RePoPoW: A Gas-Efficient Superlight Bitcoin Client in Solidity

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ABSTRACT

Superlight clients enable the verification of proof-of-work-based blockchains by checking only a small representative number of block headers instead of all the block headers as done in SPV. Such clients can be embedded within other blockchains by implementing them as smart contracts, allowing for cross-chain verification. One such interesting instance is the consumption of Bitcoin data within Ethereum by implementing a Bitcoin superlight client in Solidity. While such theoretical constructions have demonstrated security and efficiency, no practical implementation exists. In this work, we put forth the first practical Solidity implementation of a superlight client which implements the NIPoPoW superblocks protocol. Contrary to previous work, our Solidity smart contract achieves sufficient gas-efficiency to allow a proof and counter-proof to fit within the gas limit of a block, making it practical. We provide extensive experimental measurements for gas. The optimizations that enable gas-efficiency heavily leverage a novel technique which we term hash-and-resubmit, which almost completely eliminates persistent storage requirements, the most expensive operation of smart contracts in terms of gas. Instead, the contract asks contesters to resubmit data and checks their veracity by hashing it. We show that such techniques can be used to bring down gas costs significantly and may have applications to other contracts. We also identify and rectify multiple implementation security issues of previous work such as premining vulnerabilities. Lastly, our implementation allows us to calculate concrete cryptoeconomic parameters for the superblocks NIPoPoWs protocol and in particular to make recommendations about the monetary value of the collateral parameters. We provide such parameter recommendations over a variety of liveness and adversarial bound settings.

KEYWORDS

Blockchain; Superlight clients; NIPoPoWs, Solidity

1 INTRODUCTION

Blockchain interoperability [23] is the ability of distinct blockchains to communicate. This *crosschain* [10, 12, 13, 16, 22] communication enables useful features across blockchains such as the transfer of asset from one chain to another (one-way peg) and back (one-way peg) [16]. To date, there is no commonly accepted decentralized protocol that enables crosschain transactions. Currently, crosschain operations are only available to the users via third-party applications, such as multi-currency wallets. However, this treatment is opposing to the nature of decentralized currencies.

In general, crosschain-enabled blockchains A, B support the following operations:

- Crosschain trading: A user with deposits in blockchain A, makes a payment to a user in blockchain B.
- Crosschain fund transfer: A user transfers her funds from blockchain A to blockchain B. After the transfer, these funds no longer exist in blockchain A. The user can later decide to transfer any portion of the original amount to the blockchain of origin.

In order to perform crosschain operations, there must be a mechanism to allow for users of blockchain A to discover events that occur in chain B, such that a transaction occurred. A trivial manner to perform such an audit is to participate as a full node in multiple chains. This approach, however, is impractical because a sizeable amount of storage is needed to host entire chains as they grow with time. As of July 2020, Bitcoin [18] chain spans roughly 245 GB, and Ethereum [3, 20] has exceeded 350 GB[1]. Naturally, not all users are able to accommodate this size of data, especially if portable devices are used, such as mobile phones.

One early solution to compress the extensive size of blockchain is addressed by Nakamoto [18] with the Simplified Payment Verification (SPV) protocol. In SPV, only the headers of blocks are stored, saving a considerable amount of storage. However, even with this protocol, the process of downloading and validating all block headers leads to unpleasant user experience. In Ethereum, for instance, headers sum up to approximately 5.1 GB[2] of data. A mobile client needs several minutes, even hours, to fetch all information needed in order to function as an SPV client.

Towards the goal of delivering more practical solutions for blockchain transaction verification, a new generation of *superlight* clients [2, 11, 14, 15] emerged. In these protocols, cryptographic proofs are generated, that prove the occurrence of events inside a blockchain. Better performance is achieved due to the considerably smaller size of proofs compared to the amount of data needed in SPV. By utilizing superlight client protocols, a compressed proof for an event in chain A is constructed and dispatched to chain B. Under the condition that chain B supports smart contracts, the proof is then verified automatically and transparently *on-chain*. This communication is realized without the intervention of third-party applications. An interesting application of such a protocol is the communication between Bitcoin and Ethereum.

