Blockchain Consensus Protocol with Horizontal Scalability

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***Abstract*—Blockchain systems have the potential to decentralise many traditionally centralised systems. However, scalability remains a key challenge. Without a horizontally scalable solution, blockchain systems remain unsuitable for ubiquitous use. We design a novel blockchain system called CHECO. Each node in our system maintains individual hash chains, which only stores transactions that the node is involved in. A consensus is reached on special blocks called checkpoint blocks rather than on all the transactions. Checkpoint blocks are effectively a hash pointer to the individual hash chains, thus a single checkpoint block may represent a large set of transaction blocks. The consensus protocol does not imply transaction validity. Hence we include a validation protocol which allows nodes to verify that transactions are correctly recorded, which indirectly achieves consensus on transactions. We implement a prototype and evaluate it experimentally. Our results show a strong indication of horizontal scalability even in the worst case, where every transaction is made with a randomly selected node. For 1200 nodes, we were able to perform almost 5000 transactions per second, orders of magnitude higher than the 7 transactions per second limit of Bitcoin.**

I. Introduction

Bitcoin is almost 10 years old and its market capitalisation is over $60 billion USD and growing [1]. We can be reasonably sure that cryptocurrencies, even if their application is still somewhat limited, are here to stay in the foreseeable future. Driven by the success of Bitcoin, we are seeing a renaissance of consensus research [2]–[4], where the primary focus is to improve the scalability of blockchain systems. This is due to the inefficiencies of the consensus mechanism—proof-of-work (PoW). For example, Bitcoin can only do 7 transactions per second (TPS) at most [5]. While adjusting the block size (which Bitcoin has recently done via SegWit [6]) and/or the block interval may increase TPS, it also leads to centralisation as larger blocks take longer to propagate in the network, putting miners that do not have a fast network at a disadvantage [7]. Furthermore, due to the bandwidth and latency in today's network, it is not possible to achieve more than 27 TPS from simply adjusting the block size [7].

Many approaches exist for improving the scalability of early blockchains. Off-chain transactions make use of the fact that if nodes make frequent transactions, then it is not necessary to store every transaction on the blockchain, only the net settlement is necessary. The best examples are Lightning Network [8] and Duplex Micropayment Channels [9]. It promises significant scalability improvements, but complicates user experience and leads to centralisation. Each node must deposit a suitable amount of Bitcoins into a multi-signature account. A low deposit would not allow large transactions. A high deposit locks the user from using much of her Bitcoins outside the channel. In addition, the user must proactively check whether the counterparty has broadcasted an old channel state so that the user does not lose Bitcoins. Finally, creating channels with sufficient balance and also keeping it online to act as a router is expensive. A casual user is not capable of such tasks, thus it leads to centralisation.

Another way to improve transaction rate is to use traditional Byzantine consensus algorithms such as PBFT [10] in a permissioned ledger such as Hyperledger Fabric [11]. In essence, they contain a fixed set of nodes (sometimes called validating peer) that run a Byzantine consensus algorithm to decide on new blocks. Such systems can achieve much higher transaction rates, e.g. 10,000 TX/s if the number of validating peer is under 16 for PBFT [2, Section 5.2]. However, these systems do not scale, e.g. the transaction rate drops to under 5000 TX/s when the number of validating peer is 64 [2, Section 5.2]. Moreover, the validating peers are predetermined which makes the system unsuitable for the open internet.

Recent research has developed a class of hybrid systems which uses PoW for committee election, and Byzantine consensus algorithms to agree on transactions, e.g. SCP [12], ByzCoin [3] and Solidus [13]. This design is primarily for permissionless systems because the PoW leader election aspect prevents the Sybil attack [14]. This technique overcomes the early blockchain scalability issue by delegating the transaction validation to the Byzantine consensus protocol (e.g. PBFT in ByzCoin [3]). A major tradeoff of such systems is that they cannot guarantee a high level of fault tolerance when there is a large number of malicious nodes (but less than a majority). SCP, ByzCoin and Solidus all have some probability to elect more than t Byzantine nodes into the committee, where t is typically just under a third of the committee size (a lower bound of Byzantine consensus [15]). This problem is especially difficult to solve because the committee is always much smaller than the population size which usually has more than t Byzantine nodes. Again, due to the fact that these

systems must reach consensus on all transactions, none of them achieves horizontal scalability. That is, by adding new nodes into the network, the global transaction rate should increase proportionally.

Finally, a technique that does achieve horizontal scalability is sharding, e.g. Elastico [16] and OmniLedger [4]. This is done by grouping nodes into multiple committees or shards of constant size. Nodes within a single shard run a Byzantine consensus algorithm to agree on a set of transactions that belong to that specific shard. The number of shards grows linearly with respect to the total computational power in the network, hence the transaction rate also grows linearly. The biggest limitation of sharding is that it is only optimal if transactions stay in the same shard. In fact, Elastico cannot atomically process inter-shard transactions. OmniLedger has an inter-shard transaction protocol but choosing a good shard size is difficult. A large shard size would make the system less scalable because the Byzantine consensus algorithm must be run by a large number of nodes. A small shard size would result in a large number of inter-shard transactions which also hinders scalability.

Thus far, there are no systems that achieve horizontal scalability in the general case, which leads to the goal of this work. Concretely, we attempt to answer the following research question.

