CYPHERIUM YELLOW PAPER

CYPHERIUM DEVELOPMENT TEAM

1. Introduction

Blockchain is the underlying technology that has made bitcoin and all subsequent cryptocurrencies possible. A blockchain is a distributed database that records all transactions or digital events that have been executed and shared among participating parties. Each transaction is then verified by the majority of participants of the system. It contains a record of every single transaction. Bitcoin is the first and most popular cryptocurrency using blockchain technology, which first came to light when a person or collective group named 'Satoshi Nakamoto' published a white paper titled "Bitcoin: A peer to peer electronic cash system" Sprankel [2013] in 2008. Blockchain technology distributes records of its transactions throughout its network thus making the data incorruptible. Anything of value, such as land assets, cars, etc. can be traced and transacted through blockchain technology.

Blockchain-based applications called distributed ledgers are gaining more and more popularity today. Various decentralized applications have been built on top of the blockchain platform for the past few years. While many people think that blockchain technology will lead to the next technological revolution, there are a few critical limitations that need to be solved before it can start replacing the existing technologies such as the centralized internet based applications.

The first issue with bitcoin is that it can only perform very simple token transactions. One person can transfer a certain amount of bitcoin tokens to another person using the underlying blockchain and Proof-of-Work consensus mechanism to reach to a decentralized agreement among all the nodes. However, this is the only functionality that bitcoin can offer. It is impossible to use this simple functionality to replace the extremely well-designed internet.

As a result, the distributed smart contract platform was invented by various groups, including Ethereum. Compared to Bitcoin, Ethereum is more like a computing platform. It has all the features that Bitcoin has and allows third party developers to also write smart contract code and deploy to the Ethereum network in order to accomplish fairly complex business logics.

However, both Bitcoin and Ethereum are facing an even more critical problem. Due to the nature of the decentralized consensus algorithms such as PoW and a few security concerns, the total transactions per seconds for bitcoin and ethereum are only 6 to 15. On the other hand, more traditional, centralized applications such as PayPal or VISA can support hundreds of thousands of transactions per seconds. Moreover, single bitcoin transactions can take up to one hour to confirm due to security concerns. Ethereum is a little better, but it also takes several minutes to complete. When the network is busy, both may take hours to complete.

To avoid bitcoin's sluggish fate, Ethereum has decided to abandon Proof-of-Work entirely for Proof-of-Stake, which also has its drawbacks. The first is the so-called nothing-at-stake problem, which undermines the network's ability to determine which nodes are honest and which are bad actors. Fundamentally, Proof-of-Stake runs the risk of centralization. Instead of relying on cryptography and math in Proof-of-Work, Proof-of-Stake uses power wealth to determine an actor's trustworthiness.

This yellow paper presents a new blockchain that addresses the present shortcomings of current public blockchain infrastructures called Cypherium. Cypherium is designed to solve the performance bottleneck of current blockchain applications, while maintain the same level of security. Key features of Cypherium's design include double-chain consensus, federated architecture, and separate sandboxes for test and production smart contracts.

2. Architecture

The Cypherium blockchain consists of two types of blocks: key blocks and transaction blocks. Key blocks determine consensus group membership via Proof-of-Work. Consensus groups collectively decide which transactions will be included in transaction blocks. Transaction blocks contain records of transactions to be committed into the permanent ledger and do not affect consensus group membership; they are smaller and created more frequently. These features distinguish Cypherium from Ethereum and many other blockchain protocols where each block contains transactions and also determines a new miner. Another distinguishing factor of Cypherium is that each block is created by a committee (i.e. a set of nodes) rather than a single miner. Each key block removes the oldest node from the current committee and replace it with a new one. Committee members then run a variation of the Practical Byzantine Fault Tolerance protocol (PBFT) to reach consensus regarding the contents of each new block. Once consensus is reached, the block is sent to the entire network and is considered irreversible.

Following this introduction, we will discuss model details in the next sections of this chapter. Some of the notions are borrowed from well-known models, while others are specific and have to be understood from further reading.

2.1. **World State.**

All data issued to the blockchain must be deemed valid or invalid. The data verification proceeds against all previously issued data, especially blocks. A sequence of blocks forms a World State, which can be used

for verification by mapping between addresses to their corresponding account states.

An address is a 160-bit identifier and an account state holds information about that account. In a simple case, this would be the account balance, but Cypherium uses smart contracts so that the address can hold various kinds of data.

These addresses form a Merkle Patricia tree (trie), an immutable data structure that gives access to any previous version knowing only the root hash of the needed version. The root node of this structure is cryptographically dependent on all internal data, and thus, its hash can be used as a secure identity for the entire system state.

2.2. **Committee. A leader of the Committee.** In Cypherium, there is a set of participants that drive the consensus algorithms and verify issued data such as transactions and blocks. This set is called a *committee*. Every participant is identified by a unique public key. Public keys involved in the committee are called *members* of a committee.

A node may be presented in the committee by several public keys. Consider committee M.

Members of the committee can dynamically change over time, but their amount is constant. The size of M is $3f+1$ and f is constant and predefined. At least $2f+1$ members of the committee are supposed to be available and honest. This requirement arises from PBFT (Section 2.3) underlying algorithm.

There is a dedicated member of the committee which is called a *leader*. A leader drives the *reconfiguration* process (Section 2.4) and issues new *transaction blocks* (Section 2.7), while other committee members serve as witnesses that can verify leader behavior and ensure issued data is correct.

2.3. **PBFT consensus.** PBFT (Practical Byzantine Fault Tolerance) algorithm is a form of state machine replication. The blockchain is modeled as a state machine that is replicated across different nodes. Each node maintains the blockchain world state and accepts new incoming data.

