Prism Removes Consensus Bottleneck for Smart Contracts

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Abstract—The performance of existing permissionless smart contract platforms such as Ethereum is limited by the consensus layer. Prism [1] is a new proof-of-work consensus protocol that provably achieves throughput and latency up to physical limits while retaining the strong security guarantees of the longest chain protocol. This paper reports experimental results from implementations of two smart contract virtual machines, EVM and MoveVM, on top of Prism and demonstrates that the consensus bottleneck has been removed. Code can be found at https://git.sr.ht/~prism-smart-contract/prism-smart-contract.

I. INTRODUCTION

Existing permissionless smart contract platforms such as Ethereum is based on the longest chain consensus protocol, the original blockchain protocol invented by Nakamoto [2]. While maintaining high security against adversarial attacks, it is well known that the longest chain protocol suffers from poor throughput and latency performance. Hence, the performance of these platforms are limited by the consensus layer.

This limitation has led to practical congestion in the network; a noteworthy instance occurred when CryptoKitties made its debut on Ethereum, a spike of transactions rushed into the system, far exceeding Ethereum’s supported throughput. The pending transaction queue was growing quickly, and users had to increase transaction fees to incentivize miners to add their transactions to the chain. Decentralized Finance applications have been rapidly growing over the last few years and as it gets more popular in the near future, the demand will continue to grow, making the performance scaling of smart contract platforms an urgency.

Several promising efforts to scale the performance have been proposed. Almost every major live smart contract platform such as Ethereum, Algorand, and Tron are optimizing their existing smart contract engines to increase the throughput. A few others like Libra (led by Facebook) and Hyperledger (led by IBM) have taken the route of permissioned blockchains to obtain higher throughput. On the other hand, Ethereum foundation has taken the sharding approach and will roll out Ethereum 2.0 [3] with the major goal of scaling Ethereum’s smart contract platform to support higher throughput. Optimistic Rollup [4], ZK-Rollup [5], and Arbitrum [6] are other off-chain scaling solutions built on top of an existing smart contract platform such as Ethereum. In these off-chain solutions, not every validator node needs to keep track of the execution of the off-chain contracts, which leads to an improved overall efficacy but at the expense of security.

Prism [1] is a recent permissionless proof-of-work (PoW) consensus protocol which naturally scales the performance of the longest chain protocol. It provably achieves throughput and latency up to computation and communication limits of the underlying physical network, while retaining the strong security guarantees of the longest chain protocol. An implementation of Prism [7] scales performance significantly in a Bitcoin-like payment system, improving the throughput of Bitcoin by about 4 orders of magnitude. The question remains as to whether Prism can successfully support a general smart contract platform and remove the consensus bottleneck.

Not every blockchain consensus protocol can integrate with smart contract platforms. For example, SPECTRE [8] is a DAG-based high throughput consensus protocol designed for payments. However, it does not provide a total order of transactions and this makes it difficult to integrate with smart contracts which require total ordering of transactions.

This paper demonstrates that Prism can support general smart contract platforms and provide desirable security and performance. We present the design and implementation of Prism that provides a flexible interface for connecting most common smart contract virtual machines. We report experimental results from implementation of two smart contract virtual machines, Ethereum VM (EVM) and MoveVM, on top of Prism. Fig. [1a] shows throughput results for running several canonical smart contract applications on EVM on Prism, while Fig. [1b] shows analogous results for MoveVM on Prism. As can be seen, the throughputs are very close to that of virtual machine execution only without consensus, and much larger than the throughput using the longest chain protocol. Thus, we conclude that smart contract platforms built on Prism can perform without the consensus layer bottleneck.

The rest of this paper is structured as follows. In §II we discuss smart contract scaling approaches in different dimensions. §III gives a brief overview of Prism consensus protocol. In §IV we describe our design and implementation of Prism with EVM and MoveVM. We present evaluation results of various canonical applications in EVM and MoveVM, and discuss their implications in §V. Conclusion is in §VI.
The throughput of blockchains with smart contract platform can be increased at three different points on the blockchain stack. The first approach is to improve the execution speed of the virtual machine engine. A basic approach is to optimize the execution of individual op codes (followed in EVM clients such as Parity Ethereum and Geth) or by designing a new set of op codes from first principles (followed by Libra to arrive at MoveVM [9]). A more involved approach is to execute smart contracts in parallel similar to the modern design of databases such as MySql [10] and Postgres [11]. The first technique is to run multiple smart contracts in parallel where smart contracts acquire locks on a data before editing to ensure no data is simultaneously edited by more than a single smart contract; this method is used in [12], with a 33% improvement in throughput. An alternative approach uses optimistic concurrency with rollbacks; here multiple smart contracts execute in parallel (without locks) and in the case when two smart contracts running in parallel try to edit the same data, one of them is rolled back and executed later; this approach is explored in [13]–[16] where 3-4x improvement in throughput is observed. Although the improvement in throughput is significant in these methods, it exposes the blockchain to new kinds of adversarial attacks. Moreover these methods don’t address metering which is a critical component to align incentives.