[1] The size of the Bitcoin chain was derived from https://www.statista.com/statistics/647523/worldwide-bitcoin-blockchain-size/, and the size of the Ethereum chain by https://etherscan.io/chartsync/chaindefaults

[2] Calculated as the number of blocks (10,050,219) times the size of header (508 bytes). Statistics by https://etherscan.io/

Related Work. We use Non-Interactive Proofs of Proof of Work (NIPoPoWs) [15, 16] as the fundamental building block of our solution. This cryptographic primitive is *provably secure* and provides *succinct proofs* regarding the existence of an arbitrary event in a chain. Contrary to the linear growth rate of the underlying blockchain, NIPoPoWs span polylogarithmic size of blocks.

Christoglou [7] provided a Solidity smart contract which is the first implementation of crosschain events verification based on NIPoPoWs, where proofs are submitted and checked for their validity. This solution, however, is impractical due to extensive usage of resources, widely exceeding the Ethereum block gas limit.

Other attempts have been done to address the verification of Bitcoin transactions to the Ethereum blockchain, most notably BTC Relay [6].

Our contribution. Notably, no practical implementation for superlight clients exists to date. In this paper, we focus on constructing a practical client for NIPoPoWs. For the implementation of our client, we refine the NIPoPoW protocol based on a series of keen observations. These refinements allow us to leverage useful techniques that construct a practical solution for proof verification. We believe that this achievement is a decisive step towards the establishment of NIPoPoWs to the application end, therefore it is a significant progress in order to provide a widely accepted protocol that enables crosschain transactions. A summary of our contributions in this paper is as follows:

(1) We developed the first decentralized client that securely verifies crosschain events and is practical. Our client establishes a trustless and efficient solution to the interoperability problem. We implement our client in Solidity, and we verify Bitcoin events to the Ethereum blockchain. The security assumptions we make are no others than SPV [9, 21].
(2) We present a novel pattern which we term *hash-and-resubmit*. Our pattern significantly improves performance of Ethereum smart contracts [3, 20] in terms of gas consumption by utilizing *calldata* space of Ethereum blockchain to eliminate high-cost storage operations.
(3) We design an *optimistic* schema which we incorporate in the design of our client, that replaces *non-optimistic* operations. This design achieves the improvement of smart contracts' performance by enabling multiple phases of interactions.
(4) We demonstrate via application that the NIPoPoW protocol is practical, making the cryptographic primitive the first provably secure construction of succinct proofs that is efficient to implement.
(5) Cryptoeconomics. Create the section first.

Our implementation meets the following requirements:

(1) Security: The client implements a provably secure protocol.
(2) Decentralization: The client is not dependent on third-party applications and operates in a transparent, decentralized manner.
(3) Efficiency: The client comply with all environmental constraints, i.e. block gas limit and calldata size limit of Ethereum blockchain.

We selected Bitcoin as source blockchain as it the most used cryptocurrency, and enabling crosschain transactions in Bitcoin is beneficial to the vast majority of blockchain community. We selected Ethereum as the target blockchain because, besides its popularity, it supports smart contracts, which is a requirement in order to perform on-chain verification.

Structure. In Section 2 we describe the blockchain technologies that are relevant to our work. In Section 3 we put forth the *hash-and-resubmit* pattern. We demonstrate the improved performance of smart contracts using the pattern, and how it is incorporated in our superlight client. In Section 4 we show ... and. Finally, in Section 5, we discuss ...

2 PRELIMINARIES

3 THE HASH-AND-RESUBMIT PATTERN

We now introduce a novel design pattern for Solidity smart contracts that results into massive gas optimization due to the elimination of expensive storage operations.

