bc} \). The view of \( Z \), who controls \( C \) will be \((l, \sigma_A, h, pk_A, p, s, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma_{V_i'}, M'_i)\) for \( i \in [1, \ldots |V|] \).

4) Case 3: Alice is honest, and the \( C \) and some verifiers are corrupt:

a) **Real-world**: On receiving VDF request from Alice, corrupt \( C \) could pick \( l \leftarrow s \mathbb{P} \) which has already been assigned to another user or an \( l \notin \mathbb{P} \), in this case the honest majority of \( V - V' \) would not generate a signature for \( C \) identifying the \( C \). The corrupt \( V' \) could choose to generate accept messages and send them to \( C \). The \( C \) can create \( \sigma_{agg} \) using the corrupt \( V' \)'s accept messages but this would fail verification on when Alice receives \( \sigma_{agg} \) as \(|V'| < |V|/2 \). If the \( C \) had picked \( l \leftarrow s \mathbb{P} \) correctly, on receiving the accept messages and signatures from \( V \), \( C \) can still choose to create \( \sigma_{agg} \) that would fail verification, in this case Alice’s checks would fail, identifying the \( C \) as corrupt and she would not proceed further with the protocol. If the \( C \) had created \( \sigma_{agg} \) correctly, Alice would generate the \( V \) proof and send it for verification to all \( V \). Upon verification, honest members \( V - V' \), send their replies to \( C \) for aggregation. The dishonest members \( V' \) could either choose to not send a valid “accept” message for aggregation or choose to send a corrupt message for aggregation. The \( C \) could choose to create a corrupt message by aggregating less than \(|V|/2\) messages or create a junk \( \sigma'_{agg} \). Like the previous aggregation step, if the \( C \) creates a corrupt \( \sigma'_{agg} \) in this step, Alice would be able to identify the \( C \) as malicious because of the checks she does on receiving the messages from \( C \). If the \( C \) sends Alice a valid \( \sigma'_{agg} \), Alice eventually outputs \( tx_A \). \( Z \)'s view will be \((l, \sigma_A, h, pk_A, \pi, y, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma_{V_i'}, M'_i)\) for \( i \in [1, \ldots |V|] \).

b) **Ideal-world**: \( S \) needs to simulate the actions of \( V - V' \) and Alice to \( Z \). \( Z \) picks an \( l \leftarrow s \mathbb{P} \), and sends to \( S \). If \( l \) has been used before, then \( S \) would just return \( \perp \) on behalf of honest \( V \). \( Z \) can still choose to create a \( \sigma_{agg} \) with \( V' \) accept messages but when this is sent to \( S \) it would fail verification since \(|V'| < |V|/2 \). If \( Z \) picked a valid \( l \), \( S \) simulates operations of the honest verifiers and sends each \( V_i \in \{V - V'\} \) accept message to \( Z \) who creates an \( \sigma_{agg} \). This is sent to \( S \) who computes the \( V \) proof and sends to \( Z \). \( S \) also send accept messages from honest \( V \) to \( Z \) for \( C \)'s operations. Like the previous aggregation step, \( Z \) could choose to create corrupt \( \sigma_{agg} \) but this would fail verification when sent to \( S \) and the protocol would not proceed further. To proceed further, \( Z \) has to create a valid \( \sigma'_{agg} \) with the accept messages from \( > |V|/2 \) members of \( V \). Finally \( S \) simulates Alice’s signature over \((\sigma'_{agg}, M_A, M'_1, \ldots, M'_n, pk_1, \ldots, pk_n)\), creates \( tx_A \) and submits to \( F_{bc} \). The view of \( Z \), who controls \( C \) and \( V \) will be \((l, \sigma_A, h, pk_A, p, s, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma_{V_i'}, M'_i)\) for \( i \in [1, \ldots |V|] \).

