SigVM: Enabling Event-Driven Execution for Autonomous Smart Contracts

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Abstract
This paper presents SigVM, a novel blockchain virtual machine that supports an event-driven execution model, enabling developers to build autonomous smart contracts. Contracts in SigVM can emit signal events, on which other contracts can listen. Once an event is triggered, corresponding handler functions are automatically executed as signal transactions. We build an end-to-end blockchain platform SigChain and a contract language compiler SigSolid to realize the potential of SigVM. Experimental results show that our benchmark applications can be reimplemented with SigVM in an autonomous way, eliminating the dependency on unreliable mechanisms like off-chain relay servers. The development effort of reimplementing these contracts with SigVM is small, i.e., we modified on average 2.6% of the contract code.

1 Introduction
Blockchain has become a revolutionary technology that powers decentralized ledgers at internet-scale. Ethereum, the second largest blockchain, introduces smart contracts, which further fuel blockchain innovations on real-world applications in various domains, including financial systems, supply chains, and health care. A smart contract is a program operating on the blockchain ledger to encode customized transaction rules. Once deployed, the contract and the encoded rules are then faithfully executed and enforced by all participants of the blockchain platform, eliminating any potential counter-party risks in the future.

Smart contract in Ethereum can generate events, each of which is a developer-defined record of data to log state changes or contract activities that are important to external observers. To implement events, Ethereum Virtual Machine (EVM) [6] puts all generated event data into a dedicated region of the blockchain state called event logs. This region is write-only for smart contracts but can be queried by any external user who runs an Ethereum full node. The original design of the event mechanism in Ethereum is to facilitate the integration of on-chain components and off-chain components in a blockchain-powered application. For example, the transfer function of the popular ERC-20 contract for fungible tokens typically emits a transfer event besides updating the token ledger state in the contract [22]. It expects that a digital wallet application will run an Ethereum full node as its back-end, monitor these events, and update its front-end GUI accordingly to show the token balance to users.

As smart contracts become more and more complicated and inter-dependent, the existing event primitive in Ethereum becomes increasingly inadequate. In many scenarios, the correctness of one smart contract is now dependent on its timely responses to critical events from other smart contracts. For example, in Ethereum, there are oracle contracts [7, 37], which feed off-chain data, such as the digital asset prices, to the blockchain; there are also decentralized finance (DeFi) smart contracts [23, 27, 34], for which the most recent price of a digital asset is critical, e.g., collateral liquidation is required when the asset price drops below a certain threshold. The DeFi contracts therefore have to timely respond to asset price change events from the oracle contracts. Unfortunately, it is impossible to implement such an event-driven execution model in Ethereum. This is because, 1) event logs are write-only for smart contracts and a contract cannot respond to emitted events from other contracts automatically; 2) a smart contract execution can only be triggered (indirectly via function calls by external user transactions.

To this end, many blockchain applications circumvent this problem via off-chain relay servers [11]. A server constantly monitors the blockchain ledger. When a critical event from a source contract (e.g., an oracle contract) occurs, the server will send a poke transaction to a target contract (e.g., a DeFi contract) to drive the contract to respond to the event. However, this adhoc solution has two undesirable consequences. First, it creates a central point of failure that defeats the purpose of encoding transaction rules as smart contracts on blockchain platforms. If the off-chain relay server of the target contract fails, the contract will not properly respond to critical events. Secondly, the blockchain platform may not process the poke transaction timely due to insufficient transaction fees or network congestion. The target contract may undesirably interact with other users before it incorporates the critical updates carried by the poke transaction.

In this paper, we present a novel end-to-end blockchain platform that extends Ethereum to support an event-driven execution model. The core of our framework is SigVM, a
novel virtual machine that extends EVM with new opcodes to introduce signal events, a special kind of events that enables a new way for multiple contracts to interact with each other. To realize SigVM, we develop SigSolid, a modified version of Solidity programming language that can utilize new opcodes in SigVM, and SigChain, a prototype blockchain platform that implements SigVM.

In SigVM, contracts can emit signal events, on which other contracts can listen. When a contract listens to a signal event, it binds a function as its handler. When the event is triggered, the handler function will be automatically executed. This new signal event mechanism enables autonomous smart contracts to timely respond to critical events, eliminating the reliance on off-chain relay servers.

One challenge SigVM faces is how to integrate the execution of handler functions with the existing smart contract framework. In SigVM, a transaction from a user to a smart contract can emit signal events and it may therefore trigger multiple handler functions. If we naively implement the execution of these functions synchronously as function calls, the cascading execution process may cause the transaction to exceed the block gas limit. Furthermore, a user who triggers a signal event will have to pay the gas cost for the execution of all of the associated handler functions. This is undesirable, because the user triggering the event is often the service provider while the contracts containing the handler functions are service users. For example, an oracle maintainer sends a transaction to trigger an event to update the price of a digital asset in an oracle contract and this event is listened by many other contracts to react upon the price update. It is counter-intuitive to ask the oracle maintainer to pay for the execution cost of the contracts using the oracle service.

To address this challenge, SigVM executes handler functions asynchronously as signal transactions, a special kind of transactions generated by the SigVM execution engine when a signal event is emitted. These special transactions will be packed along with regular transactions in blocks. This asynchronous execution mechanism enables SigVM to circumvent the block gas limit issue. Because SigVM executes signal transactions asynchronously, miners can pack them in separate blocks. This mechanism also enables SigVM to charge the transaction fee of each signal transaction differently to introduce proper incentives. The smart contract that binds a handler function pays the transaction fee of the corresponding signal transaction in SigVM. The transaction fee will be slightly higher than the average of normal transactions in the same block\(^1\), which incentivizes miners to prioritize their execution.

Another challenge SigVM faces is the possibility that a smart contract interacts with other users undesirably before it can integrate critical state updates in an asynchronous signal transactions. Note that the centralized off-chain relay server solution faces the same challenge. The typical solution of paying high transaction fee does not eliminate this risk, because powerful miners can selectively pack hijacking transactions ahead of the signal/poking transactions (i.e., hijacking manipulations).

SigVM addresses this challenge with a novel contract event lock mechanism. If a contract has any pending signal transactions, SigVM allows to lock the contract. Any normal transactions interacting with a locked contract become no-ops. The miner who packs the transaction will receive no transaction fees and the transaction will be recycled back to pending transaction pools. It may be packed again in the future when the pending signal transactions are processed and the contract is unlocked. This mechanism effectively stops any hijacking transactions from exploiting a contract in the middle of signal event handling.

We evaluate SigVM by reimplementing 23 smart contracts from 13 popular decentralized applications that are critical to the economic ecosystem of Ethereum. Our results show that the signal event mechanism in SigVM efficiently replaces off-chain relay servers and reduces the applications’ vulnerability to hijacking manipulations. Our results also show that the SigSolid language powered by SigVM is practical to use. The development effort of migrating these contracts to SigVM is small, i.e., we modified on average 2.6% of the contract code.