Motivation. It is essential for smart contracts to store data in the blockchain. However, interacting with the storage of a contract is among the most expensive operations of the EVM [3, 20]. Therefore, only necessary data should be stored and redundancy should be avoided when possible. This is contrary to conventional software architecture, where storage is considered cheap. Usually, the performance of data access in traditional systems is related with time. In Ethereum, however, performance is related to gas consumption. Access to persistent data costs a substantial amount of gas, which has a direct monetary value. One way to mitigate gas cost of reading variables from the blockchain is to declare them public. This leads to the creation of a *getter* function in the background, allowing free access to the value of the variable. But this treatment does not prevent the initial population of storage data, which is significantly expensive for large size of data. Towards the goal of implementing gas-efficient smart contracts, several patterns have been proposed [4, 5, 8, 19].

By using the *hash-and-resubmit* pattern, large structures are omitted from storage entirety, and are contained in memory. When a function call is performed, the signature and arguments of the function is included in the transactions field of the body of a block. The contents of blocks are public to the network, therefore this information is locally available to full nodes. By simply observing blocks, a node retrieves data sent to the contract by other users. To interact publicly with this data without the utilization storage, the node *resends* the observed data to the blockchain. The concept of resending data is redundant in conventional systems. However, this technique is very efficient to use in Solidity due to the significantly lower gas cost of memory operations in relation with storage operations.

Applicability. We now list the cases in which the *hash-and-resubmit* pattern is efficient to use:

The situations in which the *hash-and-resubmit* pattern can be applied are the following:

(1) The application is a Solidity smart contract.
(2) Read/write operations are performed in large arrays that exist in storage. Rehashing variables of small size may result to negligible gain or even performance loss.
(3) The entity that operates on the structures is a full node and observes function calls to the smart contract.

Participants and collaborators. The first participant is the smart contract S that accepts function calls. Another participant is the invoker E_1, who dispatches a large array d_0 to S via a function $\mathsf{func}_1(\mathsf{d}_0)$. Note that d_0 is potentially processed in func_1, resulting to d. The last participant is the observer E_2, who is a full node that observes transactions towards S in the blockchain. This is possible because nodes maintain the blockchain locally. After observation, E_2 retrieves data d. Since this is an off-chain operation, a malicious E_2 potentially alters d before interacting with S. We denote the potentially modified d as d^*. Finally, E_2 acts as an invoker by making a new call to S, $\mathsf{func}_2(\mathsf{d}^*)$. The verification that $\mathsf{d} = \mathsf{d}^*$, which is a prerequisite for the secure functionality of the underlying contract consists a part of the pattern and is performed in func_2.

Implementation. The implementation of this pattern is divided in two parts. The first part covers how d^* is retrieved by E_2, whereas in the second part the verification of $\mathsf{d} = \mathsf{d}^*$ is realized. The challenge here is twofold:

(1) Availability: E_2 must be able to retrieve d without the need of accessing on-chain data.
(2) Consistency: E_2 must be prevented from dispatching d^* that differs from the originally submitted d.

Hash-and-resubmit technique is performed in two stages to face these challenges: (a) the *hash* phase, which addresses *consistency*, and (b) the *resubmit* phase which addresses *availability* and *consistency*.

Addressing availability: During *hash* phase, E_1 makes the function call $\mathsf{func}_1(\mathsf{d}_0)$. This transaction, which includes a function signature (func_1) and the corresponding data (d_0), is added in a block by a miner. Due to blockchain's transparency, the observer of func_1, E_2, retrieves a copy of d_0, without the need of accessing contract data. In turn, E_2 performs *locally* the same set of on-chain instructions operated on d_0 generating d. Thus, availability is addressed through observability.