5) Case 4: Alice is corrupt, and the \( C \) and all verifiers are honest:

a) **Real-world**: Alice sends a \( V \) request to \( C \) and \( V \). A corrupt Alice could choose to create a corrupt \( \sigma_A \) but this would fail verification at the \( C \) and \( V \) and the protocol would stop. To proceed Alice has to compute valid \((\sigma_A, h)\), \( C \) and \( V \) would proceed as normal and return a \( \sigma_{agg} \) to Alice. Alice could choose to send a corrupt \( V \) for verification to \( V \). Since verification would fail there would be no \( \sigma_{agg} \) generated for Alice so she cannot proceed further. If Alice computes a valid \( V \) proof, \( C \) would return a \( \sigma'_{agg} \) to her and Alice eventually outputs \( tx_A \). In \( tx_A \) Alice could choose to use a different \( M'_i \) but the hash of \( M'_i \) would not match the \( h \) signed in \( \sigma_{agg} \) and would fail verification in the smart contract which checks \( h \) matches \( M_A \), and the \( l \) and \( h \) in \( \sigma'_{agg} \) are tied to \( M_A \). Alice can only pass smart contract verification if she keeps the original \( M_A \) and valid \( \sigma_{agg} \) and \( \sigma'_{agg} \) in \( tx_A \). \( Z \)'s view will be \((l, \sigma_A, h, pk_A, \pi, y, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma_{V_i'}, M'_i)\) for \( i \in [1, \ldots |V|] \).

b) **Ideal-world**: \( S \) needs to simulate the actions of \( V \) and \( C \). \( Z \) picks a \( M_A \) and sends a request to \( C \) with \( h \) hash corresponding to \( M_A \). \( S \) simulates \( C \) and \( V \) by assigning \( l \) to \( h \) and generating a \( \sigma_{agg} \). \( \sigma_{agg} \) is sent to \( Z \) who computes the \( V \) proof. If \( Z \) decides to send a corrupted/malformed proof to \( S \), then it would fail verification and \( S \) would not generate a corresponding \( \sigma_{agg} \). The only way for \( Z \) to proceed is to compute valid \( V \) proof. Upon receiving valid proof \( S \) verifies it and generates \( \sigma'_{agg} \) which is sent to \( Z \). \( Z \) now creates \( tx_A \) and submits to \( F_{bc} \). The code associated with \( SC.id \) verifies \( \sigma'_{agg} \); the hash of \( M_A \) included in \( tx_A \) matches \((h, l, \vdash)\) in \( \sigma_{agg} \), and the \( l \) in previous tuple is same as in \( \sigma'_{agg} \). The code also checks for freshness using the \( block_{curr} \) value. If any of these checks fail verification then the smart contract would not execute in favor of \( Z \) and it would be identified as corrupt. \( Z \)'s view will be \((l, \sigma_A, h, pk_A, \pi, y, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma_{V_i'}, M'_i)\) for \( i \in [1, \ldots |V|] \).

6) Case 5: Alice and some verifiers are corrupt, and the \( C \) is honest:

a) **Real-world**: As in Case 4, if Alice sends corrupt \( \sigma_A \) the \( C \) would fail verification and not proceed further. If the \( \sigma_A \) is valid, the \( C \) picks valid \( l \) and sends to all \( V \). The corrupt minority of \( V \) could choose to not send their signatures or send corrupt signatures which the \( C \) can discard and generate a \( \sigma_{agg} \) from the honest majority in \( V \). Alice on receiving the \( \sigma_{agg} \) can choose
to send an invalid $V$ proof which would not generate accept signatures from the honest majority in $V$, $V'$ could choose to wrongly send accept signatures to $C$ if $V'$ were accepted, but since $|V'| < |V|/2$, $C$ will not generate a $\sigma'_{\text{agg}}$. If Alice computed a valid $V$ proof then she will receive a $\sigma'_{\text{agg}}$ from $C$ and Alice eventually outputs $tx_A$. As described in Case 4, Alice can only pass smart contract verification if she outputs a valid $tx_A$. $Z$'s view will be $(l, \sigma_A, h, pk_A, \pi, y, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma'_{V_i}, M'_i)$ for $i \in [1, \ldots |V|]$.

