# Parallel and Asynchronous Smart Contract Execution

Jian Liu, Peilun Li, Raymond Cheng, N. Asokan, Fellow, IEEE, Dawn Song, Fellow, IEEE,

Abstract—Today's blockchains suffer from low throughput and high latency, which impedes their widespread adoption of more complex applications like smart contracts. In this paper, we propose a novel paradigm for smart contract execution. It distinguishes between consensus nodes and execution nodes: different groups of execution nodes can execute transactions in parallel; meanwhile, consensus nodes can asynchronously order transactions and process execution results. Moreover, it requires no coordination among execution nodes and can effectively prevent livelocks. We show two ways of applying this paradigm to blockchains. First, we show how we can make Ethereum support parallel and asynchronous contract execution without hard-forks. Then, we propose a new public, permissionless blockchain. Our benchmark shows that, with a fast consensus layer, it can provide a high throughput even for complex transactions like Cryptokitties gene mixing. It can also protect simple transactions from being starved by complex transactions.

Index Terms—Blockchain, smart contract, parallel execution, asynchronous execution.

### 1 Introduction

Blockchains make digital transactions possible without relying on a central authority. One issue that hinders the wider deployment of blockchain-based applications such as cryptocurrencies [31] and smart contracts [11], is their low throughput and high latency. This is partially due to the fact that *all* blockchain nodes are required to reach consensus on the order of transactions *and* execute them.

With the progress of the blockchain consensus algorithms [10], [21], [22], [26], [27], [34], transaction execution will soon become a bottleneck. For example, CryptoKitties [38], a popular game built on Ethereum blockchain, has clogged the network due to its complex genetic algorithm. This problem will be amplified by the computational demands of future smart contract applications. A straightforward way to get rid of this bottleneck is dividing the blockchain nodes into groups (or shards) to process transactions in parallel [5], [7], [16], [28], [30], [36], [41]. However, existing approaches usually require extensive coordination but still suffer from congestion within the same group. They also require a large group size, i.e., 3f' + 1 (or 2f' + 1 [7]) nodes to tolerate f' faults in each group. Additionally, they incur livelocks for smart contracts (cf. Section 3).

Scalable execution. In this paper, we propose Saber, a novel paradigm for scalable smart contract execution, by improving a traditional Byzantine fault-tolerance (BFT) architecture, called "separating execution from consensus" [40]:

Jian Liu is with Zhejiang University,
Raymond Cheng is with University of San Francisco,
Peilun Li is with Tsinghua University,
N. Asokan is with University of Waterloo,
Dawn Song is with University of California, Berkeley.
E-mail: liujian2411@zju.edu.cn
lpl15@mails.tsinghua.edu.cn
me@raymondcheng.net
asokan@acm.org
dawnsong@cs.berkeley.edu

- 1) **Parallel execution.** It distinguishes between *consensus nodes* and *execution nodes*. For simple transactions like cryptocurrency payments, consensus nodes confirm them directly; for complex transactions that involve expensive execution, consensus nodes order them and assign them to different subsets of execution nodes (*execution groups*) for parallel execution. This can be seen as multiple instances of [40] running in parallel.
- 2) **Asynchronous execution.** When complex transactions are executed by execution nodes, consensus nodes can keep processing simple transactions in a *non-blocking* way. This can effectively protect simple transactions from being starved by complex transactions.

Compared with existing blockchain parallelization paradigms, Saber has the following advantages. First of all, it supports asynchronous execution for smart contracts. Secondly, unlike prior sharding paradigm which requires extensive coordination among execution nodes, Saber allows each individual execution node to execute the ordered transactions directly and independently. Thirdly, it only requires 2f'+1 nodes in each execution group, which can significantly reduce the group size<sup>1</sup>. Lastly, to the best of our knowledge, it is the *first* parallelization paradigm that is livelock-free for smart contracts.

We propose two ways to put Saber into practice: on the existing Ethereum blockchain, and as a standalone blockchain.

**Saber for Ethereum.** We apply Saber to Ethereum [11] and show that we can make Ethereum support parallel and asynchronous contract execution *without introducing any hard-fork*. For a transaction that invokes a smart contract with expensive execution, the consensus nodes (all Ethereum miners collectively serve as consensus nodes) simply put it into the ledger without executing it, but they lock the states associated with this transaction and

<sup>1.</sup> It only requires 70 nodes to reach a group failure probability of less than  $10^{-6}$ , whereas sharding schemes require 600 nodes.

designate an execution group for the execution. Once this transaction is confirmed, execution nodes in the designated group execute it off-chain and put the result into the ledger by making another transaction. All these rules are enforced by the smart contracts themselves without changing the underlying consensus.

Saber for a standalone blockchain. Following the Saber paradigm, we propose a new public and permissionless blockchain called SaberLedger. It leverages the state-of-the-art distributed randomness generation protocol [35] to select a (rotating) committee of consensus nodes which run a Byzantine consensus. The same randomness is used to construct groups of execution nodes. Furthermore, SaberLedger stores the whole blockchain into a distributed storage maintained by all nodes in the system, to support "state sharding".

Our contributions are summarized as follows:

- We propose Saber, a paradigm for parallel and asynchronous smart contract execution. It supports a small group size of 2f' + 1 execution nodes and it requires no coordination among execution nodes and prevents (adversarial) livelocks. (Section 4)
- We show how Saber make Ethereum support parallel and asynchronous execution without introducing any hard-fork. (Section 5)
- We propose SaberLedger, a new public, permissionless blockchain based on our proposed paradigm. It supports "state sharding" by further separating storage from consensus. (Section 6)
- We implement a prototype of SaberLedger and deploy it on a network of 3,467 nodes across 15 regions and 5 continents. The results show that it can achieve a high throughput even for complex transactions like Cryptokitties gene mixing, and it can effectively protect simple transactions from being starved by complex transactions. (Section 7)

#### 2 BACKGROUND AND PRELIMINARIES

#### 2.1 Blockchains and smart contracts

Blockchain technology has fueled a number of innovations such as cryptocurrencies [31] and smart contracts [11]. In particular, smart contracts permit execution of arbitrary code on top of blockchains. However, blockchains introduce large overheads compared with traditional architectures. For example, Bitcoin [31] can only handle  $\sim\!\!7$  transactions per second and each transaction requires one hour to be confirmed. Another reason is that every node in the system is required to execute all transactions.

Blockchains are usually permissionless, i.e., any node can join and leave at any time. Therefore, they need to be able to prevent sybil attacks. PoW naturally provides *sybil-resistant identities*, since the number of sybils that an adversary can spawn is limited by its computing resources. Another solution for sybil-resistant identities is proof-of-stake (PoS), which limits adversary's power by its wealth.