Addressing consistency We prevent an adversary E_2 from altering d^* by storing the *signature* of d in contract's state during the execution of $\mathsf{func}_1\texttt{(d)}$ by E_1. In the context of Solidity, a signature of a structure is the digest of the structure's *hash*. The pre-compiled `sha256` is convenient to use in Solidity, however we can make use of any cryptographic hash function $\mathsf{H}()$:

$$\mathsf{hash} \leftarrow \mathsf{H}(\mathsf{d})$$

Then, in *rehash* phase, the verification is performed by comparing the stored digest of d with the digest of d^*.

$$\mathsf{require}(\mathsf{hash} = \mathtt{H}(\mathsf{d}^*))$$

In Solidity, the size of digests is 32 bytes. To persist such a small value in contract's memory only adds a constant, negligible cost overhead.

We illustrate the application of the *hash-and-resubmit* pattern in Figure 1.

Sample. We now demonstrate the usage of the hash-and-resubmit pattern with a simplistic example. We create a smart contract that orchestrates a game between two players, P_1 and P_2. The winner is the player with the most valuable array. The interaction between players through the smart contract is realized in two phases: (a) the submit phase and (b) the contest phase.

Submit phase: P_1 submits an N-sized array, a_1 and becomes the holder of the contract.

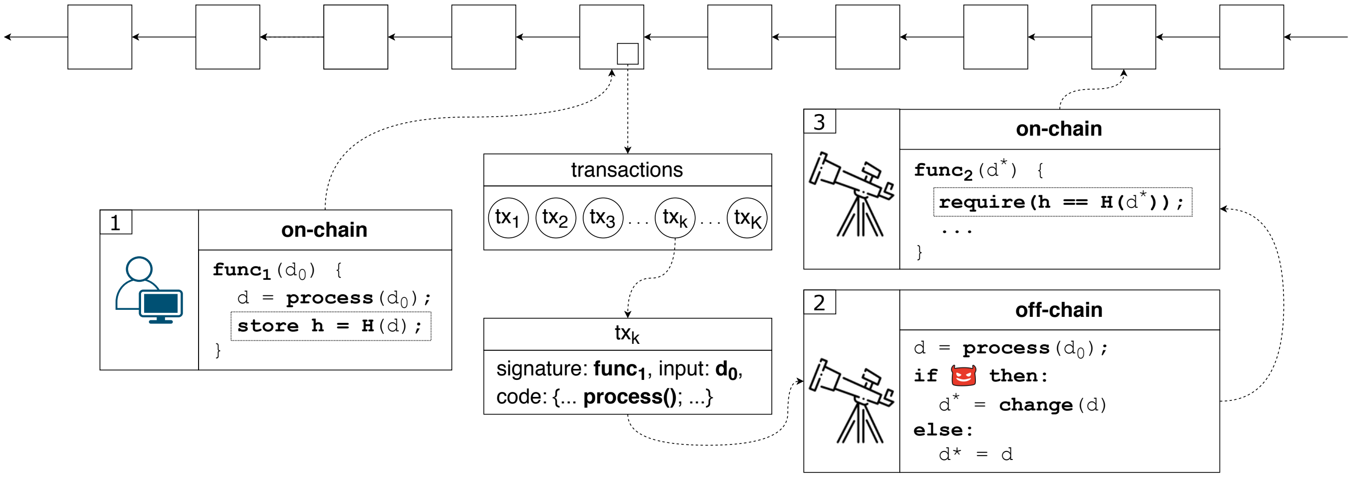
Contest phase: P_2 submits a_2. If $\mathsf{compare}(\mathsf{a}_2, \mathsf{a}_1)$ is true, then the holder of the contract changes to P_2. We provide a simple implementation for compare(), but we can consider any notion of comparison, since the pattern is abstracted from such implementation details.

We make use of the *hash-and-resubmit* pattern by prompting P_2 to provide *two* arrays to the contract during contest phase: (a) a_1^*, which is the originally submitted array by P_1, possibly modified by P_2, and (b) a_2, which is the contesting array.

