CompactChain: An Efficient Stateless Chain for UTXO-model Blockchain

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Abstract—In this work, we propose a stateless blockchain called CompactChain, which compacts the entire state of the UTXO (Unspent Transaction Output) based blockchain systems into two RSA accumulators. The first accumulator is called Transaction Output (TXO) commitment which represents the TXO set. The second one is called Spent Transaction Output (STXO) commitment which represents the STXO set. In this work, we discuss three algorithms - (i) To update the TXO and STXO commitments by the miner. The miner also provides the proofs for the correctness of the updated commitments; (ii) To prove the transaction’s validity by providing a membership witness in TXO commitment and non-membership witness against STXO commitment for a coin being spent by a user; (iii) To update the witness for the coin that is not yet spent; The experimental results evaluate the performance of the CompactChain in terms of time taken by a miner to update the commitments and time taken by a validator to verify the commitments and validate the transactions. We compare the performance of CompactChain with the existing state-of-art works on stateless blockchains. CompactChain shows a reduction in commitments update complexity and transaction witness size which in turn reduces the mempool size and propagation latency without compromising the system throughput (Transactions per second (TPS)).

I. INTRODUCTION

Blockchain has emerged as a decentralized and trustless technology for both cryptocurrencies and smart contract applications. An anonymous person named Satoshi Nakamoto introduced Bitcoin [1] as a Peer-to-Peer (P2P) network that records an append-only immutable ledger using cryptographic digital signatures and hash functions. Blockchain-based smart contract platforms like Ethereum [2], Hyperledger fabric [3] open the applications of blockchain in many areas like Internet-of-Things (IoT) [4], supply chain management [5], healthcare [6], agriculture [7], energy trading [8], etc.

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single element, which allows us to prove the fact that a
given element is included in the accumulator. Similarly,
the non-membership witness allows us to prove the fact
that a given element is not a part of the accumulator. The
RSA accumulator [11, 12, 27] is an accumulator based
on strong RSA assumption.

In [10], the authors propose a stateless blockchain for
UTXO-model and account-model blockchains using the
batching techniques on trapdoor-less RSA accumulator
[11, 12, 13]. In the UTXO-model framework, the block contains a commitment to the latest UTXO set
called the accumulator state or UTXO commitment. The
accumulator state is verified by the validators using
Non-Interactive Proof of Exponentiation (NI-PoE). The
users provide the membership witness for their coins
being spent in transaction payloads. The miners and
fullnodes verify the transactions by checking the mem-
bership witnesses against the latest accumulator state.
This framework uses batching techniques on RSA ac-
cumulators, namely batchDel and batchAdd to update
the commitment for every new block creation. The
batchDel operation deletes the spent coins or inputs
of the transaction from the UTXO commitment. The
batchAdd operation adds the new coins or outputs to the
UTXO commitment. However, the batchDel operation
aggregates membership witnesses for all inputs of the
block into a single membership witness using shamir-
Trick. The batchDel is a sequential iterative operation
with a complexity of $O(m^2)$. Where $m$ is the number
of transactions (assuming single input per transaction).
Moreover, it is not possible to exploit parallelism in the
computation. Since the complexity of batchDel operation
is quadratic in time, the efficiency drastically reduces
with an increase in the total number of inputs in a block.
It severely affects the transaction throughput (TPS). Also,
users need to rely on the service providers to
update their membership witnesses with every block of
transactions.

Minichain protocol proposed in [14] is a light-weight
stateless blockchain. Minichain consisting of two com-
mittments - STXO (Spent Transaction Output) com-
mitment, and TXO (Transaction Output) commitment
instead of a single UTXO commitment to avoid more
complex batchDel operation. The STXO commitment
is an RSA accumulator to all the spent coins or inputs
(called STXO set). The TXO commitment is based on
the Merkle Mountain Range (MMR) [15] to outputs
(called TXO set). The validators in Minichain also use
the NI-PoE to verify the STXO commitment. While
spending a coin, the user provides a non-membership
witness (Unspent proof) against STXO commitment and
a membership witness (Existence proof) in TXO com-
mittance. The existence proof consists of two Merkle
proofs. First, the coin inclusion proof to prove the coin
is committed to the TMR (Transaction Merkle Root) of
the block where the coin is generated. Second, the TMR
inclusion proof to prove that the TMR is committed to
the latest TXO commitment. However, the complexity of
the coin inclusion proof and TMR inclusion proof sizes
are $O(\log_2(m))$ and $O(\log_2(L))$. Where $L$ is the length
of the blockchain from the genesis block. $L$ is ever-
growing and increases network communication latency
due to the large membership proof size, which further
affects the TPS. This impact is huge in the blockchain
networks with high block creation rate.

In this work, we propose a compact stateless
blockchain for UTXO-model blockchain by compressing
the entire state of the blockchain into two RSA accu-
cumulators, one each for TXO commitment and STXO
commitment. The miner updates the commitments by
using two batchAdd operations on inputs and outputs.
The validators verify both commitments by checking
the NI-PoE proofs. The users provide transaction proof
consisting of membership witness for a coin in TXO
commitment and a non-membership witness against the
STXO commitment. The membership witness is also
an accumulator excluding the particular coin whose
membership is to be proved. Consequently, membership
proof is of constant size. The user needs to update the
membership and non-membership proofs for their coins
with every new block generation to make the proofs
compatible with the latest commitments. The validator
can efficiently verify the transaction proofs through the
RSA group operations.

The main contributions of this work are the following:

- We propose an RSA accumulator for the TXO com-
mitment for a constant sized transaction member-
ship proof in contrast to the ever-growing existence
proof size in minichain protocol.

- We implement CompactChain and compare the per-
formance with Boneh’s\(^1\) and Minichain protocols.
Comparing to Boneh, CompactChain has improved
the efficiency of commitment update from $O(m^2)$
to $O(m)$. Comparing to Minichain, the transac-
tion proof size has improved from $O(\log_2(m)) +
O(\log_2(L)) + O(1)$ to $O(1)$.