> *Is it possible to design a blockchain consensus protocol that is fault-tolerant and horizontally scalable?*

A blockchain consensus protocol should be application neutral, for example, PoW without the transaction logic. The protocol should be Byzantine fault tolerant up to some threshold. The threshold may be made adjustable by trading off performance. Finally, we are interested in horizontal scalability in the general case, as it enables ubiquitous use.

The key insight is to *not* reach consensus using an existing consensus algorithm (a modified HoneyBadgerBFT [2]) on transactions themselves, but on special blocks called checkpoint blocks, such that transactions are nevertheless verifiable at a later stage by any node in the network. Our main contributions are the following.

- We formally introduce a blockchain system—CHECO[1]. It uses individual hash chains and checkpoints on every node to achieve horizontal scalability in the general case for the first time.
- We analyse CHECO to ensure correctness according to our definition.
- We provide an implementation and then experiment with up to 1200 nodes, our results show strong evidence of horizontal scalability.

In Section II, we give the problem description and our system model. Section III gives the formal system architecture. Next, we argue the correctness and fault tolerance properties of our system in Section IV. We evaluate our system experimentally in Section V. Finally, we conclude our work in Section VI.

[1]Derived from "*Che*ckpoint *co*nsensus".

II. PROBLEM DESCRIPTION

We introduce the problem as a modified Byzantine consensus problem. In our model, we consider N nodes, t of which are Byzantine. Nodes in our system make transactions with each other. Transactions can be in one of three states—*valid*, *invalid* and *unknown*, defined by some function $\mathsf{get\_validity}(\cdot)$. We seek a protocol that reasonably defines these states given a transaction, but also satisfies the following properties.

- *Agreement*: If any correct node decides on the validity (except when it is *unknown*) of a transaction, then all other correct nodes are able to reach the same conclusion or *unknown*.
- *Validity*: The protocol outputs the correct result according to $\mathsf{get\_validity}(\cdot)$.
- *Scalability*: If every node makes transactions at the same rate, then as N increases, the global transaction rate should increase linearly w.r.t. N.

Note that the agreement and validity property are similar to what is often seen in Byzantine consensus problems, but there are subtle differences and relaxations. Firstly, the agreement property only holds if honest nodes do not output *unknown*. For example, for a transaction, it is OK if two honest nodes output *valid* and *unknown*, but it is not OK to output *valid* and *invalid*. Secondly, the validity is a relaxation of what is typically seen in Byzantine consensus problems, namely we do not make any guarantee on whether the transaction is *valid* even if all nodes are honest, only that it is correct according to $\mathsf{get\_validity}(\cdot)$ defined by the protocol.

The problem is purposefully made to be application neutral, i.e. there are no constraints on the semantics of transactions. This is so that the protocol can act as a backbone to many applications. Due to this fact, we also do not consider global fork prevention or detection, as some application may not need such strong guarantees such as recording the number of bytes uploaded and downloaded in Tribler [17], [18]. On the other hand, we give two alternative constructions that do have fork detection in Section III-E3.

System model. We assume purely asynchronous channels with eventual delivery. Thus in no stage of the protocol are we allowed to make timing assumptions. The adversary has full control of the delivery schedule and the message ordering of all messages. But they are not allowed to drop messages except for their own[2].

Security assumptions. The malicious nodes are Byzantine, meaning that there are no restrictions on the type of failure. We use a static, round-adaptive corruption model. That is, if a round has started, the corrupted nodes cannot change until the next round. We assume there exists a Public Key Infrastructure (PKI), and nodes are identified by their unique and permanent public key. Finally, we use the random oracle (RO) model, i.e. calls to the random oracle are denoted by $\mathsf{H} : \{0,1\}^* \to \{0,1\}^\lambda$, where $\{0,1\}^*$ denotes the space of

[2]Reliability can be achieved in unreliable networks by resending messages or using some error correction code.

finite binary strings and λ is the security parameter. Under the RO model, the probability of successfully computing the inverse of the hash function is negligible with respect to λ [19].

III. System Architecture

To describe our system, we first give an informal overview and then move on to the formal description. Unlike most blockchain systems, we do not use a global ledger. Instead, every node has their own hash chain. The nodes only store transactions (TX) that they are involved in on their hash chain. Transactions are stored in TX blocks and every block only contains one transaction. We introduce a special block called checkpoint (CP) block, which represents the state of a hash chain in the form of a hash pointer. Such data structure is called Extended TrustChain, a visualisation can be seen in Figure 1.