Since blockchains are maintained in a distributed way, an upgrade to the blockchain-based software may lead to *hard-forks*: nodes running the old version software may see the transactions adhering to the new version as invalid. During a recent hard-fork in Bitcoin, the network was divided into

two separate parts [14]: Bitcoin and Bitcoin Cash [14]. Therefore, hard-forks have the risks of partitioning the committee.

#### 2.2 Separating execution from consensus

Byzantine fault tolerant (BFT) state machine replication is a service where its state is replicated across n servers and it can handle clients' requests as a single server. One approach to build such services is *practical byzantine fault tolerance* (PBFT) [13], which requires n=3f+1 servers to tolerate f faults. In PBFT, one server, the *primary*, decides the order for clients' requests and forwards them to the other servers. Then, all servers agree on the order via a two-phase agreement to generate a *commit certificate* (CC), execute the requests and reply to the clients. Clients wait for f+1 consistent replies to complete its request.

Yin et al. propose to split all servers in a BFT protocol into two clusters: an *agreement cluster* and an *execution cluster* [40]. The agreement cluster's job is to order clients' requests via a standalone BFT protocol (e.g., PBFT), send the ordered requests to the execution cluster, and relay replies to the clients. In the execution cluster, 2f' + 1 servers are required to tolerate f' faults, which is independent of the f faults in the agreement cluster.

#### 2.3 Multisignatures and message aggregation

A *multisignature* scheme allows multiple signers to produce a compact and joint signature on common input via an Aggre operation. Any verifier that holds the aggregated public key can verify the signature in constant time. In practice, Aggre also outputs a bit map indicating which signers have (not) participated in the signing process, so that Verify can compute the aggregated public key correspondingly. For the sake of brevity, we do not explicitly mention the bit map in the rest of the paper.

Multisignatures provide a useful property for *message* aggregation, which was used in ByzCoin [27] to improve the scalability of PBFT. Alternatively, hardware-assisted secret sharing [29] can achieve the same goal with smaller overhead but requires TEEs.

#### 2.4 Randomness beacon

Many recent blockchain consensus algorithms [10], [21], [26], [28], [39] rely on a random beacon to generate randomness that is *unbiasable*, *unpredictable* and third-party verifiable. Such a random beacon is typically simulated by a distributed randomness generation protocol. Suppose there are n nodes in the system and at most f of them are malicious. A commit-then-reveal [26], [28], [35] approach can be used to simulate a random beacon. An alternative approach is based on threshold signatures [39], but it requires distributed key generation whenever the membership changes.

#### 3 PROBLEM STATEMENT

#### 3.1 System setting and assumptions

We target the setting of permissionless blockchains. There are two types of entities in the system: *clients* and *nodes*. Clients issue *transactions* to transfer funds or run smart contracts. Nodes process clients' transactions via a blockchain

consensus protocol. Notice that clients can play the role of nodes and vice versa. Each entity has a public/private key pair (pk,sk) for digital signatures, and its identity is represented by its pk. Following prior work [20], [28], [30], to against selfish mining attacks, we assume that at most 25% nodes can fail at any time point. We also assume that messages can be delivered within a certain bound  $\Delta$ . All notations in this paper are listed in Table 1.

Notation	Description			
С	client			
S	server			
CN	consensus node			
EN	execution node			
TX	transaction			
ST	state			
B	transaction block			
R	result block			
n	number of consensus nodes			
f	number of faulty consensus nodes			
m	number of execution groups			
n'	number of execution nodes in each group			
f'	number of faulty execution nodes			
v	view number			
sn	sequence number			
H()	cryptographic hash function			
pk/sk	public / private key			
Sign()/Verify()	signature generation / verification			
Aggre()	signature aggregation			
σ	signature			

Table 1 Summary of notations

#### 3.2 Parallel and asynchronous execution

Blockchain protocols are usually running in a sequential and blocking manner: a complex transaction (e.g., genetic algorithm in CryptoKitties) can congest the network so that simple transactions (e.g., cryptocurrency payments) cannot be confirmed on time. Asynchronous execution has been extensively used in web applications to improve performance and enhance responsiveness. It enables some tasks to be executed separately from the main task and notify the main thread when the execution is completed [3] In blockchain settings, *parallel and asynchronous execution* should satisfy the following requirements:

- 1) complex transactions should be executed in parallel;
- 2) avoid blocking simple transactions by complex ones.

Blockchain researchers have already begun to investigate the possibility of integrating parallel execution with blockchains [5], [16], [28], [30], [41]. They divide the blockchain nodes into different groups to process transactions in parallel. However, these solutions require extensive coordination among blockchain nodes: they require BFT within each group, and two-phase lock/commit among different groups. Specifically, transactions that involve data objects in different groups must be committed in two-phases: lock the data first and access them afterwards. If a transaction fails to acquire any of the locks, it releases all previously acquired locks and aborts. For each step of this two-phase protocol, every involved group needs to reach a Byzantine consensus.

Adversarial livelocks. Even though the above approach can prevent deadlocks, it raises the rate of aborted transactions due to lock contention (called livelocks), because transactions will abort when they compete for the same lock. Even worse, this problem also opens a channel for denial-of-service attacks: an adversary can easily abort other transactions by competing for locks. For example, two clients Alice and Bob share data objects  $o_1$  and  $o_2$  which are in two different groups  $G_1$  (near Alice) and  $G_2$  (near Bob) respectively. Suppose Bob wants to make a transaction  $TX_B$  to update both  $o_1$  and  $o_2$  ( $TX_B$  will first lock  $o_2$  and then lock  $o_1$ ). If Alice wants to make  $TX_B$  fail, she just needs to make a transaction  $TX_A$  to first lock  $o_1$  and then lock  $o_2$ . In this case, both  $TX_A$  and  $TX_B$  will fail and Alice wins. We name this attack *adversarial livelocks*.

**Group size.** As each group runs a BFT protocol, they require 3f'+1 nodes to tolerate f' faults (in each group). Based on the analysis in [28], each group requires at least 600 nodes to tolerate 25% adversarial power: Suppose all execution groups are randomly chosen from an infinite pool of potential ENs. We use binomial distribution to calculate the probability that an execution group is *not* controlled by the adversary:

$$P[f' < \lfloor \frac{n}{3} \rfloor] = \sum_{f'=0}^{\lfloor \frac{n}{3} \rfloor - 1} \binom{n}{f'} \alpha^f (1 - \alpha)^{n - f'} \tag{1}$$

where  $\alpha$ =25% is the adversarial power in the whole blockchain. In order to get a system failure probability that is less than  $10^{-6}$ , it requires at least 600 ENs in each group. The group failure probability is independent of the number of blocks being added to the chain. After a group being constructed, with a probability of  $10^{-6}$ , it is a "faulty group" (i.e., the number of failures is larger than f). This probability will stay the same even with more blocks being added to the chain.