- Through simulation results, we show the perfor-
manence improvement in network communication la-
tency and TPS compared to Minichain due to re-
duced transaction proof size.

\(^1\)We use the term Boneh’s protocol for the stateless blockchain
proposed in [10].
The rest of the paper is organized as follows - We discuss the related work in section 2. Section 2 provides the preliminaries. In section 4, we present the system architecture. In section 5, we discuss the design of CompactChain protocol. Section 6 demonstrates the performance evaluation of CompactChain in comparison with Boneh’s and Minichain protocols. In section 7, we conclude our work and discuss the future directions of research.

II. RELATED WORK

The distributed coding theory techniques like erasure-codes [16] and fountain codes [17] have been proposed for storage efficiency of the blockchain node by reducing the storage cost and still contribute to bootstrap a new node joining the network. In Dynamic distributed storage system [18], the blockchain nodes are allocated into dynamic zones and the nodes in each zone store a share of private keys using Shamir's secret-sharing [19] for encrypting the block data and apply a distributed storage codes such as [20], [24] for reducing the storage cost.

A snapshot-based block pruning technique has been proposed in [21] to prune archived blocks by creating a snapshot of the state at regular intervals. A snapshot-based consensus protocol for bitcoin-like blockchains has been proposed in [22], where the miners create a block by providing a non-interactive proofs of storing a subset of the past state snapshots. However, these techniques solve the problem of storing the historical blocks.

A stateless client concept proposed in [23] for Ethereum blockchain, where full nodes only store a state root and miners broadcast witness (a set of the Merkle branches proving the data values in block) along with the block. The validators download and verify these expanded blocks. In [15], the author proposes low-latency delayed TXO commitments based on Merkle Mountain Range (MMR) for committing to the state of all transaction outputs. In order to append a new output requires fewer storage requirements (log_2(n) mountain tips). The added output could not be removed from the MMR, instead updates the status of the spent output. While spending a coin, each transaction would be accompanied by a Merkle proof consisting of a Merkle path to the tip of a tree such that the outputs being spent were still unspent.

EDRAX [25] proposes a stateless transaction validation for UTXO based blockchain using the Sparse Merkel Tree (SMT) [26]. The coin which is being spent also includes a witness of unspent. However, the witness for a transaction being spent depends on the Merkle proof of size log_2(m).

In [10], the authors proposed a stateless blockchain scheme based on the batching and aggregating techniques for the accumulators of unknown group order. In this scheme, each block contains an accumulator, which represents a commitment to the current UTXO set. This commitment is constructed by leveraging the batching techniques for membership and non-membership proofs for the set of transactions included in the block. However, the complexity of this commitment update is of O(m^2). Where m is the number of transactions (assuming single input per transaction). The efficiency in computing the commitment reduces with the increase in number of average transactions per block.

III. PRELIMINARIES

A. State of an UTXO based Blockchain

In a UTXO-model blockchain design, the state or UTXO set [9] is a collection of the Transaction Outputs (TXO) that are unspent at a particular moment of time. Whenever a new transaction is created, it consumes a subset of the current UTXO set through inputs and creates new UTXOs through outputs. A validator in a stateful blockchain needs to keep a copy of the state as a chainstate database to verify the transaction’s validity. The validators are required to update the state with a block of transactions by deleting the UTXOs associated with inputs from the UTXO set and adding new outputs to the UTXO set.

Let S_n be the state of a blockchain until block height n and \bullet represents a state transition function. When a new block B_{n+1} is created with a set of transactions included in it, then the state of the blockchain is

\[ S_{n+1} = S_n \bullet B_{n+1} = (\ldots ((S_0 \bullet B_1) \bullet B_2) \bullet \cdots \bullet B_{n+1}) \]  

(1)

B. Stateless Blockchain

In contrast to the stateful blockchain, in stateless blockchain [10, 14] a cryptographic commitment like RSA accumulator [10] to the UTXO set is stored in every block header. The validators no longer need to store the complete UTXO set in their storage to verify the transactions, instead, the witness provided by each user for their transactions are used to verify the transaction’s validity against the latest commitment to the state. Any miner update the commitment from inputs and outputs of the transactions in the block and output a proof of correctness. The miner propagate the proof to other nodes in the network.
Let $C_n$ be a commitment to the UTXO set in block $B_n$ and $\diamond$ be the commitment update function, then the new commitment for the block at height $n + 1$ is obtained as

$$C_{n+1} = C_n \diamond B_{n+1}$$

(2)

The steps to run the network in a stateless blockchain are as follows -

1) Users broadcast transactions along with corresponding witnesses to all the nodes.
2) Miners collect new transactions into the block and update the commitment concerning the commitment of the previous block. It also outputs a proof for correctness of the commitment.
3) Each miner works on finding the Proof-of-Work (PoW) for its block.
4) When a miner finds a PoW, it broadcasts the block along with the witnesses to the transactions in the block to other nodes in the network.
5) Validators accept the block only if all the transactions in it are valid based on the transaction witnesses and the proof of correctness to the commitment is verified.
6) Nodes express their acceptance of the block by working on creating the next block in the chain.
7) The owners of the unspent coins update their transaction proofs based on the newly accepted block of transactions in the chain.

**C. RSA Accumulator**

1) **Cryptographic Assumptions:** An RSA accumulator [27], [13] is a cryptographic primitive that generates a short commitment to a set of elements with efficient membership and non-membership proofs for any element of the set.

The RSA accumulator requires the generation of a group of unknown order in which strong RSA and root assumption [10] holds, and it is based on the modular exponentiation with an RSA modulus.

Let $\mathbb{G}$ be a group of unknown order, $g \in \mathbb{G}$ be a generator of the group and $N$ be an RSA modulus such that $N = pq$, where $p$ and $q$ are strong primes [28].