In summary, this paper makes the following contributions:

- **SigVM**: a novel blockchain virtual machine that extends EVM with an event-driven execution model to enable autonomous smart contracts (§3-4).
- **Signal transaction and contract event locking**: a novel asynchronous signal transaction design to address the series of challenges of integrating SigVM with a blockchain platform (§3-4). A novel contract event locking mechanism to prevent hijacking manipulation against signal transactions (§3-4).
- **Implementation**: an end-to-end prototype blockchain platform powered by SigVM (§4).
- **Experimental evaluation**: an evaluation using 23 smart contracts from 13 popular distributed applications (§5). Our results show that SigVM is practical and it enables the development of significantly more autonomous and robust contracts.

Aside from the aforementioned technical sections, we present a motivating example of developing smart contracts in SigVM in Section 2, and discuss related work and conclusions in Sections 6 and 7.

2 Example

Listing 1 presents the simplified code snippet of parts of MakerDAO to illustrate building autonomous contracts with SigVM. Lines preceded with ‘-’ and ‘+’ are changes we made

\(^1\)The average value is computed by miners during transactions packing.
to the original implementation to adopt SigSolid. MakerDAO is a decentralized finance protocol, which provides collateral-backed stablecoin called Dai [23]. It follows the Maker Protocol to keep Dai softly pegged to USD by a fixed ratio. This is accomplished by backing Dai with crypto assets based on the market prices. In order to generate Dai, users send collaterals to the Collateralized Debt Position smart contract to create a vault. To meet the long-term solvency of the system, the ratio between the deposit to the vault and the Dai the vault owner obtains must be greater than a threshold decided by a MakerDAO governance committee at all time. Once the ratio drops below the set threshold, the Maker Protocol forces the collateral to be liquidated.

```
Listing 1. Simplied Code Snippet of MakerDAO

MakerDAO components: There are four contracts in Listing 1, Median, OSM, Spotter and Vat. A Median contract is an oracle that maintains the spot price of one digital asset type. A group of authorized maintainers send batched transactions via the feed function to report the real world spot price (line 9). The function computes the median of the reported price as the oracle spot price. The latest oracle price can be accessed via the peek function (line 4).

OSM is the acronym of Oracle Security Module. OSM delays the price obtained from Median by an hour. Based on the MakerDAO documentation, this is to allow an emergency committee to supervise the oracle prices. In case of an emergency, the committee may pause the price feed and the MakerDAO system via administrative interfaces (omitted in the code snippet). Spotter is a contract that collects spot prices from multiple OSM contracts for different kinds of digital asset collaterals.

Vat is the core vault engine which stores and tracks all the Dai and collaterals. Spotter eventually invokes Vat to file the price change (line 49). Note that all other modules rely on Vat to implement the desired finance service for users. For example, when a user joins the MakerDAO protocol to mint Dai with Ethereum or other digital assets as collaterals, MakerDAO calls the function move (line 64) in Vat to update the vault. When a user submits a transaction to liquidate a position (i.e., sell the collaterals), MakerDAO calls the function grab (line 62) to update.

Off-chain relay server poking: It is not feasible to implement this price information propagation fully on chain via function calls because the oracle maintainers and the MakerDAO administrators are different groups of people. The asset price oracle service might be used by many different DeFi contracts and the oracle maintainers are not willing to pay excess transaction fee cost for the executions of MakerDAO. Also, OSM needs to introduce one hour delay to the price feed, which is not feasible to implement on-chain in Ethereum.

MakerDAO therefore relies on off-chain relay servers to drive the price information flow. Fig. 1 illustrates the interaction between off-chain servers and the contracts. The off-chain relay servers are expected to call poke in OSM (line 28)
Security risks and loss: The off-chain relay server design has significant security risks. Knowing a reasonably accurate price for digital assets is critical for the security of MakerDAO. If the off-chain relay server fails or the network is congested so that poke transactions are not processed in time, the core MakerDAO engine would operate with outdated price information and make incorrect liquidation decisions.

On March 12, 2020, the price of crypto currencies dropped significantly. Meanwhile, the Ethereum network became overwhelmed with too many transactions. Critical poke transactions containing price information were delayed, causing the core MakerDAO engine to operate with stale prices for hours. As a result, many MakerDAO users had their positions liquidated while getting much less collateral back comparing to the amount they should have retained with the correct prices. Even after the prices returned to the required level, the collateral was auctioned because its price oracle failed to update price feed. The root cause of this event is the market crash and the network congestion, but the off-chain relay servers design exacerbated the delay during the market collapse. The total financial loss of MakerDAO users during this event is approximately $4.5M [24].

Implementation of Median, OSM, and Vat in SigSolid: To implement the desired price information flow, we define a signal event in Median (line 6) and a signal event in OSM (line 25). Instead of passively waiting for other contracts to call poke, Median emits a price feed Pr event whenever there is a valid batch of oracle price updates (line 14). This event is automatically handled by the function in OSM at line 30, which in turn emits a delayed price feed DPr event with a delay of one hour. The emitted DPr event will be eventually handled by the prUpdt function in Vat (line 56) to file the new price information. This function replaces the original poke in Spotter. The contract Spotter is merged into Vat.

Event-driven execution with SigVM: Once deployed on SigChain, the modified code in Listing 1 will enable the desirable information to flow fully on-chain. When the oracle maintainers send a transaction to invoke the function fee in Median (line 9) to provide a new price. The contract will emit the Pr event (line 15) with the calculated mean asset price as the event data. Because OSM registered the function prUpdt (line 30) as the handler for Pr event, SigVM will generate a signal transaction to invoke prUpdt with the corresponding event data as the parameter. SigVM will execute the generated signal transaction automatically and asynchronously. The transaction will cascadingly emit the DPr signal event (lines 37) with the asset price and an address id (which represents the digital asset type). This event will be emitted with a delay of one hour. Because Vat registers the function prUpdt to handle the DPr event from OSM contracts, after one hour delay, SigVM will generate and execute a signal transaction to invoke prUpdt with the asset price and the asset address.
(prog) ::= program (inst)∗
(inst) ::= (EVMinst) | (SIGinst)