**Design goals.** To this end, we want to design a paradigm for **parallel and asynchronous smart contract execution** with the following properties:

- 1) minimized size for each execution group;
- 2) no coordination among execution nodes;
- 3) no (adversarial) livelocks.

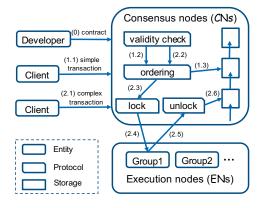


Figure 1. Overview and workflow of Saber.

## 4 SABER: PARALLEL AND ASYNCHRONOUS SMART CONTRACT EXECUTION

In existing blockchains, transaction execution is tightly coupled with consensus. We suggest that execution should be separated from consensus, which leads to Saber, a robust (e.g., livelock-free) and efficient paradigm for parallel and asynchronous smart contract execution. Fig. 1 shows the basic architecture and workflow of Saber. We distinguish between *consensus nodes* (denoted as CNs) and *execution nodes* (denoted as ENs); and we also distinguish between simple transactions (e.g., cryptocurrency payments) and complex transactions (e.g., smart contract execution):

- For a simple transaction, CNs
  - (1.1) check its validity,
  - (1.2) agree on its order,
  - (1.3) execute it (if needed) and update the blockchain;
- For a complex transaction, CNs
  - (2.1) check its validity,
  - (2.2) agree on its order,
  - (2.3) lock its associated states,
  - (2.4) assign it to an *execution group* and wait for the results, (they can keep processing simple transactions while waiting)
  - (2.5) collect the execution results,
  - (2.6) unlock the states and update the blockchain.

Notice that validity checking, transaction ordering and state locking can be done by CNs within one round of the underlying consensus protocol.

We leave it to the contract developers to decide whether a certain transaction should be simple or complex. A basic rule could be based on its execution time. Let  $t_1$  be the latency of one consensus round,  $t_2$  be the execution time of this transaction, k be the number of transactions being batched in one consensus round (cf. Section 6), and m be the number of execution groups. If

$$t_1 > \frac{k}{m} \cdot t_2$$

ENs will keep waiting for CNs. In this case, it is better to treat this transaction as a "simple" one.

Next, we explain how Saber works. Recall that Saber is a paradigm instead of a comprehensive protocol. We simplify some details (e.g., we use transactions instead of blocks) for the ease of understanding. A comprehensive protocol for permissionless blockchains is discussed in Section 6.

#### 4.1 Consensus nodes

The main job for CNs is to order transactions. We assume that there are m groups of ENs (selected by an unbiased randomness, cf. Section 6). CNs maintain a separate and independent sequence number for each of them:  $\langle sn_1,\ldots,sn_m\rangle$ . After gathering m complex transactions, CNs randomly assign each transaction to an execution group and increase the corresponding sequence number  $sn_i$ . Then, all CNs run the blockchain consensus to agree on  $\langle\langle \mathsf{TX}_1,sn_1\rangle,\ldots,\langle \mathsf{TX}_m,sn_m\rangle\rangle$ ; and send each  $\langle\mathsf{TX}_i,sn_i\rangle$  to the ith execution group. After execution, each execution group returns the execution result  $res_i$ . In the end, CNs put  $\langle\langle \mathsf{TX}_1,res_1,sn_1\rangle,\ldots,\langle \mathsf{TX}_m,res_m,sn_m\rangle\rangle$  into the ledger.

Notice that for *simple* transactions, CN directly put them into the ledger after ordering.

Other than ordering, CNs have three additional jobs: **State maintenance.** The global state of the data ledger is maintained by CNs. Namely, CNs run a Byzantine consensus protocol to ensure the consistency and availability of the data ledger. Meanwhile, CNs leave the execution to ENs and update the state based on the execution results. ENs can execute any transaction assigned to them, so that any transaction can be confirmed by one execution group within one round, instead of being divided into multiple transactions [28], [41]. This allows us to easily handle more complex transactions such as a smart contract calling other smart contracts. On the other hand, this requires every EN has access to the data ledger as well. We solve this issue in Section 6. Notice that the transactions and results are only written to the data ledger once. The structure of the ledger is the same as other blockchain protocols like Bitcoin or Ethereum.

Lock handling. There may be multiple transactions aiming to access the same state. If these transactions are assigned to different execution groups in one round, the state will diverge. We solve this problem by locking the state. Specifically, during the consensus round, CNs lock the states that this transaction wants to read/write. The locks are released only when the execution of this transaction is done. Other transactions that want to access these locks need to wait for the next round. Since all the locks are handled by CNs, there are no livelocks in our paradigm. A transaction locking all required objects gets executed and the locks will be released afterwards, i.e., no transaction can lock the acquired objects forever. A fundamental difference between livelocks and our locking scheme is: livelocks cause all related transactions fail and the attacker pays no transaction fee; in our case, an attacker locks all required objects can cause all other transactions fail, but she has to pay transaction fee. Monetary penalty is a common way to prevent denial-ofservice attack. With monetary penalty, a malicious client with resources to waste can still cause damage to the system. We remark that denial-of-service attack can happen in any smart contract system if the attacker is willing to waste resources. For example, in Ethereum, a malicious client with a fast network connection and willing to pay the gas fee, can always successfully call a smart contract and make other competing transactions fail. However, its consistency property will always be maintained. In this aspect, our scheme is equal to Ethereum.

The locks are specified by the contract developers (cf. Section 5). In particular, Fig. 4 shows how consensus nodes find the objects touched by a transaction without executing it. Developers are incentivized to reduce the gas consumption of their contracts. However, it is clearly useful if we can provide assistants for lock handling at the compiler level, so that it is easier for the developers to develop their smart contracts. We leave this as future work.

Validity checking. CNs are also responsible for checking the validity of the gathered transactions, e.g., whether a client has enough balance to make a payment, whether the required state of a transaction is locked etc. A transaction will be ignored if it cannot pass the validity checking. An alternative way of separation is to leave the validity checking to ENs. However, this leads to a denial-of-service attack which is similar to livelocks. Suppose Bob wants to make a transaction  $\mathsf{TX}_B$  to update an object  $o_B$  and he is the only one who has write permissions. Alice has a faster network connection and wants to delay the execution of  $\mathsf{TX}_B$  for k rounds. Then, Alice just needs to issue k transactions to update  $o_B$  in front of  $\mathsf{TX}_B$ . In each round, only one of these k transactions will be forwarded to ENs and the rest will be cached. In this case,  $\mathsf{TX}_B$  has to wait for k rounds until all Alice's transactions got rejected. In contrast, if we have CNs check the validity, they will immediately find all these k transactions are invalid and reject them in one round.