In this way, committee members are involved in the PBFT algorithm. A leader is the only node inside a committee that has the right to propose changes to the state. The other nodes can either agree or disagree with them. After the leader's proposal, a change has to pass three rounds in order to be applied to the state: *propose*, *prepare*, and *commit*. These rounds are driven collectively by committee members. After each round that the data has passed successfully, each node obtains a *certificate*, or a *collective signature*, that proves this fact. Hence, every change of the state is proven by a certificate and is *irreversible*, meaning once the change is applied, it can't be undone.

A slightly modified version of the PBFT algorithm is the foundation of Cypherium, which is introduced briefly in this section to simplify the understanding of further aspects of the network. There is a separate chapter which describes PBFT in further detail.

2.4. **Reconfiguration.** We define the state of a committee as a *configuration* and we enumerate configurations using non-negative integers. A set of committee members in a configuration number c will be denoted as $M(c)$.

Reconfiguration is a process in which the oldest committee member is replaced with another different participant. In this case, the number of a configuration is increased by 1 and:

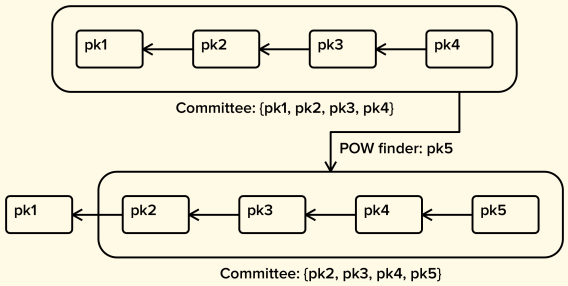
$$M(c+1) = M(c) \setminus P_{oldest} \cup P \tag{1}$$

Where P is a public key of a participant joining the committee, P_{oldest} is a public key of the member who has joined the committee first and c is a number of the configuration. After joining the committee, a participant may become a new leader.

If a node wants to join a committee, it must solve a difficult computation problem similar to what is used in Bitcoin's Nakamoto consensus. The node has to find *Proof of Work* nonce η, which satisfies

$$H(puzzle_c \oplus P \oplus \eta) \leq T \tag{2}$$

Where η is a found nonce, T is a threshold which regulates the frequency of reconfiguration. Usually, T may be chosen to cause one reconfiguration in approximately 10 minutes and can be changed over time as the result of the gain of the hash power from participants. $puzzle_c$ is hash of data which reflects the up-to-date state of the system. We will discuss the $puzzle_c$ in more details in Section 3; H is the 256 Keccak hash function; $\oplus$ stands for concatenation.



Reconfiguration process

2.5. **Key Block.** After a node has found an appropriate nonce in order to be included in a committee, it must send a *key block* with the found the nonce and other auxiliary information.

A key block consists of a header and a body.

The header includes:

version: The correct version of the protocol.

parentHash: The Keccak 256-bit hash of the parent key block header.

difficulty: A scalar value corresponding to the difficulty level of this block; T from (2).

number: A scalar value equal to the number of ancestor transaction blocks. The genesis block's number is zero.

time: A scalar value equal to the relevant output of Unix's time() at this block's inception.

extra: An arbitrary byte array containing data relevant to this block. Must have a size of 32 bytes or fewer.

nonce: A 64-bit value which, combined with $puzzle_c$ and a miner's public key, proves that a sufficient amount of computation has been carried out on this block; η from (2).

The body includes:

signature: The bytearray, a collective signature from the *commit* round of PBFT, where it is decided if a new member can join the committee.

mask: The bytearray consisting of $3f + 1$ elements, where 1 value stands on the position i if i-th member of a committee is involved in a collective signature.

leaderPubKey: The public key of a participant who found the PoW nonce and is going to become a new leader; P from (1) and (2).

outPubKey: The public key of the oldest committee member who is going to leave the committee; P_{oldest} from (1).

2.6. **Transaction.** Transactions in Cypherium are similar to those of Ethereum. There are two types of transactions: one results in message calls and the other in the creation of new accounts with associated code (known informally as 'contract creation'). Both types of transactions specify a number of common fields:

version: An Integer value, a version of the protocol.

sender: The public key of a transaction sender.

nonce: A scalar value equal to the number of transactions sent by the sender; formally T_{n}.

gasPrice: A scalar value equal to the number-total of money to be paid per unit of *gas* for all computation costs incurred during the transaction execution; formally T_{p}.

gasLimit: A scalar value equal to the maximum amount of gas that should be used in the process of the transaction execution. This is paid in advance before any computation is performed and may not be increased later on; formally T_{g}.

recipient: The 160-bit address of the message call's recipient or, for a contract creation transaction, $\varnothing$, used here to denote the only member of $\mathbb{B}_0$; formally T_{t}.

amount: A scalar value equal to the number-total of money to be transferred to the message call's recipient or, in the case of contract creation, as an endowment to the newly created account; formally T_{v}.

v, r, s: Values corresponding to the signature of the transaction and used to determine the transaction sender; formally T_{w}, T_{r} and T_{s}.

Additionally, a contract creation transaction contains:

init: An unlimited size byte array specifying the CVM-code for the account initialization procedure, formally $T_{\mathbf{i}}$.

init is an EVM-code fragment; it returns the **body**, the second fragment of code that executes every time an account receives a message call (either through a transaction or due to the internal execution of code). **init** is only executed once at account creation and gets discarded immediately after. By contrast, a message call transaction contains:

data: An unlimited size byte array specifying the input data of the message call, formally $T_{\mathbf{d}}$.

S maps transactions to the sender and happens through the ECDSA of the SECP-256k1 curve, using the hash of the transaction (excepting the latter three signature fields) as the datum to sign. For the present, we simply assert that the sender of a given transaction T can be represented with $S(T)$.

