Blockchain Backbone with Horizontal Scalability

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TODO MOTIVATION FOR RESEARCH TOPIC

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Chapter 1

Introduction

We live in a world where technologies have become vital for our welfare and success. The internet, for instance, gave us the ability of efficiently exchange information on a global scale. However, in contrast to its original design, the internet and in particular the world wide web is becoming increasingly centralised. The domain name system (root name server), certificate authorities (root CA), to name a few, carry enormous responsibilities and are a central point of failure. The same can be said for many other services such are online marketplaces, cloud services, hospitality services and even our banking system. The 2008 financial crisis is an example of the banking system making poor choices which result in a decline in consumer wealth in the order of trillions [3] and led to the European debt crisis.

Ironically, also in 2008, Satoshi Nakamoto published the Bitcoin whitepaper [30]. Which, for the first time, gave us a simple banking system in the form of a distributed ledger. It needs no central control but still incorruptable with high probability even if there are malicious parties that aim to undermine the system. We call such a ledger a blockchain.

The primary innovations are (1) its consensus model which prevents double spending, and (2) its incentive mechanism that encourages anyone (with adaquate hardware) to participate in the network and keep it running. The double spending problem can be seen as an inconsistency issue. For example, C has 5 units of currency in her account. At some instant in time, A sees that C transferred 5 units to A and B sees that C transferred 5 units to B. Hence the transaction is inconsistent with respect to the observer. Bitcoin and many of its derivatives (e.g. Litecoin[1] and Dogecoin[2]) solve the inconsistency problem with a consensus algorithm. The goal of the algorithm is reach agreement on a set of valid values, e.g. transactions. This effectively eliminates inconsistencies. In Bitcoin's case, the consensus algorithm is called *proof-of-work*. Where miners (parties that runs the Bitcoin

[1] litecoin.org

[2] dogecoin.org

network) collect transactions and compete in solving (using brute force) a difficult puzzle. The first miner to solve it generates a block containing all the collected transactions. The miner is also rewarded with new coins and transaction fees. It is important to note that every block, that is the solution of the puzzle, depends on the previous block. Hence the name blockchain. Further, due to the difficulty of the puzzle and that the majority of the parties are honest, it is unlikely for more than one blockchain to exist in the network for a long period of time. Thus every party sees a consistent blockchain which solves the double spending problem.

Bitcoin has had its ups and downs, but over it has grown into an enormous system. Its power consumption is as high as Republic of Ireland [33]. Its market cap, at the time of writing, is over 40 billion USD [13]. Many online marketplaces are using Bitcoin, for example Steam[3] and even Amazon[4]. Due to its success, people from many different disciplines began investigating in way to use blockchain technology. This includes finance [44], heathcare [15], logistics [39] and energy [4].

Sadly, as traditional blockchain systems began to gain popularity, their limitations also became apparent. Bitcoin has the infamous 7 transactions per second upper bound [47]. This is due to the fact that blocks are fixed to 1 MB are only generated on average every 10 minutes. Since every Bitcoin transaction is at least 250 bytes, it computes to about 7 transactions per second. Due to this limitation, it is not uncommon to see a long backlog of about 20,000 transactions[5]. A few months ago the backlog even reached 100,000, which meant new transactions would take at least 11 hours to hit the blockchain [40]. This issue has plagued the Bitcoin community for some time and is the root cause for the block size debate, which some calls it a civil war [42]. Parties that are for the increase in block size argue that a larger block would improve the transaction rate. Parties against it argue that it would make mining more centralised because blocks take longer to propogate through the network. It also requires a hard fork (not backward compatible), which risks consensus failure and devaluation. A recent empirical study by Croman et el. [14] has shown that increasing the block size may help. But given the bandwidth and latency constraints, it not possible to have more than 758 transactions per second. Even worse, it may give some miner an unfair lead over others. Thus fundamental changes are necessary run at the scale of centralised payment processors such as Visa [46], which is in the order of tens of thousands transactions per second.

What we have described is in fact the current state of Bitcoin. Many proposals exist with the aim to make Bitcoin more scalable. The most prominant is Seggregated Witness or SegWit [26]. It moves the signature

[3] https://store.steampowered.com/

[4] Not directly, but via https://purse.io/.

[5] https://blockchain.info/unconfirmed-transactions/

data to the end of the block and changes the block size to 4 MB. The effect is that the first 1 MB of the block is still backward compatible, thus there is no need for a hard fork. It also solves the transaction malleability problem [10] and paves the way for offchain transactions via Lightning Network [36]. Although SegWit is implemented, it is still uncertain whether the Bitcoin network will adopt it. At the time of writing, there is only 35% of the network signalling for adoptation, this is only a 10% increase since November last year[6]. Thus it may take years if ever for SegWit to be adopted. Even if it is adopted, it cannot reach the transaction rate of centralised systems.

In this work, we take the advice of Croman et el. [14] and Marko [47] and rethink the blockchain architecture. Our primary insight came from observing the differences between how transactional systems work in the real world and how they work in blockchain systems like Bitcoin. Take a restaurant owner for example, most of the time the customer is honest and pays the bill. There is no need for the customer or the restaurant owner to report the transaction to any central authority because both parties are happy with the transaction. On the other hand, if the customer leaves without paying the bill, then the restaurant owner would report the incident to some central authority, e.g. the police. On the contrary, in blockchain systems, every transaction is effectively sent to the miners, which can be seen as a collective authority. This consequently lead to limited scalability because every transaction must be validated by the authority even when most of the transaction are legitimate.

Using the aforementioned insight, we explore an alternative consensus model for blockchain systems where transactions themself do not reach consensus, but nevertheless verifiable at a later stage by any node in the network. Informally, out model works as follows. Every node stores its own blockchain and every block is one transaction. We randomly selected nodes in every round, the selected ones are called facilitators. They reach consensus not on the individual transactions, but on the state of every chain represented by a single digest, we call this state the checkpoint. If a checkpoint of some node is in consensus, then that node can proof to any other node that it holds a set of transactions that computes (form a chain) to the checkpoint. This immediately show that those transactions are tamper-proof.

We describe and analyse our idea in the remainder of this work. We begin with the problem description in Chapter 2. This is followed by a detailed formulation of the model in Chapter 3. Next, we analyse the correctness and performance of our design in Chapter 4, this is where we present our key theorems. Implementation and experimental results are discussed in Chapter 5. Finally, we compare our system with other state-of-the-art blockchain systems and conclude in Chapters 6 and 7 respectively.

[6]https://blockchain.info/charts/bip-9-segwit

Chapter 2

Problem Description

The decentralised and democratic nature of blockchain technology removes central point of control or failure. However, as we described in the Introduction, it faces a genuine scalability problem. In particular, proof-of-work based systems are unlikely to reach the transaction rate of Visa even with parameter tuning. What we wish to see is horizontal scalability. That is, by adding new nodes into the network, the global transaction rate should increase proportionally. Hence, the research question we answer in this work is the following.

> *How do we design a blockchain fabric that is fault tolerant, scalable and can reach global consensus?*

In order to make sense of our research question, we must first define *blockchain fabric*. Typical blockchain systems are application specific. For example, the application in Bitcoin (any many of its derivatives) is digital cash, the application in Namecoin is domain name registration [31] and the application in Siacoin is cloud storage [32]. Underneath these applications lies the blockchain fabric which has the goal of reaching consensus on transactions. In the case of Bitcoin it is proof-of-work (PoW). It is not concerned with the structure of the transactions, it works by simply treating transactions as a blob of data and hashes them with the previous block. Hence, we focus on blockchain fabric rather than any specific application. Because it is the scalability bottleneck and is neccessary for any blockchain based application.

In the remainder of this chapter we expand on our research question and visit each of our requirement in detail.

2.1 Global Consensus

Early blockchain systems use PoW as the consensus algorithm, but consensus algorithm and especially Byzantine[1] consensus algorithms have existece since the 80s [35, 23]. The Practical Byzantine Fault Tolerance (PBFT) algorithm introduced in 1999 by Castro and Liskov [11] is widely regarded as the first high-performance consensus algorithm. The authors show that running PBFT in Network File System (NFS) was only 3% slower than the standard unreplicated NFS. Since then, research in this area picked up pace and many more algorithms are introduced [1, 22]. With the introduction of Bitcoin's probabilistic consensus model, the field experienced a second renaissance. These include proof-of-stake protocols [6, 28], as well as protocols optimised for blockchain [25, 29].

The first objective is to reach consensus on a global *state* by standing on the shoulder of giants. Having consensus is essential in blockchain systems. It stops many types of malicious activities because agreed state must have the consent of the honest nodes in the network. We emphasise the word state because in contrary to traditional blockchains, it does not neccessarily mean the set of all transactions that has ever happened. The state can be a verifiable representation of all the transactions. As an extreme example, a single digest of the complete history can represent the state. It is even verifiable as long as there are nodes that stores the history.

2.2 Security and Fault Tolerance

The second objective is fault tolerance, where our system should be unaffected in the presence of powerful adversaries. In particular, adversaries are Byzantine meaning that they can have arbitrary behaviour. Thus anything is possible from simply ommitting messages to colluding with eachother in order to undermine the whole system. This asppect usually comes for free when using a Byzantine fault tolerant consensus algorithm.

There is another aspect of fault tolerance that is transaction verifiability. All transactions must be eventually verifiable to maintain system integrity. Further, the validation result must be consistent. For example, if two different honest nodes attempts verify the same transaction, it cannot be the case that one nodes thinks that the transaction is valid but the other thinks it is invalid.

[1]Byzantine means participants can experience arbitrary failure, more on this in Section 3.4.1.

2.3 Performance and Scalability

The last but not least, the final objective is horizontal scalability. We wish to see the performance (global transaction rate) increase as more nodes join the network. BitTorrent [12] is an example of such a system, where peers interact with each other to exchange files without any global bottleneck.

Traditional blockchain systems may run in a network of thousands of nodes, but the performance do not scale. On the other hand, as we will see in Section 3.4.1, Byzantine consensus algorithms performs well but only when in a small network. In this work we combine the ideas from both of these systems to create the first horizontally scalable blockchain fabric.

2.4 Limitations

Our work aims to significantly lower the transaction bound. However, the price to pay is that the Sybil attack [17] prevention mechanism moves from the blockchain fabric to the application layer. For example, social network based Sybil defence mechanims use graph structure of real-world relationships [49]. Online marketplaces such as Amazon use the rating of buyer and sellers. Since our system is application neutral, we do not provide an explicit Sybil defence mechanism. On the other hand, our system also has no restrictions on the Sybil defence technique and applications built on top of our system can use the best mechanism for their purpose.

Chapter 3

System Architecture

We present a design which removes the transaction rate restrictions seen in traditional blockchain systems. This is done by combining the recent HoneyBadgerBFT [29] (a purely asynchronous consensus algorithm for blockchain systems) with a modification of our prior work on TrustChain [**trustchain**]. The design is inspired by (the distributed part of) the Internet architecture as well as how transactions are performed in the real world.

The goal of this chapter is to detail our system specification. We begin our discussion with an intuitive overview of the architecture in Section 3.1. Next, we give the formal description, starting with the model and assumptions in Section 3.2. Then, the three protocols which make up the complete system, namely consensus protocol (Section 3.4), transaction protocol (Section 3.5) and validation protocol (Section 3.6). Finally, we discuss a few variations of our main design and their respective tradeoffs in Section 3.7.