Even though the current VMs have low throughput, the current bottleneck in today’s blockchain platform is the consensus protocol itself. Longest chain protocol and its current variants do not saturate the performance of the underlying VMs (refer Fig. 1 for details). Therefore, the second approach of designing high throughput consensus protocols is a natural avenue to scale smart contract platforms. One method is to move from permissionless to permissioned consensus protocols which can support high throughput, and Facebook’s Libra [17] and IBM’s Hyperledger [18] take this path. However, that sacrifices a very important characteristic of public blockchains and in this manuscript we take the approach of designing and implementing a high throughput permissionless consensus protocol, Prism, which achieves high throughput. Protocols such as OHIE [19], Algorand [20], Bitcoin-ng [21] take a similar route as Prism. To the best of knowledge, there do not exist implementations running smart contracts on top of these protocols; hence we have not been able to make a direct comparison with Prism’s performance.

The third approach is plasma and sharding. In 2015, Poon and Buterin proposed Plasma [22], along the lines of MapReduce, an off-chain scaling solution. Many offshoots of plasma have been proposed by different communities and refer the following webpage [23] for an overview. At a high level, Plasma is a network of secondary chains, each custom designed to serve different needs. These chains interact among each other and the main chain (on a need basis) to resolve conflicts using fraud proofs. This approach has weaker security properties and, in particular, susceptible to the “mass exit” attack. To overcome some of these security vulnerabilities, Ethereum 2.0 [3], near [24], polkadot [25], and Trifecta take the sharding approach which horizontally scales the throughput by running multiple instances of blockchains and pooling them to obtain high security. Even though this approach has better security than plasma, overall it has lower security compared to the pure consensus protocols in the previous paragraph.

Note that improvements in all the three approaches can be composed with each other to improve the overall throughput of blockchain platforms.

### II. RELATED WORK

The throughput of blockchains with smart contract platform can be increased at three different points on the blockchain stack. The first approach is to improve the execution speed of the virtual machine engine. A basic approach is to optimize the execution of individual op codes (followed in EVM clients such as Parity Ethereum and Geth) or by designing a new set of op codes from first principles (followed by Libra to arrive at MoveVM [9]). A more involved approach is to execute smart contracts in parallel similar to the modern design of databases such as MySql [10] and Postgres [11]. The first technique is to run multiple smart contracts in parallel where smart contracts acquire locks on a data before editing to ensure no data is simultaneously edited by more than a single smart contract; this method is used in [12], with a 33% improvement in throughput. An alternative approach uses optimistic concurrency with rollbacks; here multiple smart contracts execute in parallel (without locks) and in the case when two smart contracts running in parallel try to edit the same data, one of them is rolled back and executed later; this approach is explored in [13]–[16] where 3-4x improvement in throughput is observed. Although the improvement in throughput is significant in these methods, it exposes the blockchain to new kinds of adversarial attacks. Moreover these methods don’t address metering which is a critical component to align incentives.

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### III. OVERVIEW OF PRISM

The selection of a main chain in a blockchain protocol can be viewed as electing a leader block among all the blocks at each level of the blocktree. In this light, the blocks in the longest chain protocol can be viewed as serving three distinct roles: they stand for election to be leaders; they add
transactions to the main chain; they vote for ancestor blocks through parent link relationships. The latency and throughput limitations of the longest chain protocol are due to the coupling of the roles carried by the blocks. Prism removes these limitations by factorizing the blocks into three types of blocks: proposer blocks, transaction blocks, and voter blocks (Fig. 2). Each block mined by a miner is randomly sortitioned into one of the three types of blocks, and if it is a voter block, it will be further sortitioned into one of the voter trees.

The proposer blocktree anchors the Prism blockchain. Each proposer block contains a list of reference links to transaction blocks, which contains transactions, as well as a single reference to a parent proposer block. Honest nodes mine proposer blocks on the longest chain in the proposer tree, but the longest chain does not determine the final confirmed sequence of proposer blocks, known as the leader sequence. We define the level of a proposer block as its distance from the genesis proposer block, and the height of the proposer tree as the maximum level that contains any proposer blocks. The leader sequence of proposer blocks contains one block at every level up to the height of the proposer tree, and is determined by the voter chains.

There are \( m \) voter chains, where \( m \gg 1 \) is a fixed parameter chosen by the system designer. For example, we choose \( m = 1000 \) in our experiments. The \( i \)-th voter chain is comprised of voter blocks that are mined on the longest chain of the \( i \)-th voter trees. A voter block votes for a proposer block by containing a reference link to that proposer block, with the requirements that: 1) a vote is valid only if the voter block is in the longest chain of its voter tree; 2) each voter chain votes for one and only one proposer block at each level. The leader block at each level is the one which has the highest number of votes among all the proposer blocks at the same level (tie broken by hash of the proposer blocks.) The elected leader blocks then provide a unique ordering of the transaction blocks to form the final confirmed ledger.

By decoupling the various types of blocks, Prism can provably achieve low latency and high throughput while maintaining high security.