Let $GGen$ is an algorithm that generates the above public parameters and $\mu(\lambda)$ is a negligible function in the security parameter $\lambda$.

**Strong RSA Assumption** [10, 11, 27]: Given RSA modulus $N$ (of size $\lambda$) and a random $y \in \mathbb{Z}_N$, then it is computationally hard to find $x \in \mathbb{Z}_N$ and $l > 1$ such that $x^l \equiv y \mod N$. i.e., for all probabilistic polynomial time (PPT) adversary $A$

$$Pr \left[ x^l = y : \mathbb{G} \leftarrow GGen(\lambda), g \in \mathbb{G}; (x, l) \in \mathbb{G} \times \mathbb{Z}_N \leftarrow A(\mathbb{G}, g) \right] \leq \mu(\lambda)$$

The elements to be accumulated must be prime numbers in order to be collision-free [27] under strong RSA assumption. Let $S = \{e_1, e_2, \ldots, e_n\}$ be a set of elements to be accumulated, then the accumulator of elements of $S$ is

$$A = g^{x_1, x_2, \ldots, x_m}$$

(3)

where,

$$x_i = H_{\text{prime}}(e_i)$$

(4)

Where, $H_{\text{prime}}$ a random hash to prime function [10].

The dynamic accumulator [11] supports the addition or deletion of the elements to the accumulator.

Let $S_{\text{new}} = \{e_{m+1}, e_{m+2}, \ldots, e_n\}$ be a set of new elements to be added, then the batch addition of set $S_{\text{new}}$ update the accumulator to $A_{\text{new}} \leftarrow A^{x^*}$, where

$$x^* = x_{m+1}, x_{m+2}, \ldots, x_n.$$  

2) **Membership and Non-membership witness:** The function membership witness $w_i$ [12], batching of an element $e_i \in S$ is simply an accumulator without the element $e_i$

$$w_i = g^{\prod_{j=1, j \neq i}^{m} x_j}$$

(5)

The membership of $e_i$ in $A$ is verified by checking

$$(w_i)^{x_i} \equiv A$$

(6)

Let $e \notin S$ and $x = H_{\text{prime}}(e)$, then non-membership witness $u_x$ of $e$ in $S$ uses the fact that $\gcd(x, x^*) = \prod_{i=1}^{m} x_i = 1$. The Bezout coefficients $a$ and $b$ such that $ax + bx^* = 1$ gives the non-membership witness for $e$ is

$$u_x = (d, b) = (g^a, b)$$

(7)

The non-membership witness is verified by checking

$$d^f A^b \equiv g$$

(8)

3) **Accumulator Security (Undeniability):** The universal accumulator [12] is a dynamic accumulator with efficient update of the membership and non-membership proofs. We use the trapdoor less universal RSA accumulator [10], [29], as there is no single trusted manager exists in distributed blockchain system and updates are processed in batches.

Let generator $g \in \mathbb{G}$ and $\mu(\lambda)$ is a negligible function. The functions $\text{VerMemWit}$ and $\text{VerNonMemWit}$ verify the membership and non-membership witnesses as per the equations (6) and (8) respectively. A dynamic
universal accumulator is secure [12], [29], [10] if, for all probabilistic polynomial time (PPT) adversary $A$,
\[
P_r \left[ G \leftarrow \mathcal{G} \text{Gen}(1^k); g \in \mathcal{G}; (A, x, w, u, x) \leftarrow A(pp, g); \text{VerMemWit}(x, w, A) \land \text{VerNonMemWit}(x, u, A) \right] = \mu(\lambda)
\]

In other words, it is computationally infeasible to find both membership and non-membership proofs for an element $x \in S$. This statement is equivalent to it is computationally infeasible to find a non-membership witness for $x \in S$ or a membership witness for $x \notin S$.

4) Non-interactive proof of exponentiation (NI-PoE): Let $u, w \in \mathcal{G}$, the proof of exponentiation [10], [30] in the Group $\mathcal{G}$, when both the prover and verifier are given $(u, w, x \in \mathbb{Z})$ as inputs and prover wants to convince the verifier that $w = u^x$. Given base $u$, exponent $x$, and modulus $N$, the complexity of computing $u^x \mod N$ is $O(\log(x))$ [31]. In PoE protocol, the verifier’s work is much less than computing $u^x \mod N$, when $x \in \mathbb{Z}$ is much larger than $|\mathcal{G}|$. The PoE can be made non-interactive using the Fiat-Shamir heuristic [32].

**NI-PoE [10]**

\begin{verbatim}
Public known \{x, u, w : u^x = w\}

# Prove NI-PoE
1: \textbf{procedure} ProveNI-PoE(x, u, w)
2: \hspace{1cm} l \leftarrow H_{\text{prime}}(x, u, w)
3: \hspace{1cm} q \leftarrow \lceil \frac{1}{l} \rceil
4: \hspace{1cm} \text{return } Q \leftarrow u^q
5: \textbf{end procedure}

# Verify NI-PoE
1: \textbf{procedure} VerifyNI-PoE(x, u, w, Q)
2: \hspace{1cm} l \leftarrow H_{\text{prime}}(x, u, w)
3: \hspace{1cm} r \leftarrow x \mod l
4: \hspace{1cm} Q^r u^r = w
5: \textbf{end procedure}
\end{verbatim}

**IV. System Architecture**

We propose a stateless blockchain that is closely built on Boneh’s work [10] and Minichain [14]. The parameters used in our framework are listed in Table I. We stick to Minichain’s model with two commitments for TXO set and STXO set and address the following limitations of the Minichain protocol.

First, the size of a transaction witness consisting of existence and unspent proofs for a coin being spent depends on the length of the blockchain $L$ and the maximum number of transactions $m$ in the block with a complexity of $O(\log_2(m)) + O(\log_2(L)) + O(1)$. The length of the chain $L$ is ever-growing, and if a coin is not spent for a sufficiently long duration, then the size of the witness is very large. Second, the information being propagated in the network consists of a block and witnesses for transactions associated with that block. Since the witness size depends on $L$, it affects the end-to-end propagation latency of a block and limits the TPS.