We provide two implementations of the above described game. In Algorithm 1 we display the storage implementation, while in Algorithm 2 we show the implementation embedding the *hash-and-resubmit* pattern.

Algorithm 1 best array using storage

```
contract best-array
    best ← ∅; holder ← ∅
    function submit($a$)
        best ← $a$                              ▷ array saved in storage
        holder ← msg.sender
    end function
    function contest($a$)
        require(compare($a$))
        holder ← msg.sender
    end function
    function compare($a$)
        require($|a| \geq |\mathsf{best}|$)
        for $i$ in |best| do
            require($a[i] \geq \mathsf{best[i]}$)
        end for
        return true
    end function
end contract
```


1
on-chain
transactions
tx_1 tx_2 tx_3 … tx_k … tx_K
tx_k
signature: **func$_1$**, input: **d$_0$**,
code: {... **process()**; ...}
3
on-chain
2
off-chain

```
func1(d0) {
  d = process(d0);
  store h = H(d);
}
```

```
func2(d*) {
  require(h == H(d*));
  ...
}
```

```
d = process(d0);
if 😈 then:
  d* = change(d)
else:
  d* = d
```

Figure 1: The *hash-and-resubmit* pattern. In Stage 1, an invoker calls func$_1$(d$_0$). d$_0$ is processed on-chain and d is generated. The signature of d is stored in the blockchain as the digest of a hash function H(). In Stage 2, a full node that observes invocations of func$_1$ retrieves d$_0$, and generates d by performing the analogous processing on d$_0$ *off-chain.* An adversarial observer potentially alters d. Finally, in Stage 3, the observer invokes func$_2$(d*). In func$_2$, the validation of d is performed, reverting the function call if the signatures of originally submitted d does not match the signature of d*. By applying the *hash-and-resubmit pattern*, only fixed-size signatures of data need to be maintained on the blockchain replacing arbitrarily large structures.

Algorithm 2 best array using hash-and-resubmit pattern

```
contract best-array
    hash ← ∅; holder ← ∅
    function submit($a_1$)
        hash ← H($a_1$)                      ▷ hash saved in storage
        holder ← msg.sender
    end function
    function contest($a_1{}^*$, $a_2$)
        require(hash256($a_1{}^*$) = $hash$)    ▷ validate $a_1{}^*$
        require(compare($a_1{}^*$, $a_2$))
        holder ← msg.sender
    end function
    function compare($a_1{}^*$, $a_2$)
        require($|a_1{}^*| \geq |a_2|$)
        for $i$ in $|a_1{}^*|$ do
            require($a_1{}^*[i] \geq a_2[i]$)
        end for
    end function
    return true
end contract
```

Gas analysis. The gas consumption of the two above implementations is displayed in Figure 2. By using the *hash-and-resubmit* pattern, the aggregated gas consumption for submit and contest is decreased by 95%. This significantly affects the efficiency and applicability of the contract. Note that, the storage implementation exceeds the Ethereum block gas limit[3] for arrays of size 500 and above, contrary to the optimized version, which consumes approximately only $1/10^{th}$ of the block gas limit for arrays of 1000 elements.

Variations. In order to enable selective dispatch of a segment of interest, different hashing schemas can be adopted, such as Merkle Trees (ref) and Merkle Mountain Ranges (ref). In this variation of the pattern, which we term *merkle-hash-and-resubmit*, the signature of an array d is Merkle Tree Root (MTR). In *resubmit* phase, d$[m{:}n]$ is dispatched, accompanied by the siblings that reconstruct the MTR of d.

This variation of the pattern removes the burden of sending redundant data, however it implies on-chain construction and validation of the Merkle construction. In order to construct a MTR for an array d, |d| hashes are needed for the leafs of the MT, and $|d| - 1$ hashes are needed for the intermediate nodes. For the verification, the segment of interest d$[m{:}n]$ and the siblings of the MT are hashed. The size of siblings is approximately $log_2(|d|)$. The process of constructing and verifying the MTR is displayed in Figure 3.