A. Latency

The votes from the voter trees secure each leader proposer block, because changing an elected leader requires reversing enough votes to give them to a different proposer block in that level. Each vote is in turn secured by the longest chain protocol in its voter tree. If the adversary has less than 50% hash power, and the mining rate in each of the voter trees is kept small to minimize forking, then the consistency and liveness of each voter tree guarantee the consistency and liveness of the ledger maintained by the leader proposer blocks. However, this would appear to require a long latency to wait for each voter block to get sufficiently deep in its chain. What is interesting is that when there are many voter chains, the same guarantee can be achieved without requiring each and every vote to have a very low reversal probability, thus drastically improving over the latency of the longest chain protocol.

**Theorem 1** (Latency, Thm. 4.8 [1]). For an adversary with \( \beta < 50\% \) of hash power, network propagation delay \( D \), Prism with \( m \) chains confirms honest \( 1 \) transactions at reversal probability \( \epsilon \) guarantee with latency upper bounded by

\[
Dc_1(\beta) + \frac{Dc_2(\beta)}{m} \log \frac{1}{\epsilon} \text{ seconds,}
\]

where \( c_1(\beta) \) and \( c_2(\beta) \) are \( \beta \) dependent constants.

For large number of voter chains \( m \), the first term dominates the above equation and therefore Prism achieves near optimal latency, i.e. proportional to the propagation delay \( D \) and independent of the reversal probability.

B. Throughput

To keep Prism secure, the mining rate and the size of the proposer blocks have to be chosen such that each voter chain has little forking. The mining rate and the size of the proposer blocks have to be also chosen such that there is very little forking in the proposer tree. Otherwise, the adversary can propose a block at each level, breaking the liveness of the system. Hence, the throughput of Prism would be as low as the longest chain protocol if transactions were carried by the proposer blocks directly.

To decouple security from throughput, transactions are instead carried by separate transaction blocks. Each proposer block when it is mined refers to the transaction blocks that have not been referred to by previous proposer blocks. This design allows throughput to be increased by increasing the mining rate of the transaction blocks, without affecting the security of the system. The throughput is only limited by the computing or communication bandwidth limit \( C \) of each node, thus potentially achieving 100% utilization.

**Theorem 2** (Throughput, Thm. 4.4 [1]). For an adversary with \( \beta < 50\% \) fraction of hash power and network capacity \( C \), Prism can achieve \( (1-\beta)C \) throughput and maintain liveness in the ledger.

IV. DESIGN AND IMPLEMENTATION

We implement Prism full-node client with VMs in around 10,000 lines of Rust code. In this section, we describe the architecture of the client and highlight several design choices that are tailored to Prism consensus.

A. Architecture

Our implementation of Prism full-node client consists of two modules, Prism Consensus module and Virtual Machine
Executor (VM Executor) module. Prism Consensus module is in charge of exchanging blocks with peers, following Prism consensus to confirm blocks, and push confirmed blocks to VM Executor. VM Executor maintains the state of the confirmed ledger, i.e., the state that results from executing transactions up to the last confirmed block. When VM Executor receives new confirmed blocks from Prism Consensus, it retrieves transactions from those blocks and updates the state accordingly. This architecture is illustrated in Fig. 3.

**Prism Consensus** module can be divided into the following three parts:

1. **Blocktree Manager**, which maintains the client’s view of the blockchain, and exchanges blocks with peers;
2. **Ledger Manager**, which confirms blocks by following Prism protocol, and pushes confirmed blocks to VM Executor;
3. **Miner**, which contains a transaction memory pool and assembles new blocks.

**Blocktree Manager** consists of an event loop and a thread pool. The event loop keeps listening to events such as sending/receiving blocks, and assigns a thread from the thread pool to process it. When the client receives a new block from a peer, Blocktree Manager checks its proof of work, and stores the block locally. After that, it relays the block to peers in case they have not received it. It then checks data availability, i.e., whether all the blocks referred by reference links in this block have been received. If not, it buffers the block and defers further processing until data availability is satisfied. After data availability is satisfied, Blocktree Manager checks sortition and transaction signatures. Finally the block is inserted into Prism blocktree.

**Ledger Manager** is a busy-waiting loop that queries Blocktree Manager periodically to see whether there are new confirmed blocks, following Prism’s confirmation rule. If there are, it will retrieve the blocks from local storage and push them to VM Executor via a message-passing channel. Both Blocktree and Ledger Managers use RocksDB as the storage backend [26], [27]; this choice is made due to its high performance and ease of integration.

**Miner module** maintains a memory pool that collects pending transactions and assembles them into new blocks. The Miner module does not actually try to solve the PoW hash inequality, instead simulating the mining process by a Poisson process (of fixed growth rate, corresponding to the mining difficulty level); the Poisson processes are statistically independent across the different nodes (matching the distributed nature of PoW mining). When a new block is mined, it is pushed to Blocktree Manager, which will broadcast the block to peers. Transactions carried by assembled or received blocks are checked for duplication in the memory pool, with duplicates being purged.