(SIGinst) ::= createsignal sn | deletesignal sn | detach (m, s) | bind (m, s, gr, blk, s-r, s-m) | emit (s, s-t, d)

Figure 2. Core language signal related instructions syntax of SigVM. a∗ indicates zero or more occurrences of a.

as parameters automatically. prUpd in Vat will finally file the price change at line 49.

Contract event locking: The advantage of setting the handler function in Vat is to utilize the contract event locking mechanism in SigVM. After the one-hour delay of the DPR event, SigVM will lock the Vat contract from arbitrary regular transactions until the signal transaction that invokes prUpd is executed. This prevents Vat from interacting with potentially malicious users before it incorporates critical updates from the signal transaction, e.g., minting Dai or liquidating collaterals with outdated digital asset prices. This lock mechanism is lightweight because it only affects one contract. Other contracts deployed on the blockchain are not affected.

Transaction fees: Different from the Ethereum gas mechanism that transaction fees are always paid by external users. The transactions fees of signal transactions in SigChain are paid by the smart contracts who register the corresponding handler functions. In our example, OSM and Vat must have sufficient native token balance to cover the signal transaction fees. We believe this is a much smaller burden than maintaining an off-chain relay server to send poke transactions.

Advantages: This example highlights the advantages of SigVM. SigVM eliminates the dependency on the unreliable poking mechanism and off-chain relay servers. The execution model of SigVM guarantees that the core vault engine operates with the one-hour delayed prices reported by the oracle maintainers. Listing 1 highlights the expressiveness of SigSolid. Challenging features like time delays can be implemented in SigSolid in a straightforward way.

3 SigVM Design

This section formalizes the design of SigVM. Similar to other smart contract virtual machines like EVM [6], SigVM contains two layers, the virtual machine execution layer that dictates how SigVM executes a transaction and the block processing layer that dictates how the blockchain state evolves over multiple transactions in a block.

3.1 Core SigVM Language

Fig. 2 lists the syntax of a simple programming language used to formalize our approach. Our language extends the standard EVM operations EVMinst (e.g., load and push) with new operations SIGinst, e.g., createsignal and bind, to enable an event-driven execution model under SigVM. For brevity, in Fig. 2 we omit standard EVM operations EVMinst since they are not necessary in understanding the design of SigVM. However, our implementation of SigVM actually supports all standard EVM opcodes including arithmetic and inter-contract call operations.

In SIGinst, createsignal and deletesignal opcodes handle the creation and deletion of a signal event with name sn, respectively. The opcodes bind and detach allow handler functions to listen and unlisten to signal events.

bind(m, s, gr, blk, s-r, s-m) attaches a handler function m to a signal event s ∈ S with a gas ratio gr. The signal transaction fee is computed by miners by calculating the average gas price of regular transactions packed in the same block multiplied by 1 + gr. The last three parameters of bind dictates how the locking mechanism is enforced for the signal event: a boolean flag blk which when it is false regular transactions are allowed to execute. Otherwise, when blk is true only regular transactions initiated by accounts with addresses in the array s-r and are executing functions in the array s-m are allowed to execute. The contract is locked for other regular transactions until the pending signal transactions finish. detach(m, s) attaches a handler function m from a signal s. Finally, emit(s, s-t, d) emits signal events for signal s with a delay of d. s-t is an array of addresses that specifies the contracts that will be poked by the emitted signal. If s-t is not empty then s pokes only contracts with addresses in s-t. Otherwise, when s-t is empty, s pokes all contracts that contain handler functions attached to s. For each poked contract, a signal transaction that executes the corresponding handler function is created.

3.2 Operational Semantics

A program configuration in SigVM is a tuple µ = (gas, gcf, stack, bal, s-h, e-sig) where gas is the gas counter, gcf is composed of the persistent valuation of program variables, stack is the call stack, bal is a mapping from addresses to the corresponding balances, s-h is a mapping that maps each signal to a set of handlers that are attached to this signal, and e-sig is a set of emitted signal transactions.

The activation frames in stack are represented using tuples (i, m, ad, ℓ) where i ∈ T is a task (invocation) identifier, m ∈ M is a function name, ad ∈ A is the address of the contract that m belongs to, and ℓ is a valuation of local variables, including a program counter.

A signal identifier is a tuple s = (ad, sn), where ad ∈ A is the address of the contract emitting the signal and sn is the signal name. s-h[s] is a set of tuples (m, ad, gr, blk, s-r, s-m) where m is the name of the handler function bound to the signal s by the contract with the address ad, and gr is the gas ratio. The parameters blk, s-r, and s-m dictate the locking mechanism. blk is a boolean, s-r is an array of addresses, and s-m is an array of functions signatures. We assume that a signal s = (ad, sn) exists only if s-h[s] ̸= nil and if a signal is not attached to any method handler then we have s-h[s] = ∅.

The activation frames in the emitted signal transactions set e-sig are represented using tuples (j, s, m, ad, gr, d), where j ∈ S is a unique identifier of the signal transaction, s =
A transition labeled by `pokes all contracts with attached handlers for` to emitting a signal \( m \) to detaching handler that the contract \( \text{ad} \) (\( \text{gr} \) current contract.

the removal of the signal with the name \( s-h \) is the address of the contract containing the handler

\( a \) is the address of the contract containing the handler

\( \text{inst} \) returns the instruction at the current give some control location while next gives the next instruction to execute. gascost returns the gas price for a given opcode. We use \( \circ \) to denote sequence concatenation.

\[
\text{createsignal } sn \in \text{inst}(\ell(pc))
\]

\[
s-h[(ad, sn)] = \text{nil} \quad g := \text{gascost(createsignal)} \quad s-h := s-h[(ad, sn) \mapsto \emptyset] \quad \ell' := \ell[pc \mapsto \text{next}(\ell(pc))]
\]

\[
(gas, \_ (i, m, ad, \ell \circ stack, bal, s-h, _)) \Rightarrow [\text{createsignal } sn] \Rightarrow (gas + g, \_ (i, m, ad, \ell') \circ stack, bal, s-h', _)
\]

\[
deletesignal sn \in \text{inst}(\ell(pc))
\]

\[
s-h[(ad, sn)] \neq \text{nil} \quad g := \text{gascost(deletesignal)} \quad s-h' := s-h[(ad, sn) \mapsto \emptyset] \quad \ell' := \ell[pc \mapsto \text{next}(\ell(pc))]
\]

\[
(bind (m', s, gr, blk, s-r, s-m) \in \text{inst}(\ell(pc))) \quad s = (ad', sn) \quad s-h[s] \neq \text{nil} \quad (\_ ad, \_ ad, \_ \_ ad, \_ \_ ad, \_ \_ ad) \neq s-h[s]
\]

\[
g := \text{gascost(bind)} \quad s-h' := s-h[s \mapsto (m', ad, gr, blk, s-r, s-m) \cup s-h[s]] \quad \ell' := \ell[pc \mapsto \text{next}(\ell(pc))]
\]

\[
(gas, \_ (i, m, ad, \ell \circ stack, bal, s-h, _)) \Rightarrow [\text{bind (m', s, gr, blk, s-r, s-m)}] \Rightarrow (gas + g, \_ (i, m, ad, \ell') \circ stack, bal, s-h', _)