#### 4.2 Execution nodes

It is enough to have ENs execute  $TX_i$  directly if  $sn_i$  is sequential to the sequence numbers they have seen. This is based on the fact that, for each execution group, CNs can never assign the same sequence number to different transactions due to the underlying consensus. Therefore, we only need to make sure that the execution results returned by ENs are correct. However, in each execution group, some ENs may be faulty and they may return results that are different from the ones returned by correct ENs. In this case, CNs need to resolve this dispute and decide which result to follow. In the rest of this section, we will introduce several existing solutions as well as our solution, and we will also provide a comparison.

**Verifiable computation.** *Verifiable computation* allows a *delegator* to outsource the execution of a complex function to some *workers*, and the delegator verifies the correctness of the returned result while performing less work than executing the function itself. The state-of-the-art solution for verifiable computation in cryptography is based on *succinct non-interactive argument of knowledge* (SNARK) [8], [32]. It allows the worker to provide a constant-size proof for the correct evaluation of a *circuit*. In these cases, each execution group only requires (f'+1) ENs (workers), because each EN can only crash but cannot return wrong results. However, such solutions usually require a trusted setup, and the overhead for generating and verifying the proof is still too large to use in practice.

**Trusted execution environments (TEEs).** Another solution for verifiable computation is via TEEs [2] (such as ARM TrustZone [1] and Intel's SGX [24]), which provide protected memory and isolated execution so that adversaries can neither control nor observe the data being stored or processed inside them. SGX also allows remote verifiers to ascertain the current configuration and behavior of a device via *remote attestation*. Therefore, we can assume that each EN has a TEE and CNs only trust the results that are executed and signed by TEEs. Same as the zk-SNARK based solution, each execution group requires (f'+1) ENs.

Interactive verification. This solution was initially proposed by Canetti et al. [12]; later adopted by TrueBit [37] and Arbitrum [25]. If two ENs return different results, all CNs will collectively run as a judge and launch an interactive verification game where they have one EN act as a solver and the other as a challenger. The game proceeds in a series of rounds and each round narrows down the range of the execution in this dispute. In each round, the challenger challenges a subset of the solver's execution, and it

challenges a subset of that set in the next round, until the judge can make a final decision on whether the challenge was justified. In the end, either the cheating solver will be discovered and punished or the challenger will compensate for the resources consumed by the false alarm. This solution introduces logarithmical number of rounds in terms the complexity of the function, and each round requires CNs to reach a consensus. It requires at least one correct EN (and f' + 1 in total) in each execution group to be the challenger. Majority voting. We adopt the simplest way for dispute resolution. Assuming honest majority (2f' + 1) in each execution group, if more than half of ENs in each group return the same result, this result must be correct. Notice that CNs plus a single execution group exactly match the architecture proposed by Yin et al. [40]: CNs correspond to the agreement cluster, and the group corresponds to the execution cluster. Even though we have multiple "execution clusters", the "agreement cluster" maintains a separate sequence number for each of them and there is no co-ordination among them. Therefore, this system can be considered as m instances of the system proposed in [40] running in parallel. Following the analysis in Section 2.2 (equation 3), it requires 70 ENs in each execution group to reach a failure probability of  $10^{-6}$ .

#### 5 ASYNCHRONOUS EXECUTION FOR ETHEREUM

In this section, we show how we can add parallel and asynchronous execution to Ethereum without any hard-forks. We follow the architecture of Saber (Fig. 1): there are consensus nodes CNs and execution nodes ENs. We design a standard Ethereum smart contract for the Saber execution management. Any Ethereum developer who wants to make their contract support our paradigm needs to include this contract and use the functionality exposed via its interface for their contract development. CNs are the original Ethereum miners collectively, and they are also allowed to register with the execution management contract and run as ENs. That means the separation is only in logic. CNs run the standard Ethereum protocol as they are and the contract code will handle the execution. Since we only require 70 ENs to execute a transaction, the gas usage is much lower. Notice that the inputs and outputs of transactions are recorded in the blockchain state, and the code of smart contract is also publicly available. Therefore, new nodes that want to download and validate the entire chain can simply take the inputs, feed them into the contract code, and check if the execution results are consistent with those executed by ENs.

#### 5.1 Execution management

Fig. 2 shows the pseudocode of the execution management contract. We use a pk list to record the identities of the nodes that have been registered with this contract as ENs (line 2). Recall that each node is identified by its pk. and we assume that the pks can be used to verify multisignatures (line 19). The gas consumption for signature verification is constant, independent of the complexity of the smart contract. So using signature verification instead of execution is worthwhile for complex smart contracts.

Any Ethereum node can register as an EN by calling the *Register* function (line 8). For sybil-resistance, we require EN

to deposit some Ether to this contract account: misbehaving ENs will get punished in the same way as in proof-of-stake; otherwise they will get some transaction fees as the miners. ENs are stored in the pk list in an order according to the deposit they put, i.e., the one who deposits most will be in the head of the list.

ENs are uniformly and periodically assigned to different execution groups (line 3) via the Shuffle function (line 12). After every epoch (e.g., 1,000 confirmations), all ENs (or a subset of them) jointly run a distributed randomness generation protocol off-chain to generate an unbiased random number r. Then, they input r to the *Shuffle* function, which verifies r first (recall that one property of this randomness is third-party verifiable), re-assigns each EN to an execution group based on pk and r (line 15). Note that ENs who deposit more will also be assigned in the head of each execution group, i.e., groups[i][0] is the leader of groups[i]. Recall that each execution group requires (2f' + 1) ENs due to the requirement for majority voting. In Bitcoin or Ethereum, CNs not only make money from mining, but also from transactions fees. In our paradigm, we can distribute the transaction fees to ENs.

```
1: contract ExecutionManager
 2:
        pk[] ENs
 3:
        pk[][] groups
 4:
        TX[][] tasks
 5:
                                                               ⊳ initialized as 0
        int sid
 6:
        int m
                                               > number of execution groups
 7:
 8:
        function Register()
 9.
           add caller's pk to ENs
10:
        end function
11:
        function Shuffle(r)
12:
13:
           verify r; empty groups
14:
           for each EN in ENs
               i \leftarrow H(r, \mathsf{EN}) \bmod m; add EN to groups[i]
15:
        end function
16:
17:
18:
        function multisignature\_verify(i, M, \tilde{\sigma})
19:
            return Verify(groups[i], \tilde{\sigma}, M)
20:
        end function
21:
22:
        function signature_verify(i, j, M, \sigma)
            \textbf{return Verify}(\textit{groups}[i][j], \sigma, M)
23:
24:
        end function
25: end contract
```

Figure 2. Execution management for Ethereum.