**VM Executor** is in charge of maintaining the state database, i.e., the persistent storage for the state of the confirmed ledger. State database stores account information such as address and balance, and manage data in a hash accumulator (Merkle Patricia tree is used in Ethereum and sparse Merkle tree is used in Libra). VM Executor receives confirmed blocks from Ledger Manager, retrieves transactions from those blocks, and executes them sequentially. To execute a transaction, VM Executor first initializes a virtual machine environment, such as program counter, stack, and memory. Then it executes the instructions coded inside the transaction and/or the smart contract, during which it may interact with the state database. The execution result of a transaction will be a success or a failure, depending on whether the transaction is valid or not. Invalid transactions with failure results should be sanitized out of the confirmed ledger and have no effect on the state. Valid transactions will update the state according to the execution result. After executing all transactions in a confirmed block, VM Executor commits the updates to the state database.

We ported the VM Executors from two open source projects, Open Ethereum [28] (popularly known as Parity Ethereum) and Libra [17], and adapt the structure of transactions, the hash function, and the signature schemes to these projects respectively. The two VM Executors run single threads, with no parallel transaction execution capability. We will use the name of virtual machines, EVM and MoveVM, to refer them hereafter.
B. Highlights

The key design and implementation challenge is in translating the high throughput, low latency and high confirmation probability that Prism provides on raw block and transaction level into an application layer programming construct via the virtual machine intermediaries. On one hand, the client must process blocks and transactions at a rate much higher than most traditional blockchains. On the other hand, low latency and high confirmation probability enables confirmation of the ledger, which the implementation can benefit from. Here, we highlight several implementation choices that are tailored for Prism consensus and distinguish our implementation from traditional blockchains.

a) Confirmation: In Ethereum and other longest chain protocols, the state of the longest chain tip is used for transaction validation. However, blocks in longest chain may be switched due to honest or adversarial forking blocks. To smoothly update state when the longest chain switch happens, Ethereum’s implementation keeps a short-term journal containing actions in recent forking blocks. This makes the management of state less efficient, which is a particular impediment due to the high mining rate (and high throughput) of Prism. In our design, we find it relevant to only maintain the state of the last confirmed block; this is because of two reasons: (a) Prism guarantees confirmation with overwhelmingly high probability (e.g., $1 - 10^{-9}$) so confirmed blocks are not likely to be deconfirmed. (b) Prism does not validate transactions before including them in blocks so it is unnecessary to maintain the state of the unconfirmed latest proposer block. This not only makes maintenance more efficient, but also enables the integration with VM of BFT consensus such as MoveVM.

In traditional blockchains (Bitcoin and Ethereum), blocks are mined at a relatively low rate and a newly mined block is likely to change the longest chain. Hence in their implementation, they update state when they receive a new block. In Prism, blocks are mined at a high mining rate; confirming blocks and updating state upon receipt of a new block would be onerous – we make a design choice to update the state only when blocks are confirmed and to conduct the confirmation procedure at periodic intervals.

b) Decoupling Transaction Validation and State Update: In most traditional blockchains, transaction validation and state update are coupled with consensus. For example, Ethereum miners must make sure all the transactions in a block are valid, update Ethereum state accordingly, and record the result state root in that block. Prism, by design, decouples transaction validation and state update from consensus: Prism miners do not conduct transaction validation or update state. Only after a block is confirmed, transactions in it are validated, and state is updated accordingly. In this procedure, invalid transactions are sanitized out of the confirmed ledger. We note that invalid transactions still incur gas fees for the senders and thus a rational user has no incentive to send invalid transactions. If the transaction sender has inadequate tokens to pay the gas fee, the transaction will be treated as spam and skipped. Nevertheless this type of invalid transactions could reduce the utility of network bandwidth. To mitigate this spamming attack, miners could validate transactions with respect to their latest confirmed state, giving the adversary only a small window to create invalid transactions and spam the system.

c) No Pending Transaction Exchange: Most traditional blockchain clients exchange pending transactions in their memory pools with peers. Because the block mining rate is very low and the next block author is unpredictable, transaction exchange is necessary to ensure that pending transactions get included in the next block. This reduces network bandwidth utility since transactions are broadcast twice in the network: first as pending transactions and then as part of a block.

In Prism, pending transaction exchange can be onerous to the network bandwidth, due to the high throughput. We design our implementation to avoid exchanging pending transactions, by noting that a pending transaction can be easily included in a new block in a very short amount of time by any individual miner thanks to the high mining rate of Prism’s transaction blocks. Transaction blocks carrying pending transactions are broadcast to peers, in the same way blocks are broadcast in traditional blockchains. Notice that a user can still send a transaction to multiple miners for redundancy; however, miners need not exchange it. This avoids the waste of network bandwidth and contributes to the final high throughput.

d) Signature Verification in Consensus: Transaction signature verification is a significant fraction of total computation; this burden is only worse when the achieved throughput is higher. We design our implementation to conduct the signature verification in parallel inside Prism Consensus via the thread pool functionality. This is a departure from implementations in EVM (Ethereum) and MoveVM (Libra) which conduct signature verification inside the VM executor. Either sequentially or in parallel, signature verification burdens the VM executor and harms the throughput.