3.1 System Overview

The system consist of one data structure—Extended TrustChain, and three protocols—consensus protocol, transaction protocol and validation protocol. We first describe each component individually and then explain how they fit together in Section 3.1.4.

3.1.1 Extended TrustChain

Extended TrustChain naturally builds on top of the standard TrustChain. Thus we first describe the standard TrustChain. Our description has minor differences compared to the description in [**trustchain**]. This is to help with the description of the extended TrustChain. We remark the difference when it occurs. However, the two descriptions are functionally the same.

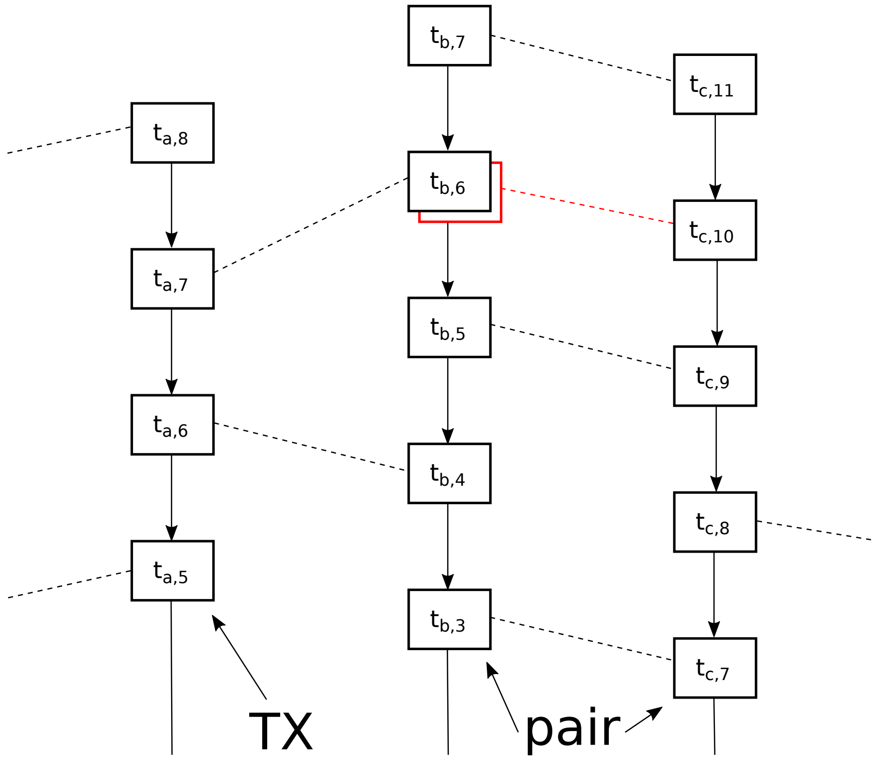


Figure 3.1: Every block is denoted by $t_{i,j}$, where i is the node ID and j is the sequence number of the block. Thus we have three nodes and three corresponding chains in this example. The arrows represent hash pointers and the dotted lines represent references. The blocks at the ends of one dotted line are pairs of each other. The red block after $t_{b,5}$ indicate a fork.

Standard TrustChain

In TrustChain, every node has a "personal" chain. Initially, the chain only contains a genesis block generated by the nodes themselves. When a node A wishes to add a new transaction (TX) with B, a new TX block is generated and then appended to A's chain. The TX block must have a valid hash pointer pointing to the previous block and a reference[1] to its *pair* on B's chain. As a result, a single transaction generates two TX blocks, one on each party's chain. An example of is shown in Figure 3.1.

If every node follows the rules of TrustChain and we only consider hash pointers, then every chain effectively forms a singly linked list. However, if a node violates the rules, then a *fork* may happen. That is, there may be more than one TX block with a hash pointer pointing back to the same

[1] This is different from the original TrustChain definition found in [**trustchain**]. In there, a TX block has two outgoing edges which are hash pointers to the two parties involved in the transaction. This work uses one outgoing edge and a reference.

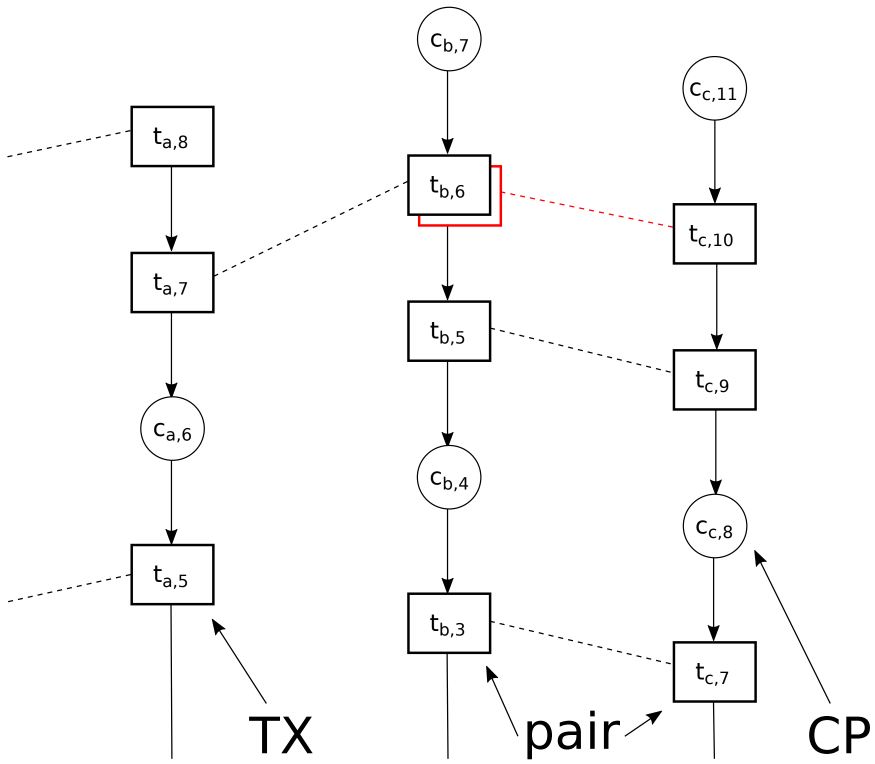


Figure 3.2: The circles represent CP blocks, they also have hash pointers (arrow) but do not have references (dotted line). Note that the sequence number counter do not change, it is shared with TX blocks.

block. In Figure 3.1, node b (in the middle chain) created two TX blocks that both point to $t_{b,5}$. If this is a ledger system it can be seen as a double spend, where the currency accumulated up until $t_{b,5}$ are spent twice.

Extended TrustChain

We are now ready to explain the Extended TrustChain. The primary difference is the introduction of a new type of block—checkpoint (CP) block. In contract to TX blocks, CP blocks do not store transactions or contain references. Their purpose is to capture the state of the chain and the state of the whole system. In particular, the state of the chain is captured with a hash pointer. The state of the whole system is captured in the content of the CP block, namely as a digest of the latest *consensus result* which we explain in Section 3.1.2. A visual representation is shown in Figure 3.2.

From this point onwards, we use TrustChain to mean the Extended TrustChain unless explicitly clarified.

3.1.2 Consensus Protocol

The consensus protocol can be seen as a technique of running infinitly many rounds of some Byzantine consensus algorithm[2], starting a new execution immediately after the previous one is completed. This is necessary because blockchain systems always need to reach consensus on new values proposed by nodes in the system, or CP blocks in our case.

The high communication complexity of Byzantine consensus algorithms prohibits us from running it on a large network. Thus, for every round, we randomly select some node—called facilitators—to collect CP blocks from every other node and use them as the proposal. The facilitators are elected using a *luck value*, which is computed using $H(\mathcal{C}_r || pk_u)$, where $\mathcal{C}_r$ is the consensus result (which can be seen as the set union of all the CP blocks collected by the facilitators) in round r and pk_u is the public key of node u. Intuitively, the election is guaranteed to be random because the output of a cryptographically secure hash function is unpredictable and $\mathcal{C}_r$ cannot be determined in advance.

A visual explaination can be found in Appendix A, it walks through the steps needed for a node to be selected as a facilitator using an example.

3.1.3 Transaction and Validation

The TX protocol is a simple request and response protocol. The nodes exchange one round of messages and create new TX blocks on their respective chains. Thus, as we mentioned before, one transaction should result in two TX blocks.

The consensus and transaction protocol by themselves do not provide a mechanism to detect forks or other forms of tampe件raing. Thus we need a validation protocol to counteract malicious behaviour. When a node wish to validate one of its TX, it asks the counterparty for the *fragment* of the TX. A fragment of a TX is a section of the chain beginning and ending with CP blocks that contains the TX and are in consensus. Upon the counterparty's response, the node checks that the CP blocks are indeed in consensus, the hash pointers are valid and his TX is actually in the fragment. The TX is valid if these conditions are satisfied. Intuitively, this works because it is hard (because a cryptographically secure hash function is second-preimage resistant) to create a different chain that begins and ends with the same two CP blocks but with a different middle section.

3.1.4 Combined Protocol

The final protocol is essentially the concurrent composition of the three aforementioned protocols, all making use the Extended TrustChain data

[2]More accuratly it is ACS or asynchronous subset consensus, we describe ACS in Section 3.4.1.

structure.

Our subprotocol design gives us the highly desireable non-blocking property. In particular, we do not need to "freeze" the state of the chain for some communication to complete in order to create a block. For instance, a node may start the consensus protocol, and while it is running, create new transactions and validate old transactions. By the time the consensus protocol is done, the new CP block is added to whatever the state that the chain is in. It is not necessary to lock the chain while the consensus protocol is running and then unlock it afterwards.

3.2 Model and Assumptions

This section and the ones following it give a technical treatment of what the content in System Overview. For notational clarity, we use the following convention (adapted from [29]) throughout this work.

- Lower case (e.g. x) denotes a scalar object or a tuple.
- Upper case (e.g. X) denotes a set or a constant.
- Sans serif (e.g. $\mathsf{fn}(\cdot)$) denotes a function.
- Monospace (e.g. `ack`) denotes message type.

Further, we use $a||b$ to denote concatination of the binary representations of a and b.

We assume purely asynchronous channels with eventual delivery. Thus in no circumstance do we make timing assumptions. The adversary has fully control of the delivery schedule and the message ordering of all messages. But they are not allowed to drop messages except for their own[3].

We assume there exist a Public Key Infrastructure (PKI), and nodes are identified by their unique and permanent public key. Finally, we use the random oracle 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 finite binary strings and λ is the security parameter [5].

In our model we consider N nodes, which is the population size. n of them are facilitators, t out of n are malicious and the inequality $n \geq 3t+1$ must hold. This is from the work of Pease, Shostak and Lamport, where they show a network of n nodes cannot reach Byzantine agreement with $t \geq n/3$. Further, the inequality $N \geq n+t$ must also hold. This is due to our system design, which becomes clear in Section 3.4.3.

