A Scale-out Blockchain for Value Transfer with Spontaneous Sharding

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Abstract. Blockchain technology, sometimes known by its applications like cryptocurrencies, suffers from the scalability problem mainly due to the unideal throughput of Byzantine fault tolerance consensus algorithms. Recently, many blockchains have been proposed to achieve scale-out throughput, i.e., the throughput of the system grows with the number of nodes. In this paper, we propose a novel scale-out blockchain system for the most considered type of ledgers, we call Value Transferring Ledgers, in which a transaction is a transfer of positive value from one node to another. In our system, nodes commonly agree on a main chain and individually generate their own chains. We propose a locally executable validation scheme with uncompromised validity and scalable throughput. Furthermore, a smart transacting algorithm is introduced so that the system is spontaneously sharded for individual transactions and achieves scale-out throughput.

Keywords: Blockchain, distributed ledger, Byzantine fault tolerance, scale-out, off-chain

1 Introduction

Blockchain technology, made popular by Bitcoin [1], can be described as a distributed append-only database maintained by distributed nodes instead of some central authorities. One of the most well-known applications of blockchain technology is cryptocurrency, in which the blockchain is in the form of a distributed ledger, i.e., the data is transactions which are records of value exchanges between nodes. A crucial part of the blockchain technology is the consensus algorithm which guarantees that all honest nodes in the network keep a consistent ledger of valid transactions. The consensus algorithm can be divided into two categories, the Nakamoto-like consensus algorithms such as Proof-of-Work (POW) [1] or Proof-of-Stake (POS) [2,3] and Byzantine fault tolerance (BFT) consensus algorithms such as PBFT [4]. For distributed ledger type of blockchain, most of the consensus algorithms effectively achieve the following conditions.

- **Agreement (Consistency)**: Two honest nodes should not have disagreement on the validity of a transaction.

- **Validity (Correctness)**: Invalid transactions cannot be validated by honest nodes.
- **Termination (Liveness):** All transactions will be eventually known by all honest nodes.

The term "effectively" infers that strictly speaking, the above conditions are not achievable in asynchronous networks [5,6]. By compromising on either the asynchronous assumption [4] or one of the conditions like probabilistic termination [7,8], the above-mentioned conditions can be achieved in asynchronous network. However, blockchains with either Nakamoto-like consensus or BFT consensus are limited in scalability, i.e., the communication cost per transaction in bits (CCPT) is lower bounded by $O(N)$.

For Nakamoto-like consensus [9], the POW based scheme used in Bitcoin introduced rational assumptions, incentives, and punishments on malicious behaviors to achieve scalable throughput. However, this scheme and some other POW or POS based schemes have limitation in the transaction rate to meet the synchronous requirements [10]. Separation of the block and transactions from the leader selection would remove the dependency of the duration of the consensus process on the transaction rate, which results in $O(N)$ CCPT [3,11,12].

On the other hand, BFT algorithms rely heavily on the communication between nodes and have a message complexity of $O(N^2)$ for traditional algorithms like [4,7,8]. This results in a severe performance degradation as the population of the network grows to above two digits [10]. Recent scalable BFT algorithms such as [13,14,15,16] reduce the CCPT to $O(N)$ either by packing up transactions or opportunistically running a much simpler scheme with traditional schemes as the back-up for the worst scenario.

1.1 Scale-out Blockchain Solutions

The blockchains with the CCPT of $O(N)$ are commonly referred as "scalable blockchains", which suggests that the throughput will not increase with the number of nodes and the computation and communication capacities in the network. Recently, several solutions have been proposed to achieve $O(1)$ CCPT, sometimes referred as "scale-out" throughput, by reducing the number of validators and recordkeepers for each transaction. Here, we introduce three types of such schemes.

- **Off-chain Solutions:** This type of approaches are mostly associated with some existing blockchain systems as the main chain. Each node holds their transactions locally, sometimes referred as "off-chain", and only sends a description or the eventual outcome of these transactions to the "main chain", referred as "on-chain". Since there is no guarantee on the "off-chain" transactions, either validation nodes are introduced to validate and endorse these transactions [17,18] or economical deposit should be provided for the transactions [19,20]. In both cases, the validity condition is compromised due to centralization or the economical constraint.