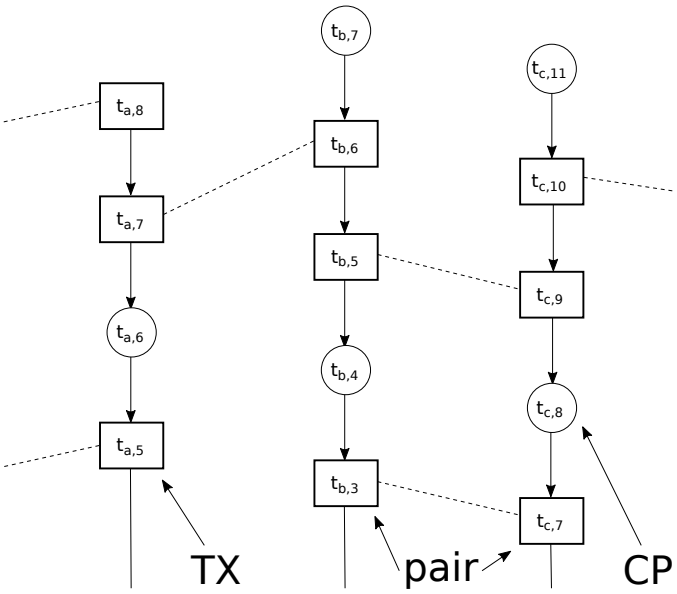


Fig. 1: Visualisation of the Extended TrustChain. $t_{u,i}$ represents a TX block on u's chain with a sequence number of i. $c_{v,j}$ represents a CP block on v's chain with a sequence number of j. A transaction is represented by a *pair* of TX blocks, one on each of the party's chain.

We randomly elect n special nodes called facilitators in every round. The facilitators reach consensus on CP blocks using an existing consensus algorithm—asynchronous subset consensus from HoneyBadgerBFT [2]. The consensus result is essentially a set of CP blocks from (nearly) all the nodes. While this gives us a consensus on a representation of the global state, it does not imply consensus on transactions. To this end, we introduce a validation protocol that allows any nodes to challenge any other node to produce a set of TX blocks that computes to the CP block in consensus, achieving implicit consensus on transactions. Since the transaction and validation protocols only make point-to-point communication, we achieve horizontal scalability.

The formal description is given next, it consists of one data structure—Extended TrustChain, and three protocols—consensus protocol, transaction protocol and validation protocol. The complete protocol can be seen as the concurrent composition of the sub-protocols.

A. Extended TrustChain

Each node u has a public and private key pair—pk_u and sk_u, and a chain B_u. The chain consists of blocks $B_u = \{b_{u,i} : i \in \{0, \ldots, h-1\}\}$, where $b_{u,i}$ is the ith block of u, and h is the height of the block (i.e. $h = |B_u|$). We often use $b_{u,h}$ to denote the latest block. There are two types of blocks, TX blocks and CP blocks. If T_u is the set of all TX blocks in B_u and C_u is the set of all CP blocks is B_u, then it must be the case that $T_u \cup C_u = B_u$ and $T_u \cap C_u = \varnothing$. The notation $b_{u,i}$ is generic over the block type. We assume there exists a function $\mathsf{typeof} : B_u \to \{\tau, \gamma\}$ that returns the type of the block, where τ represents the TX type and γ represents the CP type.

Definition 1. Transaction block
The TX block is a six-tuple, i.e

$$t_{u,i} = \langle \mathsf{H}(b_{u,i-1}), seq_u, txid, pk_v, m, sig_u \rangle.$$

We describe each item in turn.

1) $\mathsf{H}(b_{u,i-1})$ *is the hash pointer to the previous block.*
2) seq_u *is the sequence number which should equal* i*.*
3) $txid$ *is the transaction identifier, it should be generated using a cryptographically secure pseudo-random number generator by the initiator of the transaction.*
4) pk_v *is the public key of the counterparty* v*.*
5) m *is the transaction message, which can be seen as an arbitrary string.*
6) sig_u *is the signature created using* sk_u *on the concatenation of the binary representation of the five items above.*

TX blocks come in pairs. In particular, for every block

$$t_{u,i} = \langle \mathsf{H}(b_{u,i-1}), seq_u, txid, pk_v, m, sig_u \rangle$$

there exist one and only one pair

$$t_{v,j} = \langle \mathsf{H}(b_{v,j-1}), seq_v, txid, pk_u, m, sig_v \rangle,$$

if the nodes follow the transaction protocol (described in Section III-C). Note that the $txid$ *and* m *are the same, and the public keys refer to each other. Thus, given a TX block, these properties allow us to identify its pair.*

Definition 2. Checkpoint block
The CP block is a five-tuple, i.e.

$$c_{u,i} = \langle \mathsf{H}(b_{u,i-1}), seq_u, \mathsf{H}(\mathcal{C}_r), r, sig_u \rangle,$$

where $\mathcal{C}_r$ *is the consensus result (which we describe in Definition 3) in round* r*, the other items are the same as the TX block definition.*

The genesis block in the chain must be a CP block in the form of

$$c_{u,0} = \langle \mathsf{H}(\perp), 0, \mathsf{H}(\perp), 0, sig_u \rangle,$$

where $H(\perp)$ can be interpreted as applying the hash function on an empty string. The genesis block is unique because every node has a unique public and private key pair.

Definition 3. Consensus result

Our consensus protocol runs in rounds. Every round is identified by a round number r, which is incremented on every new round. The consensus result is a tuple, i.e.

$$\mathcal{C}_r = \langle r, C \rangle,$$

where C is a set of CP blocks agreed by the facilitators of round r.

Here we define an important property which results from the interleaving nature of CP and TX blocks. It is used in our validation protocol (discussed in Section III-D).