\]

\[
detach (m', s) \in \text{inst}(\ell(pc)) \quad s = (ad', sn) \quad (m', ad, s-r \_ wait, s-m) \in s-h[s]
\]

\[
g := \text{gascost(detach)} \quad s-h' := s-h[s \mapsto s-h[s] \setminus (m', ad, s-r \_ wait, s-m)] \quad \ell' := \ell[pc \mapsto \text{next}(\ell(pc))]
\]

\[
(gas, \_ (i, m, ad, \ell \circ stack, bal, s-h, _)) \Rightarrow [\text{detach (m', s)}] \Rightarrow (gas + g, \_ (i, m, ad, \ell') \circ stack, bal, s-h', _)
\]

\[
emit (s, s-t, d) \in \text{inst}(\ell(pc))
\]

\[
g := \text{gascost(emit)} \quad e-sig' := \text{emitSig(s, e-sig, s-h, s-t, d)} \quad \ell' := \ell[pc \mapsto \text{next}(\ell(pc))]
\]

\[
(gas, \_ (i, m, ad, \ell \circ stack, bal, s-h, e-sig) = [\text{emit (s, s-t, d)}] \Rightarrow (gas + g, \_ (i, m, ad, \ell') \circ stack, bal, s-h, e-sig')
\]

\begin{algorithm}
\caption{Signals to emit.}
\begin{algorithmic}[1]
\Procedure{emitSig}{s, e-sig, s-h, s-t, d}
\State \( Q \leftarrow e-sig; \)
\State \textbf{output} \( Q; \)
\For{each \((m, ad, gr, \_ ad, \_ s-m) \in s-h[s]\)}
\If{\( s-t = e \) or \( ad \in s-t \)}
\State \( f \in \mathbb{F} \)
\EndIf
\EndFor
\State \( Q \leftarrow (j, s, m, ad, gr, d) \cup Q; \)
\EndProcedure
\end{algorithmic}
\end{algorithm}

\textbf{Figure 3.} Program semantics in SigVM. For a function \( f \), we use \( f[a \mapsto b] \) to denote a function \( g \) such that \( g(c) = f(c) \) for all \( c \neq a \) and \( g(a) = b \). The function inst returns the instruction at the current give some control location while next gives the next instruction to execute. gascost returns the gas price for a given opcode. We use \( \circ \) to denote sequence concatenation.

\( (ad', sn) \) is the signal identifier, \( m \) is the handler method name, \( ad \) is the address of the contract containing the handler method, \( gr \) is the gas ratio, and \( d \) is the delay.

\textbf{Algorithm 1} Signals to emit.

\textbf{3.3 Transaction Execution}

\textbf{Blockchain state:} A blockchain state in SigVM is a tuple \( \sigma = (h, bcf, s-h, eh-sig) \) where \( h \) is the current block height, \( bcf \) maps each account address ad to \( bcf(ad) = (\text{non}, b, gcf, c) \).
Algorithm 2 Signal transactions partition.

1: procedure sigPartition(h, eh-sig, e-sig)
2:  \( Q \leftarrow eh-sig; \)
3:  output \( Q; \)
4:  for each \((j, s, m, ad, gr, d) \in e-sig\)
5:      \( h' \leftarrow h + d \)
6:  \( Q \leftarrow Q\{h' \mapsto (j, s, m, ad, gr) \cup Q[h']\}; \)
7: end procedure

where non is the account nonce, b is the account balance, gcF is the persistent valuation of contract variables, and c is the immutable contract code. eh-sig is a mapping that maps each block height to a set of emitted signal transactions pending until the block height is attained to be executed. For a block height \( h \), the activation frames in the emitted signal transactions set \( eh-sig[h] \) are represented using tuples \((j, s, m, ad, gr)\), where \( j \) is the unique signal transaction identifier, s is the signal identifier, \( m \) is the handler method name, ad is the address of the contract containing the handler method, and gr is the gas ratio.

Transactions execution: Fig. 4 presents the transaction execution rules for SigVM. We use \( \sigma = [ttx] \Rightarrow \sigma' \) to denote the blockchain state transition from \( \sigma \) to \( \sigma' \) after executing a transaction \( ttx \). In SigVM, we note three kinds of transactions: (1) create transaction which creates a new account and transfers balance, (2) regular transaction which executes a smart contract method and transfers balance, and (3) signal transaction which is a special transaction generated by signal emitted in previous blocks and does not transfer balance.

A transition labeled by createTx \((ad, non, b_0, m, c, gp)\) corresponds to an account creation transaction initiated by the account with the address \( ad \) and nonce \( non \), transferring a balance \( b_0 \) to the new contract account. \( c \) parameter is for the code of a smart contract to deploy in the new account and \( m \) is the name of constructor method in the contract. \( gp \) is the gas price paid by the sender to execute the transaction. The transition creates a fresh address \( ad_0 \) for the new account and ensures that the balance of the sender is sufficient for the transaction. Also, the transition includes an execution of the constructor method \( m \), i.e., \( \rho_m \), over the newly created contract initial state. The emitted signal transactions map \( eh-sig \) is updated with the newly emitted signals during the execution of \( m \), i.e., \( e-sig \) using the function sigPartition that partitions emitted signal transactions based on the values of the block height \( h \) and the delay period \( d \) defined in Algorithm 2.

A transition labeled by regularTx \((ad, ad, m, val, gp)\) corresponds to a regular transaction initiated by the account with the address \( ad \), targeting the method \( m \) in the contract associated with the address \( ad \), and transferring a balance \( val \) to \( ad \). \( gp \) is the gas price paid by the sender to execute the transaction. The transition ensures that the balance of the sender is sufficient for the transaction. To ensure that the regular transaction is not executing a locked smart contract because of pending signal transactions we define a boolean function lockPerm which returns true when the regular transaction is allowed to execute and false otherwise.

\[
\text{lockPerm}(h, s-h, eh-sig, ad, m, ad, gr) = \forall s \in \mathbb{S}.
\]

\( (\forall h' \leq h, \exists (s, _, ad, _, _) \in eh-sig[h') \land (\exists! (s, ad, _, blk, s-r, m) \in s-h[s]. ~blk \lor (ad \in s-r \land m \in s-m)) ) \)

\( \exists! \) denotes unique existential quantifier. \( \text{lockPerm} \) returns true when there are no pending signal transactions ready to be executed and are associated with the contract \( ad \), that is targeted by the current regular transaction or for any pending signal transaction that can be executed we have that regular transactions initiated by \( ad \) and are calling the method \( m \) are allowed to execute. If a contract detaches a handler from a signal while signal transactions are queued, regular transactions will be blocked until the signal transactions are executed (lockPermission returns false).

A transition labeled by signalTx \((j, s, m, ad, gr)\) corresponds to a signal transaction executing a method \( m \) in the contract with the address \( ad \). \( gr \) is the gas ratio. Similar to above, the transition ensures that the balance of \( ad \) is sufficient for the transaction. We remove the executed signal transaction from the set of pending signal transactions at a block height less or equal to the current block height, i.e., \( \exists h' \leq h (j, s, m, ad, gr) \in eh-sig[h'] \).

Block execution: an execution of a new block of transactions \( blc \) in SigVM is a sequence \( \sigma_0 = \text{inc}_0 \Rightarrow h_1 \sigma_1 := \text{inc}(\sigma_0) = \text{inc}(\text{tx}_1) \Rightarrow h_2 \sigma_2 := \text{tx}_2 \Rightarrow h_3 \sigma_3 = \ldots \Rightarrow \text{tx}_{n-1} \Rightarrow h_n \sigma_n \) of transitions starting in the initial blockchain state \( \sigma_0 = (h, \text{bcf}_0, s-h_0, \text{eh-sig}_0) \) and leading to a blockchain state \( \sigma_n = (h+1, \text{bcf}_n, s-h_n, \text{eh-sig}_n) \) where the transition \( \sigma_0 = \text{inc}_0 \Rightarrow h_1 \sigma_1 := \text{inc}(\sigma_0) \) simply increments the block height in the blockchain state \( \sigma_0 \) resulting in \( \sigma(0) = (h+1, \text{bcf}_0, s-h_0, \text{eh-sig}_0) \) and \( \text{tx}_1, \ldots, \text{tx}_{n-1} \) are the transitions of the transactions constituting the block \( blc \), i.e., \( blc = \{\text{tx}_1 \ldots \text{tx}_{n-1}\} \).