- **Directed Acyclic Graph (DAG) Solutions:** In another type of approaches, we call DAG solutions, the transactions are not structured in a chain, but in a DAG [21,22]. The validity condition is compromised since the validity of the transaction is not absolute. Instead, the validity is dependent on the (directly or indirectly) outgoing edges of the transaction, which represents the nodes that have validated it.
- **Sharding Solutions:** Recently, sharding solutions, which artificially divide the network, have been widely studied and discussed [23,24,25,26]. They include schemes that fairly and randomly divide the network into small shards with vanishing probability of any shard having an overwhelming number of adversaries. Hence, the BFT consensus algorithms is run only within the shards and the CCPT is then $O(g^2)$ ($O(g)$ if scalable BFT is used) where g is the size of the shard. However, the validity condition is also compromised in the sense that the sharding is only feasible when the ratio of adversaries in the network is small.

All aforementioned solutions have the potential to scale out since the termination property is compromised, i.e., a transaction is not necessarily known to or validated by the whole network, but a part of it.

1.2 Our Contributions

The main contributions of this paper are the following.

- We introduce the Value Transferring Ledgers (VTL) which bring in some realistic interpretation of the ledger. We make use of the properties that distinguish value transferring transactions from generic data which is considered by traditional BFT problems. First of all, a valid value transferring transaction has some proof which could be used to prove its validity. Then, the receiver of an unspent transaction is the current owner of the transferred value. Hence, he is motivated to show the proof of the validity of this transaction to other nodes.
- We propose an off-chain based blockchain system which consists of an existing blockchain as the main chain, an individual chain for each node containing its own transactions, and a locally executable validation scheme which achieves uncompromised agreement and validity conditions.
- For any transaction pattern, the CCPT of our system is upper bounded by $O(N)$, which suggests scalable throughput. Moreover, we introduce the spontaneous sharding that allows our system to scale out, i.e., reduces the CCPT to $O(1)$.

1.3 Content of This Paper

In this paper, we propose a novel scale-out blockchain system for VTL. In Section 2, we introduce our model, design, and all important primitives. In Section 3, we introduce our validation scheme, prove the correctness of it, and show the achieved BFT conditions. We analyze the performance of our scheme and introduce the concept of spontaneous sharding which results in scale-out throughput in Section 4. In Section 5, we conclude our paper with possible topics for further exploration.

2 Model and System Description

Our system has an off-chain structure, in which the hashes of batches of transactions, rather than individual transactions, are recorded on the main chain. In this paper, we emphasize on our novelties and contributions. Hence, some other elements are simplified to the most comprehensive level, e.g.,

- We consider a simple value transferring system where every node holds some initial value. The mining of new coins are not considered.
- Transactions have one sender and one receiver.
- We consider a weak asynchronous network with $f \leq \lfloor \frac{N-1}{3} \rfloor$ Byzantine adversaries, just as the one used in [4], so that PBFT can be straightforwardly applied.

In this section, we introduce the model, the design of our system, as well as the VTL. Furthermore, we give definitions for some terms that will be used throughout the paper.

2.1 Network Model

We consider a weak asynchronous network of N nodes connected with a Peer-to-Peer infrastructure, in which the message delay of any honest node is upper bounded by t. Each node holds some initial value that could be transacted with others. We assume that there are $f \leq \lfloor \frac{N-1}{3} \rfloor$ Byzantine adversaries and we have the following definitions for honest nodes and adversaries.

Definition 1 (Honest nodes and Adversaries). Honest nodes *will follow the rules and only make valid transactions, which are the transactions that they can (eventually) validate.* **Adversaries** *can behave arbitrarily.*

The network is assumed to be permissioned, i.e., the nodes are known to each other by their identity numbers $n \in \{1, 2, \ldots, N\}$. We also assume that there exists a public key infrastructure (PKI) and nodes can link between the identity number and the public key of each node. Besides, we assume that there exists an unbreakable hash function $Y = H(X)$ and digital signature scheme $Y = Sig_i(X)$ based on the public-private key pairs where node i is the signer. Moreover, we introduce the "chain" as a data structure that consists of an ordered sequence of blocks. Each block consists of multiple transactions and a hash digest of the previous block, except for the first block, namely the genesis block.

2.2 System Structure

Transactions We use a similar transaction based structure as the unspent-transaction-as-output structure described in [1] and give the following definitions for transaction and unspent transaction.