Definition 4. Enclosure and agreed enclosure

If there exist a tuple $\langle c_{u,a}, c_{u,b} \rangle$ for a TX block $t_{u,i}$, where

$$a = \underset{k, k<i, \textit{typeof}(b_{u,k})=\gamma}{\arg\min} (i-k)$$

$$b = \underset{k, k>i, \textit{typeof}(b_{u,k})=\gamma}{\arg\min} (k-i),$$

then $\langle c_{u,a}, c_{u,b} \rangle$ is the enclosure of $t_{u,i}$. Intuitively, that is the two closest CP blocks that surround $t_{u,i}$. Some TX blocks may not have any enclosure, then its enclosure is $\perp$. Agreed enclosure is the same as enclosure with an extra constraint where the CP blocks must be in some consensus result $\mathcal{C}_r$.

Definition 5. Fragment and agreed fragment

If the enclosure of some TX block $t_{u,i}$ is $\langle c_{u,a}, c_{u,b} \rangle$, then its fragment *$F_{u,i}$ is defined as $\{b_{u,i} : a \leq i \leq b\}$. Similarly,* agreed fragment *has the same definition as fragment but using agreed enclosure. For convenience, the function* $\textit{agreed\_fragment}(\cdot)$ *represents the agreed fragment of some TX block if it exists, otherwise $\perp$.*

B. Consensus Protocol

Our scalable consensus protocol runs on top of Extended TrustChain. It uses an unmodified asynchronous subset consensus (ACS) algorithm as the key building block. The objectives of the protocol are to allow honest nodes always make progress (in the form of creating new CP blocks), compute correct consensus result in every round and have an unbiased election of facilitators. Concretely, we define the necessary properties as follows.

Definition 6. Properties of the consensus protocol

$\forall r \in \mathbb{N}$, the following properties must hold.

1) Agreement*: If one correct node outputs a set of facilitators $\mathcal{F}_r$, then every node outputs $\mathcal{F}_r$*
2) Validity*: If any correct node outputs $\mathcal{F}_r$, then*
   a) *$|\mathcal{C}_r| \geq N - t$ and each CP in $\mathcal{C}_r$ belong to a different node*[3].
   b) *$\mathcal{F}_r$ must contain at least $n - t$ honest nodes and*
   c) *$|\mathcal{F}_r| = n$.*
3) Termination*: Every correct node eventually outputs some $\mathcal{F}_r$.*
4) Fairness*: Every node with a CP block in $\mathcal{C}_r$ should have an equal probability of becoming a member of $\mathcal{F}_r$.*

These properties are similar to Byzantine consensus properties but there are subtle differences. Firstly, they are properties for every node in the network and not just the facilitators. Secondly, they must be satisfied for all rounds, because a failure in one round will lead to failures in subsequent rounds.

1) Bootstrap Phase: As with many distributed systems, there must be a bootstrap phase which sets up the system. Imagine that there is some bootstrap oracle, that initiates the code on every node. The code satisfies all the properties in Definition 6. Namely, every node has the same set of valid facilitators $\mathcal{F}_1$ that are randomly chosen. This concludes the bootstrap phase. For any future rounds, the consensus phase is used.

2) Consensus Phase: The consensus phase begins when $\mathcal{F}_r$ is available to all the nodes. Note that $\mathcal{F}_r$ indicates the facilitators that were elected using results of round r and are responsible for driving the ACS algorithm in round $r+1$. The goal is to reach agreement on a set of new facilitators $\mathcal{F}_{r+1}$ that satisfies the four properties in Definition 6.

There are two scenarios in the consensus phase. First, if node u is not the facilitator, it sends $\langle \texttt{cp\_msg}, c_{u,h} \rangle$ to all the facilitators. Second, if the node is a facilitator, it waits until $N - t$ messages of type `cp_msg` are received. Invalid messages are removed. That is blocks with invalid signatures and blocks signed by the same key. With the sufficient number of `cp_msg` messages, it begins the ACS algorithm and some $\mathcal{C}'_{r+1}$ should be agreed upon by the end of it. Duplicates and blocks with invalid signatures are again removed from $\mathcal{C}'_{r+1}$ and we call the final result $\mathcal{C}_{r+1}$. We have to remove invalid blocks a second time (after ACS) because the adversary may send different CP blocks to different facilitators, which results in invalid blocks in the ACS output, but not in any of the inputs.

The core of the consensus phase is the ACS protocol, it is based on the construction described in HoneyBadgerBFT [2]. We do not use the full HoneyBadgerBFT due to the following. First, the transactions in HoneyBadgerBFT are first queued in a buffer and the main consensus algorithm starts only when the buffer reaches an optimal size. We do not have an infinite stream of CP blocks, thus buffering is unsuitable. Second, HoneyBadgerBFT uses threshold encryption to hide the content of the transactions. But we do not reach consensus on transactions, only CP blocks, so hiding CP blocks is meaningless for us as it contains no transaction information.

Continuing, when $\mathcal{F}_r$ reaches agreement on $\mathcal{C}_{r+1}$, they immediately broadcast[4] two messages to all the nodes—first the consensus message $\langle \texttt{cons\_msg}, \mathcal{C}_{r+1} \rangle$, and second the signature message $\langle \texttt{cons\_sig}, r, sig \rangle$. The reason for

[3] $\mathcal{C}_r$ is a tuple but we abuse the notation here by writing $|\mathcal{C}_r|$ to mean the number of CP blocks in the second element of $\mathcal{C}_r$.