(3)
$$L_T(T) \equiv \begin{cases} (T_{\mathrm{n}}, T_{\mathrm{p}}, T_{\mathrm{g}}, T_{\mathrm{t}}, T_{\mathrm{v}}, T_{\mathbf{i}}, T_{\mathrm{w}}, T_{\mathrm{r}}, T_{\mathrm{s}}) & \text{if } T_{\mathrm{t}} = \varnothing \\ (T_{\mathrm{n}}, T_{\mathrm{p}}, T_{\mathrm{g}}, T_{\mathrm{t}}, T_{\mathrm{v}}, T_{\mathbf{d}}, T_{\mathrm{w}}, T_{\mathrm{r}}, T_{\mathrm{s}}) & \text{otherwise} \end{cases}$$

Here, we assume all components are interpreted by the RLP as integer values, with the exception of the arbitrary length byte arrays $T_{\mathbf{i}}$ and $T_{\mathbf{d}}$.

(4)
$$\begin{array}{lllllll} T_{\mathrm{n}} \in \mathbb{N}_{256} & \wedge & T_{\mathrm{v}} \in \mathbb{N}_{256} & \wedge & T_{\mathrm{p}} \in \mathbb{N}_{256} & \wedge \\ T_{\mathrm{g}} \in \mathbb{N}_{256} & \wedge & T_{\mathrm{w}} \in \mathbb{N}_{5} & \wedge & T_{\mathrm{r}} \in \mathbb{N}_{256} & \wedge \\ T_{\mathrm{s}} \in \mathbb{N}_{256} & \wedge & T_{\mathbf{d}} \in \mathbb{B} & \wedge & T_{\mathbf{i}} \in \mathbb{B} & \end{array}$$

where

(5)
$$\mathbb{N}_{\mathrm{n}} = \{P : P \in \mathbb{N} \wedge P < 2^n\}$$

The address hash $T_{\mathbf{t}}$ is slightly different: it is either a 20-byte address hash or, in the case of being a contract-creation transaction (and thus formally equal to $\varnothing$), it is the RLP empty byte sequence and thus the member of $\mathbb{B}_0$:

(6)
$$T_{\mathbf{t}} \in \begin{cases} \mathbb{B}_{20} & \text{if } \quad T_{\mathrm{t}} \neq \varnothing \\ \mathbb{B}_0 & \text{otherwise} \end{cases}$$

2.7. **Transaction Block.** Besides key block, Cypherium also utilizes *transaction block*. The goal of this type of block is to carry sent transactions. Compared to key blocks, transaction blocks are issued much more frequently: a block per approximately 20 seconds.

The transaction block is the collection of relevant pieces of information (known as the block *header*), H, together with information corresponding to the comprised transactions, $\mathbf{T}$.

parentHash: The Keccak 256-bit hash of the parent transaction block's header, in its entirety; formally H_{p}.

stateRoot: The Keccak 256-bit hash of the root node of the state trie after all transactions are executed and finalizations are applied; formally H_{r}.

transactionsRoot: The Keccak 256-bit hash of the root node of the trie structure populated with each transaction in the transactions list portion of the block; formally H_{t}.

receiptsRoot: The Keccak 256-bit hash of the root node of the trie structure populated with the receipts of each transaction in the transactions list portion of the block; formally H_{e}.

logsBloom: The Bloom filter composed from indexable information (logger address and log topics) contained in each log entry from the receipt of each transaction in the transactions list; formally H_{b}.

number: A scalar value equal to the number of ancestor transaction and key blocks. The genesis block has a number of zero; formally H_{i}.

gasLimit: A scalar value equal to the current limit of gas expenditure per block; formally H_{l}.

gasUsed: A scalar value equal to the total gas used in transactions in this block; formally H_{g}.

timestamp: A scalar value equal to the relevant output of Unix's time() at this block's inception; formally H_s.

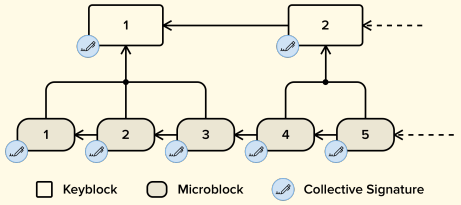
extraData: An arbitrary byte array containing data relevant to this block. This must be 32 bytes or less; formally H_x.

keyblockHash: The Keccak 256-bit hash of the header of the last applied key block.

keySignature: The bytearray, a collective signature from the *commit* round of PBFT, where it was decided that this block is correct.

isKeyReward: A Boolean value indicating whether a block is formed by transactions curring rewards for previous committee members.

exceptions: The bytearray consisting of $3f + 1$ elements, where one value stands on the position i iff i-th member of a committee is **not** involved to collective signature *keysignature*.



Transaction and key blocks

3. Consensus algorithm

At a high level, Cypherium runs a Byzantine consensus protocol driven by a committee. The acting committee commits transactions into a linearizable log using a modified version of PBFT (Castro et al. [1999]). The log forms a World State within the system. We say each consensus decision fills a *slot* in the state and can either be a batch of transactions or a reconfiguration event. The first type of decision is analogous to a block in Bitcoin. The second type records the membership change in the committee. The slot number is equal to a number of transaction and key blocks committed before.

Cypherium consensus algorithm relies on Solida consensus algorithm (Abraham et al. [2016]), which relies on PBFT algorithm; int this case, participants of a committee may be either honest or Byzantine. Cypherium's design is also influenced by ByzCoin (Kogias et al. [2016]), where honest participants always follow the predefined protocol and work within the frame of a model that is strictly defined and the same for all participants. An honest node behaves properly, but does not satisfy the model due to some external factors treated as a Byzantine node.

3.1. Model.

Before describing the protocol, we would like to limit a model where the system is considered.

3.1.1. *Network.* We consider a permissionless setting in which nodes use their public keys as pseudonyms and can join or leave the system at any time. Nodes are connected to each other in a peer-to-peer network with a small diameter.