Definition 2 (Transaction). *A transaction* tx_i *is a five-tuple:* $tx_i = \langle \mathrm{Source}_i, s_i, d_i, a_i, r_i \rangle$ *where* Source_i *is the set of transactions which are used as the source,* s_i *is the sender,* d_i *is the receiver,* a_i *is the transacted value, and* r_i *is the remaining value.*

Definition 3 (Unspent Transaction). *A transaction* tx_i *is an unspent transaction if there is no transaction* tx_j *which is valid and* $tx_i \in \mathrm{Source}_j$. *We will explain the term "valid" in Subsection 2.3.*

Off-chain Part Each node has its own blockchain, namely individual chain. It consists of transactions which are sent by it. We define an individual chain as an ordered set $\{B_{u,1}, B_{u,2}, \ldots,\}$ and a block as an ordered set $B_{u,k} = \{H(B_{u,k-1}), t_{u,k,1}, t_{u,k,2}, \ldots\}$, where $t_{u,k,l}$ is a transaction. The first blocks of the chains $B_{u,1}$ are called genesis blocks. In our system, we assume that there is an initial value assigned to each node. The initial value is assigned in the same fashion as a transaction, with no source. The sender and receiver of this transaction are both the node itself.

The size of a block can be arbitrary. Periodically, nodes send *Abstracts* to the *main chain* (will be introduced in the next paragraph). The abstract is defined as the following.

Definition 4 (Abstract). *An abstract of block* $B_{u,k}$*, denoted by* $A_{u,k}$*, is a four-tuple:* $A_{u,k} = \langle u, k, H(B_{u,k}), Sig_u(u, k, H(B_{u,k})) \rangle$.

On-chain Part We consider a blockchain with PBFT as its consensus algorithm and the blocks consist of *Abstracts* signed by the corresponding nodes. This chain is called the *main chain*. We assume that the abstracts of all genesis blocks are in the main chain. Since it has been proved that the PBFT can reach BFT consensus on messages in our network [4], we simply see the main chain as a reliable and secure primitive in our system and all abstracts included on the main chain reaching BFT consensus. Honest nodes will send abstracts of their newest blocks to the main chain and create new blocks every τ seconds, which is chosen accordingly to the duration of the consensus process.

2.3 Confirmation, Validity, and Proof

The transactions on individual chains are arbitrary with neither tamper-proof nor prevention from double spending. The transactions will be tamper-proof if an abstract of a block that comes after it is contained in the main chain. We call them confirmed transactions. Here, we give the formal definitions of a confirmed transaction and a confirmed block.

Definition 5 (Confirmation). *A block $B_{u,k}$ is confirmed if an abstract of this block or a block after this one, i.e., $A_{u,k'}, k' \geq k$ is on the main chain and for all abstracts of node u denoted by $A_{u,l}$ that are on the main chain and $l \leq k'$, $A_{u,l}$ is compliant to their corresponding blocks. A transaction $tx_i = \langle \mathrm{Source}_i, s_i, d_i, a_i, r_i \rangle$ is a confirmed transaction of node u if $tx_i \in B_{u,k}, s_i = u$, and $B_{u,k}$ is confirmed. We call $B_{u,k}$ and tx_i are confirmed by $A_{u,k'}$.*

The confirmation of a transaction suggests that it is tamper-proof as if it is on-chain and it is signed.

Property 1 (Confirmed Transactions). If $tx_i = t_{u,k,l}$ is a transaction that confirmed by abstract $A_{u,k'}, k' \geq k$, then there does not exist a chain of confirmed blocks $\{B'_{u,1}, B'_{u,2}, \ldots, B'_{u,k'}\}$ such that $t'_{u,k,l} \neq tx_i$ and all hashes are correct.

The formal proof of this property is given in Appendix A. By Property 1, when a transaction is confirmed, the position and content of it cannot be changed. Then, we define the validity of a transaction in a traditional fashion as classical distributed ledgers.

Definition 6 (Validity of a Transaction). *A transaction $tx_i = \langle \mathrm{Source}_i, s_i, d_i, a_i, r_i \rangle$ is valid if and only if the following conditions hold.*

- **Confirmed***: tx_i is confirmed.*
- **Valid sources***: All transactions in $tx_j \in \mathrm{Source}_i$ are valid.*
- **Value equality***: The original value equals to the sum of the transacted value and the remaining value, i.e., $\sum_{tx_j \in \mathrm{Source}_i} r_j = a_i + r_i$.*
- **No double spending**[1]*: Assuming $tx_i = t_{u,k,l}$, for any $tx_j \in \mathrm{Source}_i$, if there exists a valid transaction $tx_{i'} = t_{u,k',l'}$ that $tx_j \in \mathrm{Source}_{i'}, k' \leq k$, then $tx_{i'} = tx_i, k' = k, l' = l$.*

We then give the definitions of the validation function and the validity proof of a transaction.