#### 5.2 Running example: CryptoKitties

We take CryptoKitties as a running example to explain how to use Saber for parallel and asynchronous Ethereum contract execution without hard-forks. CryptoKitties is a popular game built on the Ethereum blockchain [15], which allows players to buy, collect, breed and sell digital cats. Fig. 3 shows the pseudocode of its contract with only a *giveBirth* function (adapted from [18]), which runs an expensive gene mixing algorithm to create a new cat (line 7). This complex genetic algorithm has clogged the Ethereum network recently: the number of unconfirmed transactions has remained consistently above 15,000 [38]. Next, we show how to improve the throughput by executing the *giveBirth* function in a parallel and asynchronous manner.

```
1: contract CryptoKitties
 2:
        Kitty[] kitties
 3:
 4:
        function giveBirth(matronID)
 5:
            matron \leftarrow kitties[matronID]; check matron's validity
            sireID \leftarrow matron.siringWithID; sire \leftarrow kitties[sireID]
 6:
 7:
            childGenes \leftarrow mixGenes(matron.genes, sire.genes)  \triangleright expensive
            kitten \leftarrow creatKitty(childGenes); add kitten to kitties
 9.
        end function
10: end contract
```

Figure 3. Original CryptoKitties.

Fig. 4 shows the Saber-version of CryptoKitties contract. It has a variable called em, which is initialized with the contract address of ExecutionManager (line 2). Therefore, we can directly use the ExecutionManager contract via em. A transaction TX calling the giveBirth function will call the giveBirth\_lock function instead (line 6). CNs first check if the targeted matron has been locked (line 7), i.e., being accessed by other transactions. If not, they check matron's validity (line 10), e.g., whether it is a valid cat, whether it is pregnant, and whether its time has come. Then, they designate an idle execution group for the execution of TX (line 10). They also record the current block number, i.e., height of the current blockchain (line 12). Next, they lock this matron by putting \( \text{matronID}, \, \text{groupID}, \text{blockNum,TX} \) into the locks array (line 13), and put TX into the tasks array of the designated execution group (line 14). Finally, they put this transaction into the ledger and update the state, as normal Ethereum miners.

Once TX is confirmed on the blockchain, each  $\mathsf{EN}_i$  in the designated execution group runs the mixGenes function off-chain, signs the result childGenes, and sends the signature  $\sigma_i$  to the group leader groups[i][0]. The group leader combines the received 2f'+1 signatures into a single multisignature  $\widetilde{\sigma}$ , and issues another transaction TX' calling the  $giveBirth\_unlock$  function. If other ENs in groups[i] did not see TX' after a timeout, they send  $\sigma_i$ s to the second leader groups[i][1], so on and so forth, until TX' appears.

Upon receiving TX', CNs first check if TX has been confirmed and verify the multisignature  $\tilde{\sigma}$  (line 22). Then, they add the new *kitten* to the *kitties* array (line 23), unlock *matronID* (line 24) and remove TX from *tasks* (line 25). Recall that all ENs are acting as CNs as well. So all ENs' states converge at this point even though they are in different execution groups.

#### 6 SABERLEDGER

In this section, we propose a new public and permissionless blockchain called SaberLedger. Its overview is shown in Fig. 5. Labels show the workflow: the client first sends transactions to CNs (1.1); CNs forward the transactions to ENs (1.2); ENs read the state from the distributed storage (1.3) and return the execution results to CNs (1.4). After an epoch, CNs run randomness beacon the rotate CNs as well as ENs (2.1); ENs write back their cached sate to the storage (2.2). Overall, SaberLedger follows the Saber paradigm with the following augmentations:

1) batch processing by putting transactions into blocks;

```
1: contract SaberCryptoKitties
        Execution Manager\ em
                                    ▷ initialized with the contract address
 2:
 3:
        Kitty[] kitties
 4:
        \langle int, int, int \rangle[] locks
                                             ▷ ⟨kittyID, groupID, blockNum⟩
 5:
        function giveBirth_lock(matronID)
 6:
 7:
           if matronID is in locks
 8:
              cache TX; return

    ► TX is the calling transaction

           else
10:
               check kitties[matronID]'s validity; groupID := em.sid
11:
               em.sid := (em.sid + 1) \mod em.m
12:
               blockNum := current_block_number
13:
               add \(\rmatronID, groupID, blockNum\)\) to locks
               add TX to em.tasks[groupID]
14:
15:
        end function
16:
       ▷ Nodes in groups[groupID] execute TX off-chain and generate a
17:
    multisignature \tilde{\sigma} for \langle childGenes, TX \rangle
18:
19:
       function giveBirth\_unlock(matronID, childGenes, <math>\tilde{\sigma})
20:
           if matronID is in locks
21.
               get groupID, blockNum and TX from locks
22:
               return if (current_block_number) - blockNum < 13 or
    em.multisignature_verify(groupID, \langle childGenes,TX \rangle, \widetilde{\sigma}) is false
23:
               kitten ← creatKitty(childGenes); add kitten to kitties
24:
               remove (matronID, groupID, blockNum) from locks
25:
               remove TX from em.tasks[groupID]
26:
        end function
27: end contract
```

Figure 4. CryptoKitties in Saber paradigm.

- 2) proof-of-stake (PoS) for sybil-resistant identities;
- 3) BFT for the underlying consensus;
- 4) epoch transitions via a randomness beacon;
- 5) "state sharding" via a distributed storage.

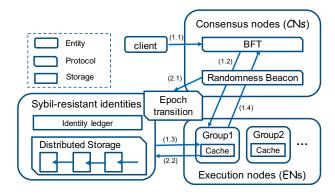


Figure 5. Overview of SaberLedger.

#### 6.1 Identity management and epoch transitions

All nodes maintain a separate ledger called *identity ledger* to record the sybil-resistant identities. One can get all the required pks from the identity ledger. This ledger can be implemented as a smart contract that is similar to Fig. 2. Any user can participate in SaberLedger (i.e., become a sybil-resistant identity) by generating a key pair locally and making a deposit to this contract. Their identities are recorded in a pk list. The identity ledger also has a separated pk lists to record CNs and groups of ENs for all epochs.

We assume that an initial set of CNs was chosen in the bootstrapping phase of the system, and they run a distributed randomness generation protocol (i.e., randomness beacon, cf. Section 2) to generate an unbiased random number to build m execution groups, each of which has n'=2f'+1 ENs. All participants are ranked according to the deposit they put, and the execution groups are built in the same way as in Section 5 (line 15 in Fig. 2). Each execution group has a leader which is the one who deposits most in that group.

To prevent an adaptive adversary from compromising more than a threshold number of CNs, as well as ENs in each execution group, we need to periodically rotate them from the underlying sybil-resistant identities. After an epoch, CNs run the randomness generation protocol again to rotate CNs and ENs. The duration for each epoch depends on the required time for an adaptive adversary to compromise a node. Following OmniLedger [28], we only rotate a subset of nodes to minimize the chances of a temporary loss of liveness. After rotating, they move to the next epoch.

#### 6.2 "State sharding" via a distributed storage

SaberLedger further shards state by storing the blockchain in a distributed storage maintained by all nodes in the system. Specifically, all nodes run a distributed storage (e.g., IPFS [9]) that only supports *read* and *write* operations. CNs need to keep track of the version numbers and hashes of the last write operation for each state.