In this work, we propose the RSA accumulator for TXO commitment to address the above limitations. The architecture of the proposed stateless blockchain is shown in Fig. 1, 2.

**TXO Commitment:** To reduce the size of the existence proof of a coin in the Minichain protocol and further to improve the efficiency of the network communication, we propose replacing MMR-based TXO commitment with an RSA accumulator. We use batch addition to update the TXO commitment in every block by adding a set of new outputs in $T_n$ of the block $B_n$ to the TXO

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**TABLE I**

| Symbols      | Description                                      |
|--------------|--------------------------------------------------|
| $B_n$        | Block at height $n                               |
| $T_n$        | Set of all transactions in $B_n$                 |
| TXO set      | Set of all transaction outputs                   |
| STXO set     | Set of all spent transaction outputs             |
| $TXO_n$      | Transaction outputs (TXOs) in $B_n$              |
| $STXO_n$     | Spent Transaction outputs (STXOs) in $B_n$       |
| $TXOk_n$     | All TXOs from block $B_k$ to block $B_n$        |
| $STXOk_n$    | All STXOs from block $B_k$ to block $B_n$       |
| $TXO_C_n$    | Commitment to $TXO$ set in block $B_n$          |
| $STXO_C_n$   | Commitment to $STXO$ set in block $B_n$         |
| $\Pi_{TXO}$  | NI-PoE proof for $TXO_C_n$                      |
| $\Pi_{STXO}$ | NI-PoE proof for $STXO_C_n$                     |
| $u_n(x)$     | Membership witness to prove $x \in TXO$ set     |
| $u_n(x)$     | Non-membership witness to prove $x \notin STXO$ set |

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**Fig. 1.** Block header composition mainly contains two RSA accumulators - $TXO_C$ (TXO commitment) and $STXO_C$ (STXO commitment)
Fig. 2. Block validation procedure

commitment in the previous block. When a user wants to spend a coin, he provides a membership witness that specifies the coin included in the TXO commitment. The witness is a single RSA group element, which can be verified using single modular exponentiation.

**STXO Commitment**: The STXO commitment is also an RSA accumulator to represent the STXO set in the block header. The user provides a non-membership witness against the latest STXO commitment to prove that the coin is not yet spent. When a new block is created in the network, the user who did not spend the coin updates the non-membership witness using spent coins in the block.

**STXO cache and Witness height**: When the commitments of the blockchain changes before processing a transaction, the user needs to update the membership and non-membership proofs of the coin being spent, which is very unfriendly to the users. We use the STXO cache introduced by Minichain, which contains the STXOs of the latest \( M \) blocks. The validator can still verify the non-membership proof is valid by simply querying the STXO cache without updating the proof to the latest STXO commitment by the user.

We introduce the Witness height \( (h) \) to specify the height of the block till where the membership and non-membership proofs got updated so that the user need not update and resubmit the proofs with every new block creation (or change of the state) after submission of the transaction. While submitting proofs for a coin being spent user provides the witness height \( h \). The validator can verify the membership and non-membership proofs against the TXO and STXO commitments of the block at a height equal to \( h \) such that \( (n - M) \leq h \leq n \). Where \( n \) is the latest block height, and \( M \) represents the length of the STXO cache.

V. COMPACTCHAIN DESIGN

In this section, we discuss the design of the CompactChain protocol - TXO commitment, STXO commitment, witness height, STXO cache, update commitments, transaction witness generation and verification and, finally, update witness. Let \( \lambda \) be a security parameter and \( TXO\_C_n \) and \( STXO\_C_n \) commitments to TXO and STXO sets in \( n^{th} \) block. The tuple \( (w_n(x), u_n(x)) \) denotes the membership and non-membership proofs of a coin \( x \) in TXO and STXO sets computed/updated till the block at height \( n \). For brevity, we have omitted mod \( N \) from every modular exponentiation operation in the RSA group with modulus \( N \).
A. Update TXO and STXO Commitments
The block header in the proposed protocol contains two RSA accumulators called $TXO_C$ and $STXO_C$ to accumulate TXO and STXO sets. The RSA accumulator is cumulative. Thereby, the miner updates the commitments for every block using the commitments from the previous block. The functions to update TXO and STXO commitments are described in Algorithm 1.

The commitments update algorithm takes inputs, and outputs of a block are input parameters. It returns updated commitments and proof of correctness for the updated commitments using the RSA accumulator’s batching techniques. For instance, $TXO_{C,n-1}$ and $STXO_{C,n-1}$ are the latest commitments to TXO and STXO sets. While generating a new block $B_n$, the miner computes the new accumulators $TXO_{C,n}$ and $STXO_{C,n}$. Firstly, the $UpdateTXO_C$ function takes the TXOs (outputs of all transactions) from $T_n$ and calculate the prime representatives of each output in TXOs using $H_{\text{prime}}$ function and computes the product of all prime representatives denoted as $p$. Finally, the modular exponentiation of base $TXO_{C,n-1}$ with exponent $p$ updates the TXO commitment to $TXO_{C,n}$. Similarly, the $UpdateSTXO_C$ function takes the STXOs (inputs) from $T_n$ as input and update the STXO commitment to $STXO_{C,n}$.

The miner also generates NI-PoE proofs $\Pi_{TXO}$ and $\Pi_{STXO}$ for both accumulators using the $ProveNI-PoE$ function to show that the commitments are updated correctly. The validators need not compute the updated commitments, instead, they can verify the proofs generated by miner using $VerifyComm$ function. The products calculated in the $VerifyComm$ function are much larger, and recalculating the updated commitments is inefficient to the validator. So, the $VerifyNI-PoE$ function used in the $VerifyComm$ improves the verification efficiency of the validator.