Our threat model is as follows. We use a restricted version of the adaptive corruption model. The first restriction is that corrupted node can only

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

change across rounds. That is, if a round has started, the corrupted nodes cannot changed until the next round. The second restriction is that the adversary, presumably controlling all the corrupted nodes, is forgetful. Namely the adversary may learn the internal state such as the private key of a corrupted node, but if the node recovers, then the adversary must forget the private key. This is realistic because otherwise the adversary can eventually learn all the private keys and sabotage the system. Finally, we assume computational security. That is, the adversary can run polynomial-time algorithms but not exponential-time algorithms efficiently.

3.3 Extended TrustChain

The primary data structure used in our system is the Extended TrustChain. Each node u has a public and private key pair—pk_u and sk_u, and a chain B_u. The chain consist of blocks $B_u = \{b_{u,i} : k \in \{0, \ldots, h-1\}\}$, where $b_{u,i}$ is the ith block of u, and $h = |B_u|$. 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 TX blocks of u and C_u is the set of CP blocks of 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 exist 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.

3.3.1 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.

6. sig_u is the signature created using sk_u on the concatination of the binary representation of the five items above.

The fact that we have no constraint on the content of m is in alignment with our design goal—application neutrality.

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*

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

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.

3.3.2 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 Section 3.3.3) in round r, the other items are the same as the TX block definition. Note that unlike in our prior work [41], CP blocks and TX blocks do not have independent sequence numbers.

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 $\mathsf{H}(\perp)$ 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.

3.3.3 Consensus Result

Our consensus protocol runs in rounds as discussed in Section 3.1. 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.

3.3.4 Chain Properties

Here we define a few important properties which results from the interleaving nature of CP and TX blocks.

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

$$a = \operatorname*{arg\,min}_{k, k<i, \texttt{typeof}(b_{u,k})=\gamma} (i-k)$$

$$b = \operatorname*{arg\,min}_{k, k>i, \texttt{typeof}(b_{u,k})=\gamma} (k-i),$$

then $\langle c_{u,a}, c_{u,b} \rangle$ is the *enclosure* of $t_{u,i}$. Note that $c_{u,a}$ is the more recent CP block. Also, some TX blocks may not have any subsequent CP blocks, then its enclosure is $\perp$.

If the enclosure of some TX block is $\langle c_{u,a}, c_{u,b} \rangle$, then its *fragment* is defined as $\{b_{u,i} : a \leq i \leq b\}$. For convenience, the function $\mathsf{fragment}(\cdot)$ represents the fragment of some TX block if it exists, otherwise $\perp$.

Agreed enclosure is the same as enclosure with an extra constraint where the CP blocks must be in some consensus result $\mathcal{C}_r$ and also must be the smallest enclosure. That is, suppose a chain is in the form $\{c_i, c_{i+1}, t_{i+2}, c_{i+3}\}$[4] and c_i, c_{i+1}, c_{i+3} are in $\mathcal{C}_r, \mathcal{C}_{r+1}, \mathcal{C}_{r+3}$ respectively, then the agreed enclosure of t_{i+2} is $\langle c_{i+1}, c_{i+3}\rangle$ and cannot be $\langle c_i, c_{i+3}\rangle$. Similarly, *agreed fragment* has the same definition as fragment but using agreed enclosure. We define its function to be $\mathsf{agreed\_fragment}(\cdot)$ which we use later in the validation protocol (Section 3.6).

3.4 Consensus Protocol

Our consensus protocol runs on top of Extended TrustChain. It is directly related to the creation of CP blocks. 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 unbiased election of facilitators. Concretely, we define the necessary properties as follows.

Definition 1. Properties of the consensus protocol
$\forall r \in \mathbb{N}$, *the following properties must hold.*

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

These properties may look like Byzantine consensus properties (which we describe next in Section 3.4.1) but they have some 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 the whole system falls apart if one of the property cannot be satisfied in one of the rounds.

Before describing the protocol in detail, we take a brief detour to give background on the asynchronous subset consensus. This is the primary building block of our protocol.

[4] Usually the notation is of the form $c_{u,i}$, but the node identity is not important here so we simplify it to c_i

3.4.1 Background on Asynchronous Subset Consensus

The best way to explain asynchronous subset consensus (ACS) is to contrast it with the typical Byzantine consensus. We adapt the description from [48, Chapter 17].

Definition 2. Byzantine Consensus
There are n nodes, of which at most t might experience Byzantine fault. Node i starts with an input value v_i. The nodes must decide for one of those values, satisfying the the following.

1. Agreement: *If a correct node outputs v, then every node outputs v.*

2. Validity: *The decision value must be the input value of a node.*

3. Termination: *All correct nodes terminate in finite time.*

A node under Byzantine fault means that it can have arbitrary behaviour. For example not sending message or colluding with other Byzantine nodes to undermine the entire system. Note that the decision is on a single value. This is in contrast to ACS which we describe next.

ACS shares many similarities with Byzantine consensus. But it is an especially useful primitive for blockchain systems. It allows any party to propose a value and the result is the set union of all the proposed values by the majority. This is the primary difference with Byzantine consensus. Concretely, ACS needs to satisfy the following properties (adapted from [29]).

Definition 3. Asynchronous Subset Consensus
There are n nodes, of which at most t might experience Byzantine fault. Node i starts with an non-empty set of input values C_i. The nodes must decide an output C, satisfying the following.

1. Agreement: *If a correct node outputs C, then every node outputs C.*

2. Validity: *If any correct node outputs a set C, then $|C| \geq n - t$ and C contains the input of at least $n - 2t$ nodes.*

3. Totality: *If $n-t$ nodes receive an input, then all correct nodes produce an output.*

ACS has the nice property of censorship resiliance when compared to other consensus algorithms. For instance, Hyperledger and Tendermint uses Practical Byzantine Fault Tolerance (PBFT) [11] as their consensus algorithm. In PBFT, a leader is elected, if the leader is malicious but follows the protocol, then it can selectivly filter transactions. In contract, every party in ACS are involved in the proposal phase, and it guarantees that if $n - 2t$ parties propose the same transaction, then it must be in the agreed output. Thus, if some value is submitted to at least $n - 2t$ nodes, it is guaranteed to be in the consensus result. For a detailed description of ACS we refer to the HoneyBadgerBFT work [29].

The main drawback with ACS and also Byzantine consensus algorithms is the high message complexity. Typically, such protocols have a message complexity of $O(n^2)$, where n is the number of parties. Hence, it may work with a small number of nodes, but it is infeasible for blockchain systems where thousands of nodes are involved.

3.4.2 Bootstrap Phase

Now we have all the necessary information to describe our consensus protocol. We begin with the bootstrap phase and then move onto the actual consensus phase.

Recall that facilitators are computed from the consensus result, but the consensus result is agreed by the facilitators. Thus we have a dependency cycle. The goal of the bootstrap phase is to give us a starting point in the cycle.

To bootstrap, imagine that there is some bootstrap oracle, that initiates the code on every node. The code satisfied all the properties in Definition 1. Namely every node has the same set of valid facilitators $\mathcal{F}_1$ that are randomly choosen. This concludes the bootstrap phase.

In practice, the bootstrap oracle is most likely the software developer and some of the desired properties cannot be achieved. In particular, it is not possible to have the fairness property because it is unlikely that the developer knows the identity of every node in advance.

3.4.3 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 result of round r and are responsible for driving the ACS protocol 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 1.

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 it has received $N - t$ messages of type `cp_msg`. Invalid messages are removed, namely blocks with invalid signatures and duplicate 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 the 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.

At the core of the consensus phase is the ACS protocol. While any ACS protocol that satisfies the standard definition will work, we use a simplification of HoneyBadgerBFT [29] as our ACS protocol because it is the only (to the best of our knowledge) consensus algorithms designed for blockchain systems. 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 transactional information.

Continuing, when $\mathcal{F}_r$ reaches agreement on $\mathcal{C}_{r+1}$, they immediately broadcast 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 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 asks. First, it creates a new CP block using $\mathsf{new\_cp}(\mathcal{C}_{r+1}, r+1)$ (Algorithm 2). Second, it computes the new facilitators using $\mathsf{get\_facilitator}(C, n)$ (Algorithm 1) and updates its facilitator list to the result. This concludes the consensus phase and brings us back to the beginning of the consensus phase.

Algorithm 1 Function $\mathsf{get\_facilitator}(C, n)$ takes a list of CP blocks C and an integer n, sort evey element in C by its luck value (the λ-expression), and outputs the smallest n elements.

$\mathsf{take}(n, \mathsf{sort\_by}(\lambda x.\mathsf{H}(x || pk \text{ of } x), C))$

Algorithm 2 Function $\mathsf{new\_cp}(\mathcal{C}_r, r)$ runs in the context of the caller u. It creates a new CP block and appends it to u's chain.

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

3.4.4 Relationship with α-Synchroniser

TODO

3.5 Transaction Protocol

The TX protocol, shown in Algorithm 4, is run by all nodes. It is also known as True Halves, first described by Veldhuisen [45, Chapter 3.2]. Node 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 $\langle \mathtt{tx\_req}, t_{u,h} \rangle$ 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 $txid$.

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

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

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

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 high concurrency where we can call $\mathsf{new\_tx}(\cdot)$ multiple times without waiting for the corresponding $\mathtt{tx\_resp}$ messages.

3.6 Validation Protocol

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

3.6.1 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 transaction $t_{u,i}$ is captured by the function $\mathsf{get\_validity}(t, F)$ (Algorithm 5). The first four conditions (up to Line 21) essentially check whether the fragment is the one that the verifier needs. If it is not, then the verifier cannot make any decision and return *unknown*. This is likely to be the case for new transactions because $\mathsf{agreed\_fragment}(\cdot)$ would be $\perp$. The next two conditions checks for tampering or missing blocks, if any of these misconducts are detected, then the TX is invalid.

Note that the validity is on a transaction (two TX blocks with the same $txid$), rather than on one TX block owned by a single party. 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 ommitted 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.

Further, the caller of $\mathsf{get\_validity}(t_u u, i, F_{v,i})$ is not necessarily u[5] Any node w may call $\mathsf{get\_validity}(t_u u, i, F_{v,i})$ as long as the caller w has an agreed fragment of $t_{u,i}$—$F_{u,i}$. $F_{u,i}$ may be readily available if $w = u$ or it may be from some other `vd_resp` message, which we describe next in the validation protocol.

3.6.2 Validation Protocol

With the validity definition, we are ready to construct a protocol for determining the validity of transactions. The protocol is a simple response and request protocol (Algorithm 6). 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 4. Properties of the validation protocol

1. Correctness*: The validation protocol outputs the correct result according to the aforementioned validity definition.*
2. 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*.*
3. Liveness*: Any valid transactions can be validated eventually.*

[5] In practice it often is because after completing the TX protocol the parties are incentivised to check that the counterparty "did the right thing".

Algorithm 5 Function $\mathsf{get\_validity}(t_{u,i}, F_{v,j})$ validates the transaction $t_{u,i}$. $F_{v,j}$ is the corresponding fragment received from v.

We assume there exist a valid $F_{u,i}$, namely the agreed fragment of $t_{u,i}$. The caller is w, it may be u but this is not necessary.