Upon receiving a complex transaction associated with some states ST (e.g., *matron* in Fig. 3), CNs only forward TX and the version numbers of ST to ENs, who read ST from the distributed storage and make sure the version numbers match. Then ENs execute the transaction and write the updated states ST' back to the distributed storage, which accepts ST' only if it has been signed by all ENs in that execution group. ENs will notify CNs when the writing is done. After receiving the notification from ENs, CNs check the version numbers of the states from the storage and unlock the states if the version numbers are correct.

To reduce write frequency, ENs cache all the updated states and write them to the storage once. Naively, after execution, the execution nodes need to write back the state to the storage immediately so that followup transactions access this state can be executed. However, this requires the execution nodes read and write the state very frequently, introducing a large overhead. To avoid this, we have the execution nodes cache the state, and have the consensus nodes forward the followup transactions to the execution group holding the corresponding state. In this case, CNs keep track of which ST have been assigned to which execution group, and keep forwarding the transactions that are associated to that ST to the same execution group. This works except that there is a transaction that is associated to ST and ST' which have been assigned to two different execution groups. In this case, CN will notify these two groups to write back ST and ST' to the storage.

#### 6.3 Consensus and execution

As in BFT, clients send transactions to the primary consensus node  $\mathsf{CN}_p$  (cf. Section 2). If their transactions did not appear on the blockchain (in the distributed storage)

after a timeout, they send those transactions again to all CNs

After gathering enough transactions,  $\mathsf{CN}_p$  puts the valid ones into *transaction blocks*. For simple transactions like cryptocurrency payments,  $\mathsf{CN}_p$  put them into a single transaction block B. Then, all  $\mathsf{CNs}$  together run BFT to put B into the distributed storage.

For each complex transaction  $\mathsf{TX}_i$ ,  $\mathsf{CN}_p$  finds all its associated states  $\mathsf{ST}_i$  and locks them (in a way as shown in Fig. 4). Other transactions requiring  $\mathsf{ST}_i$  have to either be assigned to the same execution group or wait for the next round. Then,  $\mathsf{CN}_p$  puts all transactions arbitrarily and uniformly into m transaction blocks  $\langle B_1, \ldots, B_m \rangle$  and assigns a sequence number  $sn_i$  to each  $B_i$ . Recall that  $\mathsf{CNs}$  maintain a separate and independent sequence number for each execution group.

 $\mathsf{CN}_p$  sends  $\langle\langle B_1,sn_1\rangle\dots,\langle B_m,sn_m\rangle\rangle$  to all other CNs, who will check the validity of all  $\langle\mathsf{TX}_i,\mathsf{ST}_i\rangle$ s and also check if there are multiple transactions in different blocks accessing the same state. Then all CNs run BFT to agree on the proposal. In the end of the BFT round, they generate a commit certificate CC (cf. Section 2) for each  $\langle B_i,sn_i\rangle$ .

Next,  $\mathsf{CN}_p$  sends each  $\langle B_i, sn_i, CC \rangle$  to all ENs in the ith execution group. To distribute the loads, the leader in each execution group coordinates the communication between  $\mathsf{CN}_p$  and ENs. Specifically,  $\mathsf{CN}_p$  only sends  $\langle B_i, sn_i, CC_i \rangle$  to the group leader, who further distributes them to all ENs in that group. Then, each EN reads the states from the distributed storage and executes the transactions in  $B_i$  following the same order as they are being put into  $B_i$ , updates the corresponding states, and puts the updated states into a result block  $R_i$ . It also generates a signature for  $\langle R_i, sn_i \rangle$ . The group leader gathers signatures from ENs and returns  $\langle R_i, sn_i, \widetilde{\sigma}_i \rangle$  to all ENs, where  $\widetilde{\sigma}_i$  is a multisignature signaling that  $\langle R_i, sn_i \rangle$  has been output by all ENs in that execution group. ENs write  $\langle R_i, sn_i, \widetilde{\sigma}_i \rangle$  back to the distributed storage or their local cache, and notify  $\mathsf{CN}_p$ .

Recall that we follow the same architecture as [40]: the agreement job of consensus nodes is to order clients' requests via a standalone BFT protocol (e.g.,PBFT), send the ordered requests to the execution nodes, and relay replies to the clients. Then,  $\mathsf{CN}_p$  is exactly the BFT primary in [40], and the view change procedure of BFT works for  $\mathsf{CN}$  as well.

#### 7 IMPLEMENTATION AND EVALUATION

#### 7.1 Experimental setup

In order to systematically evaluate the performance of SaberLedger, we build a simulation framework allowing us to easily define the conditions and control the experiments.

First, we setup a cluster of 3,467 Amazon EC2 t2.micro VMs across 15 regions and 5 continents to introduce real network latency. Each VM contains 1 2.3GHz vCPU, 1 GB memory and runs Amazon Linux 2.

Second, we assign 70 ENs to each execution group, which leads to a group failure probability of less than  $10^{-6}$ , base on the analysis in [28]. As a comparison, existing sharding protocols require  $\sim\!600$  nodes to reach the same failure probability, because they require at least 3f'+1 nodes in each shard. We only require 2f'+1 nodes in each group.

We can easily change the group size to make a trade-off between robustness and efficiency.

Third, we run SputnikVM [17] – a blockchain virtual machine for Ethereum – on each EN, so that we can test SaberLedger with different types of Ethereum transactions ranging from simple cryptocurrency payments to CryptoKitties gene mixing algorithm. Furthermore, we store the blockchain state in IPFS [9], but we cache the state as we discussed in Section 6.2.

Last, recall that the bottleneck of SaberLedger is its consensus layer. To this end, we make the consensus layer as a parameter as well. We simulate the consensus layer by having it agree on a 1 MB block for every consensus round, with different rates:

- 0.1 rounds/s, which corresponds to the performance of current PoW-based or PoS-based consensus.
- 1 rounds/s, which corresponds to the performance of current BFT consensus, e.g., PBFT [13], Byzcoin [27].
- 10 rounds/s, which conjectures the future of consensus protocols, e.g., EOS [23] and others.

Assuming 1 MB block contains 2,000 transactions (following Bitcoin and OmniLedger [28]), these consensus layers correspond to different throughputs of 200 TX/s, 2,000 TX/s and 20,000 TX/s<sup>2</sup> respectively. The advantage of this setup allows us to easily use different consensus layers.