We adopt the network model of Pass et al. (Pass et al. [2017]): bounded message delay of Δ that is known a priori to all participants. Note that this is the standard synchronous network model in distributed computing, though Pass et al. call it "asynchronous networks." This means that Bitcoin does not behave like a conventional synchronous protocol. In a conventional synchronous protocol, participants move forward in synchronized rounds of duration Δ, but Bitcoin does nothing of this sort and has no clear notion of rounds.

So, whenever a participant sends a message to another participant, the message is guaranteed to reach the recipient within Δ time. For convenience, we define Δ to be the end-to-end message delay bound. If there are multiple hops from the sender to the recipient, Δ is the time upper bound for traveling all those hops. Our protocol uses computational puzzles (i.e. PoW). Similar to Bitcoin, the difficulty of the puzzle is periodically adjusted so that the expected time to find a PoW stays at D. D should be set significantly larger than Δ.

Our synchronous network model raises a few immediate questions:

Is the bounded message delay assumption realistic for the Internet? This depends a lot on the parameter Δ. With a conservative estimate, say $\Delta = 5$ seconds, and Byzantine fault tolerance, the assumption may be believable. Fault tolerance also helps here. Participants who experience slow networks and are unable to deliver messages within Δ are considered Byzantine. In Cypherium, we require the assumption that adversarial participants and slow participants collectively control no more than about 1/3 of the mining power.

Why do we use PBFT if the network is synchronous? There are protocols that can tolerate $f < n/2$ Byzantine faults in a synchronous network (Katz and Koo [2009], Ren et al. [2017]). By requiring $f < n/3$, PBFT preserves safety under asynchrony; however, this seems unnecessary given that we assume synchrony. We adopt PBFT (with modifications) because it is an established protocol that provides responsiveness. Most protocols that tolerate $f < n/2$ are synchronous and not responsive because they advance in rounds of duration Δ. If the actual latency of the network is better than Δ — either because the Δ estimate is too pessimistic (the network is faster in the common case), or the network speed has improved over time — a responsive protocol would offer better performance than a synchronous one. In other words, we opt to use an asynchronous protocol in a synchronous setting, essentially abandoning the strength of the bounded message delay guarantee in order to run as fast as the network permits. Like all PoW-based blockchains, we rely on synchrony for safety in the worst-case scenarios.

3.1.2. *Adversary consideration.* As we've mentioned, honest participants always follow the prescribed protocol and are capable of delivering a message to other honest participants within Δ time. We will consider the worst-case scenario when Byzantine participants are controlled by a single adversary and can thus coordinate their actions. At any time, Byzantine participants collectively control no more than ρ fraction of the total computation power.

We assume it takes time for the adversary to corrupt an honest participant. It captures the idea that it takes time to bribe a miner or infect a clean host. Most committee-based designs (Decker et al. [2016], Kogias et al. [2016], Pass and Shi [2017]) require this assumption. Otherwise, an adversary can easily violate safety by corrupting the entire

committee. This is formalized as a delayed adaptive adversary by Pass and Shi (Pass and Shi [2017]). Specifically, we assume that even if the adversary started corrupting a member as soon as it emerged with a PoW, the member would have already left the committee by the time of corruption. Whether this assumption holds in practice remains to be examined.

3.2. **The Protocol.**

3.2.1. *Basic notions.* Here we describe the protocol outside reconfiguration (i.e. when no miner has found a PoW for the current puzzle). This part consists of two sub-protocols: *steady state* under a stable leader (Section 3.2.2) and *view change* to replace the leader (Section 3.2.3). Committee members monitor the current leader, and if the leader does not show progress in a given period of time, members support the next leader. The new leader has to learn what values have been proposed, and possibly re-propose those values.

When a new miner finds a PoW, the system switches to the *external leader* for reconfiguration. The successful miner would act as the leader L for reconfiguration and try to be elected onto the committee. When the L's reconfiguration proposal is committed (i.e. becomes a consensus decision), reconfiguration is finished and the system starts processing transactions under the new committee with L being the leader. At this point, L becomes a committee member, so the system seamlessly transitions back to internal leaders.

Each configuration can have multiple lifespans, and each lifespan can have many views. We use consecutive integers to number configurations, lifespans within a configuration, and views within a lifespan.

The lifespan number is the number of PoWs (honest) that committee members have seen so far in the current configuration. Intuitively, when a new PoW is found, the lifespan of the previous PoW ends.

For this purpose, we will associate each leader with a configuration-lifespan-view tuple (c, e, v) and rank leaders by c, e, and v in this order of priority. Each (c, e, v) tuple also defines a steady state where the leader of that view, denoted as $L(c, e, v)$, proposes values for members to commit. The view tuple and the leader role are managed as follows.

- Upon learning that a reconfiguration event is committed into the ledger, a member M increases its configuration number c by 1 and resets e and v to 0. $L(c, 0, 0)$ is the member newly added by the previous reconfiguration consensus decision.
- Upon receiving a new PoW for the current configuration, a member M increases its lifespan number e by 1 and resets v to 0. M now supports the finder of the new PoW as $L(c, e, 0)$ $(e \geq 1)$.
- Upon detecting that the current leader is not making progress (timed out), a member M increases its view number v by 1. $L(c, e, v)$ $(v \geq 1)$ is the l-th member on the current committee, by the order in which they joined the committee, where $l = (H(c, e)+v) \mod n$, and H is a hash function.

As long as the protocol ensures safety, members agree on the identities of these leaders. For views of the form $(c, e, 0)$ with $e \geq 1$, members may not agree on the leader's identity if they receive multiple PoWs out of order. This is not a problem for safety because the situation is similar to having an equivocating leader and a BFT protocol can tolerate leader equivocation. However, contending leaders in a view may prevent progress. Luckily, members will time out and move on to views (c, e, v) with $v \geq 1$. Unique leaders in those views will ensure liveness.

It is crucial that our protocol forbids pipelining to simplify reconfiguration: a member M sends messages for a slot s only if it has committed all slots up to $s - 1$. Let $M(c, e, v, s)$ be the set of members who are currently in view (c, e, v) and working on a slot s. Each honest member M can belong to only one set at a time.