$c_{v,a} \leftarrow \mathsf{first}(F_{v,j})$
$c_{v,b} \leftarrow \mathsf{last}(F_{v,j})$
if $c_{v,a}$ or $c_{v,b}$ are not in consensus **then**
    return *unknown*
end if ▷ v has agreed fragment

if $|F_{v,j}| > L$ **then**
    return *unknown*
end if ▷ fragment not too long

if sequence number in $F_{v,j}$ is correct (sequential) **then**
    if hash pointers in $F_{v,j}$ is wrong **then**
        return *unknown*
    end if
end if ▷ correct TrustChain structure

$c_{u,b} \leftarrow \mathsf{last}(F_{u,i})$
if $c_{u,b}$ is not created using the same $\mathcal{C}_r$ as $c_{v,b}$ **then**
    return *unknown*
end if ▷ correct consensus round

$txid, pk_v, m \leftarrow t_{u,i}$
if number of blocks of $txid$ in $F_{v,j} \neq 1$ **then**
    return *invalid*
end if ▷ TX exists

$txid', pk'_u, m' \leftarrow t_{v,j}$
if $m \neq m' \vee pk_u \neq pk'_u$ **then**
    return *invalid*
end if ▷ no tampering

return *valid*

Algorithm 6 Validation protocol

Upon $\langle \texttt{vd\_req}, txid \rangle$ from v
  $t_{u,i} \leftarrow$ the transaction identified by $txid$
  $F_{u,i} \leftarrow \mathsf{agreed\_fragment}(t_{u,i})$
  send $\langle \texttt{vd\_resp}, txid, F_{u,i} \rangle$ to v
Upon $\langle \texttt{vd\_resp}, txid, F_{v,j} \rangle$ from v
  $t_{u,i} \leftarrow$ the transaction identified by $txid$
  set the validity of $t_{u,i}$ to $\mathsf{get\_validity}(t_{u,i}, F_{v,j})$

We make two remarks. First, just like the TX protocol, we do not block at 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 a later consensus rounds. But these fake pairs only pollutes the chain of v and can never be validated because the round is incorrect.

3.7 Design variations and tradeoffs

Up to this point, we have discussed our protocol in the context of the model and assumptions defined in Section 3.2. In this section, we explore a few design variations which we can make if we relax our model. These variations do not have the same theoretical elegance as our original model. But they enable better performance, allow us to apply our design in the fully permissionless setting and improves privacy.

3.7.1 Use epidemic protocol instead of broadcast protocol

One of the final steps in our consensus protocol is to broadcast the consensus result and signatures to every other node (Section 3.4.3). While this guarantees delivery (since we assumed reliable channel), it is wasteful. For example, if every facilitator is honest, a node would receive n consensus results which are identical when only one is necessary.

An optimisation we can do is to use an epidemic protocol [18] (also known as gossiping)) instead of our broadcast approach. Typical epidemic protocols works as follows. Every node buffers every message it receives up to some buffer size b. Then it forwards the messages t number of times. Every time the message is sent to f random neighbours, f is often called the fanout. The upside of using epidemic protocol is that the communication cost is distributed more evenly between nodes. This is especially true with a lazy push approach the node who just received a message would push the message ID to its f random neighbours, and only push the full message if the neighbour explicitly requests for the message [24]. With this, nodes typically only need to receive one consensus result message instead of n.

A down side of epidemic protocol is that it usually takes $O(\log N)$ time to infect the whole network, whereas broadcasting uses constant time. Another downside of some epidemic protocols (e.g. eager push) is that it is difficult to guarantee delivery. It is especially true when the parameters are not choosen correctly in a network that is only partially connected (but every node is nevertheless reachable). If the delivery cannot be guaranteed, then we cannot guarantee liveness in our consensus protocol because a future facilitator may miss the memo. Picking parameters are difficult in practice because the network configuration is unknown and the total number of nodes might also be unknown.

3.7.2 Using timing assumption in the permissionless setting

Our model is purely asynchronous, where we make no timing assumptions anywhere in the protocol. In many applications however, it is often fine to make timing assumptions. For example, TCP relies on timeout for its retransmission and the nLockTime property in Bitcoin transactions makes the transaction unspendable until some time in the future (either Unix time or block height) [7]. One limitation of our system is that we use the parameter N in our algorithms, which makes it unsuitable for the permissionless environment where users can join and leave at will. In this section we show how making a timing assumption would allow us to operate in the permissionless setting.

At the start of our consensus phase (Section 3.4.3), facilitators must wait for $N - f$ `cp_msg` messages. This is the only place where we used N as a parameter. 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. Again, choosing the parameter D is difficult and depends on a number of factors such as the network condition, message size, and so on. Overestimating it would make agreed fragments much longer than usual, which increases communication costs for validation. Underestimating it would lead to unfairness where users that are too late do not have a chance to be selected as a facilitator in the next round. Nevertheless, there is a significant gain for making the timing assumption and that is the ability to operate in the permissionless setting which we explain next.

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 fulfill its oblication by completing the consensus protocol (but without proposing its own CP block) before leaving. Otherwise the $n \geq 3t + 1$ condition may be violated.

3.7.3 Privacy preserving validation protocol

TODO

3.7.4 Global probabilistic fork detection

TODO

Chapter 4

Analysis of Correctness and Performance

Up to this point we described our system specification in detail. Of course, specification along does not establish any truths. In this chapter, we analyse two aspects of our system. First we show it has the desired properties. That is, the properties of the consensus protocol and the validation protocol (Definition 1 and Definition 4 respectively) should hold. Then we analyse the performance, especially the throughput, and show that it out performs classical blockchain systems.

4.1 Correctness in the Presense of Faults

Our first objective is to show that Definition 1 holds for our consensus protocol. Then, building on top of it, we show Definition 4 holds for the validation protocol. The resulting theorem shows that only using CP blocks in the consensus algorithm implies consensus on TX blocks, in other words, implicit consensus.

4.1.1 Analysis of the Consensus Protocol

We begin our analysis by establishing truths on the four properties in Definition 1, namely agreement, validity, fairness and termination. Using these results, we use mathematical induction to show that they hold for all rounds.

Lemma 1. *For an arbitrary round r if $\mathcal{F}_r$ is known by all correct nodes and one correct node outputs a list of facilitators $\mathcal{F}_{r+1}$, then all correct nodes output $\mathcal{F}_{r+1}$.*

Proof. The argument follows from the protocol description. Given that $\mathcal{F}_r$ is known, correct nodes will send CP blocks to all members in $\mathcal{F}_r$. The ACS algorithm starts independently whenever the facilitator has $N - t$ valid CP blocks (recall from Section 3.4.3 that invalid blocks are ones with an invalid signature or has a duplicate signature). It cannot make progress until $n-t$ honest facilitators start algorithm, but this eventually happens because there are $N-t$ correct nodes and all correct facilitator eventually receives $N-t$ valid CP blocks. At the end of ACS, some $\mathcal{C}_{r+1}$ is created, and is broadcasted along with the signature of the facilitators. Due to the agreement property of ACS (Definition 3), every correct node should receive at least $n-t$ valid signatures on the agreed $\mathcal{C}_{r+1}$. Thus they use $\mathcal{C}_{r+1}$ to generate a new CP block and compute new facilitators. Since $\mathsf{get\_facilitators}(\cdot)$ is a deterministic algorithm and the input $\mathcal{C}_{r+1}$ is in agreement, the output $\mathcal{F}_{r+1}$ is also in agreement. □

Lemma 2. *For an arbitrary round r, if $\mathcal{F}_r$ is known by all correct nodes and any correct node outputs $\mathcal{F}_{r+1}$, then (a) $|\mathcal{C}_{r+1}| \geq N-t$ must hold for the $\mathcal{C}_{r+1}$ which was used to create $\mathcal{F}_{r+1}$, (b) $\mathcal{F}_{r+1}$ must contain at least $n-t$ honest nodes and (c) $|\mathcal{F}_{r+1}| = n$.*

Proof. The validity follows from the validity property of ACS and the definition of our model, namely $N \geq n+t$ and $n \geq 3t+1$. Given $\mathcal{F}_r$, since $N \geq n+t$, there is at least n nodes that would send their CP block to $\mathcal{F}_r$. From the validity property of ACS, we know the output must contain the input of at least $n-2t$ nodes. But $n-t$ facilitators must have received $N-t$ valid CP blocks, so $|\mathcal{C}_{r+1}| \geq N-t$, this proves (a). There are $n-t$ honest nodes in $\mathcal{F}_{r+1}$ follows from the model, this proves (b). Finally, since $N-t \geq (n+t)-t = n$ and $\mathsf{get\_facilitators}(\cdot)$ outputs n items, $|\mathcal{F}_{r+1}| = n$ and this proves (c). □

Lemma 3. *For an arbitrary round r, if $\mathcal{F}_r$ is known by all correct nodes then every node with a CP block in $\mathcal{C}_{r+1}$, should have an equal probability to be elected as a facilitator in $\mathcal{F}_{r+1}$.*

Proof. We have already established that $|\mathcal{C}_{r+1}| \geq N-t \geq n$ from Lemma 2. Then the proof directly follows from the random oracle model. Recall that the luck value is computed using $\mathsf{H}(\mathcal{C}_{r+1}, || pk_u)$. Since pk_u is unique for every node that has a CP block in $\mathcal{C}_{r+1}$, the output of $\mathsf{H}(\cdot)$ is uniformly random. This effectively generates a random permutation so every node has the same probability of being in the top n for the ordered sequence, namely the output of $\mathsf{get\_facilitators}(\cdot)$. □

Lemma 4. *For an arbitrary round r, if $\mathcal{F}_r$ is known by all correct nodes then every correct node eventually outputs some $\mathcal{F}_{r+1}$.*

Proof. This follows directly from the properties of the channel (eventual delivery) and the termination property of ACS. That is, $\mathcal{F}_r$ eventually receives all the CP blocks required to begin ACS. ACS eventually terminates. Finally the results are eventually disseminated to all the nodes. □

From Lemmas 1, 2, 3 and 4, we have shown that the 4 properties of Definition 1 holds when assuming the existance of some $\mathcal{F}_r$. Thus, to proof the whole of Definition 1, we need to proof these 4 properties under the universal quantifier. We do this using mathematical induction.

Theorem 1. *For all rounds, the consensus protocol satisfies agreement, validity, fairness and termination (Definition 1).*

Proof. We proof using mathematical induction.

In the base case, agreement, validity fairness and termination follows directly from the bootstrap protocol, due to the bootstrap oracle. Note that the result is $\mathcal{F}_1$, which indicates the facilitators that are agreed in round 1, who are responsible for driving the ACS protocol in round 2.

For the inductive step, we assume that the 4 properties hold in round r and prove that they also hold in round $r + 1$. Using Lemmas 1, 2, 3 and 4, it directly follows from modus ponens that these properties hold for $r + 1$. Due to the principals of mathematical induction, these properties hold for all r. $\square$

4.1.2 Correctness of Validation

The consensus protocol (on CP blocks and facilitators) is the backbone for consensus on transactions. In this section we build on top of Theorem 1 to show that most (except liveness) properties in Definition 4 can be satisfied.