B. Transaction witness Generation & Verification
The TXO commitment combines all the generated coins (outputs) and, the STXO commitment combines all the spent coins (inputs). While spending a coin, the user submits a proof along with the transaction to show the validity of the coin. The transaction proof consisting of two parts - First, the proof for the coin’s existence in TXO set and the unspent proof for the non-existence of the coin in the STXO set.

The existence proof indicates the coin is generated some time before and is a part of the TXO set represented by TXO commitment. Similarly, the unspent proof indicates the coin is not yet spent such that

### Algorithm 1 Commitments Update Algorithm

```
# System Initialization
1: procedure Setup(\lambda)
2: \ G \leftarrow GGEN(\lambda)
3: g \leftarrow G
4: TXO_C_0 \leftarrow g
5: STXO_C_0 \leftarrow g
6: return TXO_C_0, STXO_C_0
7: end procedure

# Update TXO_C function
1: procedure UpdateTXO_C(TXO_C_{n-1}, T_n)
2: p = 1
3: for output in $T_n$.Outputs do
4: \ p \leftarrow H_{\text{prime}}(output)
5: end for
6: TXO_C_n \leftarrow (TXO_C_{n-1})^p
7: \Pi_{TXO} \leftarrow ProveNI-PoE(TXO_C_{n-1}, p, TXO_C_n)
8: return TXO_C_n, \Pi_{TXO}
9: end procedure

# Update STXO_C function
1: procedure UpdateSTXO_C(STXO_C_{n-1}, T_n)
2: p = 1
3: for input in $T_n$.Inputs do
4: \ p \leftarrow H_{\text{prime}}(input)
5: end for
6: STXO_C_n \leftarrow (STXO_C_{n-1})^p
7: \Pi_{STXO} \leftarrow ProveNI-PoE(STXO_C_{n-1}, p, STXO_C_n)
8: return STXO_C_n, \Pi_{STXO}
9: end procedure

# Verify updated commitments
1: procedure VerifyCom($T_n$, TXO_C_{n-1}, STXO_C_{n-1}, TXO_C_n, STXO_C_n, \Pi_{TXO}, \Pi_{STXO})
2: p_1 = 1, p_2 = 1
3: for output, input in $T_n$ do
4: \ p_1 \leftarrow H_{\text{prime}}(output)
5: \ p_2 \leftarrow H_{\text{prime}}(input)
6: end for
7: b_1 \leftarrow VerifyNI-PoE(TXO_C_{n-1}, p_1, TXO_C_n, \Pi_{TXO})
8: b_2 \leftarrow VerifyNI-PoE(STXO_C_{n-1}, p_2, STXO_C_n, \Pi_{STXO})
9: return $b_1 \land b_2$
10: end procedure
```
it is not a member of the STXO set represented by STXO commitment. In other words, the user needs to generate membership proof corresponding to the latest TXO commitment and non-membership proof against the latest STXO commitment. We stick to a procedure that a user generates transaction witness using the TXOs and STXOs of the block where the coin is generated and apply subsequent witness update for every new block of transactions.

1) Existence Proof (Membership witness in TXO set): The existence proof of a coin in the TXO set is a membership witness corresponding to the latest TXO commitment. The user generates the proof using the CreateMemWit function and the validator verify it using the VerifyMemWit function as shown in Algorithm 2.

CreateMemWit function: Suppose a coin \( x_k \) is generated at block \( B_k \), then \( x_k \in TXO set \) and accumulated to \( TXO \_C_k \). The user constructs the membership witness \( w_k(x_k) \) for \( x_k \in TXO set \) as follows - Firstly, the function collects all the TXOs from \( TXO_k \) excluding \( x_k \) and computes their prime representatives. Then, it computes the product of all these prime representatives, denoted as \( p \). Finally, the modular exponentiation of the base \( TXO \_C \_k \) with exponent \( p \) generates the witness \( w_k(x_k) \).

VerifyMemWit function: Suppose \( w_k(x_k) \) is a membership witness of the coin \( x_k \in TXO set \). Any validator verifies the membership witness by checking \((w_k(x_k))^t \equiv TXO \_C_k \), where \( t = H_{\text{prime}}(x_k) \).

2) Unspent proof (Non-membership witness in STXO set): The unspent proof of a coin is a non-membership witness corresponding to the latest STXO commitment. The functions CreateNonMemWit and NonMemWitVerify are used to generate and verify proof for a new coin, as shown in Algorithm 2.

CreateNonMemWit function: Suppose a coin \( x_k \) is generated at block \( B_k \) and \( x_k \notin STXO set \), the user constructs a non-membership witness \( u_k(x_k) \) of \( x_k \) corresponding to \( STXO \_C_k \) as follows. The function collects all the STXOs from \( STXO_k \) and computes their prime representatives. Then, it calculates the product of all these prime representatives denoted as \( p \). Since \( gcd(t,p) = 1 \), where \( t = H_{\text{prime}}(x_k) \) the unspent proof \( u_k(x_k) = (d = (STXO \_C \_k)^{-1}) \), where \( a \) and \( b \) are Bezout’s coefficients of \( t \) and \( p \) such that \( at + bp = 1 \).

VerifyNonMemWit function: Suppose \( u_k(x_k) \) is a non-membership witness of \( x_k \notin STXO set \) computed by a user with the STXO set till block \( B_k \). Any validator can verify it by checking \( d^t (STXO \_C_k) = (STXO \_C_k)^{at} (STXO \_C_k)^{bp} = STXO \_C_k \).