[4] An alternative to using broadcasting is to use an epidemic protocol [20], as long as it can guarantee delivery.

sending `cons_sig` is the following. Recall that channels are not authenticated, and there are no signatures in $\mathcal{C}_{r+1}$. If a non-facilitator sees some $\mathcal{C}_{r+1}$, it cannot immediately trust it because it may have been forged. Thus, To guarantee authenticity, every facilitator sends an additional message that is the signature of $\mathcal{C}_{r+1}$.

Upon receiving $\mathcal{C}_{r+1}$ and at least $n - f$ valid signatures by some node u, u performs two tasks. First, it creates a new CP block using $\mathsf{new\_cp}(\mathcal{C}_{r+1})$ (Algorithm 1). Second, it computes the new facilitators using $\mathsf{get\_facilitator}(\mathcal{C}_{r+1}, n)$ (Algorithm 2), and updates its facilitator set to the result. This concludes the consensus phase and brings us back to the state at the beginning of the consensus phase, so a new round can be started.

Algorithm 1 Function $\mathsf{new\_cp}(\mathcal{C}_r)$ runs in the context of the caller u. It creates a new CP block and appends it to u's chain.

$\langle r, \_\rangle \leftarrow \mathcal{C}_r$
$h \leftarrow |B_u|$
$c_{u,h} \leftarrow \langle \mathsf{H}(b_{u,h-1}), h, \mathsf{H}(\mathcal{C}_r), r, sig_u \rangle$
$B_u \leftarrow B_u \cup c_{u,h}$

Algorithm 2 Function $\mathsf{get\_facilitator}(\mathcal{C}_r, n)$ takes the consensus result $\mathcal{C}_r$ and an integer n, then sorts the CP blocks C by the luck value (the λ-expression), and outputs the smallest n elements.

$\langle r, C\rangle \leftarrow \mathcal{C}_r$
$\mathsf{take}(n, \mathsf{sort\_by}(\lambda x.\mathsf{H}(\mathcal{C}_r || pk \text{ of } x), C))$

C. Transaction Protocol

The TX protocol, shown in Algorithm 4, is run by all nodes. It is also known as True Halves, first described informally by Veldhuisen [21, Chapter 3.2]. Nodes that wish to initiate a transaction calls $\mathsf{new\_tx}(pk_v, m, txid)$ (Algorithm 3) with the intended counterparty v identified by pk_v and message m. $txid$ should be a uniformly distributed random value, i.e. $txid \in_R \{0,1\}^{256}$. Then the initiator sends $\langle \texttt{tx\_req}, t_{u,h}\rangle$ to v.

Algorithm 3 Function $\mathsf{new\_tx}(pk_v, m, txid)$ generates a new TX block and appends it to the caller u's chain. It is executed in the private context of u, i.e. it has access to the sk_u and B_u. The necessary arguments are the public key of the counterparty pk_v, the transaction message m and the transaction identifier $txid$.

$h \leftarrow |B_u|$
$t_{u,h} \leftarrow \langle \mathsf{H}(b_{u,h-1}), h, txid, pk_v, m, sig_u \rangle$
$B_u \leftarrow B_u \cup \{t_{u,h}\}$

A key feature of the TX protocol is that it is non-blocking. At no time in Algorithm 3 or Algorithm 4 do we need to hold the chain state and wait for some message to be delivered before committing a new block to the chain. This allows for a high level of concurrency where we can call $\mathsf{new\_tx}(\cdot)$ multiple times without waiting for the corresponding `tx_resp` messages.

Algorithm 4 The TX protocol which runs in the context of node u.

Upon $\langle \texttt{tx\_req}, t_{v,j}\rangle$ from v
  $\langle \_, \_, txid, pk_v, m, \_\rangle \leftarrow t_{v,j}$
  $\mathsf{new\_tx}(pk_u, m, txid)$
  store $t_{v,j}$ as the pair of $t_{u,h}$
  send $\langle \texttt{tx\_resp}, t_{u,h}\rangle$ to v
Upon $\langle \texttt{tx\_resp}, t_{v,j}\rangle$ from v
  $\langle \_, \_, txid, pk_v, m, \_\rangle \leftarrow t_{v,j}$
  store $t_{v,j}$ as the pair of the TX with identifier $txid$

D. Validation Protocol

Up to this point, we do not provide a mechanism to detect tampering. The validation protocol aims to solve this issue. The protocol is also a request-response protocol. But before explaining the protocol itself, we first define what it means for a transaction to be valid.

1) Validity Definition: A transaction can be in one of three states in terms of validity—*valid*, *invalid* and *unknown*. Given a fragment $F_{v,j}$, the validity of the TX block $t_{u,i}$ with its corresponding fragment $F_{u,i}$ is captured by the function $\mathsf{get\_validity}(t_{u,i}, F_{u,i}, F_{v,j})$ (Algorithm 5). Note that $t_{u,i}$ and $F_{u,i}$ are assumed to be valid, otherwise the node calling the function would have no point of reference. This is not difficult to achieve because typically the caller is u, so it knows its own TX block and the corresponding agreed fragment. If the caller is not u, it can always query for the agreed fragment that contains the transaction of interest from u.

We stress that the *unknown* state means that the verifier does not have enough information to continue with the validation protocol. If enough information is available at a later time, then the verifier will output either *valid* or *invalid*.