Lemma 5. *The validation protocol outputs the correct result according to the validity definition.*

Proof. The algorithm (Algorithm 5) is the validity definition. $\square$

Theorem 2. *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*.*

Proof. We proof by contradiction. Without loss of generality, for some transaction t with an agreed fragment F, node u decides *valid* but node v decides *invalid*. Then there exist a fragment $F' = \{\ldots, t', c'\}$ which u received that contains a valid pair of t—t'. There also exist a fragment $F'' = \{\ldots, t'', c''\}$ which v received that does not contain or contains an invalid pair—t''. In both cases, the $\mathsf{get\_validity}(\cdot)$ function must have reached Line 21. Due to Theorem 1, we have $c' = c''$, otherwise the result would be *unknown*. Since $c'(= c'') = \langle \mathsf{H}(t'), \ldots \rangle$ we must have $\mathsf{H}(t') = \mathsf{H}(t'')$ and $t' \neq t''$ (because t'' is invalid). In other words, whoever sent F'' must be able to create some t'' that has the same digest as t'. But we assumed that the adversary can only perform polynomial-time algorithm, so in order to find t'' it needs to query the random oracle exponentially many times. Thus we have a contradiction and this completes the proof. $\square$

Theorem 2 is our first major result. It shows that consensus on CP blocks would lead to consensus on TX blocks when the nodes are running the validation protocol. Just like in our prior work [41], we call this behaviour implicit consensus. One of the main advantages over running a consensus algorithm on all the transactions is that the rate of transaction is no longer dependent on the consensus algorithm—ACS. This enables horizontal scalability where adding new nodes would lead to higher global transaction rate. In addition, a convenient consequence Theorem 2 is unforgeability. That is, no polynomial time adversary is able to create two chains $F = \{\dots, t, c\}$ $F' = \{\dots, t', c\}$ with correct hash pointers and the same end of chain c.

4.1.3 Impossibility of Liveness

While Theorem 2 is a major result that allows significantly improved performance over traditional blockchain systems, it is not perfect. Now we show a negative result, where the liveness property of Definition 4 cannot be attained. Meaning that trasanctions with adversaries cannot always be validated.

Lemma 6. *There exist a valid transactions that cannot be validated eventually.*

Proof. We proof by providing a counterexample. Suppose nodes u and v correctly perfomed the TX protocol which resulted a transaction t. Then when u wants to validate t, it does so by sending `vd_req` message to v. v can act maliciously and ignore all `vd_req` message, thus t can never be validated. □

Although this is a negative result, it does not put the adversary in an advantageous position. If the adversary is observed to ignore validation requests, then the honest nodes may prefer not to transact with her in the future. Thus, to stay relevant in the system, the adversary need to comply to the protocol.

4.2 Performance

This section aims to analytically answer our research question. That is, does the global throughput increase linearly with respect to the population size? We begin by looking at the communication and time complexity of the consensus protocol, and then the bandwidth requirement for a single transaction. We build on top of those results to analyse do the global throughput analysis.

4.2.1 Communication complexity of the consensus protocol

The consensus protocol can bee seen as three parts. Thus the communication complexity is the sum of these three parts. The first part is when every node sends their CP block to all the facilitators, which is $O(Nn)$ since there are N nodes and n facilitators. Or simply $O(N)$ if we consider n as a constant.

The second part is ACS. The communication complexity of ACS is $O(n^2|v|+\lambda n^3 \log n)$ [29], where $|v|$ is the size of largest message and λ is the security parameter. Note that the security parameter is the same as the one for our random oracle described in Section 3.2. In particular, it is from the use of $\mathsf{H}(\cdot)$ in the reliable broadcast phase in ACS. In our system, we wish to understand the scalability properties. Thus we consider the complexity as a function of N rather than n or λ. Since $|v|$ is at most all the CP blocks from every node, we have $|v| = cN$, where c is a constant representing the size of one CP block. Therefore the communication complexity of ACS in our system is $O(N)$. Since we use a constant n, $O(N)$ communication complexity also holds for a single facilitator.

The third and final part is the dissemination, where the facilitators broadcast the consensus result along with their signatures. For the same reason as the first part, this is also $O(N)$. Thus the combined communication complexity when n is a constant is $O(N)$.

4.2.2 Duration of the consensus protocol

In order to make arguments on bandwidth or throughput, which are concepts that depend on time, we must make some assumptions regarding our computational model to make arguments on the duration of the consensus protocol. Note that it is not the same as the time complexity typically used in distributed systems. In analysis of distributed systems, time complexity is often in terms of the number of rounds. For example, ACS runs in a constant number of rounds because its subprotocols—reliable broadcast and binary Byzantine consensus—also run in a constant number of rounds. However, in practice, making a unit of communication always has some overhead associated with it, for example serialising and writing it to some network socket. Hence, for the remainder of our performance analysis, we add the following to our computational model. For every unit of communication, we assume they take some non-negligible but constant time to perform. Hence, from Section 4.2.1 and the fact that the consensus protocol uses a constant number of rounds, it follows that the consensus protocol has a duration of $O(N)$.

4.2.3 Communication Cost for Transactions

With the analysis on the duration of the consensus protocol, we are ready to analyse the amount of data required to be transmitted over a link per transaction, which we call the communication cost per transaction. We know that to create and then validate a transaction, the communication cost per transaction is of $O(l)$, where l is the length of the agreed fragment. This can be seen from the fact that the largest message by far is the `vd_resp` message, which contains the agreed fragment. The other messages (`tx_req`, `tx_resp` and `vd_req`) are constant factors. If we assume that every node performs transactions at a constant rate of r_{tx} per second. Then

$$l = r_{\text{tx}} D_{\text{c}},$$

where D_{c} is the duration a round of the consensus protocol. But from Section 4.2.2, we know that D_{c} is of $O(N)$, thus the communication cost per transaction is $O(N)$. This is intuitive because round duration would be longer if there are more CP blocks (more N), which means that the agreed fragments are longer (assuming nodes transact at a constant rate). The behaviour is also verified experimentally in Chapter 5.

4.2.4 Global Throughput

Using our results so far, we are able to analyse the global throughput. First we clarify the bandwidth definition, which is "the data rate at which a network link or a network path can transfer" [38]. Now, suppose every node has some fixed bandwidth per link C and N links. They also make transactions at r_{tx} per second. Then we have the inequality

$$NC \geq r_{\text{tx}} l,$$

where l is the length of the the agree fragment as before. The inequality suggests that the rate for which transactions and validations are made cannot exceed the total bandwidth of all the links.

We note that the inequality does not hold if the node is only transacting with a small sample of some subset of the population. This is because it cannot use all the bandwidth available in all the links. For instance, if the node is only transacting with one other node, then it can only use the bandwidth of one link which is only C. However, if that is the case, we can intelligently cache the `vd_resp` messages. Thus multiple transactions can be validated with a single `vd_resp` message. For this work, we analyse the worst case where every node transacts with a random node from the population, and a new `vd_resp` must be sent for every `vd_req` message.

Consider the case where the system is making use of all the bandwidth, i.e. $NC = r_{\text{tx}} l$. Recall that l is of $O(N)$, that means LHS and RHS both grow linearly with respect to N. Hence, there exist some constant r_{tx} that makes use of all the available bandwidth regardless of N. Finally, if every node in the network is transacting at a constant rate, then the global throughput (in terms of transactions per second) is of $O(N)$. If the system is not making use of all the bandwidth. We also maintain a constant transaction rate by the same argument. Thus a global throughput is also $O(N)$. We verify both of these claims experimentally in **??**.

4.3 Effect of A Highly Adverserial Environment

Our last study consideres the effect when the number of adversaries is more than t. This is useful because in practice it is difficult to guarantee that t satisfied $n \geq 3t+1$, especially when N is large. Hence we are interested in the probability for this to happen under our facilitator election process.

The problem can be formulated as follows. Suppose an urn contains N balls, t are black and $N-t$ are white. If n balls are drawn uniformly at random without replacement, what is the probability that $\lfloor \frac{n-1}{3} \rfloor$ are black? The random variable X in this case is the number of black balls, or the number of successful events. It follows the hypergeometric distribution since we pick balls *without* replacement [43]. Hence, we are interested in the following probability.

$$1 - \sum_{k=0}^{\lfloor \frac{n-1}{3} \rfloor} \Pr[X = k] = 1 - \sum_{k=0}^{\lfloor \frac{n-1}{3} \rfloor} \frac{\binom{t}{k}\binom{N-t}{n-k}}{\binom{N}{n}}$$

This is not in closed form, but we can visualise the effect in Figure 4.1. We set the population size N to 2000 and plot the probability of more than $\lfloor \frac{n-1}{3} \rfloor$ successful events for different numbers of draws. Evidently, if the number of black balls (traitors) is a third of the population (666 out of 2000) we have about 0.5 probability of electing more than $\lfloor \frac{n-1}{3} \rfloor$ black balls for sufficiently large n. Thus, we cannot expect the system to function correctly when the expected value is close to the number of black balls that we can tolerate.

On the other hand, due to the fact that hypergeometric distributions have light tails, that is "faster-than-exponential fall-off" [43], the probability for picking more than $\lfloor \frac{n-1}{3} \rfloor$ black balls when the expected value is much smaller than $\lfloor \frac{n-1}{3} \rfloor$ is small. We can use tail inequality to bound the probability of picking more than $\lfloor \frac{n-1}{3} \rfloor$ black balls when only $n\alpha$ are black where $0 \leq \alpha \leq \lfloor \frac{n-1}{3} \rfloor / n$. The tail inequality is

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

where $E[X] = n\alpha$. We are interested in $\Pr[X \geq \lfloor \frac{n-1}{3} \rfloor + 1]$, so

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

Putting τ back into the tail inequality we get the following bound.

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

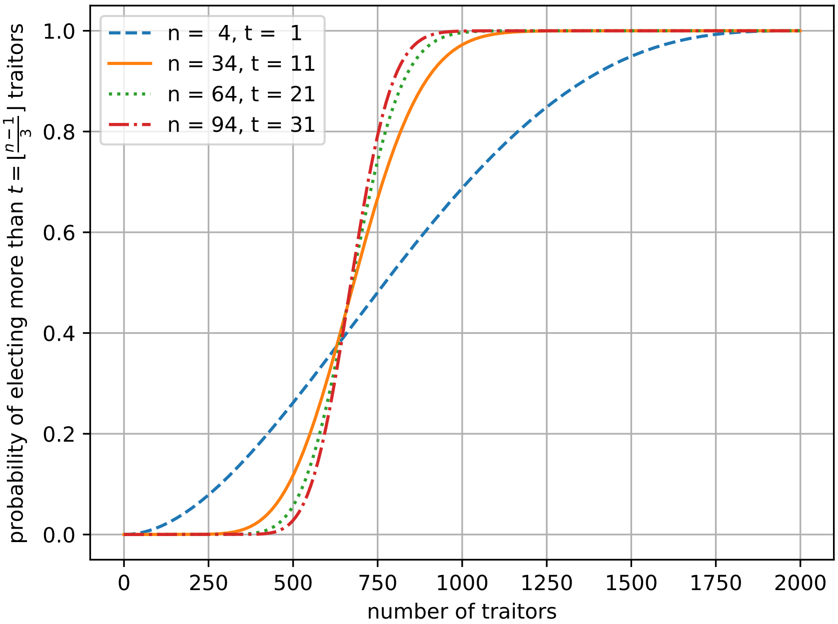


Figure 4.1: Plot of the probability of selecting more than $\lfloor \frac{n-1}{3} \rfloor$ black balls for different numbers of

The bound is not tight, but it is useful for for picking parameters. For some fixed n, since $0 \leq \alpha \leq \lfloor \frac{n-1}{3} \rfloor / n < (\lfloor \frac{n-1}{3} \rfloor + 1)/n$, the probability is maximum when the squared term is minimum at $\alpha = \lfloor \frac{n-1}{3} \rfloor / n$. The probability is minimum when the squared term is maximum at $\alpha = 0$. Hence, if n is known, then we can pick a α such that the probability becomes small. On the other hand, if α is fixed, but small, we may increase n to achieve the same. To put this into perspective, suppose $n = 1000$ and $\alpha = 1/20$, then the probability to draw more black balls than the threshold is only 2×10^{-48}.