To better compare SaberLedger with previous state-ofthe-art, we set three baselines for our benchmarks:

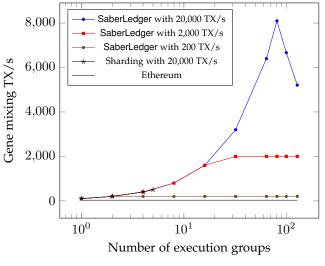
- Throughput of current Ethereum, i.e., 30 TX/s at most.
- Throughput of Ethereum-like systems with different consensus layers, i.e., 200 TX/s, 2,000 TX/s and 20,000 TX/s respectively (for simple transactions).
- Throughput of current sharding protocols with different consensus layers, i.e., 200 TX/s, 2,000 TX/s and 20,000 TX/s respectively (for simple transactions).

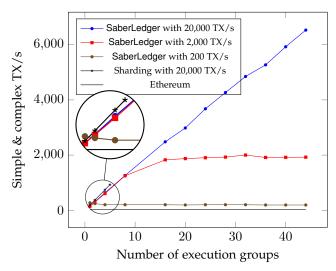
Our evaluation captures the setting with failures: if crash nodes is fewer than f', performance is unaffected. If it is more (or if a group cannot be formed), consensus nodes just stop forwarding requests to that group and wait for the next epoch to rotate groups. This only results in fewer groups. The worst case performance can be shown from the results of only one execution group. However, we assume this case rarely happens because faulty nodes will get punished.

#### 7.2 Evaluation results

**Performance with complex transactions.** We first assume that all the workloads are complex transactions (i.e., Cryptokitties gene mixing), which gives us an estimate on the lower bound performance of SaberLedger. We run the experiments with a varying number of execution groups and measure the peak throughput (TX/s) when the system is saturated. Note that each EN will receive a transaction block of size  $\frac{1}{m}$  MB, where m is the number of execution groups. Intuitively, the workload for each EN decreases as m increases. The results shown in Fig. 6(a) validate this conjecture: as more execution groups being added, the

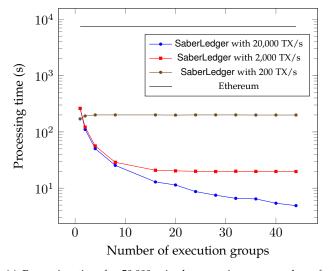
2. Notice that this throughput cannot be achieved by current public blockchains. For example, current CPU can only verify  $\sim$ 3,500 ECDSA signatures per second. However, this figure is used to conjecture the future of consensus protocols.

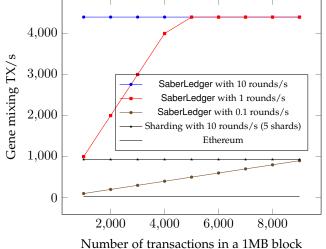




(a) Throughput for gene mixing transactions vs. number of execution groups. (2,000 transactions in 1MB block).

(b) Throughput for real-world workloads with a mix of simple and complex transactions vs. number of execution groups. (2,000 transactions in 1MB block)





execution groups. (2,000 transactions in 1MB block)

(c) Processing time for 50,000 mixed transactions vs. number of (d) Throughput for gene mixing transactions vs. batch sizes (44 execution groups).

Figure 6. Evaluation results.

performance of SaberLedger keeps increasing until reaching the bottleneck of the consensus layer. Specifically, for a fast consensus layer (20,000 TX/s, blue line), the throughput of SaberLedger increases until reaching a throughput of 8,100 TX/s, after which the signature verification becomes a bottleneck. For a medium consensus layer (2,000 TX/s, red line), its throughput increases linearly until it reaches the bottleneck of its consensus layer when the number of the execution groups is 20. For a slow consensus layer (200 TX/s, brown line), its throughput is almost the same as its consensus layer. As a baseline, we also show the throughput of Ethereum, which is below 30 TX/s. In principle, the throughput of Ethereum should be similar with the brown line. However, in Ethereum, each block on average only batches 100 transactions due to the total gas limit for each block. In SaberLedger, we can set a much higher gas limit and batch more transactions in one block, since each EN is only required to execute a subset of transactions. Remarks:

- SaberLedger can achieve a high throughput even for complex transactions like Cryptokitties gene mixing.
- When there is no separation (the case of one execution group), even if the consensus layer is fast (20,000 TX/s), the throughput is still very low (100 TX/s).
- Recall that sharding protocols require 600 nodes in each shard. With 3,467 nodes (5 shards), sharding protocols can reach a throughput of at most ~500 TX/s, even with a fast consensus layer (20,000 TX/s). With the same number of nodes and consensus layer, SaberLedger can reach a throughput of 4,201 TX/s. This demonstrates the prominent advantages of separating execution from consensus.

Performance with mixed workloads. In SaberLedger, simple transactions like cryptocurrency payments are confirmed asynchronously, independent of complex transactions. Therefore, the advantage of SaberLedger will become more prominent if we consider real-world workloads that mix simple transactions with complex transactions. To this

end, we retrieve around 50,000 transactions of recent 500 Ethereum blocks (from height 5,998,827 to 5,999,326) from Etherscan [19], and run these transactions on SaberLedger. To be conservative, we treat all contract invocations as complex transactions and assign them to different execution groups; and we treat cryptocurrency payments as simple transactions and confirm them directly in consensus layer. We check if the sender or receiver address is a contract address by querying Etherscan's API. Among these transactions, 47% of them are simple and 53% of them are complex. Furthermore, we treat two transactions as "conflict" as long as they are invoking the same contract, and one of them will be cached for the next round. Fig. 6(b) shows that the peak throughput of SaberLedger for mixed transactions is significantly higher than only considering complex transactions (in Fig. 6(a)). For example, when the number of execution groups is 32, SaberLedger can process another 1,000 simple transactions in addition to 3,200 complex transactions (for fast consensus). Fig. 6(c) shows that it takes 7s-7min for SaberLedger to process all these 50,000 transactions depending on the number of execution groups and consensus layer. As a comparison, by inspecting the timestamps on the Ethereum blockchain, we found Ethereum requires 2 hours to finish processing these transactions. Remarks:

- Asynchronous execution can effectively protect simple transactions from being starved by complex transactions, thus significantly improving the throughput.
- In Ethereum-like systems or sharding protocols, complex transactions can block the processing of simple transactions. In the worst case, simple transactions have to wait until all complex transactions to be executed (at least 53 seconds).

Performance with a varying number of transactions in one 1MB block. As we mentioned, SaberLedger can have a higher gas limit and batch more transactions in one block. In principle, 1MB block can include around 9,000 Ethereum transactions<sup>3</sup>. So the throughput of SaberLedger can be improved if we batch more transactions in every block. To this end, we set both the number of execution groups and the group size as constants (44 execution groups) and run experiments with different batch sizes. Fig. 6(d) shows that, for a slow consensus layer (200 TX/s, brown line), its throughput increases linearly as the batch size increases. For a medium consensus layer (2,000 TX/s, red line), its throughput increases linearly until it reaches the bottleneck of its execution layer (around 4,400 TX/s). For a fast consensus layer (20,000 TX/s, blue line), the throughput of SaberLedger is exactly the same as its execution layer. **Remarks:** 

- As the throughput for consensus layer increases, the execution layer becomes a bottleneck. However, we conjecture that the blockchain network will become larger in the future. So we can introduce more execution groups.
- For Ethereum-like systems and sharding protocols, increasing the batch size have no significant effect on throughput, as execution is the bottleneck and it blocks the processing.