Note that the validity is on a transaction, i.e. two TX blocks that form a pair. It is defined this way because the malicious sender may create new TX blocks in their own chain but never send `tx_req` messages. In that case, it may seem that the counterparty, who is honest, purposefully omitted TX blocks. But in reality, it was the malicious sender who did not follow the protocol. Thus, in such cases, the whole transaction identified by its $txid$ is marked as invalid.

2) Validation Protocol: Our validation protocol, shown in Algorithm 6, is designed to classify transactions according to the aforementioned validity definition. If u wishes to validate some TX with ID $txid$ and counterparty v, it sends $\langle \texttt{vd\_req}, txid\rangle$ to v. The desired properties of the validation protocol are as follows.

Definition 7. Properties of the validation protocol

1) Agreement*: If any correct node decides on the validity (except when it is* unknown*) of a transaction, then*

Algorithm 5 Function get_validity$(t_{u,i}, F_{u,i}, F_{v,j})$ validates the transaction represented by $t_{u,i}$. We assume $F_{u,i}$ is always correct and contains $t_{u,i}$. $F_{v,j}$ is the corresponding fragment received from v.

if $F_{v,j}$ is not a fragment created in the same round as $F_{u,i}$ **then**
  return *unknown*
$\langle \_, \_, txid, pk_v, m, \_ \rangle \leftarrow t_{u,i}$
if number of blocks of $txid$ in $F_{v,j} \neq 1$ **then**
  return *invalid*
$t_{v,j} \leftarrow$ the TX block with $txid$ in $F_{v,j}$
$\langle \_, \_, txid', pk_u, m', \_ \rangle \leftarrow t_{v,j}$
if $m \neq m' \vee txid \neq txid'$ **then**
  return *invalid*
if $t_{u,i}$ is not signed by $pk_u \vee t_{v,j}$ is not signed by pk_v **then**
  return *invalid*
return *valid*

all other correct nodes are able to reach the same conclusion or unknown*.*

2) Validity*: The validation protocol outputs the correct result according to the aforementioned validity definition.*
3) Liveness*: Any valid (invalid) transaction is marked as valid (invalid) eventually.*

Algorithm 6 Validation protocol which runs in the context of u

Upon $\langle$vd_req$, txid\rangle$ from v
  $t_{u,i} \leftarrow$ the transaction identified by $txid$
  $F_{u,i} \leftarrow$ agreed_fragment$(t_{u,i})$
  send $\langle$vd_resp$, txid, F_{u,i}\rangle$ to v
Upon $\langle$vd_resp$, txid, F_{v,j}\rangle$ from v
  $t_{u,i} \leftarrow$ the transaction identified by $txid$
  if $F_{u,i}$ and $F_{v,j}$ are available and $F_{u,i}$ is the agreed fragment of $t_{u,i}$ **then**
    set the validity of $t_{u,i}$ to get_validity$(t_{u,i}, F_{u,j}, F_{v,j})$

We make two remarks. First, just like the TX protocol, we do not block any part of the protocol. Second, suppose some $F_{v,j}$ validates $t_{u,i}$, then that does not imply that $t_{u,i}$ only has one pair $t_{v,j}$. Our validity requirement only requires that there is only one $t_{v,j}$ in the correct consensus round. The counterparty may create any number of fake pairs in later consensus rounds. But these fake pairs only pollutes the chain of v and can never be validated.

E. Design Variations and Tradeoffs

In this section, we explore a few design variations, some of them require a relaxed version of our original model. They enable better performance and allow us to apply our design in the fully permissionless setting.

1) Using Timing Assumption in the Permissionless Setting: At the start of our consensus phase (Section III-B2), facilitators must wait for $N - f$ cp_msg messages. The use of N makes our system unsuitable for the permissionless setting. To introduce timing, instead of waiting for $N - f$ messages, we wait for some time D, such that D is sufficiently long for honest nodes to send their CP blocks to the facilitators. Consequently, this removes the need for a PKI because the collected CP blocks may be from nodes that nobody has seen in the past.

The new protocol handles churn as follows. Suppose a new node wish to join the network and the facilitators are known (this can be done with a public registry). It simply sends its latest CP block to the facilitators. Then, in the next round, the node will have a chance to become a facilitator just like any existing node. To leave the network, nodes simply stop submitting CP blocks. There is a subtlety here which happens when the node is elected as a facilitator in the following round. In this case, the node must fulfil its obligation by completing the consensus protocol, but without proposing its own CP block, before leaving. Otherwise, the $n \geq 3t + 1$ condition may be violated.

2) Optimising Validation Protocol Using Cached Agreed Fragments: One more way to improve the efficiency of the validation protocol is to use a single agreed fragment to validate multiple transactions. Concretely, for node A, upon receiving an agreed fragment from node B, rather than validating a single transaction, A attempts to validate all transactions performed with B in the unknown state, in that fragment.

The benefit of this technique is maximised when a node only transacts with one other node. In this case, the communication of one fragment is sufficient to validate all transactions in that fragment. In the opposite extreme, if every transaction that the node makes is with another unique node, then the caching mechanism would have no effect.