4 Implementation

In this section we describe an implementation of an end-to-end blockchain platform that supports SigVM. Our implementation consists of two main components: SigSolid, an extension of Solidity language together with a compiler to support SigVM features, and SigChain, a blockchain client based on the Openethereum client [41]. As input, our implementation accepts smart contracts written in SigSolid and it then deploys and executes them using SigChain. Our implementation supports all EVM opcodes with the addition of SigVM opcodes for signal events presented in Section 3.

4.1 SigSolid

Our SigSolid language provides high-level language features for using SigVM opcodes to create, bind, and emit signal events while maintaining support for all Solidity language
(non\_s, b, gcf\_s, c) = bcf\_ad \quad b \geq gp + b \quad ad \in \mathbb{A} \quad fresh

\forall ad \in \mathbb{A}, bcf[ad] = (\_ , b\_, \_ ) \implies bal_{[ad]} := b \quad bal_{1} := bal_{[ad]} \implies bal_{[ad_{1}]} \quad b_{ad} \implies bal_{[ad_{n}]} + b_{0}

gcf_{0} := init(ad_{n}) \quad \ell_{0} := locinit(gcf_{0}, m) \quad (gas, gcf, e, bal, s-h').e-sig) := \rho_{m}(0, gcf_{0}, (i, m, ad_{1}, \ell_{0}), bal_{2}, s-h, e)

gp \geq gas \times unitGasPrice(h) \quad eh-sig' := signalsPartition(h, eh-sig, e-sig)

bcf_{1} := updBal(bcf, bal) \quad bcf_{2} := bcf_{1}[ad_{s} \implies (non+s + 1, bal[ad_{s}]) - gp, gcf_{s}, c); \quad ad_{d} \implies (non_{s}, bal[ad_{s}], gcf_{s}, c)]

(h, bcf_{s-h}, eh-sig) := [ createTx (ad_{s}, non_{s}, b, m, c, gp) ] \implies (h, bcf_{s-h}, eh-sig')

\exists h' \leq h. eh-sig[h'] = (j, s, m, ad_{s}, g) \quad gcf_{s} \quad (non_{s}, b, gcf_{s}, c) = bcf_{ad}

gp := gas \times unitSigGasPrice(h, gr) \quad b_{t} \geq gp \quad \forall ad \in \mathbb{A}. bcf[ad] = (\_ , b\_, \_ ) \implies bal_{[ad]} := b

\ell_{0} := locinit(gcf_{0}, m) \quad (gas, gcf, e, bal, s-h').e-sig) := \rho_{m}(0, gcf_{0}, (i, m, ad_{1}, \ell_{0}), bal_{2}, s-h, e)

eh-sig_{s} := eh-sig[h' \implies q] \quad eh-sig_{t} := signalsPartition(h, eh-sig_{s}, e-sig)

bcf_{1} := updBal(bcf, bal) \quad bcf_{2} := bcf_{1}[ad_{s} \implies (non+s + 1, bal[ad_{s}]) - gp, gcf_{s}, c)]

(h, bcf_{s-h}, eh-sig) := [ signalTx (j, s, m, ad_{s}, gr) ] \implies (h, bcf_{s-h}, eh-sig_{s})

\textbf{Figure 4.} Transactions execution rules. init returns the initial state of a contract persistent variables. unitGasPrice returns the unit gas price at the block h. unitSigGasPrice returns the average unit gas price payed by regular transactions packed in the block h multiplied by 1 + gr. updBal(bcf, bal) returns bcf_{1} s.t. for every bcf[ad] = (non, b, gcf, c), bcf_{1}[ad] = (non, bal[ad], gcf, c).

- **Signal declaration**: The statement signal S(paramType) declares a signal event S where paramType is the list of data types associated with the event parameters. SigSolid compiler translates the above statement into SigVM createSignal opcode.

- **Handler declaration**: using the keyword handler a function is declared as a signal handler. For instance, function foo(...) handler [...] corresponds to defining a handler function foo.

- **Bind signal**: The statement foo.bind(addr, S, gr, blk, sigR, sigM) binds the handler function foo to a signal event S of a contract stored in the address addr. gr is the gas ratio. blk, sigR, and sigM are the parameters for the locking mechanism to enforce. The above statement translates into SigVM bind opcode.

- **Detach signal**: The statement foo.detach(addr, S) detaches the handler function foo from the signal event S of the contract stored in the address addr. The above statement translates into SigVM detach opcode.

- **Emmit signal**: The statement S.emit(param).target(t).delay(d) emits a declared signal event S where parm are the passed values of signal parameters, t is an array of addresses of the recipients intended by the emitted signal, d is a non-negative integer that specifies the number of blocks as the delay. The above statement translates into SigVM emit opcode.

4.2 SigChain

Our SigChain extends OpenEthereum [41] to support signal transaction execution. In particular, it extends the OpenEthereum EVM with the implementations of SigVM signal instructions. The execution of a signal transaction in SigChain is similar to that of a regular transaction. The main difference is that it starts at a handler function attached to emitted signal rather than a user specified function. The blockchain state is augmented with signal events related fields that we presented in Section 3. Also, it maintains a list of all accounts with pending signal transactions which provides an efficient method for miners to retrieve pending signal transactions.

In SigChain, a smart contract who registers a handler function will pay the transaction fee cost of the associated signal transaction. If the smart contract is unable to pay the fee of its signal transaction, the signal transaction execution will stay in the pending transaction pool until the contract obtains sufficient native tokens to cover the fee. Note that simple native token transfer transactions that interact with
the fallback method of the contract are not affected by the contract locking mechanism by default.

**Enforcing contract locking:** In SigChain we extend the transaction pool implementation in OpenEthereum. In particular, when processing a block SigChain checks that for each: (1) regular transaction whether the transaction is allowed under the locking mechanism or the pending signal transaction queue for the contract is empty; and (2) signal transaction that the transaction is indeed the next transaction in the pending queue. If these verification steps fail, the transaction will not be executed and will have no effect. Miners who pack the transaction will receive no transaction fee reward from the transaction. SigChain also enforces contract event locking at the boundary of inter-contract calls. It checks whether the caller and the called function are permitted under the locking mechanism or the pending signal transaction list of the callee is empty. If the check fails, the whole transaction will be reverted with no effect and the miner will receive no transaction fee reward. Note that for the delegate call opcode, the check is skipped because delegate calls do not change the state of the callee.

Note that SigVM can handle denial-of-service attacks in which an attacker triggers a large number of signal events to block regular transactions of a victim contract. Such attacks are possible only when the victim contract listen to an event from a contract deployed by the attacker in a way that blocks regular transactions. Even so, the contract locking mechanism in SigVM allows the victim contract to remove the locking partially by specifying a list of trusted addresses for which regular transactions are not blocked.