Definition 7 (Validation Function, Validity Proof, and Validation Scheme). *Given a set of data we called* validity proof $\mathcal{P}(tx)$ *and a function we called* validation function $y = \mathsf{V}(tx, \mathcal{P}(tx))$*, if $\mathsf{V}(tx, \mathcal{P}(tx)) = \mathsf{valid}$ if and only if tx is valid, we call $y = \mathcal{P}(tx)$ and $y = \mathsf{V}(tx, \mathcal{P}(tx))$ form a* validation scheme.

2.4 Value Transferring Ledgers

We introduce a special type of ledgers in which the transactions are records of value transfers. The concept itself is rather comprehensive and realistic. For

[1] We define this property exclusively for a block, i.e., if there are multiple transactions using the same source in a block, instead of letting the first one to be valid and invalidating the rest, we invalidate all of them. Note that if there are multiple transactions using one source in different blocks, then the first one could be valid and then the rest are invalid.

instance, in cryptocurrencies, transactions are records of the transferring of the currency. The main difference of VTL from other types of databases is that in VTL, every transaction is a transfer of some positive value, which suggests the following. Firstly, the receiver of a transaction is the holder of that value until it is spent again. In this period, this value can be considered as his property and he would take full initiative and responsibility of proving the existence and the authenticity of the value. If he fails to do so, it will be considered as against his own interest. For instance, if the value is considered as money, the holder of the money is motivated to prove the money is real when he uses it for purchase. A failure in proving will cause the purchase to fail, which is against his own interest.

Secondly, the concern of the nodes is the authenticity of the value instead of the transaction records. Hence, nodes will only check the past transaction records if the records are parts of the proof which support the authenticity of the value that they concern. Otherwise, nodes have no interest and will not care about the validity of a past transaction.

Here, we give the formal descriptions of the properties of VTL. Throughout this paper, we use the term "node u is curious about transaction tx_i" to represent that node u knows tx_i and would like to check the validity of it.

Property 2 (History disinterest). A node u is curious about a spent transaction tx_i only when it is curious about an unspent transaction tx_j and the validity of tx_j is necessary for the validity of tx_i.

Property 3 (Rational Receiving). A node u is curious about transaction tx_i if it is the receiver of tx_i and does not know the validity of it.

Property 4 (Rational Owner). If node u is the receiver of a valid and unspent transaction tx_i, it will provide the validity proof of tx_i to any node once it is requested.

In practice, it is not rational for a node to validate an unspent transaction if it is not the receiver of it since validation is resource consuming. Hence, we have an alternative version for Property 3 to minimize the cost in a resource-limited network.

Property 5 (Rational and Cost-saving Receiving). A node u is curious about transaction tx_i **if and only if** it is the receiver of tx_i and does not know the validity of it.

This property will not effect the correctness of our scheme. It will be applied in the performance analysis for simplicity.

3 Validation Scheme

In this section, we first introduce our validation scheme by describing the validity proof and the validation function of a transaction. Then, we prove the correctness of this scheme and show the BFT consensus achieved by valid transactions in VTL model.

3.1 Validity Proof and Validation Function

Here we define the validity proof of a transaction tx_i.

Definition 8 (Validity Proof). *Assuming that* $s_i = u$ *for transaction* tx_i, $tx_i \in B_{u,k}$, *and there exists an abstract* $A_{u,k'}, k' \geq k$ *in the main chain, a validity proof* $\mathcal{P}(tx_i)$ *is the union of a set of all blocks before and including* $B_{u,k'}$ *and the proofs of all transactions in* Source_i*, i.e.,* $\mathcal{P}(tx_i) = \{B_{u,k''} | k'' \leq k'\} \cup \{B_{v,l} | B_{v,l} \in \mathcal{P}(tx_j), tx_j \in \mathrm{Source}_i\}$.

By Definition 8, the validity proof of $tx_i \in B_{u,k}$ includes the chain of u from the genesis block to the block $B_{u,k'}, k' \geq k$ which has an abstract in the main chain. Moreover, it also includes the chains of the sources of this transaction, and recursively the sources of the sources until the genesis block.

In the following lemma, we show that the proofs of valid transactions can always be collected by nodes who are curious about them.