V. Evaluation

In this section we describe our experiments and performance results of our implementation of a prototype client designed based on the guidelines highlighted in the previous section. We describe experiment settings and the applications that we use to measure [V-A]. Then we present the throughput and confirmation latency results of Prism integrated with two virtual machines, EVM and MoveVM, from which we analyze that Prism removes the consensus bottleneck [V-B] [V-C]. In addition, we measure how our design and implementation of Prism scales with more network participants [V-D].

A. Experiment Setting

We evaluate our implementation of Prism by integrating it with two smart contract virtual machines: EVM Prism and MoveVM Prism respectively. The performance (upper bound) baselines are provided by VM Executor Only (single node, no consensus) and Prism Consensus Only (no smart contract platform, raw transaction throughput), VM Executor Only experiment feeds transactions to VM Executor running on a single node and demonstrates the optimal throughput of the VM Executor. Prism Consensus Only experiment runs consensus with raw blocks and transactions and measures the raw data throughput. It shows the performance that the consensus is able to support. In addition, we also implement Ethereum’s
consensus protocol (essentially the longest chain protocol) and its performance provides a (lower bound) baseline.

**Applications:** We evaluate a suite of canonical applications, which can be classified into three categories.

1) **Basic applications:** We evaluate two basic applications: **Native Payment and Do Nothing.** Native Payment transactions are payments of native tokens in those smart contract platforms. Do Nothing is a contract with a void function, and is the simplest possible contract.

2) **Benchmark applications:** To test Prism client with standard computation or storage read/write, we propose two applications: CPU Heavy and IO Heavy. CPU Heavy runs a worst case of quick sort for an integer array of length 255. IO Heavy does key-value pair write 255 times followed by key-value pair read 255 times for both forward and backward order (thus total 510 times). The value type is bytes32 in EVM and bytearray in MoveVM, which are both 256-bit data type.

3) **Realistic applications:** As a counterpoint to the above applications, we evaluate here the performance with respect to two real world applications: ERC20 and CryptoKitties. ERC20 is an Ethereum token standard [29], and we implement it by using the reference implementation in [30]. CryptoKitties is a game that allows users to breed virtual pets. The genes of offspring are determined by a function named **mixGenes** that mixes the genes of its parents [31]. We adopt mixGenes function in our experiments, and feed random parent genes to it. This function is significantly computational heavy compared to basic applications.

Applications for EVM are developed in Solidity programming language. We use the official Solidity compiler v0.6.3 to compile all smart contracts to bytecode except for CryptoKitties, which follow the version v0.4.18 in the contract. We set the compiler to Constantinople version and enable the default optimization. When creating a smart contract in EVM, an account address is created and bytecode is stored under the address. Applications for MoveVM are developed in Move IR. The smart contracts are first published as modules under the sender’s address and then are called via scripts. We use Move IR compiler to compile the modules and scripts to bytecode. We have basic applications and benchmark applications and they have the same functionality as corresponding applications for EVM. Native tokens in MoveVM have essentially the same function as ERC20 tokens in EVM, hence ERC20 experiment for MoveVM is unnecessary. As the Move language is in rapid development and not yet mature at the moment of our experiments, it is not straightforward to implement CryptoKitties in MoveVM.

Table I presents the statistics of applications. Transaction sizes differ because we pass different input parameters to these applications. Number of instruction and gas are indicators of the complexity in terms of both computation and storage read/write. MoveVM does not provide the statistics for number of instruction.

To generate the workloads for our evaluations, we implement a transaction generator that periodically generates transactions and push them into the mempool, generating different transaction types for different applications. We cap the generation rate according to the throughput of VM Executor Only experiment, in order not to exhaust the virtual machine.

We acquire data from the first 100 million transactions on Ethereum to derive a distribution on the number of transactions sent and received by an account. We sample our transactions using this distribution to mimic the usage of Ethereum in our experiments. In our experiments we use 10,000 accounts in total for both sender and receiver. The transaction generator of each node is initialized with 10,000 key pairs; one key pair for each account. In order to mimic the usage of Ethereum for Native Payment and ERC20, each node randomly and independently draws a sender and a receiver address from the aforementioned distribution. Other applications like Do Nothing, CryptoKitties, CPU Heavy, and IO Heavy have a fixed receiver (EVM) or no receiver (MoveVM) and hence we only sample the sender address.

**Experiment environment.** We perform our experiments on Amazon EC2’s 100 c5d.4xlarge instances. Each instance has 16 CPU cores, 32 GB memory, and NVMe SSD storage. Each instance hosts one Prism client and they are connected to form a random 4-regular topology; the diameter of the network is 6. To emulate a realistic peer-to-peer network, we introduce a propagation delay of 120 ms on each link to match the typical delay in Ethereum’s network [32], and a rate limiter of 300 Mbps for both ingress and egress traffic, except for Prism Consensus Only experiment where the rate limiter is 600 Mbps.