3) Total Fork Detection: The validation algorithm guarantees that there are no forks within a single agreed fragment. This is sufficient for some applications such as proving the existence of some information. However, for applications such as digital cash where every block depends on one or more previous blocks, our scheme is not suitable. For such applications, we need to guarantee that there are no forks from the genesis block leading up to the TX block of interest.

We offer two approaches to do total fork detection. First and the easiest solution is to simply ask for the complete chain of the counterparty. The verifier can be sure that there are no forks if the following holds.

1) The hash pointers are correct.
2) All the CP blocks are in consensus.
3) The TX of interest is in the chain.

We use this approach in our prior work on Implicit Consensus [22]. Nodes employ caching to minimise communication costs, we call this effect spontaneous sharding.

The second approach is probabilistic but with only a constant communication overhead over our current design. For a node, observe that if all of its agreed fragments has a transaction with an honest node, then the complete chain is effectively validated in a distributed manner. The only way for an attacker to make a fork is to make sure that the agreed

fragment containing the fork has no transactions with honest nodes. Such malicious behaviour is prevented probabilistically using a challenge-response protocol as follows. Suppose node A wish to make a transaction with node B. A first sends a challenge to B asking it to prove that it holds a valid agreed fragment between some consensus round specified by A. If B provides a correct and timely response, then they run the transaction protocol as usual. Otherwise, A would refuse to make the transaction.

IV. Correctness and Fault Tolerance Analysis

We evaluate our system analytically to ensure the desired properties (Definition 6 and Definition 7) hold. An informal argument is given in this section, we refer to **checo**?? for an in-depth analysis.

A. Correctness of the Consensus Protocol

Recall that the consensus protocol properties (Definition 6) has four items—agreement, validity, termination and fairness. The first three hold due to the following facts.

- The CP blocks sent to the facilitators are eventually delivered and then ACS eventually starts.
- Agreement, validity and termination hold for ACS as they are the properties of ACS and are proven to hold in [2].
- The consensus result and signatures are eventually disseminated to all the nodes, so honest nodes must hold the same result as the honest facilitators.

Fairness holds because we model $\mathsf{H}(\cdot)$ as a query to the random oracle. Sorting nodes by the luck value $\mathsf{H}(\mathcal{C}||pk)$ can be seen as a random permutation of a list of nodes. Therefore every node has the same probability of becoming a facilitator.

B. Correctness of the Validation Protocol

Using the previous result, we show that the agreement and validity properties (from Definition 7) hold for the validation protocol.

The validity property holds because we use $\mathsf{get\_validity}(\cdot)$ in the validation protocol. The agreement property holds because we model $\mathsf{H}(\cdot)$ as a query to a random oracle. Suppose two honest nodes decided on two different states, *valid* and *invalid* for the same transaction. For that to happen, two agreed fragments must exist for the same transaction, but these fragments must also have the same agreed enclosure. Recall that blocks form a hash chain. So this is not possible unless the adversary can compute the inverse of $\mathsf{H}(\cdot)$ with high probability.

Liveness, unfortunately, does not hold in our model. A malicious node can act honestly when running the transaction protocol, but then never respond to any validation requests. Therefore there are transactions that can never be validated. Nevertheless, the malicious node will be at an economic loss if it is not responsive because honest nodes are less likely to make contact with nodes that do not respond to validation requests.

A stronger version of the validity definition exists. That is, if two honest nodes make a transaction, then the transaction state is always valid in addition to our current validity definition. Under our purely asynchronous model, we cannot guarantee this stronger version. Since the adversary can delay any message for any amount of time, it can make sure all `tx_req` messages are delivered in a round later than the round which the message is sent. Effectively, the transaction pair would always be in different rounds and the validation protocol would not output *valid*. We believe in a relaxed model, i.e. a weakly synchronous model, a stronger validity definition is possible.

C. Fault Tolerance

Finally, we consider the effect when the number of adversaries is more than t. This is useful because in practice it is difficult to guarantee that t satisfies $n \geq 3t+1$, especially when N is large. Hence we are interested in the probability for this to happen under our facilitator election process. The problem is modelled by a hypergeometric distribution, where the random variable X is the number of malicious nodes. For our system to fail, we are interested in the following probability.

$$\Pr[X \geq \lfloor \frac{n-1}{3} \rfloor + 1]$$

Let $E[X] = n\alpha$ where $0 \leq \alpha \leq \lfloor \frac{n-1}{3} \rfloor / n$. Using the tail inequality found in [23]

$$\Pr[X \geq E[X] + \tau n] \leq e^{-2\tau^2 n},$$

and setting

$$\tau = \frac{\lfloor \frac{n-1}{3} \rfloor + 1}{n} - \alpha,$$

we arrive at the following bound

$$\Pr[X \geq \lfloor \frac{n-1}{3} \rfloor + 1] \leq e^{-2\left(\frac{\lfloor \frac{n-1}{3} \rfloor + 1}{n} - \alpha\right)^2 n}.$$

The bound is not tight, but it is useful for picking parameters for the desired level of fault tolerance. If n is known, then we can pick a α such that the probability becomes small. On the other hand, if α is fixed, we may increase n to achieve the same. Furthermore, hypergeometric distributions have light tails with "faster-than-exponential fall-off" [23]. So the probability of picking more than $\lfloor \frac{n-1}{3} \rfloor$ malicious nodes drops of exponentially as the expected value moves away from $\lfloor \frac{n-1}{3} \rfloor$. To put this into perspective, suppose $n = 1000$ and $\alpha = 1/5$, i.e. a fifth of the nodes are malicious. Then the probability to elect more malicious nodes than the threshold is only 2.6×10^{-16}.