Lemma 1 (Feasibility of the Proof Collection). *If a node* u *is curious about a valid transaction* tx_i*, then it can always identify a node* v *such that it would provide the proof of* tx_i*.*

Proof. If tx_i is an unspent transaction, this lemma directly follows from Property 4 since the receiver of tx_i will provide it. If tx_i is a spent transaction, then by Property 2, u will only be curious about tx_i if u is curious about an unspent transaction tx_j and the validity of tx_i is required for the validity of tx_j. By Definition 8, we have $\mathcal{P}(tx_i) \subset \mathcal{P}(tx_j)$. Hence, by Property 4, u can collect the proof of tx_j from the receiver of tx_j. □

By Lemma 1, the proof of a transaction tx_i can always be collected via point-to-point communication. However, although by our model the receiver of the unspent transaction is motivated to provide the correct proof, the requester of the proof will not accept it as a proof without his own verification. We give the Proof Verification Algorithm $\mathsf{Ver}(\mathcal{P}(tx_i))$ in Appendix B. If $\mathsf{Ver}(\mathcal{P}(tx_i)) = \mathsf{pass}$, it suggests that $\mathcal{P}(tx_i)$ is indeed a validity proof for transaction tx_i since the algorithm is a direct translation from the definition of the validity proof.

Then, we define the validation function as Algorithm 1.

Here, we show that the proposed validity proof and validation function forms a validation scheme as defined in Definition 7.

Theorem 1. $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) = \mathsf{valid}$ *if and only if* tx_i *is valid.*

This theorem holds since our scheme is a straightforward translation of the definition of the validity. The detailed proof is given in Appendix C.

3.2 BFT Satisfactory

In this section, we show that our system satisfies the agreement and validity condition of BFT as described in [13,14] with a compromised termination condition for all valid transactions.

Algorithm 1 Validation Function $\mathsf{V}(tx_i, \mathcal{P}(tx_i)), tx_i = \langle \text{Source}_i, s_i, d_i, a_i, r_i \rangle \in B_{u,k}$

```
#Validity Proof Check
if Ver(P(tx_i)) ≠ pass then return unknown
#Equality Check
if ∑(all remaining values from Source_i) ≠ a_i + r_i then return unknown
#Double-Spending Check
for B_{u,m}, m = [1 : k] do
    for All transactions tx_j in B_{u,m} do
        if Source_j ∩ Source_i ≠ ∅ and tx_i ≠ tx_j then return unknown
#Source Check
for all transactions tx_j in Source_i do
    if V(tx_j, P(tx_j)) ≠ valid then return unknown
return valid
```

Theorem 2 (BFT Satisfactory). *Our system satisfies the following conditions in VTL model. Here, we use the term "node u validates a transaction tx_i" to represent that node u runs a validation function on tx_i with the result* valid*.*

– **Agreement(Consistency)***: If an honest node validated a transaction, then, if another honest node is curious about this transaction, it will also validate it.*
– **Validity(Correctness)***: If an honest node proposed a transaction and at least one honest node is curious about it, this transaction will be validated by at least one honest node.*
– **Termination(Liveness):** *If a transaction is proposed by an honest node, then all honest nodes that are curious about it can collect the proof of it.*

Proof.

– **Agreement:** If a transaction tx_i is validated by an honest node, i.e., $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) = \mathsf{valid}$, then, by Theorem 1, tx_i is valid. By Property 1, if another node is curious about tx_i, the proof can be collected. Then, since the validation function is deterministic, another curious honest node will also run the validation function and the result will be valid.
– **Validity:** If a transaction is proposed by an honest node, by the definition of the honest node, that node can eventually validate it, i.e., at a certain time T_0, we have $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) = \mathsf{valid}$. Then, by Lemma 1, the proof of this transaction can be collected. Then, since the validation function is deterministic, the honest node that is curious about it will validate it.
– **Termination:** If a transaction is proposed by an honest node, at a certain time T_0, we will have $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) = \mathsf{valid}$ with the same reason as stated above. Then, tx_i is valid by Theorem 1 and by Property 1, any nodes that is curious about it can collect the proof of it. ☐

The insight of Theorem 2 is the following. Firstly, we explicitly focus on achieving BFT consensus for valid transactions. Then, for each valid transaction, we introduce the curious nodes based on Property 2 of the VTL model, which sets a constraint on the nodes that would like to know and validate the transaction and thus compromises the termination condition. However, we prove that the agreement and validity conditions are not compromised.

4 Performance Analysis and Spontaneous Sharding

In this section, we will give theoretical explanations for the scale-out claim that we made for the throughput, i.e., the CCPT could be reduced to $O(1)$. First we show that the throughput of our system is scalable even in the worst case. Then, we propose a simple smart transacting algorithm which could result in spontaneous sharding of the network for each transaction and scale-out throughput. Simulation results are given to support our claim.