C. Transaction Witness Update

When a user wants to spend a coin, he must submit existence and unspent proofs to show the coin’s validity. The submitted proofs might expire due to a delay in network communication, or the miners did not process the transaction in the latest created blocks. In order to bound proofs with the latest commitments, the user must update and resubmit the transaction and witness until the transaction is processed. To address this problem, we require two essential tools. First, the user needs to specify the height of the block \( h \) called witness height, where the proofs and commitments are bounded together. The validator checks the membership and non-membership proofs corresponding to \( TXO \_C_h \) and \( STXO \_C_h \). Second, each validator needs to store the STXOs of the latest \( M \) blocks (STXO cache) in their database to process the transaction in the subsequent \( M \) blocks. If the latest block height is greater than \( h \), the validator checks that the transaction inputs are consumed in the future blocks by simply querying the STXO cache to avoid the double spending of the coin. The most recent witness updated coins can be further updated by the users themselves using the UpMemWit and UpNonMemWit functions as shown in Algorithm 3. The witness update is independent of the size of the sets \( TXO set \) and \( STXO set \), which makes a user no need to store the TXO and STXO sets with them.

UpMemWit function: Let \( w_n(x_k) \) be the membership witness of the coin \( x_k \) generated in block \( B_k \). The user can update till \( B_n (n > k) \) using UpdateMemWit. Firstly, the function gets all the TXOs from block height \( k+1 \) to \( n \), denoted as \( TXO_{k+1:n} \) and converts them to prime representatives. Then, it computes the product \( p \) of all these prime representatives and returns \( w_n(x_k) \) using a single modular exponentiation. To verify the updated witness, one check that \((w_n(x_k))^t \equiv TXO \_C_n \) (Where, \( t = H_{\text{prime}}(x_k) \)), which holds as 

\[
(w_n(x_k))^t = (w_k(x_k))^d = (TXO \_C_k)^d = TXO \_C_n
\]

UpNonMemWit function: Let \( u_k(x_k) = (d,b) \) be non-membership witness of the coin \( x_k \) generated in block \( B_k \). The user can update till \( B_n (n > k) \) using UpdateNonMemWit. Firstly, the function gets all the STXOs from block height \( k+1 \) to \( n \) and convert them to prime representatives. Then, it calculates the product of all these prime representatives,
Algorithm 2 Witness Generation and Verification Algorithm

#Prove membership in TXO_C_k for x_k generated in B_k
1: procedure CreateMemWit(x_k, TXO_k, TXO_C_{k−1})
2: for txo in TXO_k do
3: if txo ≠ x_k then
4: p* = H_{prime}(txo)
5: end if
6: end for
7: return w_k(x_k)
8: end procedure

#Verify Membership Witness for x_k generated in B_k
1: procedure VerifyMemWit(w_k(x_k), x_k, TXO_C_k)
2: t ← H_{prime}(x_k)
3: b ← ((w_k(x_k))^t == TXO_C_k)
4: return b
5: end procedure

Algorithm 3 Witness Update Algorithm

#Prove non-membership against STXO_C_k for x_k generated in B_k
1: procedure CreateNonMemWit(x_k, STXO_k, STXO_C_{k−1})
2: for stxo in STXO_k do
3: p* = H_{prime}(stxo)
4: end for
5: a, b ← Bezout(H_{prime}(x_k), p)
6: d ← (STXO_C_{k−1})^a
7: return u_k(x_k) ← (d, b)
8: end procedure

#Verify Non-Membership Witness u_k(x_k) for x_k generated in B_k
1: procedure VerifyNonMemWit(STXO_C_k, STXO_C_{k−1}, x_k, u_k(x_k))
2: t ← H_{prime}(x_k) and d, b ← u_k(x_k)
3: return (d^t (STXO_C_k)^b == STXO_C_{k−1})
4: end procedure

#Update membership proof from block k to n
1: procedure UpMemWit(x_k, w_k(x_k), TXO_k+1:n)
2: for txo in TXO_k+1:n do
3: p* = H_{prime}(txo)
4: end for
5: return w_n(x_k) ← (w_k(x_k))^p
6: end procedure

#Update non-membership proof from block k to n
1: procedure UpNonMemWit(x_k, u_k(x_k), STXO_k+1:n)
2: for stxo in STXO_k+1:n do
3: p* = H_{prime}(stxo)
4: end for
5: a_0, b_0 ← Bezout(H_{prime}(x_k), p)
6: r ← a_0b_0, d ← d (STXO_C_k)^r
7: return u_n(x_k) ← (d^t, b_0b)
8: end procedure

denoted as p. It calculates Bezout coefficients of \( t = H_{\text{prime}}(x_k) \) and \( p \) as \( a_0 \) and \( b_0 \). Finally, the updated non-membership witness \( u_n(x_k) = (d^t, b^t) \). To verify it, one check that, \( d^t (STXO_C_m)^b = STXO_C_{k−1} \), which holds as,

\[
D = (STXO_C_m)^b = (STXO_C_k)^{rt} (STXO_C_{m})^{b_0b} = (STXO_C_k)^{a_0b_0t} (STXO_C_{k})^{b_0b_0p} = (STXO_C_k)^{b(a_0t+b_0p)} = (STXO_C_k)^b = STXO_C_{k−1}
\]

D. Security Analysis

In this section we describe the attacker model for double-spend attack of a transaction and analyse the security of the CompactChain against this attack.

1) Attacker Model: We describe the two attacker models on CompactChain construction as follows -

1) Double-spend attack: Let a coin \( x \) is generated in block \( B_i \) as an output of one of the transactions in \( B_i \), i.e., \( x \in T_i.\text{Outputs} \). \( x \) is odd prime. Now, the coin \( x \in TXO \text{ set} \) and \( x \notin STXO \text{ set} \).

The owner of the coin \( x \) computes the transaction witness \( W_x = (w_i(x), u_i(x)) \) for \( x \) from \( TXO_i \) and \( STXO_i \) using Algorithm 2. Let the updated witness after the creation of the block \( B_n \) is \( W'_x = (w_n(x), u_n(x)) \). When the user wants to spend the coin \( x \) in transaction \( tx \) with \( x \) as one of the inputs in \( tx \), he submits \( W'_x \) along with \( tx \). Let \( n < h < n + M \) such that \( tx \in B_h \).