Before we start to describe a protocol, let us introduce you several notations. Throughout the protocol we send other nodes messages, so let's describe basic notions we use for these messages:

$$\circledast(Tag, a_1, a_2, ..., a_k, \sigma_K)$$

By this tuple we mean message with fields $a_1, a_2, ..., a_k$, and a message itself has a *tag*. Tags are used to distinguish messages and determines which fields will follow it.

$\circledast$ stands for a serialized message broadcasted over the network to all committee members. We also can use designation $\circledast_X$ which means a message is sending to the X node.

σ_K is a signature of all previous elements of the tuple that was made with a private key corresponding to the K node, including the Tag.

3.2.2. *Steady State.* In a Steady State a committee is defined and doesn't change over time:

- a set of nodes which form the committee is known and doesn't change. A public key and a public commitment are known for each node;
- a committee leader is known, it's a member of the committee, and it doesn't change.

During a steady state, the leader proposes a block to be added to the Ledger. Committee members validate and approve the proposed block; if the block is accepted into the Ledger, we say that the block is committed. Similar to the plain PBFT protocol, the process of committing each block into history consists of several phases, where nodes exchange messages and form a consensus during each phase. A witness of the reached consensus is called a certificate.

In a plain PFBT protocol, a certificate consists of $2f + 1$ similar messages signed by different nodes. These messages are broadcast from node to node, where every node can form its own version of a certificate.

In Cypherium, a steady state is similar to plain PFBT except for two main differences:

- There are no checkpoints, and instead of periodical checkpoints we send a $notify$ message after committing each block;
- Certificates are formed using Schnorr multisignatures, so nodes are required to generate and publish public commitment values V_i together with their public keys; V_i values are used by the Leader to construct certificates.

We refer to Steady State phases in the same way that Solida does: propose, prepare, commit and notify.

In the remaining part of the chapter, we will introduce a certificates construction process and then describe phases

of a Steady State. Successful execution of those phases will commit value into the Ledger.

• **Certificates construction**

Cypherium uses Schnorr multi-signature algorithm (Schnorr [1991]) to construct certificates in a process that consists of several steps. The Leader forms a challenge by combining a public commitment of each committee node. Each committee member signs data using the challenge and a node's private commitment. Lastly, the Leader combines all signatures into a multi-signature which forms a certificate when combined with a public challenge.

More specifically, before sending a *Propose* message a leader forms collective challenges G^P and G^C from a public commitment V_i of committee members *which was published by each node together with its signature.*

$$G^P = H(V||S_p)$$

$$G^C = H(V||S_c)$$

Where $V = V_0 * V_1 * \ldots * V_{n-1}$, V_i is a public commitment of a i-th node; H is a cryptographic hash; $||$ stands for a concatenation; S_p is a proposed message with *Prepare* tag; S_c is a proposed message with *Commit* tag. The leader computes collective challenges and broadcasts it with a *Propose* message to committee members. Committee members then use challenges to sign corresponding messages: at first *Prepare* message and then, if it's accepted, *Commit* message.

Challenge G^P should be used to sign a message S_p in the following way: $r_i = v_i - G^P * x_i$, where v_i is a private commitment corresponding to V_i; x_i is a private key corresponding to X_i; $V_i = g^{v_i}$ and $X_i = g^{x_i}$, g is a given and well-known generator of a group G. A signature itself is a pair of (G^P, r_i).

Signatures from all signing participants can be combined into a certificate. An aggregated signature is a pair (G^P, r) consisted of a challenge G^P and a sum $r = \sum_i r_i$.

To verify resulting signature, one needs to compute $V' = G^r * (X_0 * X_1 * \ldots * X_m)^c$ and check that c equals to $H(V'||S)$, where r and c are from *signature*; S is a certified message; X_i are public keys.

Challenge G^C is used in the similar way to sign and verify *Commit* message.

• **propose** The leader L forms a transaction block from a set of valid transactions tx, broadcasts the transaction block, and broadcasts

$$\circledast(Propose, (H^P, \sigma'_L), viewId, G^p, G^c, \sigma_L)$$

message, where H^P is a header of a newly constructed block signed by the Leader as σ'_L; $viewId$ is a current configuration-lifespan-view tuple (c, e, v) the leader aware of; G^P and G^C are collective challenges for propose and commit phases; σ_L is a leader's signature of the proposed message.

After receiving $(Propose, (H^P, \sigma'_L), viewId, G^p, G^c, \sigma_L)$ message with a transaction block, a member $M \in M(c, e, v, s)$ checks if it's valid by making sure that all the following statements are true:

- $L = L(c, e, v)$ and L has not sent a different proposal
- tx is a set of valid transactions which can be applied to World State
- H^P corresponds to a block's body tx and σ'_L is a valid signature of H^P

• **prepare** After receiving the *Propose* message and checking its validity, a committee member M signs a body of the message using G^P as described earlier. When the signing process is finished, a node M broadcasts a *Prepare* message:

$$\circledast(Prepare, (H^P, \sigma'_M), viewId, \sigma_M)$$

where H^P is a header of a proposed block signed with σ'_M; σ_M is a signature of *Prepare* message.

Once a member receives signed *Prepare* messages from **all** participants involved into a signing process, the member aggregates signatures into an acceptance certificate A. Aggregated signatures are a pair consisted of the sum of r_is and G^P. Once the node M constructed an acceptance certificate, we say that it's accepted a corresponding proposed block with a header H^P.

• **commit** Upon accepting H^P, a node M broadcasts

$$\circledast(Commit, (H^C, \sigma'_M), viewId, \sigma_M)$$

where H^C is a header which references the accepted block *(H^P and H^C are similar but contain different tags to differentiate between header types)*; σ'_M and σ_M are signatures.