b) **Ideal-world:** $S$ needs to simulate the actions of $V \rightarrow V'$ and $C$ to $Z$. $Z$ picks a $M_A$ and sends a request to $C$ with hash $h$ corresponding to $M_A$. If $h$ or $\sigma_A$ are invalid then $S$ would not generate $l$ and the protocol would fail. If valid request is received from $Z$, $S$ assigns $l$ to $h$ and sends to $Z$. If $V'$ controlled by $Z$ sends corrupt signatures to $S$, it can just ignore those messages and output a $\sigma_{\text{agg}}$ to $Z$ by simulating the honest majority of $V$'s actions. If $Z$ decides to send corrupt proof to $S$, then it would fail verification and $S$ would not generate a corresponding $\sigma'_{\text{agg}}$. As in previous step, corrupt $V'$ messages corresponding to $V$ proof from $Z$ can be ignored by $S$. The only way for $Z$ to proceed is to compute valid $V$ proof. Upon receiving valid proof $S$ verifies it and generates $\sigma_{\text{agg}}$ which is sent to $Z$. $Z$ now creates $tx_A$ and submits to $F_{bc}$. As described in Case 4, $Z$ can only pass smart contract verification if $tx_A$ contains valid signatures and $M_A$. $Z$'s view will be $(l, \sigma_A, h, pk_A, p, s, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma'_{V_i}, M'_i)$ for $i \in [1, \ldots |V|]$.

7) **Case 6:** Alice and the $C$ are corrupt, and all verifiers are honest:

a) **Real-world:** If Alice sends corrupt $\sigma_A$ to the $C$ and $V$, or if Alice sends a valid request but $C$ chose a corrupt $l$ similar to Case 2, the $V$ will not send accept signatures to $C$ since the request or $l$ will not pass verification. The $C$ can create corrupt $\sigma_{\text{agg}}$ but this would fail verification eventually at the smart contract. If the $\sigma_A$ is valid and the $C$ picks valid $l$, the $V$ will reply with accept messages so $C$ can generate a valid $\sigma_{\text{agg}}$ Alice on receiving the $\sigma_{\text{agg}}$ can choose to send an invalid $V$ proof which would not generate accept signatures from the honest majority $V \rightarrow V'$ and $C$ can compute a valid $\sigma'_{\text{agg}}$. Alice eventually outputs $tx_A$. As described in Case 4, $C$ can only pass smart contract verification if she outputs a valid $tx_A$. $Z$'s view will be $(l, \sigma_A, h, pk_A, \pi, y, tx_A, block_{curr}, pp, \sigma_V, M_i, \sigma'_{V_i}, M'_i)$ for $i \in [1, \ldots |V|]$.

b) **Ideal-world:** $S$ needs to simulate the actions of $V$ to $Z$. $Z$ picks a $M_A$ and sends to $S$, the hash $h$ corresponding to $M_A$, $\sigma_A$, and $l$. If $h$ or $\sigma_A$ are invalid then $S$ would not generate $V$ signatures for $Z$. $Z$ cannot compute valid $\sigma'_{\text{agg}}$, but this would fail verification in the code of the $SC.id$ smart contract. If valid request and $l$ is received from $Z$, $S$ sends $V$ signatures to $Z$ and $Z$ generates $\sigma_{\text{agg}}$. If $Z$ decides to send corrupt proof to $S$, then it would fail verification and $S$ would not generate corresponding accept signatures from $V$ to send to $Z$. Therefore, next stage, the $Z$ can create corrupt $\sigma'_{\text{agg}}$, but this would fail verification eventually at the $SC.id$ smart contract. The only way for $Z$ to proceed is to compute valid $V$ proof. Upon receiving valid proof $S$ verifies it and generates $V$ signatures which are forwarded to $Z$. $Z$ generates a valid $\sigma'_{\text{agg}}$. Creates $tx_A$, and submits to $F_{bc}$. As discussed in Case 4, $Z$ can
output a corrupt $tx_A$ but the verification checks in the smart contract code will fail. Z's view will be $(l, \sigma_A, h, pk_A, p, s, tx_A, block_{curr}, pp, \sigma_{V_i}, M_i, \sigma_{V_i}', M_i')$ for $i \in [1 \ldots |V|]$. 