4.1 Communication Cost Per Transactions

In our system, the main chain is using PBFT with $O(N^2)$ message complexity. However, the number of transactions associated with one abstract in the main chain are arbitrary and independent of the main chain. As a result, the communication cost of the main chain can be made into a negligible term in CCPT if we choose the number of transactions associated with one abstract to be $\omega(N^2)$. The duration of the consensus process still plays an important role in the latency of our system. However, note that the PBFT-based scheme is used only for easy comprehension and can be easily replaced by other scalable and low latency blockchain systems to improve the latency of our system.

Then, in our system, the CCPT is in fact the cost in collecting the proof of that transaction, which varies from transaction to transaction. For easier analysis, we make a few assumptions. We assume that rational nodes will not care about invalid transactions and thus will not try to re-collect the proof of a transaction if it is failed for a number of times. In other words, malicious nodes cannot spam invalid proofs to jam the network. In this case, the CCPT of invalid transactions are irrelevant and the CCPT of our system can be represented by $O(hp)$, where h is the average number of nodes that is curious about a valid transactions before it is spent (once it is spent, the proof is included in the proof of another unspent transaction) and p is the average size of the proofs. For the simplicity in analysis, we only consider the resource limited network with Property 5. In that case, the CCPT of our system is $O(p)$ since $h = 1$.

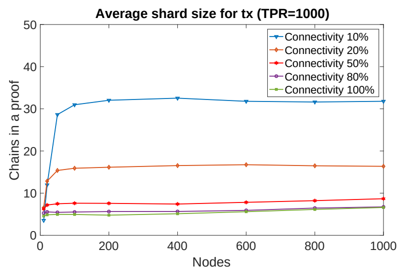
Now we focus on the size of the proof. In general, the proof of a transaction tx_i includes the chains of the sender, the senders of all sources of this transaction, and the senders of recursively the sources of the sources. In practice, the storage is traded for validation efficiency, i.e., the validated transactions and their proofs are stored and the proofs of new transactions are collected incrementally. Then, in the worst case when the proof of any transaction includes the chains of all nodes, if the storage is not limited, all nodes merely need to be updated with all transactions in the network. This can be done with no more than $O(N)$ CCPT since by Property 4 and Lemma 1, a point-to-point based collection is sufficient to guarantee reliability and there is no need for BFT reliable broadcast schemes. A better case would be that the transaction pattern is separated into fractions and the nodes only make intra-fraction transactions. In that case, the proof of any transaction contains the chains of only the nodes in their fractions and the proof size of a transaction is $O(g)$, where g is the size of the fraction. As a result, our system achieves scale-out throughput.

4.2 Spontaneous Sharding

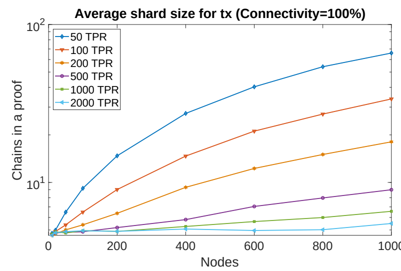
Here, we consider a more general case that the transaction pattern is not separated into small fractions and show that our system could still achieve scale-out throughput if all nodes behave rationally. We call this spontaneous sharding. The idea behind the spontaneous sharding is simple: rational nodes will try to minimize their transmission costs by minimizing the proof size of each transaction. Then, according to the information about the chains that the receiver already has, the sender will choose from all its unspent transactions for the ones with the least amount of required proofs. For example, node 1 has transacted with a receiver node 2 with proofs including the chains from nodes $\{3, 4, 5, 6\}$. Then, for all future transactions that it makes to node 2, it will prefer to use the unspent transactions with proofs that consist of the chains from $\{3, 4, 5, 6\}$ so that it only needs to update these chains. In other words, if all nodes are rational, the value of a transaction will tend to only cycle in a group of nodes instead of the whole network. As a result, for each transaction, the network is spontaneously sharded. We give a smart transacting algorithm in Appendix D for rational nodes, which simply lets the sender detect the chains that the receiver already has and choose the sources accordingly.

Here we show some simulative results of spontaneous sharding. We assume that each node only transacts with c nodes in the network with equal probability. The transacted amount is a fixed fraction of his balance. The confirmation time and the transaction rate are t_0 and R, respectively. Hence, for each transaction, a node will minimize the proof size of the transactions in this round by deliberately choosing from $t_0 R$ transactions confirmed by its last on-chain abstract, which is called transactions per round (TPR). We consider a stable state with sufficient transactions been made by each node. In the simulation, we focus on the spontaneous sharding, i.e., the average number of chains required as proof for each transaction.