Similar to a prepare phase, when a member receives signed *Commit* messages from **all** participants involved into a signing process, the member aggregates signatures into a commit certificate C. A commit certificate is constructed similarly to a Prepare certificate by using *Commit* messages instead of *Prepare* message and by using G^C challenge *(from Propose message)* instead of using G^C. Once the node M constructed a commit certificate C, we say that it's committed a corresponding proposed block with a header H^C.

• **notify** Upon committing h, a committee member M broadcasts

$$\circledast(Notify, H^C, \sigma_M)$$

where H^C is a header of a committed block.

3.2.3. *View Change.* A Byzantine leader cannot violate safety but can prevent progress by simply not proposing. Thus, in PBFT, every honest member M monitors the current leader and if no new slot is committed after some time, M abandons the current leader and supports the next leader. Since we have assumed a worst-case message delay of Δ, it is natural to set the timeout based on Δ. A particular timeout value is 4Δ or 8Δ.

Now we will consider events and messages which happen within the View Change subprotocol:

• **view-change** Whenever a member M moves to a new slot s in a steady state, it starts a timer T. If T has reached 4Δ and M still has not committed a slot s, M abandons the current leader and broadcasts:

$$\circledast(ViewChange, viewId, \sigma_M)$$

where $ViewChange$ is a tag indicating a view-change message; σ_M is a signature of a tuple consisted of all previous elements of the message made using M's private key.

• **view-change-ready** Upon receiving $2f+1$ matching $ViewChange$ messages for $viewId$, if a member M is not in a view higher than $viewId$, it sends

$$\circledast_{L'}(ViewChangeReady, viewId, V)$$

message to a new leader $L' = L(c, e, v+1)$, where $ViewChangeReady$ is a tag indicating that the member

received $2f+1$ messages, $viewId$ is the same tuple as in $ViewChange$ message; V is *view-change certificate*, basically it is a map from a public key of a $ViewChange$ message sender to its σ; $\circledast_X$ stands for a serialized message sent to a member X. This message is supposed to notify a new leader about a view-change event as soon as possible.

After that, if M does not receive a $NewView$ message from L' within 2Δ, M abandons L' and broadcasts:

$$\circledast(ViewChange, next(viewId), \sigma_M)$$

where $next(viewId)$ is a function increasing a passed view of passed $viewId$ by one.

• **new-view** Upon collecting $2f+1$ matching $ViewChange$ messages for $viewId = (c, e, v)$, received either from $ViewChange$s messages or from a $ViewChangeReady$ message, the new leader $L' = L(c, e, v+1)$ concatenates them into a view-change certificate V and broadcasts

$$\circledast(NewView, next(viewId), V, \sigma_{L'})$$

. After that, L' enters a new view $(c, e, v+1)$.

Upon receiving a $(NewView, viewId, V, \sigma_{L'})$ message, if a member M is not in a view higher than $viewId$, it enters a view $viewId$ and starts a timer T. If T reaches 8Δ and still no new slot is committed, M abandons L' and broadcasts

$$\circledast(ViewChange, viewId, \sigma_M)$$

.

• **status** Upon entering a new view $viewId$, M sends

$$\circledast_{L'}((Status, viewId, H^C, H^A, \sigma'_M), C, A, \sigma_M)$$

where $L' = L(c, e, v)$ is a new leader, implying $viewId = (c, e, v)$; H^C is a header hash of a block committed in the previous slot, and C is a corresponding commit certificate; H^A is a header hash of a block accepted by M in the current slot, and A is the corresponding acceptance certificate (H^A and A is None if M has not accepted any value for the current slot).

Status message is used when a committee leader changes after a view-change event to let a new leader know about the latest committed payload and the latest accepted payload.

We call an inner part of the message (i.e., excluding C, A) its header. Upon receiving $2f+1$ status, L' concatenates the $2f+1$ status headers to form a status certificate S.

L' then picks a status message that reports the highest last-committed slot $s*$ (which can be obtained from H^c); if there is a tie, L' picks the one that reports the highest ranked accepted value in slot $s*+1$. Let two certificates in this message be $C*$ and $A*$ (A* might be None).

• **repropose** The new leader L' broadcasts

$$\circledast(Repropose, viewId, H^{C*}, C*, H^{A*}, A*, S, \sigma_{L'})$$

where H^{C*} and $C*$ denote respectively a header of the highest committed block and a corresponding certificate (from the previous step); H^{A*} and $A*$ denote respectively a header of the highest accepted block and a corresponding certificate. Both may be equal to None;

The repropose message serves two purposes. Firstly, $C*$ allows everyone to commit a slot $s*$. Secondly, it reproposes H^{A*} for a slot $s*+1$ and carries a proof $(S, A*)$ that H^{A*} is safe for a slot $s*+1$. The repropose message is considered invalid if any of the following conditions is violated:

- $s*$ is not the highest committed slot
- C is not for a slot $s*$
- $A*$ is not for the highest ranked accepted value for $s*+1$
- h^{A*} is not the value certified by A

Upon receiving a valid repropose message, a member M commits a slot $s*$ if it has not already committed; them M executes the **prepare/commit/notify** steps as in the steady state for a slot $s*+1$, and marks all slots $> s*+1$ fresh for view $viewId$. At this point, the system transitions into a new steady state.

3.2.4. *Reconfiguration.* To join a committee a node has to find a nonce η which satisfies

$$H(puzzle_c \oplus P \oplus \eta) \leq T \tag{7}$$

Upon finding a PoW, a miner tries to join the committee by driving a reconfiguration consensus as an external leader. To do so, it must first broadcast the PoW to committee members.