In Solidity, different hashing operations vary in cost. An invocation of sha256(d), copies *data* in memory, and then the *CALL* instruction is performed by the EVM that calls a pre-compiled contract. In the current state of the EVM, *CALL* costs 700 gas units, and the gas paid for every word when expanding memory is 3 gas units [20]. Consequently, the expression $1 \times$ sha256(d) costs less than $|d| \times$sha256(1) operations. A different cost policy applies for keccak [1] hash function, where hashing costs 30 gas units plus 6 additional

[3] As of July 2020, the Ethereum block gas limit approximates 10,000,000 gas units

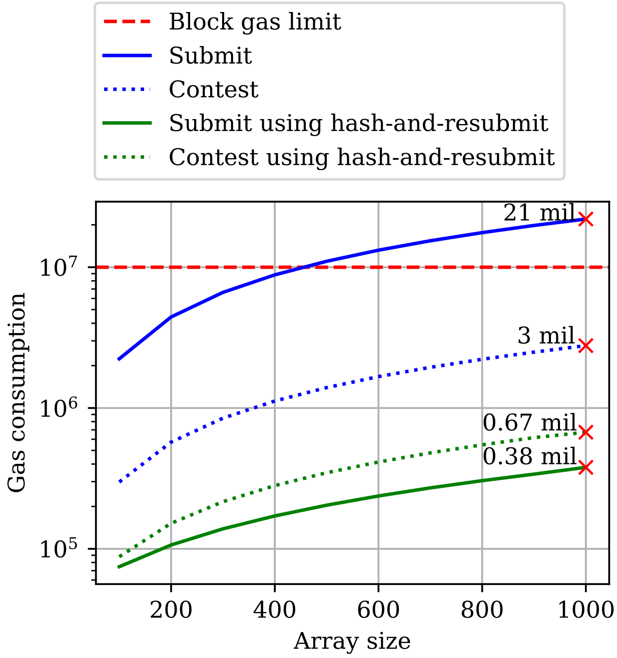


Figure 2: Gas-cost reduction using the *hash-and-resubmit* pattern. By avoiding gas-heavy storage operations, the aggregated cost of submit and contest is decreased significantly by 95%.

Operation	Gas cost
load(d)	$d_{bytes} \times 68$
sha256(d)	$d_{words} \times 3 + 700$
keccak(d)	$d_{words} \times 6 + 30$

Table 1: Gas cost for operations as of July 2020.

gas far each word for input data [20]. The usage of keccak dramatically increases the performance in comparison with sha256, and performs better than plain rehashing if the product of on-chain processing is sufficiently larger that the originally dispatched data. Costs of all related operations are listed in Table 1.

The merkle variation can be potentially improved by dividing d in larger chunks than 1 element. We leave this analysis for future work.

In Table 2 we display the operations needed for hashing and verifying the underlying data for both variations of the pattern as a function of data size. In Figure 4 we demonstrate the gas consumption for dispatched data of 10KB, and varying size of on-chain process product.

Consequences. The most obvious consequence of applying the *hash-and-resubmit* pattern variations is the circumvention of storage structures, a benefit that saves a substantial amount of gas, especially in the cases where these structures are large. To that extend, smart contracts that exceed the Ethereum block gas limit become practical. Furthermore, the pattern enables off-chain transactions, significantly improving the performance of smart contracts.

phase per variance	plain hash and resubmit	merkle hash and resubmit
hash	H(d)	$\mathsf{H}(\mathsf{d}_{elem}) \times \lvert\mathsf{d}\rvert$ $\mathsf{H}(\text{digest}) \times (\lvert\mathsf{d}\rvert - 1)$
resubmit	load(d) + H(d)	$\mathsf{load}(\mathsf{d}[m{:}n])$ + $\mathsf{load}(\mathit{siblings})$ + $\mathsf{H}(\mathsf{d}[m{:}n])$ + $\mathsf{H}(\mathit{digest}) \times \lvert\mathit{siblings}\rvert$

Table 2: Summary of operations for *hash-and-resubmit* pattern variations. d is the product of on-chain operations and d_{elem} is an element of d. H is a hash function, such as sha256 or keccak, *digest* is the product of H(.) and *siblings* are the siblings of the Merkle Tree constructed for d.