**Parameters.** For EVM Prism and MoveVM Prism, we choose a high adversarial hash power capability of $\beta = 0.4$ and a very low deconfirmation probability $\epsilon = 2 \times 10^{-9}$. We use $m = 1000$ voter chains and cap the size of transaction blocks to be 200 tx/block. Given the testbed with 120 ms peer-to-peer delay, we tune the mining rate of Prism’s proposer and voter blocks to be 0.08 block/s, at which the empirical forking rate is less than 0.11 in all experiments, and thus it ensures the security of Prism. We tune the mining rate of transaction blocks

| Table I: EVM and MoveVM application statistics. |
|-----------------------------------------------|
| EVM                                           |
| Native Payment                               |
| Do Nothing                                   |
| CPU Heavy                                    |
| IO Heavy                                     |
| ERC20                                        |
| Crypto-Kitties                               |
| EVM Tx Size (Bytes)                          |
| 533                                          |
| 353                                          |
| 567                                          |
| 567                                          |
| 601                                          |
| 631                                          |
| EVM Gas                                      |
| 21000                                       |
| 21394                                       |
| 334390                                      |
| 435244                                      |
| 26602                                       |
| 140000                                      |
| EVM Num of Instruction                       |
| 0                                           |
| 32                                          |
| 88417                                       |
| 25364                                       |
| 309                                         |
| 25000                                       |
| MoveVM Tx Size (Bytes)                       |
| 424                                         |
| 329                                         |
| 365                                         |
| 366                                         |
| N/A                                         |
| MoveVM Gas                                   |
| 43076                                       |
| 629                                         |
| 2275420                                     |
| 2956846                                     |
| N/A                                         |
| N/A                                         |

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2Since we pass random inputs to CryptoKitties, the number is also random and we present an approximation in the table.

3Forking rate is calculated by $1 - \frac{\# blocks in longest chain}{\# blocks}$. 

\[ m = 1000 \text{ voter chains} \]
differently for different applications to match the throughput of VM Executor Only experiment: In EVM Prism, Native Payment 108; Do Nothing 180; ERC20 70; CryptoKitties 3.78; CPU Heavy 1.08; IO Heavy 2.34 block/s. In MoveVM Prism, Native Payment 12.6; Do Nothing 7.2; CPU Heavy 1.44; IO Heavy 3.06 block/s.

For the Prism Consensus Only experiment, we increase the size of transaction blocks to 400 tx/block and the mining rate to 200 block/s. As for the Ethereum experiment, we use a mining rate of 0.1 block/s and a block size of 200 tx/block, which resemble the live Ethereum parameters.

As shown in Table II, for EVM Prism, the throughput is 21.355 tx/s and the latency is 17.284 ms for the native payment application, which resembles the live Ethereum parameters. For CryptoKitties, the throughput is 12.6 tx/s and the latency is 22.372 ms.

TABLE II: Throughput in terms of tx/s on EVM applications.

| Application        | EVM Executor Only | EVM Prism | Prism Consensus Only | Ethereum |
|--------------------|-------------------|-----------|----------------------|----------|
| Native Payment     | 21535             | 18660     | 98022                | 1725     |
| Do Nothing         | 35723             | 35329     | 97473                | 1725     |
| CPU Heavy          | 207               | 197       | 2144                 | 1725     |
| IO Heavy           | 467               | 447       | 92144                | 1725     |
| ERC20              | 13095             | 11210     | 86931                | 1725     |
| CryptoKitties      | 710               | 661       | 82798                | 1725     |

B. Throughput and Latency of EVM

In this experiment, we measure the transaction throughput and confirmation latency of various applications in EVM Prism and analyze the difference in throughput for different applications. We also compare the throughput with EVM Executor Only experiment, the optimal throughput of EVM on a single node. If the former is able to reach the latter, then the throughput of our Prism client is very close to the optimal throughput of the virtual machine and we can conclude that Prism removes the consensus bottleneck for smart contracts. Finally, we compare EVM Prism with Prism Consensus Only to study whether Prism is able to support even higher throughput without the limitation of the virtual machine. This experiment would also indicate whether EVM Prism’s performance can be further improved if the underlying virtual machine becomes faster.

Throughput: As shown in Table II, for EVM Prism, the throughput of two basic applications is able to reach 18K and 35K tx/s respectively. For ERC20, EVM Prism gets 11K tx/s. The throughput of these three applications shows that we have a good chance to get above ten thousand tx/s for those applications that do not involve heavy computation or storage read/write. The reason that Do Nothing is almost twice as fast as Native Payment is that for Do Nothing, the VM Executor module updates the account information of a random sender per transaction and a fixed receiver contract account, whereas for Native Payment it updates a random sender and a random receiver account information. As a result, the VM Executor needs to maintain the state database and hash accumulator for half account information updates in Do Nothing as that in Native Payment.