• **new-lifespan** Upon finding a PoW, a miner broadcasts it to the committee members:

$$\circledast(NewLifespan, minerPk, nonce, puzzle, viewId, \sigma_{miner})$$

Upon receiving a new valid PoW for the current configuration (that M has not seen before), M forwards the PoW to other members:

$$\circledast(NewLifespan, minerPk, nonce, puzzle, viewId, \sigma_M)$$

M then enters view $(c, e+1, 0)$, sets the PoW finder as its 0-th leader $L' = L(c, e+1, 0)$ of the new lifespan, and starts a timer T. If T reaches 8Δ and still no new slot is committed, then M abandons L' and broadcasts

$$\circledast(ViewChange, (c, e+1, 0), \sigma_M)$$

• **status** Upon entering a new lifespan, M sends to L'

$$\circledast((Status, (c, e, 0), H^C, H^A, \sigma'_M), C, A, \sigma_M)$$

where H^C, H^A, C and A are defined the same way as in the View Change sub-protocol. Upon receiving $2f+1$ status, L' constructs $s*$, S, $C*$ and $A*$ as in View Change.

• **repropose and reconfigure** Let H^C be the committed value in the highest committed slot $s*$ among S. Let H^A be the highest ranked accepted value (can be None) into slot $s*+1$ among S. Note that H^C and H^A are certified by $S, C*$ and $A*$. Now depending on whether H^C and H^A are transactions or reconfiguration events, the new external leader L' takes different actions:

- If H^C corresponds to a reconfiguration event to configuration $c+1$, then L' simply broadcasts C and terminates. Terminating means L' gives up its endeavor to join the committee (it is too late and some other leader has already finished reconfiguration) and starts working on $puzzle(c+1)$.
- If H^C corresponds to a block with a batch of transactions, and H^A is a reconfiguration event to configuration $c+1$, then L' broadcasts

$$\circledast(Repropose, (c, e, 0), H^C, C*, H^A, A*, S, \sigma_{L'})$$

and then terminates.

– If H^C corresponds to a block with a batch of transactions, and H^A is None (it means that $A*$ is None, too), then L' tries to drive the reconfiguration consensus into a slot $s*+1$ by broadcasting:

$$\circledast(Repropose, (c, e, 0), H^C, C*, H^{A'}, A*, S, \sigma_{L'})$$

where $H^{A'}$ is a header reconfiguration event that lets L' join the committee. If this proposal becomes committed, then starting from a slot $s*+2$, the system reconfigures to the next configuration and L' joins the committee replacing the oldest member.

– If H^C and H^A are both batches of transactions, then L' first reproposes H^A for a slot $s*+1$ by broadcasting:

$$(Repropose, (c, e, 0), H^C, C*, H^A, A*, S, \sigma_{L'})$$

After that, L' tries to drive a reconfiguration consensus into a slot $s*+2$ by broadcasting:

$$(Propose, (c, e, 0), (H^{A'}, \sigma_{L'}), G^p, G^c, \sigma_{L'})$$

where $H^{A'}$ is a header of reconfiguration event that lets L' join the committee. If this proposal becomes committed, then starting from a slot $s*+3$, the system reconfigures to the next configuration and L' joins the committee replacing the oldest member.

Whenever a committee node doesn't know if the message by L' was reproposed or proposed, it can request this data by sending

$$\circledast_{L'}(RequestPayload, H^P)$$

where H^P is hash of unknown data, which can be obtained from reproposed or proposed message received from L'.

4. Cypherium Virtual Machine (CVM)

4.1. **Structure.** The Cypherium blockchain comes with a virtual machine environment for executing its smart contracts. In order to ensure the maximum flexibility and quality of the smart contract execution, we decided to integrate two separate virtual machines into the CVM. Namely, we incorporate the Ethereum Virtual Machine (EVM) along with an in-house implementation of the Java Virtual Machine (JVM). Therefore, all of the smart contracts that are written for the EVM can be executed with CVM seamlessly without any further complications or conversions. Our JVM implementation is also compatible with the Java 1.8 standard, including the bytecode format and the class files.

Figure 1 depicts the development and execution stack of the CVM. The smart contract can be written in either the Java language or the Solidity language which will then be compiled by the respective compilers and associated development tools into the bytecode form. The bytecode is stored as a field in the corresponding **transaction** data structure. Upon execution, the CVM execution environment will be responsible for picking up the appropriate underlying virtual machine to execute on.

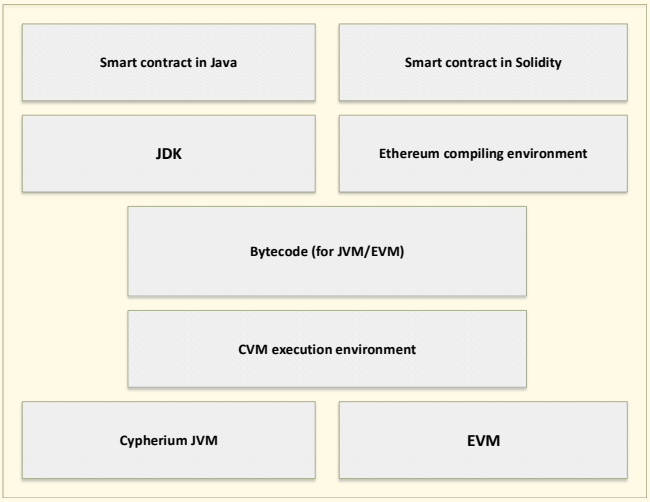


Figure 1. CVM development and execution stack

4.2. **Execution environment.** The bytecode is stored in the **data** field of a **transaction** from 2.6. The CVM execution environment determines the target virtual machine to execute the underlying bytecode on by looking up the magic number in the first 4 bytes (**CA FE BA BE** for a JVM bytecode and otherwise for an EVM bytecode). Algorithm 1 describes the switching mechanism.