Since \( x \in STXO_h \), then \( x \in STXO \text{ set} \). i.e., the coin has been spent in block \( B_h \). Suppose, a probabilistic polynomial time (PPT) adversary \( A_1 \)
Theoretical Comparisons

In this section, we test the performance of CompactChain protocol by comparing it with Boneh’s [10] and Minichain\(^2\) [14] protocols. We test the performance of commitments update by miners, transaction witness generation, updation by users. We also test the verification of the NI-PoE proofs for commitments, and transaction witnesses by validators. We also examine the proof size and test performance of the propagation latency of a block in association with transaction throughput. The results shown are averaged over 10 iterations. We have implemented our experiments based on the implementation of [33] in C++. We use the RSA modulus of 3072-bits, 128-bit prime representative and 256-bit Merkle root. We run all our experiments for miner, validator, and user tasks on a machine equipped with Intel(R) Core(TM) i5 – 8250U CPU @ 1.60 GHz processor and 8 GB of RAM. Our experiments are available at [43].

A. Theoretical Comparisons

We discuss the theoretical comparison of CompactChain with Boneh’s and Minichain protocols. The comparisons are shown in Table II. All these algorithms depend on the number of coins generated \(k\) (outputs), the number of coins consumed \(d\) (inputs), and the number of transactions \(m\) in the block.

B. Commitments update and verification

In this section, we test the performance of Commitment update and verification discussed in Algorithm 1 and compare with the accumulator updates in Boneh’s and Minichain protocols. While creating a new block, the miner must update the commitments due to new TXOs and STXOs.

Fig. 3 shows the comparison of the time consumed for updating the commitments in Boneh’s work, Minichain and CompactChain concerning the number of transactions \(m\) (we are assuming \(k = d\)). Boneh’s accumulator update consumes much larger time than Minichain and CompactChain due to the \(O(m^2)\) complexity of the \(batchDel\) operation used for accumulator update. For 1000 transactions, Boneh’s accumulator update consumes \(\approx 240\) seconds, whereas Minichain and CompactChain took \(\approx 1\) second. The Minichain requires one \(batchAdd\) operation for \(d\) number of spent coins for updating \(STXO_C\). Minichain also updates \(TXO_C\) by adding a new \(TMR\) in MMR tree.

\(^2\)Minichain\(^+\) in [14] is considered as Minichain.
In the CompactChain, two $\text{batchAdd}$ operations are required, one for $\text{STXO}_C$ ($d$ number of spent coins) and $\text{TXO}_C$ ($k$ number of generated coins) updates. The $\text{batchAdd}$ depends on the generation of prime representatives for each element to be accumulated. While creating a new block, $d$ new elements add to $\text{STXO}_C$, and $k$ elements add to $\text{TXO}_C$.

To improve the efficiency of our implementation, we performed computation of prime representatives in parallel as each element is independent of others. Then the computation of updating the commitments $\text{TXO}_C$ and $\text{STXO}_C$ are performed in parallel as the set of elements to be added to each commitment are independent. We also exploited parallelism in implementing the Minichain. The slight bias in time taken for commitments update between CompactChain and Minichain is due to additional computation time for calculating prime representatives of $k$ elements added to $\text{TXO}_C$.

In both Minichain and CompactChain, the time to update the commitments increases linearly with the transaction count. Fig. 4 shows the time taken by a validator for verifying the commitments updates in Boneh’s work, Minichain and CompactChain. The verification depends on the computation of the prime representatives and the product of the prime representatives. In Minichain, the validator needs to verify a NI-PoE proof for one RSA accumulator, and Merkle proof for MMR peaks update. Whereas Boneh’s work and CompactChain validator verify two NI-PoE proofs.

The validator verifies each NI-PoE proof independently with a constant number of group operations. We have exploited parallelism in commitments verification similar to commitments update. The verification time increases with an increase in transaction count shown Fig. 4.

C. Transaction Witness generation and verification

The validator needs to verify the existence and unspent proofs of a transaction in both Minichain and CompactChain. The unspent proof is the same in both, but the existence proof is different in size and structure. In Minichain, the validator needs to verify two Merkle proofs - transaction inclusion proof in TMR, and TMR inclusion proof in the latest TXO commitment. We assume the length of the chain $L = 2^{20}$ and $m = 2^{10}$. In CompactChain, the existence proof is an RSA group element, and the validator verifies it by single modular exponentiation. In Boneh’s protocol, the validator verifies a single unspent proof (membership in
the UTXO commitment) of the transaction’s input in the latest commitment.

Table III shows the comparison of the proof size and verification time. The results show that the proof size of the CompactChain has decreased compared with Minichain for the \( m \) and \( L \) values as mentioned earlier. Since the existence and unspent proofs are independent, the proof verification is performed in parallel.

D. Transaction witness update

In CompactChain, the existence and unspent proofs change with commitments as new blocks are created in the network. We assume that the number of inputs and outputs are equal and, Fig. 5 shows that the transaction witness update time for Boneh’s, Minichain and CompactChain. In Minichain, the time taken for existence proof update is negligible. Boneh’s witness update requires two sequential events for batch deletion of inputs from the witness, then batch addition of outputs to the witness. In CompactChain, we implemented a witness update similar to the commitments update by exploiting the parallelism. The time taken by a user to update the witness increases linearly with the transaction count in all three protocols.