### 4.3 Gas Mechanism

To incentivize miners to pack signal transactions as soon as possible, signal transactions pay a higher gas price than regular transactions. In SigChain, we set the gas price of signal transactions to be the average gas price of regular transactions in the block multiplied by one plus the gas incentive ratio set during handler binding. This mechanism ensures that the gas price of signal transactions will always be competitive comparing to regular transactions. Miners will always be incentivized to pack signal transactions even in the presence of regular transactions with high fees. Because these regular transactions will raise the gas price of signal transactions, thus miners earn the profits by packing signal transactions instead of other regular transactions with low gas fees.

To avoid situations where the average gas price of regular transactions cannot be determined due to an overabundance of signal transactions, SigChain sets a separate gas limit for signal transactions to reserve room for regular transactions. SigChain limits the total gas consumption of signal transactions in a block to be less than $\frac{1}{10}$ of the block gas limit. We set this limit based on the current Ethereum ratio between contract internal and regular transactions of $1 : 9$ [21].

### 5 Evaluation

In this section we outline an empirical study of SigVM using 23 contracts from 13 decentralized applications (DApps) on Ethereum using the implementation described in Section 4. Our empirical study is driven by the following questions:

1. Can SigVM enable autonomous contracts? Specifically, can we implement popular smart contracts from Ethereum in SigVM to eliminate off-chain relay servers?
2. Is SigVM easy to use? What is the development effort of implementing smart contracts in SigVM?
3. What kinds of security risks are associated with off-chain relay server solutions? Can the contract event lock mechanism in SigVM eliminate these risks?

#### 5.1 Benchmark

Our benchmark set contains 23 contracts from 13 DApps deployed on Ethereum, including MakerDAO [23], Compound [27], and Augur [36]. Compound is a decentralized lending service platform where users could deposit one type of digital asset as collateral to borrow another type of digital asset from its shared pool. Augur is a decentralized prediction market where users bet on future result of real-world events. The supplementary material contains descriptions for the other DApps. In total, the 13 DApps manage more than $3B$ of digital assets on the Ethereum network, making up an essential part of the Ethereum economic ecosystem.

Table 1 outlines some characteristics of our benchmark. Each DApp contains one or more contracts that are inter-dependent with each other but are maintained by different groups of users. In our evaluation, we focus on 23 contracts (column Contract) that are relying on off-chain relay servers to invoke poke functions.

#### 5.2 Evaluation

**Contracts in SigSolid:** We reimplemented the benchmark contracts in SigSolid with the goal of eliminating off-chain relay servers from the picture. Because SigSolid is compatible with Solidity, our modification is merely replacing the poke functions with SigSolid signal event statements. We are able to reimplement all 23 contracts in SigSolid. Columns $se$ and $hf$ in Table 1 present the number of declared signal events and the number of declared handler functions in the new contract implementation, respectively. We note that the new code is typically simpler than the original contract code while the reimplementation effort is moderate. For instance, Column $diff$ presents the number of lines difference between the new and old code.

**Validation and analysis:** We deployed the new contracts implementation together with the remaining components of the 13 applications in our SigChain platform. We validated that all three benchmark applications function correctly with the new contract code. We select the three applications MakerDAO, Compound, and Augur as case studies and we report our experience in analyzing the code of the new contracts.
Table 1. Empirical results. Characteristics of applications: lines of code (loc) and number of poke functions (pf). Characteristics of applications using signal events: number of signal events (se), number of handler functions (hf), and lines of code difference (df).

| Application | Contract | Solidity | SigSolid |
|-------------|----------|----------|----------|
| MakerDAO    | Median   | 1 175    | 1 177 2  |
|             | OSM      | 2 178    | 1 174 6  |
|             | Spot&Vat | 1 116    | 0 116 5  |
| Compound    | Timelock | 3 113    | 1 115 12 |
| Augur       | Universe | 1 711    | 1 727 15 |
| MultiSig    | MultiSig | 1 256    | 1 270 19 |
| HistoricalPriceFeed | HistoricalPrice | 1 564    | 1 555 4  |
| Idex        | Exchange | 1 1223   | 1 1231 8 |
| Aave        | LendingPool | 1 355   | 1 359 4  |
| Metronome   | Metronome | 1 125    | 1 133 8  |
| DAIHardFactory | DAIHard | 1 505    | 1 533 29 |
| KyberDxMarket | PriceFeed | 1 201    | 0 203 2  |
|             | DSValue  | 2 22     | 1 26 4   |
|             | Medianizer| 1 195    | 0 197 2  |
| DutchExchange | PriceFeed | 1 201    | 0 203 2  |
|             | DSValue  | 2 22     | 1 26 4   |
|             | Median    | 1 2604   | 0 2606 2 |
| PriceFeed   | PriceFeed | 1 201    | 0 203 2  |
|             | DSValue  | 2 22     | 1 26 4   |
|             | Median    | 1 199    | 0 201 2  |
| OracleInterface | PriceFeed | 1 201    | 0 203 2  |
|             | DSValue  | 2 22     | 1 26 4   |
|             | Medianizer| 1 483    | 0 485 2  |

5.2.1 Case Study: MakerDAO. As described in Section 2, we reimplemented the three contracts in the oracle components of MakerDAO, eliminating the dependency on off-chain relay servers. The new contracts powered by SigVM ensure that the core MakerDAO engine will always operate with the updated price of its underlying digital asset. In addition, before the MakerDAO contract processes these price feed signals transactions, by lock mechanism, other transactions like liquidation and bidding will be put on-hold to avoid them operating with stale price information.

5.2.2 Case Study: Compound. Compound protocol is a decentralized market to lend or borrow assets. Users communicate with the Compound contracts to supply, withdraw, borrow and repay assets. In the protocol, the key parameters of the market, such as interest rate, risk model and underlying price, are managed by a decentralized government body in Compound [27]. Any proposals of updating the parameters must be voted for approval and queued in TimeLock contract. To give market participants time to react for any parameter changes, the queued proposals will be executed in the required delay specified in the proposals.

We reimplemented the TimeLock contract in SigSolid and validated it with our SigChain platform. Listing 2 presents the simplified code snippet of TimeLock.sol in Compound
Figure 5. Malicious Hijacking Manipulation Rate Line Chart

In SigSolid, we eliminate the dependency on poke transactions with the signal event mechanism. We define a new signal event called TimeUp at line 11. The queueTransaction function will emit this event with the specified delay (line 25). Instead of being a public function, the executeTx function is declared as an event handler (line 28). When the contract is constructed, we bind executeTx as the handler for TimeUp events in the same contract. Thus, executeTx will be automatically executed once the specified delay time (measured in the number of blocks) has past after each TimeUp event. Many conditional checks in executeTx are removed because they are guaranteed by the execution engine of SigVM.