In Fig 1(a), it is shown that if the ratio of the connectivity c/N is fixed, the number of chains included in the proof of a transaction tend to be a constant as the network grows large. For example, if each node transacts with 20 percent of nodes in the network, eventually, the proof of each node will only contains the chains of around 15 nodes. Hence, the transmission costs of each transaction is $O(15)$.



(a) Variant ratios of connectivity.



(b) Full connectivity with variant transactions per round (TPR).

5 Conclusion and Future Work

In this paper, we proposed a novel blockchain system for the most considered type of distributed ledgers which we called VTL. In VTL, we assume that nodes are rational and will be motivated to prove their possessed value. Our system has a very simple and fully decentralized structure that does not introduce any node serving as "validator". Our system achieves uncompromised agreement and validity conditions on the valid transactions and has a potential to scale out by spontaneous sharding.

For future work, we believe the following topics are interesting for further exploration.

– **Supportive to conditional payments/smart contracts:** We conjecture that conditional payments and smart contracts can also by supported by this system with modified data structure and validation scheme as long as each transaction includes some value transferred to at least one of the receiver.
– **Real-world Implementation:** In this paper we simulated the spontaneous sharding for randomly connected network. We conjecture that our system will out-scale in real-world networks as well due to the "small world" phenomenon [27], e.g., if the transaction chain behaves similarly to the acquaintance chain, any node only needs to collect chains of six other nodes for the proof any transaction as suggested by the "six degrees of separation".
– **Exploiting the features of data:** Recently, [16,28] also proposed the separation of the validity and agreement, i.e., distinguishing transactions from generic data considered by traditional BFT consensus schemes and treating valid and invalid transaction differently. As a result, BFT consensus schemes can be modified accordingly to achieve higher throughput. In this paper, we further exploited the features of value transfers, i.e., a transaction represents a transfer of real value which is interested by the receiver. By doing that, a scale-out throughput is achieved. We believe that in many scenarios, the throughput of BFT consensus can be improved if the features of the data are taken into account.

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A Proof of Property 1

Proof. We proof this property by contradiction. If there exists a chain $\{B'_{u,1}, B'_{u,2}, \ldots, B'_{u,k'}\}$ which consists of confirmed block and $t'_{u,k,l} \neq tx_i$. First of all, confirmed blocks suggest that all abstracts of $\{B'_{u,1}, B'_{u,2}, \ldots, B'_{u,k'}\}$ is on the main chain. Then, since $t_{u,k,l} = tx_i$ is confirmed by an abstract $A_{u,k'}$, all abstract of the chain $\{B_{u,1}, B_{u,2}, \ldots, B_{u,k'}\}$ are also on the main chain. Moreover, since the abstracts are signed and the digital signatures are assumed to be unbreakable, the chains $\{B'_{u,1}, B'_{u,2}, \ldots, B'_{u,k'}\}$ and $\{B_{u,1}, B_{u,2}, \ldots, B_{u,k'}\}$ will have the same set of abstracts of node u on the main chain, which includes $A_{u,k'}$ as the abstract of both $B'_{u,k'}$ and $B_{u,k'}$. Since the hash function is assumed to be unbreakable, we have $B'_{u,k'} = B_{u,k'}$. Then, if $t'_{u,k,l} \neq tx_i$, then we will have $B'_{u,k} \neq B_{u,k}$ and $B'_{u,k'} = B_{u,k'}, k' \geq k$, which contradicts our assumption of the unbreakable hash function. □

B Proof Verification Algorithm

Here we give the Proof Verification Algorithm as Algorithm 2.

C Proof of Theorem 1

Proof. We first prove that if $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) = \mathsf{valid}$ then tx_i is valid. It directly follows from the four checks in Algorithm 1 since they are exactly the conditions in Definition 6.