For the CryptoKitties application, EVM Prism achieves 661 tx/s due to its computational heavy nature. Similar things happen for CPU Heavy and IO Heavy, which get 197 and 447 tx/s respectively. According to the statistics in Table II these applications require more than 25K instructions in the virtual machine, which explains their low throughput. However, the low throughput in both EVM Prism and EVM Executor Only also indicates that EVM has a large opportunity to improve the efficiency of execution. We write exactly the same CPU Heavy application in Java and run in JVM, and we get a throughput over 90K tx/s. Considering the large gap between 197 and 90K, we believe that EVM has the potential to execute instructions more efficiently. We don’t compare IO Heavy or CryptoKitties since they are not as straightforward to implement as a standalone program in Java.

Is Prism consensus the bottleneck? For all EVM applications, EVM Prism reaches 85% of EVM Executor Only throughput. This high percentage indicates that EVM Prism is able to reach the optimal EVM throughput very closely. As for Prism Consensus Only, we can see the high throughput over 80K tx/s for all applications. This high number illustrates the ability of supporting high throughput without the limitation of the virtual machine. It also shows that if the virtual machine becomes faster in the future, Prism is able to support its performance as well. Hence, Prism consensus is not the throughput bottleneck; the virtual machine itself is the bottleneck.

Compared to 21 tx/s in Ethereum experiment, which adopts Nakamoto’s longest chain consensus, it is clear that the current Ethereum is limited by consensus.

Latency: The end to end latency of a transaction consists of two parts: confirmation latency and execution latency. Confirmation latency is the time between a transaction is gen-

Fig. 4: Time series plot of throughput for Do Nothing application in EVM Prism. Around the first 30 seconds there is no processed transaction, since the clients are just started and have not extend the ledger yet. This phenomenon occurs in all Prism experiments.

All experiments are run for at least 10 minutes. As we see in the time series plot of throughput (Fig 4), in the first several seconds, the nodes don’t process any transaction because they just started mining blocks and there are not enough blocks to extend the confirmed ledger. This phenomenon only happens at the beginning and does not affect the performance afterwards. Hence, the final throughput calculation involves the average performance over the last 9 minutes of the experiment.
Prism’s confirmation rule guarantees a confirmation latency regardless of its throughput. In all Prism experiments including EVM Prism, MoveVM Prism, and Prism Consensus Only, the confirmation latency is no more than 130 seconds. Notice that this latency is achieved with adversarial ratio $β = 0.4$ and reversal probability $\epsilon = 2 \times 10^{-9}$. To provide the same latency under the same condition in Ethereum, it needs to wait for $(k = 267)$-deep [8] and it translates to 2670 seconds if a block is mined in 10 seconds on average.

**Resource utility:** In a Prism client, the Prism Consensus module uses multiple threads to process messages from/to peers efficiently. The VM Executor module, on the contrary, runs in a single thread. In addition, RocksDB uses a few threads in the background. In total, a Prism client should only use no more than 50 threads. In our experiments, the live usage of CPU never exceeds 50% per core on average (notice that one instance has 16 CPU cores). Though, there are possible optimization to do in the future. For example, give a high priority to the VM Executor thread to prevent competing CPUs with the Prism Consensus module.

By profiling the CPU usage of a client in *EVM Prism Do Nothing* experiment, we find that transaction signature verification takes up to 39.2% of total CPU time (excluding mining), a relatively high percentage. When the experiment is running at high throughput, the requirement of a large amount of signature verification is a major bottleneck; this emphasizes the importance of removing signature verification from the VM Executor module. In our design, we have moved signature verification into the Prism Consensus module, thus freeing the VM Executor from this heavy burden.

The VM Executor of EVM is implemented efficiently with abundant number of in-memory cache. However, it leaves a heavy memory burden on the VM Executor; we found that the VM Executor does not free memory efficiently, and the memory usage increases along with the workload. This is one possible future optimization for EVM.

Table III provides a breakdown statistics for three Prism block types in *EVM Prism Do Nothing* experiment. We can see that transaction blocks take up to 71.2% of total generated block data, other two blocks only 28.8%. This indicates that the majority of utilized bandwidth contributes to the high throughput (transaction blocks), whereas Prism overhead takes up only a small fraction (proposer and voter blocks). For other *EVM Prism* (and *MoveVM Prism*) experiments, this breakdown statistics will remain similar except for transaction blocks. The higher the throughput, the higher the transaction block data and percentage. Thus, we do not analyze the breakdown statistics for other experiments.

| # Mined Block | Block Data | Data Percentage |
|---------------|------------|----------------|
| Proposer Block | 44 | 4.0 MB | 4.0% |
| Voter Block    | 47166     | 25.2 MB | 24.8% |
| Transaction Block | 107514 | 72.2 MB | 71.2% |

### C. Throughput and Latency of MoveVM

In this experiment, we measure the transaction throughput and confirmation latency for *MoveVM Prism*. We observe similar bottleneck and latency between this experiment and EVM experiment, whereas there are also discrepancies in terms of throughput.