We deployed the modified TimeLock contract together with the rest of Compound smart contracts in SigChain. Our results show that the deployed Compound application in SigChain can operate successfully and there is no need to run off-chain server to poke the executeTx function anymore.

5.2.3 Case Study: Augur. Augur is a decentralized prediction market where users can bet on future real-world outcomes [36]. Augur markets follow four stages: creation of the market, trading, reporting outcomes and prediction settlement. During reporting stage, one of the reporters report results of a real-world event by staking REP tokens on one of the outcomes of the market. If a Dispute Bond port results of a real-world event by staking REP tokens the market. If a Dispute Bond port results of a real-world event by staking REP tokens to the new alternative outcome. This process happens every 24 hours.

The contract that implements this process in Augur is Universe. The design of the contract is that every 24 hours, the sweptInterest function has to be executed so that the contract can finalize the last round results and can start a new round if required. Because this functionality is not feasible to implement in EVM, Augur instead relies on external users to periodically poke sweptInterest.

Listing 3 presents the code snippet of our Universe contract implementation in SigSolid. We define a delay signal event called DSig at line 5 and we define a handler function called Update for this event (lines 10-14). The handler function calls sweptInterest. It also recursively emits the DSig event with a delay of one day (the number of blocks) at the end (line 14). Therefore once the first DSig event is triggered (via the start_emit function), the Update function will be automatically invoked once every 24 hours.

We deployed the new Universe contract together with the rest of contracts in Augur in our SigChain platform. The deployed version of Augur operates successfully and the sweptInterest function is automatically called every 24 hours as expected. This example highlights the expressiveness of SigSolid powered by SigVM. This recursive event handler pattern enables developers to create customized infinite timer ticks conveniently. The desired handler function will be automatically and periodically invoked as signal transactions by the execution engine of SigVM, as long as the contract has enough native tokens to pay for the transaction fee of the recurring transactions.

5.3 Eliminate Risks of Off-chain Relay Server

We describe an experiment to quantitatively study malicious hijacking manipulations caused by relying on off-chain relay server to drive execution. We also evaluate whether SigVM can eliminate those associated risks.

Malicious hijacking manipulation: Using off-chain relay servers to simulate event-driven execution models may make the contract vulnerable to malicious hijacking manipulations. Miners may pack an interference transaction before a poke transaction for an event and therefore the contract will execute the interference transaction in an incorrect state.

We setup an experiment with the MakerDAO contracts to quantitatively illustrate this problem. We start an Ethereum network with a block generation rate of one block per second. We developed a random transactions generator to generate three types of transactions, 1) simple transfer transactions that do not interact with MakerDAO, 2) MakerDAO transactions, and 3) poke transactions that attempt to update price for MakerDAO. In the experiment, the ratio of the three kinds of transactions is 10 : 4 : 1, respectively. The gas price for
the three transactions follows the normal distribution with an average: 15, a standard deviation: 2, and a maximum: 50.

Fig. 5 presents, using an off-chain relay server, the chance of manipulating other MakerDAO transactions to be executed ahead of a poke transaction as we increase the transaction throughput. Hijacking manipulation occurs starting from a transaction rate \( \geq 30 \) TPS (Transactions Per Second) and goes as high as 0.0125 when the throughput is 70 TPS. We repeat the experiments with the new MakerDAO contracts in our SigChain platform by replacing poke transactions with the automatic signal event mechanism. The hijacking manipulation never occurs because of our novel contract event lock mechanism. The lock mechanism has minimum impact on the performance because the miners are incentivized to pack signal transactions as soon as possible.

6 Related Work

Event-driven proxy services: On Ethereum, there are a number of proposals involving proxy service of function executions in response to event emission. EventWarden [29] is a proxy service for a user to create a smart contract specifying events to listen, the function handler to call when an event occurs, and the service fee for the executor. Executors of the system monitor the event log, invoke the specified function, and earn a service fee in return. Similarly, Ethbase [13] provides a registry smart contract where users can deposit and subscribe to an automatic function invocation service. When the specified event is seen in the log, miners invoke the callback function accompanied by a proof of the event emission to the registry. Both EventWarden and Ethbase are variants of off-chain relay server solutions, although they provide incentives on chain via smart contracts so that any external user could act as an off-chain relay server to send poke transactions to claim the reward. They share similar weakness as the off-chain relay server solution, i.e., the reliance on external users to send poke transactions timely and their willingness to pay high enough fees for these poke transactions to be packed timely. Different from these approaches, our solution modifies the blockchain system to enable native support of an event-driven execution. SigVM brings the whole execution process on-chain and completely eliminates the dependency on off-chain relay actors.

Smart contracts programming: In addition to Solidity, a number of new languages have been designed for smart contracts programming, including, Vyper [40], Simplicity [33], Liquidity [32], Sophia [2], Move [5], DeepSEA [39], and Obidian [8]. Unlike SigVM, the above languages do not support an event-driven execution model. Interestingly, because the event-driven execution model is highly demanded and many smart contracts are unsecurely simulating such an execution model via off-chain relay servers, SigVM also improves the security of these contracts by eliminating the need of such insecure practice. Also the aforementioned languages either introduces new syntaxes that leads to new learning curve for developers or suppress expressiveness in order to gain security guarantees. On the other hand, SigSolid is a practical extension on Solidity with minor changes in the syntax while improving security and usability of the language.

Recent smart contract languages such as Rholang [9], Scilla [38], and Nomos [10] replace inter-contract function calls with message-passing mechanisms to eliminate bugs like re-entrance. Although those message-passing mechanisms are also asynchronous, they behave otherwise like function calls and cannot implement the desired event-listener model to eliminate off-chain relay servers. In fact, it would be difficult to implement many DeFi contracts like MakerDAO in those languages, because these contracts depend on synchronous inter-contract function calls. Making a function call asynchronous via message-passing may make such a contract vulnerable to malicious manipulation attacks that front-run the asynchronous message-passing transaction.