Algorithm 2 Proof Verification Algorithm $\mathsf{Ver}(\mathcal{P}(tx_i)), tx_i \in B_{u,k}$

#Verify the chain including this transaction
$\mathsf{count} \leftarrow 0$
$\mathsf{absmark} \leftarrow 0$
for $B_{s_i,m}, m = 1 : \max$ **do** ▷ Check the integrity of the chain
  if $tx_i \in B_{s_i,m}$ **then** $\mathsf{count}++$
  if $m \neq 1$ **and** first element in $B_{s_i,m} \neq H(B_{s_i,m-1})$ **then return** fail
  if $A_{s_i,m}$ is included in the main chain **then**
    $\mathsf{absmark} \leftarrow m$
    if $H(B_{s_i,m}) \notin A_{s,m}$ **or** $Sig_u(u, k, H(B_{u,k}))$ is not correct **then return** fail
if $\mathsf{absmark} < k$ **then return** fail ▷ Check the confirmation
if $\mathsf{count} \neq 1$ **then return** fail ▷ Check the existence of the transaction
#Verify the chains of the sources
for all $tx_j \in \text{Source}_i$ **do**
  if $\mathsf{Ver}(tx_j) \neq \mathsf{pass}$ **then return** fail
return pass

We then show that if $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) \neq \mathsf{valid}$ then tx_i is not valid. To prove this, we first prove the statement "if $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) \neq \mathsf{valid}$ and $\forall tx_j \in \text{Source}_i, \mathsf{V}(tx_j, \mathcal{P}(tx_j)) = \mathsf{valid}$, then tx_i is not valid."

We prove this statement by contradiction. Assuming that there exists a transaction tx_k such that $\mathsf{V}(tx_k, \mathcal{P}(tx_k)) \neq \mathsf{valid}$ but for all $tx_j \in \text{Source}_k, \mathsf{V}(tx_j, \mathcal{P}(tx_j)) = \mathsf{valid}$, and tx_k is valid.

By our algorithm, at least one of the four checks other than the "**Source Check**" is failed. If the step "**Proof Check**" fails, it suggests that a proof $\mathcal{P}(tx_i)$ does not exist, which contradicts the assumption that tx_i is valid. If the step "**Equality Check**" fails, it contradicts the **Value equality** condition of valid transaction. If the step "**Double-Spending Check**" fails, it contradicts the **No double spending** condition of valid transaction.

We then prove that if $\mathsf{V}(tx_i, \mathcal{P}(tx_i)) \neq \mathsf{valid}$ then tx_i is not valid by contradiction. If this does not hold, then there must exist a transaction that violates the statement proved above. This transaction might be tx_i, the source of tx_i, or recursively one in the sources of the sources. □

D Smart Transacting Algorithms

Here we give a smart transacting algorithms $\text{Source}_i = \mathsf{ST}(d_i, a_i, \mathcal{C}_u)$ in Algorithm 3 for rational nodes, where node u intends to send an amount of a_i to node d_i in transaction tx_i and $\mathcal{C}_u$ is a collection of all transactions and proofs recorded in node u.

Note that Algorithm 3 is a non-interactive algorithm. The choice of the sources is much easier in an interactive fashion, in which the receiver simply tells the sender the chains that he has for the second step of Algorithm 3. Both

Algorithm 3 Non-interactive Smart Transacting Algorithm $\mathsf{Source}_i = \mathsf{ST}(d_i, a_i, \mathcal{C}_u)$

#Step 1: Check for all unspent transactions
$\mathsf{UT} \leftarrow$ all unspent tx_i that are in $\mathcal{C}$.
#Step 2: Determine the chains that d already has according to $\mathcal{C}$
$\mathsf{Collected} \leftarrow \emptyset$
for each tx_i in $\mathcal{C}$ **and** $d_i = d$ **do**
  $\mathsf{chains}_i \leftarrow \{v | \mathcal{B}_v \in \mathcal{P}(tx_i) \cap \mathcal{C}_u\}$ ▷ All chains in the proof of tx_i according to $\mathcal{C}_u$
  $\mathsf{Collected} \leftarrow \mathsf{Collected} \cup \mathsf{chains}(i)$
#Step 3: Find the sources which has the least amount of chains to send
for all $\mathsf{Source}_n \subset \mathsf{UT}$ such that the sum amount no less than a_i **do**
  $\mathsf{Proof}_n \leftarrow$ union of all $\mathcal{P}(tx_i), tx_i \in \mathsf{Source}_n$
  $\mathsf{NChains}_n \leftarrow \{v | \mathcal{B}_v \in \mathsf{Proof}_n\}$
  $\mathsf{ToCollect}_n \leftarrow \mathsf{NChains}_n / \mathsf{Collected}$
return Source_l where $\mathsf{ToCollect}_l = \min(|\mathsf{ToCollect}_n|)$

interactive and non-interactive algorithms will result in spontaneous sharding. For a stable network with sufficient transactions been made by each node, either interactive or non-interactive schemes will have similar performance since the transaction pattern is fixed and each node should already have enough prior knowledge for the chains that each receiver has.