**Throughput:** As shown in Table IV the throughput of two basic applications is only 1.2K and 2.2K tx/s respectively; this is an order smaller than that of *EVM Prism*. In private communication [33], core Libra developers have indicated to us that improving the performance of MoveVM is work under progress – when this improvement transpires, our Prism client can fully utilize that as well. Benchmark applications get 255 and 546 tx/s and are higher than those of *EVM Prism*, indicating that MoveVM is more efficient at executing instructions. The CPU *Heavy* throughput numbers, however, is still far below that of JVM, so we believe MoveVM has the potential to execute instructions more efficiently as well.

| Throughput in terms of tx/s on MoveVM applications. |
|-----------------|-----------------|-----------------|-----------------|
| Native Payment Do Nothing | CPU Heavy | IO Heavy |
| MoveVM Executor Only | 1441 | 2501 | 269 | 585 |
| MoveVM Prism | 1172 | 2243 | 249 | 512 |
| Prism Consensus Only | 123222 | 158802 | 143140 | 142749 |

**Is Prism consensus the bottleneck?** For all MoveVM applications, *MoveVM Prism* reaches 81% of MoveVM *Executor Only* throughput. This phenomenon is similar to EVM and indicates that *MoveVM Prism* is able to reach the optimal MoveVM throughput. As for *Prism Consensus Only*, we can see the high throughput over 120K tx/s as well. Similar to the case of EVM, we conclude that Prism removes the consensus bottleneck for MoveVM, and the virtual machine itself is the bottleneck.

**Latency:** Prism guarantees a confirmation latency regardless of the throughput, and we do observe that in all Prism experiments including *MoveVM Prism*, the average confirmation latency is no more than 130 seconds.

**Resource utility:** *MoveVM Prism* maintains a good memory usage, which is kept under 3.2 GB in all experiments. The live usage of CPU never exceeds 32% per core on average; compared to *EVM Prism* experiment, this CPU utility reduction is due to smaller throughput and more efficient signature verification. MoveVM adopts Ed25519 signature [34] which is faster than ECDSA [35] adopted by EVM.
D. Scalability

In this experiment, we evaluate Prism’s ability to scale with more network participants. We use a larger number, 300, EC2 instances and use the same propagation delay and rate limiter. We use a random 5-regular topology for 300 nodes, keeping diameter the same with that of 100 nodes. We also keep the same Prism parameter, including the overall mining rate, thus the individual mining rate is modified. By our design, only the Prism Consensus module is related to scaling with more network participants, since only it communicates with peers. In addition, Prism Consensus module’s performance is not affected by which application it is running. Hence, it suffices to experiment with one VM and application to demonstrate Prism’s scalability and we use EVM Prism and Native Payment in the experiment.

The experiment for 300 nodes also runs for 10 minutes. However, it is hard to collect the fine-grained metrics for such a high number of nodes. So we calculate the overall metrics at the end of the experiment (all 10 minutes), in contrast to previous calculation (last 9 minutes).

Table [V] compares the performance between 100 and 300 nodes. The throughput and latency are very similar; the difference is due to the randomness of the experiments. The forking rate 0.113 in 300 nodes is a little larger than that in 100 nodes, and is mainly due to more hops and higher delay to propagate blocks throughout the peer-to-peer network, as we can see that the average path length is higher in the 300-node topology. This can be easily solved by increasing the degree (the number of peers per node). Though, this forking rate is small enough to ensure the security of Prism consensus.

TABLE V: Performance of EVM Prism Native Payment, with different network topologies.

| #Node | Degree | Average Path Length | Diameter | Throughput | Confirmation Latency (s) | Forking |
|-------|--------|---------------------|----------|------------|------------------------|---------|
| 100   | 4      | 3.55                | 6        | 17268      | 96                     | 0.102   |
| 300   | 5      | 3.84                | 6        | 17417      | 80                     | 0.113   |

Resource utility on each node is also similar. In the 300-node experiment, the live usage of CPU never exceeds 50% per core on average. The heavy memory burden of the VM Executor module is also similar to that in 100-node experiment.

We conclude that Prism is able to scale to a large number of network participants, as long as the underlying peer-to-peer network provides a topology with reasonable block propagation delay. We can achieve similar throughput, latency, and security in those cases.

VI. Conclusion

Blockchain research thus far has progressed in a compartmentalized manner: algorithms and protocols (many focused on consensus) are designed and studied separately from the upper layer wrappers (virtual machine, application programming) they will interact with. This is in contrast with Nakamoto’s Bitcoin design that was envisioned and designed as a complete system. This layering philosophy works well when the consensus layer is the bottleneck and much work can be expended to improve the performance (indeed, this is the case with many blockchains, including Ethereum). Prism is a recent consensus algorithm, closely inspired by Nakamoto’s longest chain protocol, with theoretically optimal throughput and latency. In this paper we explore how Prism fits with two smart contract virtual machines, EVM and MoveVM, by implementing Prism underneath these virtual machines. We demonstrate that Prism seamless merges with both these VMs: our implementation approaches the optimal virtual machine throughput for a large variety of applications. This result means that Prism not only removes the consensus bottleneck of bare metal throughput and latency but also when interacting with two popular smart contract platforms. Further improvement of the smart contract performance would have to come from new designs of virtual machines and compilers and architectures capable of parallel execution of smart contracts. The early research in this area [13]. [36] now takes on added urgency.

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