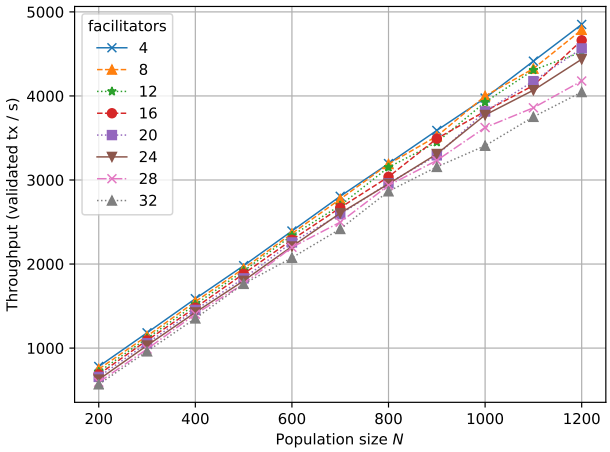
V. Implementation and Evaluation

The prototype implementation can be found on GitHub.

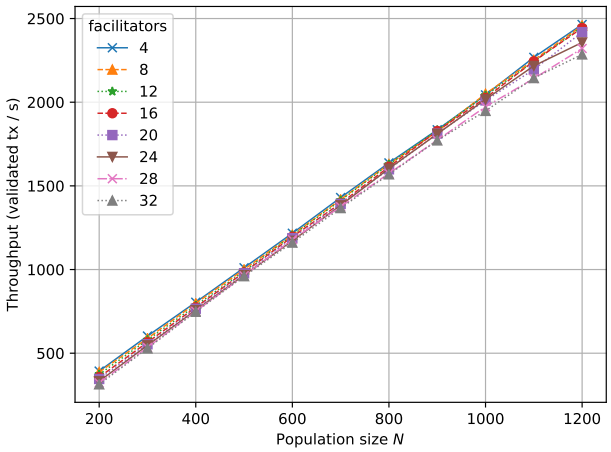
https://github.com/kc1212/checo

It implements the three protocols and the Extended TrustChain. We also implement the caching optimisation discussed in Section III-E2. It is written in the Python programming language[5]. The cryptography primitives we use are

[5]https://www.python.org/



(a) Every node make transactions with a fixed node.



(b) Every node make transactions with a random node.

Fig. 2: Global throughput increases as the population increases when every node transact at the same rate. Making transactions with fixed nodes results in a higher throughput because of the caching mechanism.

SHA256 for hash functions and Ed25519 for digital signatures. Both of which are provided by libnacl [6].

We run the experiment on the DAS-5[7] with up to 1200 nodes. Every node makes transactions at 2 per second. Since Bitcoin transactions are approximately 500 bytes [24], we use a uniformly random transaction size sampled between 400 and 600 bytes.

The global throughput results are shown in Figure 2. We consider Figure 2a as the ideal case, where nodes only make transactions with a fixed node. We consider Figure 2b as the worst case, where nodes make transactions with random nodes and the caching mechanism is unlikely to be used. Observe that the transaction rate is much lower in Figure 2b. This is because the communication of an agreed fragment is necessary to verify every transaction (no caching), putting a strain on our network infrastructure. In practice, we do not expect such behaviour to occur as it is possible to cache agreed fragments.

For Figure 2a, the magnitude of our throughput may not be self-evident at first glance. Recall that we fixed the transaction rate to 2 TPS, but how is it possible to have around 4800 transactions per second for 1200 nodes (which is 4 TX/s)? This is due to the way validated transactions are calculated. Transactions are between two parties, hence if every node makes two transactions per second, every node also expects to receive two transactions per second. Hence, for every node, the TX blocks are created at 4 per second. Validation requests are sent at the same rate, which explains the magnitude.

Overall, the throughput has a linear relationship with the population size. This result is a strong indication of the horizontal scalability which we aimed to achieve. For more experimental results refer to **checo**??.

[6]https://pypi.python.org/pypi/libnacl

[7]https://www.cs.vu.nl/das5/

VI. Conclusion

We introduced an application neutral blockchain system which we call CHECO. The checkpoint block is added to the existing TrustChain data structure for use in our consensus protocol. The round based consensus protocol uses ACS as a building block to reach consensus on checkpoint blocks. The consensus result lets nodes elect new facilitators and create new checkpoint blocks. To make transactions, nodes use the transaction protocol, which is adapted from an existing work called True Halves. Finally, we introduce a validation protocol which ensures that if an agreed fragment for some transaction exists, then nodes reach agreement on the validity of that transaction. The novelty of the validation protocol is that it uses point-to-point communication, i.e. nodes only validate the transactions of interest, this enables our horizontal scalability property.

We achieve the properties described in the Problem Description (Section II). Namely, our protocol achieves agreement and validity as we argued in Section IV-B. Further, the horizontal scalability is demonstrated in Section V, in the ideal case as well as the worst case. In the future, we hope to apply our system to a concrete application and evaluate its performance.

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