Chapter 5

Implementation and Experimental Results

Henceforth, we evaluate out system experimentally and compare the results with the theoretical analysis. We begin this chapter by a description of the implementation in Section 5.1. Then, we move on to describing our experimental setup in Section 5.2. Finally, **??** presents our experimental results and our evaluation. Our experiment primarily focuses on the consensus duration and the throughput.

5.1 Implementation

The prototype implementation can be found on GitHub.

`https://github.com/kc1212/consensus-thesis-code`

It is written in the event driven paradigm, using the Python programming language[1] and the Twisted[2] library for networking.

The structure of the implementation is primarily made up of three modules—`acs`, `trustchain` and `node`. `acs`, as its name suggests, implements ACS. ACS uses erasure code in one of its subprotocols (reliable broadcast). Thus we use the liberasurecode[3] library for its Reed-Solomon error correcting code functionality. An implementation detail is that liberasurecode cannot create more than 32 code blocks[4], we discuss the effect of this in Section 5.2. The `acs` module provides a small interface to the caller to start and stop the consensus process and also retrieve results. The `trustchain` module

[1] `https://www.python.org/`

[2] `https://twistedmatrix.com/`

[3] `https://github.com/openstack/liberasurecode`

[4] The 32 code blocks limitation is hardcoded in the source file, see `https://github.com/openstack/liberasurecode/blob/0794b31c623e4cede76d66be730719d24debcca9/include/erasurecode/erasurecode.h#L35`

implements the Extended TrustChain data structure. It also provides the essential algorithm necessary to interact with Extended TrustChain such as new_tx($\cdot$), new_cp($\cdot$), agreed_fragment($\cdot$) and so on. Since this is a prototype implementation, we only store the data structure in memory and not on disk. Finally, the `node` module ties everything together. It implements the the consensus protocol, the transaction protocol and the validation protocol.

Every node keeps a persistent TCP connection with every other node. This creates a fully connected network for our experiment. It is certainly not ideal in real world scenarios where nodes may have limited resources (e.g. sockets). But as a prototype, it is sufficient to run a network of over a thousand nodes and experiment with it.

Finally, the cryptography primitives we use are SHA256 for hash functions and Ed25519 for digital signatures. Both of which are provided by libnacl [5].

5.2 Experimental Setup

The the goal of the experiment is to run the three protocols—consensus protocol, transaction protocol and validation protocol—simultaneously and analyse the throughput, consensus duration and other related metrics. We investigate these properties under the following four parameters.

1. The transaction rate r_{tx} per node. This is not comparable to the others because it is fixed at 2 TX/s. Nevertheless, it is a good value because, as we show later, it hits a bottleneck in extreme cases which helps us understand the limitations of our design.

2. The number of facilitators $n \in \{12, 16, \ldots, 32\}$. Unfortunately, the maximum n is 32 because the limitation in liberasurecode mentioned in Section 5.1.

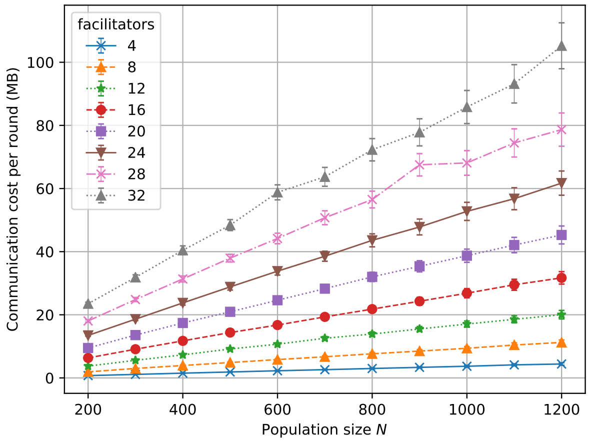
3. The population size $N \in \{200, \ldots, 1200\}$. N stops at 1200 is due to our physical setup, which we describe next.

4. The two modes of transaction. The first mode or the ideal mode is that nodes only transact with their immediate neighbour. This minimises the data volume per validated transaction because agreed fragment can be cached. The second mode is in the other extreme, where every transaction is with a random node out of the N nodes in the system, thus the agreed fragment is unlikely to be cached.

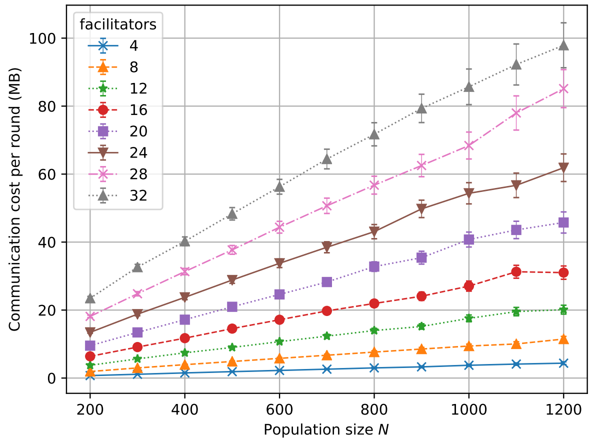
The experiment is run on the DAS-5 (The Distributed ASCI Supercomputer 5[6]). From now on, we use "machines" to refer to DAS-5 nodes and nodes to refer to a running instance in our system. On DAS-5 we use up to

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

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



(a) Transactions are with fixed neighbours



(b) Transactions are with random neighbours

Figure 5.1

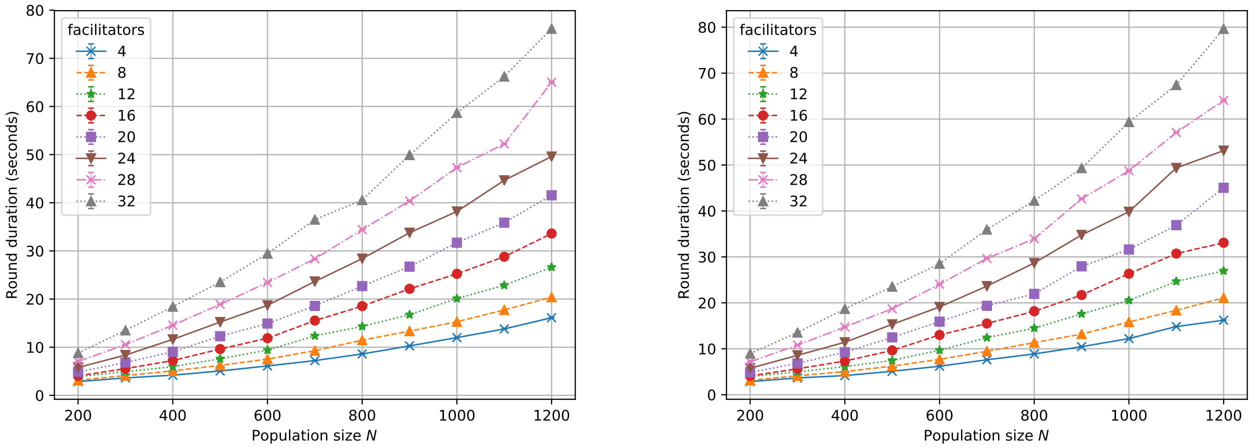
30 machine, for each machine we use 40 nodes. This gives us the aforementioned 1200 number. With this setup, we cannot run more nodes because the every machine only has 65535 ports available (minus the reserved ones). But 40 nodes each need 1200 TCP connections which is 48000 TCP connections per machine and that is inching close to the limit. While it is possible to have many more TCP connections per machine, but it requires additional network interface which is something we do not control on the DAS-5.

To coordinate nodes on many different machine, we employ a discovery server to inform every node the IP addresses and port numbers of every other node. It is only run before the experiment and is not used during the experiment.

5.3 Communication cost for a round

The remainder of this chapter follows the same structure as the performance analysis in Section 4.2, where we check our theoretical evaluation with our experimental results.

Figure 5.1 show the relationship between communication cost and population. The most important aspect is that these results show a linear increase. This reinforces our analytical result in Section 4.2.1. Note that regardless of whether the transactions are performed with a random neighbour or with a fixed neighbour, the magnitude of the communication cost are similar. Both peak at about 100 MB. This is expected because the consensus protocol is decoupled from the transaction protocol and the validation protocol. Finally, the rate for which the communication cost increases is higher when



(a) Transactions are with fixed neighbours

(b) Transactions are with random neighbours

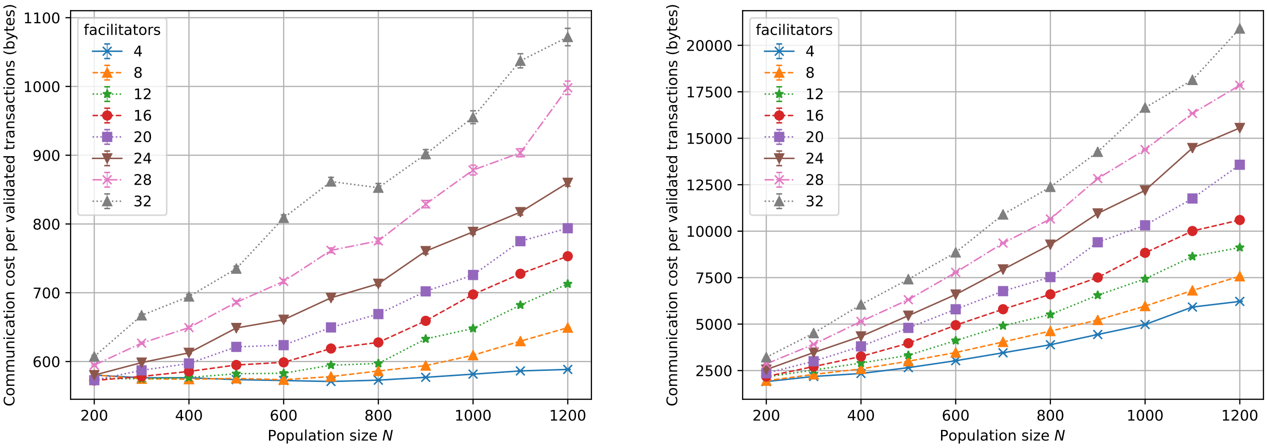
Figure 5.2

the number of facilitators are higher. This is also expected because the ACS algorithm has a n^2 term in its communication complexity.