E. Memory Consumption

We compare the memory consumption of existing stateless blockchains against Bitcoin. Comparison is analyzed on three aspects (i) RAM Usage, (ii) Disk Usage, and (iii) Memorypool Usage. The comparison was performed on real-time data of Bitcoin from Jan 2017 to Jan 2022. RAM Usage, considers memory usage while storing stxo-cache in the case of CompactChain and MiniChain, and whereas Bitcoin requires the whole UTXO-set. Since Boneh has no cache mechanism we consider only current block. Fig. 6 shows the RAM usage from 2017 to 2022. Bitcoin consumes the highest memory, 19GB due to the ever-growing UTXO set size. CompactChain consumes 170.61 MB of RAM. MiniChain consumes 0.05 MB lesser than CompactChain because CompactChain’s TXO commitment is 356 bytes larger than MiniChain’s. Boneh consumes the least space due to the lack of caching mechanism, however, underpinned by commitment update speeds. Stateless blockchains can be practically realizable on resource constraint IoT devices as validators due to their low RAM usage. Disk Usage, considers the size required to store the whole blockchain. Fig. 7 shows the disk usage, as expected Bitcoin consumes the highest because one has to store entire blocks of the blockchain. In contrast, stateless blockchains need to store only block headers, therefore consuming very less space. As pointed out earlier, CompactChain consumes slightly higher header space than MiniChain. Nevertheless, CompactChain consumes 573 MB only which enables edge devices to act as Validators.
### Table III
Comparison of Transaction witness size (in bytes) [verification time (in seconds)]

|                | Existence proof (per Tx) | Unspent proof (per Tx) | Verification time per Tx (parallel execution) | Verification time for 1000 Txs (Parallel execution with 16 threads) |
|----------------|--------------------------|------------------------|-----------------------------------------------|-------------------------------------------------------------------|
| Boneh          | –                        | 384 [0.00067]          | 0.00067 s                                     | 0.193 s                                                           |
| Minichain      | 960 [0.00025]            | 400 [0.0011]           | 0.00117 s                                     | 0.306 s                                                           |
| CompactChain   | 384 [0.00056]            | 400 [0.0010]           | 0.00115 s                                     | 0.303 s                                                           |

### Table IV
Comparison of Maximum TPS

|                                | Boneh | Minichain | CompactChain |
|--------------------------------|-------|-----------|--------------|
| Tx Verification latency (in sec) (for 500 Txs) [Max TPS] | 0.193 [2590.67] | 0.306 [1634] | 0.303 [1650] |
| Commitments Update latency (in sec) [Max TPS]            | 235.62 [2.12] | 0.97 [515.46] | 0.99 [505] |
| Consensus latency (in sec) [Max TPS]                      | 2.08 [240.38] | 3.57 [140]  | 3.03 [165]  |
| Maximum TPS                                               | 2.12  | 140       | 165          |

---

**Fig. 8. Comparison of Memorypool Usage**

Memory Pool or Mempool\(^3\) Usage considers the size of unconfirmed transactions received and corresponding proofs (if any). A validator in the stateless blockchain need to store the proofs for transactions of the Mempool, whereas Bitcoin does not. Fig. 8 indicates that Bitcoin least space, however, MiniChain consumes enormously high space due to large MMR proofs compared to constant sized Non-Membership witness of CompactChain. Boneh’s implementation has only single proof thereby consuming least space among stateless-blockchains.

\(^3\)Mempool is a database which consists of the valid unconfirmed transactions in the network. A high Mempool size indicates more network traffic which will result in longer average confirmation time and higher priority fees. While creating a new block miner or block producer pick the transactions from Mempool.

**Fig. 9. Performance of propagation latency of a block in the network**

Simulations [40, 41, 42] for propagation latency. We choose a total of 13000 [35] nodes with 10 miners having hash rate distribution [38] as per in the bitcoin network. We choose the average upload bandwidth of the nodes as 50 Mbps [37].

We assume the average size of a transaction (with single input and single output) as 250 bytes with a total block size of 0.25 MB (1000 transactions). We use the total block validation time of a validator from Fig. 4 (commitments verification time) and Table III (transactions verification time). The information to be propagated in the network also consists of the transaction proof with sizes as listed in Table III. Fig. 9 shows the total information propagation from the first observation of a block at the miner to reach all nodes in the network.

In Bitcoin [1], the consensus is defined in probabilistic terms and a block is valid if at least 50 percent of the
nodes receive it. So, consensus latency is defined as time to reach a block to 50 percent of the nodes in the network. In Fig. 9, the dots in red colour indicate the consensus latency in each protocol.

G. Maximum TPS

We test the maximum TPS of the system by considering the performances of transaction verification, commitment updates, and consensus latency. We assume each block with 500 transactions, and each transaction consists of two inputs and two outputs. Table IV shows the comparison of maximum TPS in all three frameworks. The results show that the maximum TPS in Boneh’s work is restricted to 2.12 TPS due to the complex commitment update. Although having two RSA accumulators CompactChain has improved maximum TPS over Minichain due to a reduction in the size of the information to be propagated in the network.

VII. CONCLUSIONS AND FUTURE RESEARCH

(i) Summary of research and conclusion - In this paper, we propose a stateless UTXO-model blockchain called compactChain, where the state of the blockchain is comprised of two commitments similar to Minichain. We introduce the RSA accumulator-based TXO commitment, in contrast to the MMR-based TXO commitment in Minichain. We analyze the security of the system based on the strong RSA assumption.

(ii) Comparison with Boneh’s work and Minichain- the theoretical and experimental results show the improvement in the time complexity of the commitment update from $O(m^2)$ to $O(m)$ compare with Boneh’s stateless blockchain. The CompactChain reduce the transaction proof size from $O(\log(m)) + O(\log(L)) + O(1)$ to $O(1)$ compare with Minichain without compromising the system throughput.

(iii) Practical implications - CompactChain allows resource constraint devices to become validators due to marginal RAM usage, disk space and less memory pool size, retaining the decentralization property of the blockchain.

(iv) Paper limitations and future work - The future work will focus on an alternate consensus algorithm to the PoW, which is based on the proof of commitments (PoC) by using the number of transactions as a difficulty level. Sharding technology divides a whole Blockchain network into multiple groups and allows participating nodes to process and store the disjoint set of transactions. For securing the sharded-blockchains, the participating nodes should be reshuffled randomly among the shards, making a node download the state of the newly allocated shard. We focus on integrating the CompactChain with sharded technology to avoid downloading a state for every reshuffle that improves startup time.

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