General purposes programming languages such as JavaScript support event-driven asynchronous programming. However, they are not commonly used to write smart contracts.

Security and correctness validation: Another path taken by many to improve the security of smart contract programming is through static verification and runtime validation tools. There is a rich body of literature on detecting vulnerabilities in smart contracts through static analysis and modular verification [4, 25, 26, 30, 31, 35]. For instance, ith , Oyente [30] uses symbolic executions to verify smart contracts against various attacks including re-entrance and mishandled exception attacks. Verx [35] uses delayed abstraction to detect and verify temporal safety properties automatically. Sobysynthesis [28] inserts runtime checks to enforce customized validation rules. KEVM [25] defines a formal semantics of EVM in \( \mathcal{K} \) and verifies smart contracts against user-defined specifications. These techniques enhance security of smart contract programming mostly by preventing unintended behaviors in smart contract codes and cannot be used to eliminate the dependency on off-chain relay servers.

Scheduled transaction execution: Bitcoin supports a native mechanism called timelocks [3] to delay transaction execution. The transaction-level timelock feature can be utilized by specifying an execution delay with the nLocktime field. Additional timelock features, Check Lock Time Verify (CLTV) and Check Sequence Verify (CSV), were introduced later to the scripting language. CLTV limits the availability of the associated Unspent Transaction Output (UTXO) until a certain age. CSV utilizes the the value of nSequence, a transaction field, to prevent mining of a transaction until the time limit specified for the UTXO is met. These features are proven to be useful in layer 2 designs, such as state channels and the Lightning Network. The timelock features provides a convenient way to delay transaction execution on Bitcoin. However, with the lack of programmability on Bitcoin network and the difficulty of generalizing such a design to non-UTXO networks, the usability of such a design
is limited. Another implementation of delayed or periodic transaction is to setup relay servers through the network client as we have discussed before this is not desirable.

7 Conclusion

As smart contracts become more complicated and inter-dependent with each other, the event-driven execution model is an increasingly demanded feature. Unsatisfied by current blockchain virtual machines, smart contracts start to use unreliable mechanisms such as off-chain relay servers to securely simulate event-driven execution. SigVM provides the first blockchain virtual machine with an integrated solution to natively enable event-driven execution models on-chain. It paves the way for developers to build fully autonomous and robust smart contracts in future.

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Appendix

A Applications Descriptions

MultiSigWallet With TimeLock [42]: The Smart contract program serves to allow multiple parties to agree on transactions before execution. Once all of the parties confirm one transaction, the transaction will be executed by anyone in a required delay. In most cases, a relay server is responsible to poke to execute after the delay. In order to eliminate the need of relay server, we reimplemented the contracts in SigSolid and the transaction is executed in the form of signal transaction. In function confirmTransaction(), a signal event with transaction ID is emitted once all of the owners confirm. In the contract GetUserExecuteTransaction of a user, the handler function multiSigWalletExecution() binds with the signal. After a required delay, the signal transaction of the user is executed and function executeTransaction() is invoked to execute the determined transaction.

Historical Price Feed [16]: The contract is used to store updated historical price data from an off-chain oracle. The function poke() should be manually invoked every 24 hours in order to update prices periodically. In SigSolid, a signal event is declared without including any parameters. poke() is the corresponding handler function which emits the signal event inside. In this way, poke() signal transaction is always executed periodically to update the price data.

Idex [43]: Idex is a platform which provides ERC-20 Token trading on Ethereum. Function executeTrade() in Exchange contract is responsible for settling trade orders. Once the chain propagation period has elapsed, executeTrade() invalidate all trade orders whose timestamp is lower than the one provided. In SigSolid, similar with Historical Price Feed, by setting empty signal emission in a handler function, order invalidations are executed every chain propagation period.

Aave [1]: Aave protocol is a decentralized lending pools protocol on Ethereum. Function liquidationCall() will be invoked by relay servers to check and liquidate under collateralized position. There is a price update from an oracle price under such manual checking. In order to mitigate the unexpected delay caused by relay server poking, SigSolid introduces a periodical liquidation check mechanism similar with Historical Price Feed. In contract LendingPoolLiquidationManager of Aave, by setting empty signal emission in a handler function, the price is updated from oracle periodically. In the contract of users, the handler function binding with the empty signal will invoke liquidationCall() to check regularly.

Metronome [18]: Metronome is a DeFi trading market for a type of ERC-20 token on Ethereum. In contract Metronome, function poke(address a) is used to create a reward from the funds of account a who has not idled in the last 10 minutes. The user who invokes invest() in the last 10 minutes is regarded as being under Not-Idle status. In SigSolid, poke() is set as a handler function. In invest(), First detach poke() with a old signal event if binding before. Then poke() is re-bound with the signal with the sender address. Then the signal is emitted with the required delay. The purpose of re-binding action is to update the handler function execution timestamp if the user keeps non-idle with the required delay. Then function poke() will be executed without the function call from reply servers.

DAIHardFactory [14]: Contract DAIHardFactory provides a DAI trading platform. One trade process has five sequential phases. A fixed time interval called "autoabortInterval" is defined. During each phase, once "autoabortInterval" has passed, function abort() is executed by anyone to abort from the phase. Otherwise, the next phase will be executed. In SigSolid, at the beginning of each phase execution, a signal event with current phase type is emitted. After a delay of "autoabortInterval", the corresponding handler function first checks whether the current phase has changed or not. Next it aborts from the phase if the phase is not changed.

Contracts similar with MakerDAO: KyberDxMarketMaker [17], DutchExchange [15], PriceFeed [19] and OracleInterface [20] shown in the last four rows of Table 1 provide price oracle service similar with MakerDAO. Users should use relay servers to manually poke to retrieve the latest price periodically. SigSolid mitigates the unexpected delay caused by relay servers. The price oracle emits the price signal in a single transaction. All of the handlers of users are executed after a required delay.