We are also interested in how communication costs translate to time. Hence, for the same experiment we also record the duration in seconds, which is shown on the vertical axis instead of communication cost and plot as before (**??**). Interestingly, the duration is not entirely linear. We attribute this behaviour to the extra time needed to hash the CP blocks in the consensus result to compute the luck value. Since if N increases, every node must also perform more hash operations. These result do not conform to analytical result in Section 4.2.2. Nevertheless, the difference is minor and there are ways to optimise the luck value computation. For example, the luck value can be computed by the facilitators and are sent with the consensus result. Then the non-facilitator nodes simply checks that they are correct.

5.4 Communication Cost for Transaction and Validation

Recall that in Section 4.2.3 we argued that the communication cost per verified transaction is of $O(N)$. To verify the argument, we plot the relationship between the communication cost and population size in Figure 5.3. We observe a nearly linear relationship, which is due to the nearly linear relationship of the communication duration mentioned before. Again, we believe the difference is minor and it is possible to remove the extra overhead.



(a) Transactions are with fixed neighbours

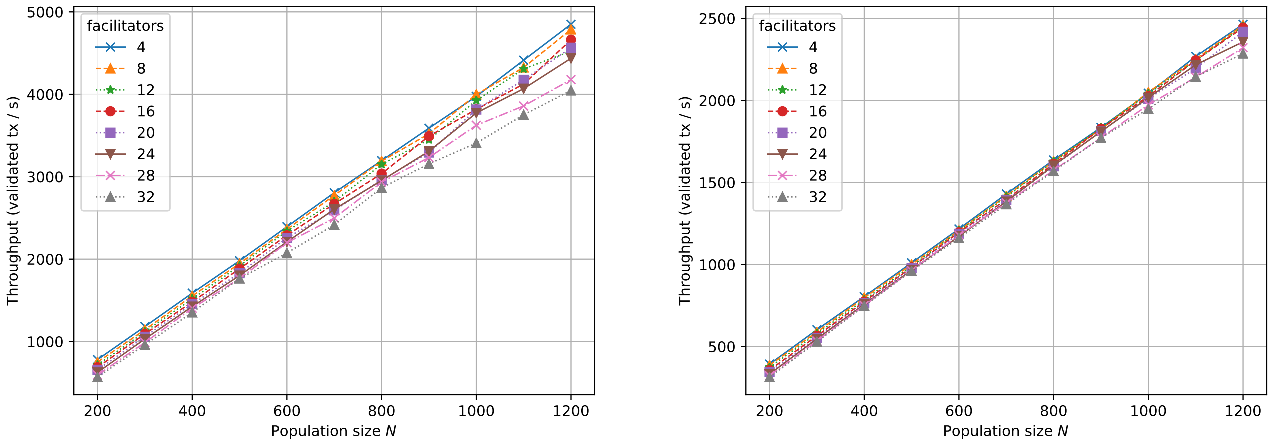
(b) Transactions are with random neighbours

Figure 5.3: Communication cost per verified transaction

More interestingly, there is a large difference in communication cost between the two modes of transaction. When transacting with only one neighbour, the communication cost is low because only one agreed fragment needs to be communicated for every round in order to validate all transactions of that round. This is because agreed fragments are cached. On the other hand, if every node is transacting with a random node, then it is likely the case that one agreed fragment needs to be communicated for every transaction. Hence the communication cost we see in Figure 5.3b is much higher than in Figure 5.3a.

Some fluctuations exist in Figure 5.3a, this is due to our caching mechanism. We send validation requests at the same rate as transactions. Upon receiving an (remote) agreed fragment, the caching mechanism inspects all the transactions in the agreed fragment and attempts to verify as many as it can, rather than just the transaction in the original validation request. However, it may be the case that the agreed fragments arrive later than the validation request interval. Then it is possible to have sent two or more validation requests for the transaction in the same local agreed fragment. In this case, the remote would respond with two or more of the same agreed fragments, which results in extra (wasted) communication cost, and this is the source of the fluctuation seen in Figure 5.3a. The result in Figure 5.3b reinforces our argument because it is a lot more stable because for every transaction it is almost always the case that an agreed fragment is needed to validate it.

5.5 Global Throughput



(a) (b)

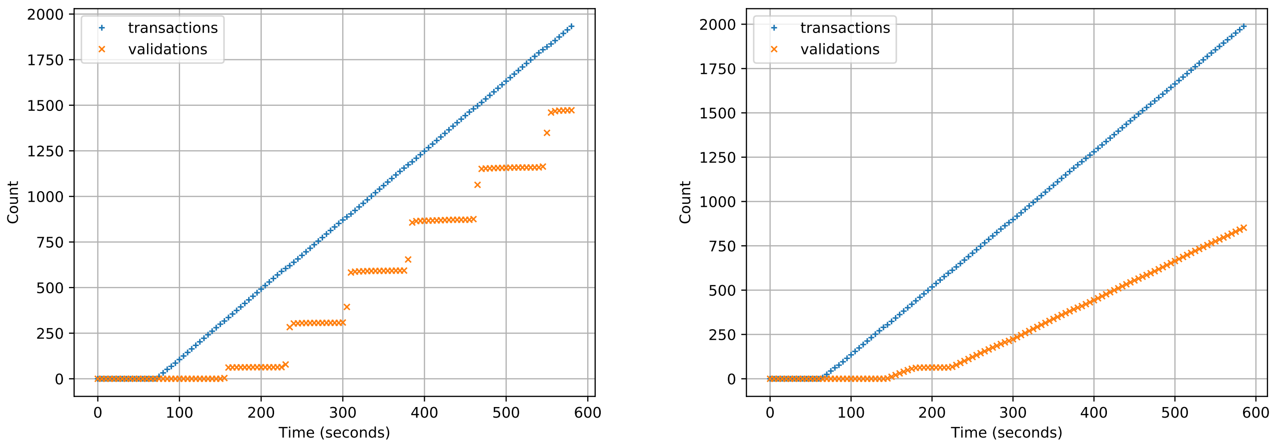
Figure 5.4: Global throughput

The global throughput results are shown in Figure 5.4. Evidently, 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. It also matches with our analytical result.

Note that the throughput decreases as the number of facilitators increases. This is due to the additional communication cost for running ACS with a high number of facilitators. That is, if the network is congested then the nodes may not have enough bandwidth to send validation responses timely.

For Figure 5.4a, the magnitude of our throughput may not be self-evident at first glance. Recall that we fixed our r_{tx} to 2, but how is it possible to have around 4800 transactions per second for 1200 nodes (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 seoncd, 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.

The difference in magnitude between Figure 5.4a and Figure 5.4b is also interesting. It is caused by the caching mechanism mentioned earlier. If an agreed fragment needs to be transmitted to validate every transaction then it puts a toll on the network infrastructure. The low transaction rate in Figure 5.4b is caused by fact that the network infrastructure cannot keep up with our demand. We demonstrate this issue from a different perspective in Figure 5.5. The graph is plotted by counting the number of transac-



(a) (b)

Figure 5.5

tions and the number of validated transactions every 5 seconds for one node running in a network of 1200 nodes and 32 facilitators. In Figure 5.5a, the number of validated transaction changes as a step function. This means that transactions are validated in bursts, and the validation protocol can "keep up" with the transactions. Note that the horizontal "lines" where no new validated transactions are made are roughly 70 seconds, this matches with our result in Figure 5.2a. On the other hand in Figure 5.5b, the validation protocol clearly cannot "keep up" with the rate which the transactions are made. As a result, the global throughput is lower when transacting with random nodes than only with neighbours.

Chapter 6

Related Work

Having analysed our system both theoretically and experimentally, we dedicate this chapter on comparing our results with related work. Blockchain technology has seen a surge in recent years from both the industry and academia. We classify the various blockchain systems by their consensus approach and divide them into the following categories:

1. classical blockchain systems,
2. classical blockchain with offchain transactions,
3. permissioned systems,
4. hybrid systems and
5. blockchains without global consensus.

A few systems from each of these categories are compared with our design.

6.1 Classical Blockchain Systems

This category represent systems with a probabilistic probabilistic consensus algorithm. That is, transactions never reach consensus with a probability of 1. The typical examples are proof-of-work based systems such as Bitcoin, Ethereum and other Altcoins. In Bitcoin, the level of consensus of a block[1] is determined how deep it is in the Bitcoin blockchain, also called the number of confirmation. The probability of a block being orphaned drops exponentially as the depth increases [30]. Nevertheless, the probability of the highest block being orphaned is non-negligible. The advantage of this type of consensus is that it can be used in a large network and is reasonably secure. Attackers can not out pace honest users in finding new blocks unless they have a

[1]Note that a block in Bitcoin contain many transactions whereas our TX block only contain a single transaction.

majority of the hash power. The disadvantage however is that transactions are never in consensus with a probability of 1—no consensus finality. Also, the performance is limited due to the fact that blocks are of fixed size and are generated at fixed intervals.

Our system significantly improves upon Bitcoin and other classical blockchain systems in performance, scalability and consensus finality. The results described in Chapter 4 and Chapter 5, show that we have horizontal scalability, where more nodes result in more global throughput. Further, we do not have the aforementioned probabilistic behaviour, once some consensus result is decided, it cannot be orphaned, thus our consensus is final. The leadership election is also not ideal in classical blockchain systems. Mining can be seen as a technique to elect a single leader. The leader has full control of what goes into the block thus it may selectively censor transactions. We use ACS, so as long as the CP block is in $n - 2t$ nodes, it is guaranteed to be in consensus.

However, the security aspect falls short of the "honest majority" security model that classical blockchains claim to have[2]. Our system risks going into erroneous state if the inequality $n \geq 3t + 1$ is not satisfied. Classical blockchain systems also have an incentive mechanism, thus they do not depend on altruistic nodes and encourages participation. Our system on the other hand does not have an incentive mechanism because we make no assumptions on the application.

6.2 Offchain Transactions

Offchain transactions make use of the fact that, if two or more parties frequently make 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 [36] and full duplex channels [16]. These use the Bitcoin blockchain to store the net settlement and a payment channel to conduct offchain transactions.

Offchain transaction systems are implemented using multi-signature addresses [9] and hashed time-locked Bitcoin contracts [8]. If two parties wish to make transactions, they open a time-locked payment channel with a multi-signature Bitcoin address (for two parties it would be a 2-of-2 signature address). Transactions happen off the Bitcoin blockchain and are signed by both parties. These transactions have a timestamp and only contain the net amount since the start of the payment channel. Before the payment channel expires, the latest of such transactions is sent to the multi-signature address. If multiple transactions are sent to the payment channel, the latest one is used. After payment channel is closed, the net transaction is propagated to

[2] Recently it was shown that doing selfish-ming would give the adversary an unfair advantage when she only controls 25% of the mining power [19]

the Bitcoin blockchain.

The advantages of such systems is that they act as add-ons to Bitcoin wish already has a large number of users. Thus, if enough of the network wish for it (by setting a new block version), then a large number of users will instantly benefit from it. It also shares the advantages of Bitcoin such as security and incentives.

On the other hand, offchain transactions also suffers from the problem of Bitcoin. Proof-of-work is still problematic as it consumes an unreasonable amount of power. Further, sidechain transactions are limited only to an exchange of cryptocurrency, it is less general than typical Bitcoin transactions which may be a simple smart contract. Time-locked contracts have a strong dependency on timing, thus disputes may arise when the payment channel is just about to close. Our system is purely asynchronous and make no assumption on timing, in fact we assume the adversary has control of the message delivery time and order.