Algorithm 1 CVM execution environment

```
code := transaction->code ▷ Read the bytecode from the transaction
magic := code[0:3]        ▷ Read the first 4 bytes of the bytecode
if magic == 0xCAFEBABE then
    JVM_engine(code)
else
    EVM_engine(code)
end if
```

5. Future Work

5.1. **Security.** An attacker cannot forge a transaction of another user without first obtaining the user's private key. In the worst-case scenario, without harvesting private keys, the attacker can only attempt to recall its own transactions by modifying the blockchain history. However, this too could not succeed as all nodes must check if a key block contains enough Proof-of-Work before accepting it and all of the associated transaction blocks. If a node becomes aware that another validator is maliciously excluding it from the committee, the node can broadcast view change to other validators and have the malicious validator removed from the committee. Merely corrupting 1/3 validators would be insufficient, though, for the attacker to rewrite the blockchain history. A malicious actor would also have to outvote the remaining 2/3 of honest validators to get the transaction block passed, and to do so would require over 2/3 total computing power in the network. In the unlikely event that an attacker is able to outrun all honest nodes, it can only reverse its own past payments, ultimately yielding less profit than participating honestly in the network. The rest of the nodes can still verify all transactions if they are willing to do so. The validators do not receive their

reward immediately, but only after they have validated all transaction blocks designated to them. If a node goes offline during any round, it will not receive any reward, and thus, the network incentivizes nodes to continue validating throughout their term.

5.1.1. *IP Conceal.* It is ideal that we could hide our IPs from the external world in order to avoid various security issues such as DDOS. To do so, Cypherium uses a mechanism called "IP group", inside which several virtual IPs (VIP) are assigned. Each VIP can be binded with a real IP of a node. This is essentially a many-to-one mapping, where one or more VIPs can be binded with a single real IP. If for any reason a node is down, its VIPs can be reassigned to its nearby peers. Each IP group has a single external IP address. During consensus, a request will be routed to the the IP address of the VIP and we design a load balancing algorithm to distribute the load to one of its internal VIPs. After each consensus operations (i.e. verification, pre-commit, commit, etc.), it will send out the response message to the external world, which is the same as out current PBFT mechanism. Our current reconfiguration allows us to change a single committee node, so this can easily be extended it to change a single IP group during reconfiguration. However, reward handling might become tricky, as we will now have to take care of all the nodes inside a particular IP group and decide how to best distribute rewards to a node inside a IP group even if it didn't do much work of the consensus (due to the natural imbalance of the consistent hashing algorithm).

5.2. **Micro Service.** Currently, a node has to deploy all of the functional code and handle all executions. When the application is small, this architecture is fine. However, our platform will inevitably grow and this process will become more difficult for us to extend. Micro service architecture is a strong candidate to help us solve such issues. For example, if we decide to add a new storage layer into our platform, such as IPFS, certain nodes can apply to become a storage nodes if they have big disks, but other limiting resources such as CPU and network bandwidth. These nodes can only deploy our IPFS module and do not have to deploy any other modules. They will use well defined interfaces to communicate with other peers with different functionalities.

5.3. **Simulation and Load Testing Environment.** We are in the process to testing our platform with a private chain beta testing. Due to the limitations of beta testing, we are currently not able to test real customer traffic. Instead, we will develop a generic load testing mechanism to support our current version of the platform, as well as any future extensions.

6. Conclusion

Proof-of Work remains the only consensus mechanism that keeps the promise of blockchain's decentralized revolution. Introducing Proof-of-Work as the node election mechanism enables anonymous participation in which benevolent actors can join or exit the network at will, while still ensuring that the network is secure and resistant to Sybil attacks. Elected nodes will only hold temporary positions to verify transactions, therefore, the network will remain decentralized despite some federated architecture.

With Cypherium, confirmation time will no longer stifle the growing demands of scalable blockchains. Decoupling the mining process and transaction verification reduces confirmation time to the instantaneous standards of modern processing . In an ecosystem where promise and expectation have risen high enough to rush and frustrate the practical implementations of distributed ledger technology, our system uniquely addresses the issues currently facing many next-generation permissionless blockchains.

References

Ittai Abraham, Dahlia Malkhi, Kartik Nayak, Ling Ren, and Alexander Spiegelman. Solida: A blockchain protocol based on reconfigurable byzantine consensus. *arXiv preprint arXiv:1612.02916*, 2016.

Miguel Castro, Barbara Liskov, et al. Practical byzantine fault tolerance. In *OSDI*, volume 99, pages 173–186, 1999.

Christian Decker, Jochen Seidel, and Roger Wattenhofer. Bitcoin meets strong consistency. In *Proceedings of the 17th International Conference on Distributed Computing and Networking*, page 13. ACM, 2016.

Jonathan Katz and Chiu-Yuen Koo. On expected constant-round protocols for byzantine agreement. *Journal of Computer and System Sciences*, 75(2):91–112, 2009.

Eleftherios Kokoris Kogias, Philipp Jovanovic, Nicolas Gailly, Ismail Khoffi, Linus Gasser, and Bryan Ford. Enhancing bitcoin security and performance with strong consistency via collective signing. In *25th {USENIX} Security Symposium ({USENIX} Security 16)*, pages 279–296, 2016.

Rafael Pass and Elaine Shi. Hybrid consensus: Efficient consensus in the permissionless model. In *31st International Symposium on Distributed Computing (DISC 2017)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2017.

Rafael Pass, Lior Seeman, and Abhi Shelat. Analysis of the blockchain protocol in asynchronous networks. In *Annual International Conference on the Theory and Applications of Cryptographic Techniques*, pages 643–673. Springer, 2017.

Ling Ren, Kartik Nayak, Ittai Abraham, and Srinivas Devadas. Practical synchronous byzantine consensus. *arXiv preprint arXiv:1704.02397*, 2017.

Claus-Peter Schnorr. Efficient signature generation by smart cards. *Journal of cryptology*, 4(3):161–174, 1991.

Simon Sprankel. Technical Basis of Digital Currencies, 2013. URL `http://www.coderblog.de/wp-content/uploads/technical-basis-of-digital-currencies.pdf`.