#### 8 RELATED WORK

Hybrid consensus Another solution to avoid having all nodes execute all transactions is hybrid consensus [4], [27], [33], which uses a slow permissionless blockchain protocol to bootstrap a fast permissioned blockchain protocol. For example in [27], a committee is elected by sliding a fixedsize window over a permissionless blockchain. Then, nodes in the committee run a BFT protocol to agree on the order of transactions and execute them, and other nodes just follow the results. They achieve Visa-level throughput for cryptocurrency payments. However, execution is still a bottleneck for smart contracts that require expensive executions. HyperLedger Fabric Researchers in IBM propose an execute-order-validate paradigm for their permissioned blockchains [7]. In their paradigm, clients send transactions to multiple execution nodes (called endorsers, which is specified by the smart contracts) first. The endorsers execute the transactions independently and return the signed results (called endorsement) to the clients. Each client collects endorsements until reaching the endorsement policy, and then submits them to a BFT-based ordering service, which establishes a total order on all endorsements and atomically broadcasts them. Compared with our consensus nodes, their ordering service is more generic: only does ordering but leaves the validation and ledger updates to the receivers. This paradigm supports parallel execution, but suffers from the same livelock issues as the sharding approaches: different endorsers may execute the same set of transactions in different order, in which case, all transaction fail as it requires multiple endorsers to produce the same result.

**ParBlockchain** Amiri et al. [6] propose a similar order-execute paradigm called OXII, based on which, they propose a permissioned blockchain called ParBlockchain. However, they do not have multiple execution groups, instead, all execution nodes execute all transactions (cf. Figure 2 and 3 of [6]). As a result, SaberLedger has a much higher level of parallelism. Furthermore, in ParBlockchain, each execution nodes needs to multicast the execution results to all others, which introduce  $O(n^2)$  communication complexity, whereas we have O(n) communication complexity.

TrueBit and Arbitrum TrueBit [37] and Arbitrum [25] also target the execution issues for smart contracts. They also delegate the execution to a set of execution nodes and use interactive verification to resolve dispute (cf. Section 4.2). As we discussed, the dispute resolution strategy in Saber requires much less communication as well as coordination between consensus nodes and execution nodes. In addition, Saber further considers lock handling, which was ignored in TrueBit and Arbitrum. Table 2 summarizes the comparisons between SaberLedger and related work.

#### 9 LIMITATIONS

Regardless of the various benefits brought by our paradigm, we have to admit that it has two limitations. First, it changes the coding paradigm of smart contracts: the contract developers need to enumerate all dependencies when they develop the contract. It is clearly useful if we can provide assistants for lock handling at the compiler level, so that it is easier for the developers to develop their smart contracts. We leave this as future work. The second limitation is that

	No livelocks	No intra-shard co-ordination	No inter-shard co-ordination	# BFT rounds
Sharding [36] [28] [5]	Х	Х	Х	3
HyperLedger [7]	Х	<b>√</b>	<b>√</b>	1
ParBlockchain [6]	-	√	-	1
TrueBit/Arbitrum [37] [25]	-	<b>√</b>	-	logarithm
SaberLedger	√	√	√	1

Table 2 Comparison with related work.

the monetary counter-incentive can only alleviate denial-ofservice attacks, instead of totally eliminating them.

#### 10 CONCLUSION

In this paper, we propose a novel paradigm for parallel and asynchronous smart contract execution. It neither requires extensive coordination nor suffers from (adversarial) livelocks, and it requires a small group size. We propose two ways to put this paradigm into practice. We first apply it to Ethereum and show that we can make Ethereum support parallel and asynchronous execution without any hardforks. Then, we propose a new public and permissionless blockchain SaberLedger, and show its performance by implementing a prototype.

#### **ACKNOWLEDGMENTS**

The work was supported in part by Zhejiang Key R&D Plans (Grant No. 2021C01116, 2019C03133), National Natural Science Foundation of China (Grant No. 62002319, U20A20222) as well as a grant from China Zheshang Bank.

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Dawn Song is a Professor in the Department of Electrical Engineering and Computer Science at UC Berkeley. Her research interest lies in AI and deep learning, security and privacy. She is the recipient of various awards including the MacArthur Fellowship, the Guggenheim Fellowship, the NSF CAREER Award, the Alfred P. Sloan Research Fellowship, the MIT Technology Review TR-35 Award, and Best Paper Awards from top conferences in Computer Security and Deep Learning. She is an ACM Fellow and an

IEEE Fellow. She is ranked the most cited scholar in computer security (AMiner Award). She obtained her Ph.D. degree from UC Berkeley. Prior to joining UC Berkeley as a faculty, she was a faculty at Carnegie Mellon University from 2002 to 2007. She is also a serial entrepreneur and has been named on the Female Founder 100 List by Inc. and Wired25 List of Innovators.



Jian Liu is a ZJU100 Young Professor at Zhejiang University. Before that, he was a post-doctoral researcher at UC Berkeley. He got his PhD in July 2018 from Aalto University. His research is on Applied Cryptography, Distributed Systems, Blockchains and Machine Learning. He is interested in building real-world systems that are provably secure, easy to use and inexpensive to deploy.



**Peilun Li** received the BE degree from the Institute for Interdisciplinary Information Sciences, Tsinghua University, China, in 2015. He is currently working towards the PhD degree in the Institute for Interdisciplinary Information Sciences, Tsinghua University, China. His current research interests include distributed systems and blockchains.



Raymond Cheng is an Adjunt Faculty in the Department of Computer Science at the University of San Francisco. Before that, he was a Co-Founder and CTO of Oasis Labs and a post-doctoral researcher at UC Berkeley. He got his PhD from University of Washington and M.Eng and B.S. from MIT. He has contributed novel research papers in the areas of distributed systems and security, most recently in the area of privacy-preserving systems that give users better control over their data and spread digital

freedom of speech and information to citizens around the world.



N. Asokan is a Professor of Computer Science at the University of Waterloo (since 2019) where he holds a David R. Cheriton Chair. He is also an adjunct professor at Aalto University. He was a Professor of Computer Science at Aalto University from 2013 to 2019 and at the University of Helsinki from 2012 to 2017. Between 1995 and 2012, he worked in industrial research laboratories designing and building secure systems, first at the IBM Zurich Research Laboratory as a Research Staff Member and then at Nokia

Research Center, most recently as Distinguished Researcher. He is an ACM Fellow and an IEEE Fellow.