6.3 Permissioned Systems

This category of systems use Byzantine consensus algorithms (discussed in Section 3.4.1). In essence, they contain a fixed set of nodes, sometimes called validators, that run a Byzantine consensus algorithm to decide on new blocks. This is known as a permissioned system where the validators must be pre-determined. Some examples include Hyperledger and Tendermint. The consensus algorithm used in these two systems is PBFT.

A nice aspect of Byzantine consensus and in particular PBFT is that it can handle much more transactions than classical blockchain systems. But our system has the potential to perform beyond that of PBFT because we represent many transactions with a single CP block, enabling horizontal scalability. Furthermore, since PBFT relies on a leader, it is not censorship resiliant. Our system on the other hand has the benifits of ACS where CP blocks cannot be censored. Finally, our system is able to work in the permissionless setting by simply submitting new CP blocks to the facilitators. It can even be adapted to work in the permissioned by simply removing the luck value computation.

What we wish to have which is in Hyperledger is a smart contract system (also known as chaincodes in Hyperledger). We hope to design and implement smart contracts by adding additional logic to the transaction protocol and the validation protocol. Such functionalities we believe is better to be built into the backbone rather than having it as an add on.

6.4 Hybrid Systems

Hybrid systems are very recent inventions. Just like our work, they are attempts on solving the problems of traditional blockchains. The main characteristic of these systems is that they use a classical blockchain technique, i.e. proof-of-work, to elect a committee and prevent Sybils. And then they use a Byzantine consensus algorithm to actually reach consensus on a set of transactions within the committee. Some examples are SCP [27], ByzCoin [21] and Solidus [2].

Our approach share many similarities with the hybrid systems. First, we also elect a committee (facilitators) to drive consensus. But we do not have proof-of-work for Sybil defence because we believe it is possible to do it efficiently, e.g. using NetFlow [34]. Secondly, our use of CP blocks and ACS is also unique. This creates a much higher throughput and enables censorship resiliance as mentioned earlier. For instance, ByzCoin performs just below 1000 TPS with a thousand nodes whereas we peak at 8000 TPS.

A major side effect of these hybrid systems is that they cannot guarantee correctness when there is a large number of malicious nodes. Our system has the same issue. For SCP, ByzCoin and Solidus, they all have some probability to elect more than n Byzantine nodes into the committee. This problem is especially difficult solve because the committee is always much smaller than the population size which has more than t Byzantine nodes, thus electing more than t nodes into the committee in always a possibility. Classical blockchain do not have this problem because they do not use Byzantine consensus. The permissioned systems work around this problem by trusting validators.

6.5 Blockchains Without Global Consensus

Tangle [37], Corda [20] and the original TrustChain [**trustchain**] do not use global consensus at all. By avoiding global consensus, they are able to achieve extreme scalability. Just like our approach, these blockchains are also application neutral where transactions can contain arbitrary data.

Our system can be considered as the same as these types of blockchains but with a lightweight consensus protocol. Consensus might not be applicable in all applications. But we believe it is important for detecting and preventing fraud. The example in Figure 3.1 on page 10 demonstrates this. If b makes a fork and a and c have no way to communicate (e.g. the adversary may control parts of the network) , then c is tricked to believe that her transaction with b is valid. Only when c sees a conflicting chain is she able to tell that the transaction is invalid. But c does not know the true end-of-chain of b, thus she can never know whether her transaction is valid. This is not possible in our system because b cannot convince c unless he can compute exponential time algorithms (this is finding the second preimage for a hash function).

However, consensus and validation comes at a cost that do not exist in Tangle, Corda or the original TrustChain. Our transaction rate is affected by the validation protocol in the worst case scenario as we saw in **??**.

Chapter 7

Conclusion

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Appendix A

Consensus Example

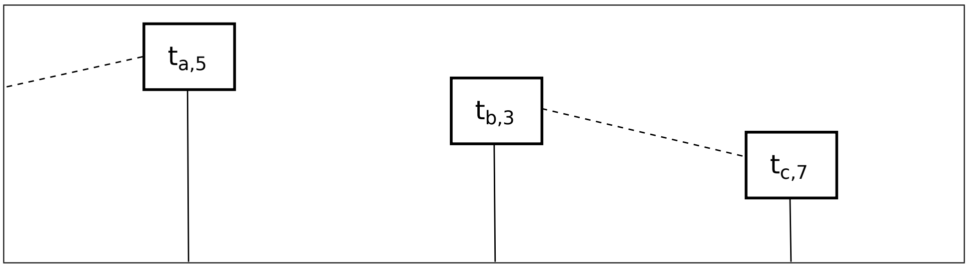

Figure A.1: Initial state

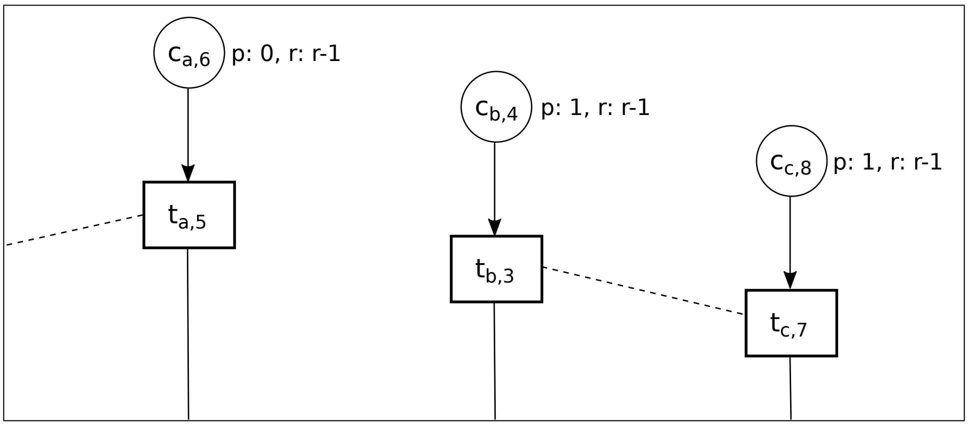

Figure A.2: Initial state

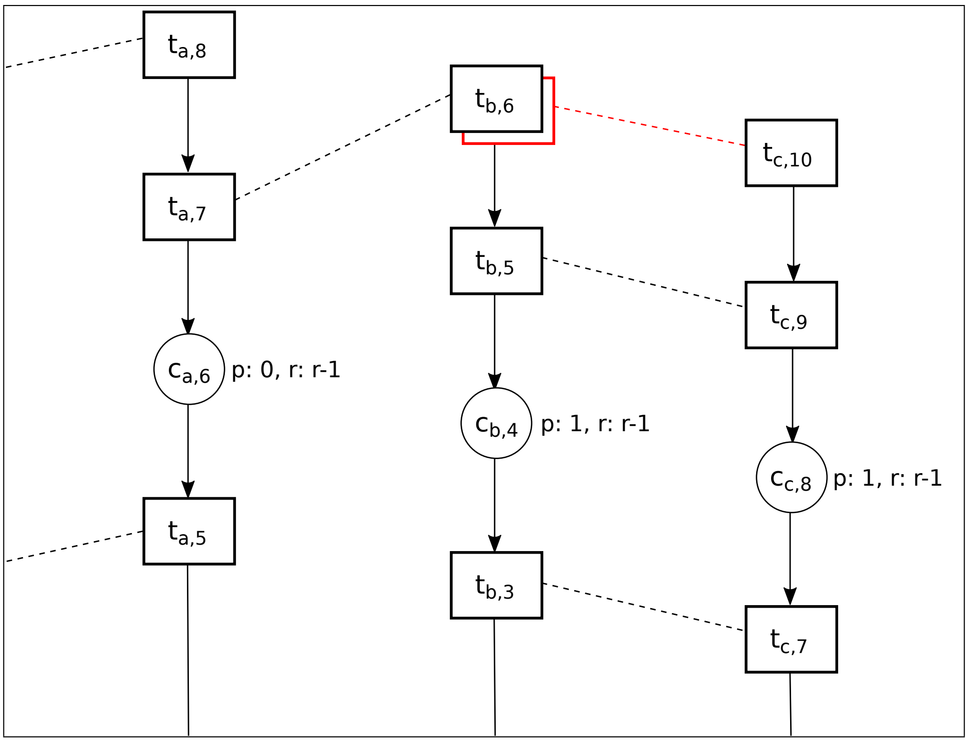

Figure A.3: Initial state

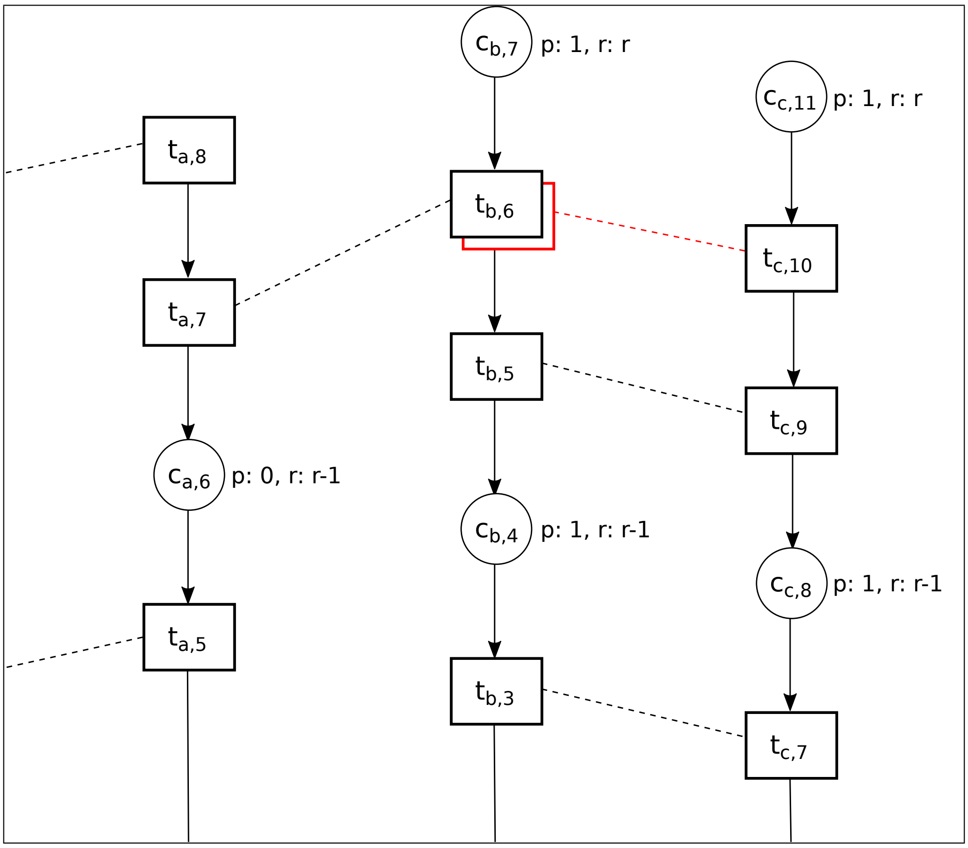

Figure A.4: Initial state