Known uses. To our knowledge, we are the first to combine the notion of the transparency of the blockchain with data structures signatures to eliminate storage variables from Solidity smart contracts by resubmitting data.

Enabling NIPoPoWs. We now present how the *hash-and-resubmit* pattern is used in the context of the NIPoPoW superlight client. The NIPoPoW verifier adheres to a submit-and-contest-phase schema, and the inputs of the functions are arrays that are processed on-chain. It is, therefore, a suitable case for our pattern.

In *submit* phase, a *proof* is submitted, which, in the case of falsity, it is contested by another user in *contest* phase. The user that initiates the contest is a node and monitors the traffic of the verifier. The input of submit function includes the submit proof (π_{subm}) that indicates the occurrence of an *event* (e) in the source chain, and the input of contest function includes the contesting proof (π_{cont}). A successful contest of π_{subm} is realized when π_{cont} has a better score. The score evaluation process is irrelevant to the pattern and remains unchained. The size of proofs is dictated by the value m. We consider $m = 15$ to be sufficiently secure.

In previous work, NIPoPoW proofs are maintained on-chain, resulting to extensive storage operations that limit the applicability of the contract considerably. In our implementation, proofs are not stored on-chain, and π_{subm} is retrieved by the node from calldata. Since we assume a trustless network, π_{subm} potentially alters by the node. We denote the potentially changed π_{subm} as π^*_{subm}. In *contest* phase, π^*_{subm} and π_{cont} are dispatched in order to enable the *hash-and-resubmit* pattern.

For our analysis, we create a chain similar to the Bitcoin chain with the addition of the interlink structure in each block as in [7]. Our chain spans 650,000 blocks, which represent a slightly enhanced Bitcoin chain[4]. From the tip of our chain, we branch two chains that span 100 and 200 additional

[4] Bitcoin spans 631,056 blocks as on May 2020. Metrics by https://www.blockchain.com/

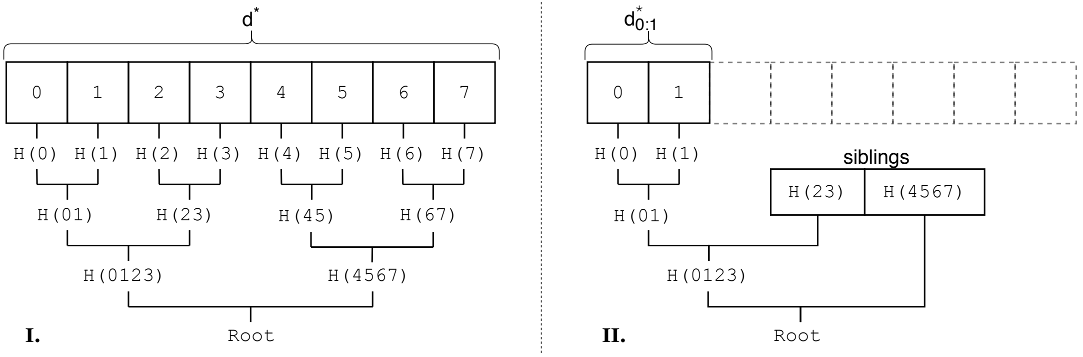


Figure 3: I. The calculation of root in *hash* phase. II. The verification of the root in *resubmit* phase. $\mathsf{H}(k)$ denotes the digest of element k. $\mathsf{H}(kl)$ denotes the result of $\mathsf{H}(\mathsf{H}(k) \mid \mathsf{H}(l))$

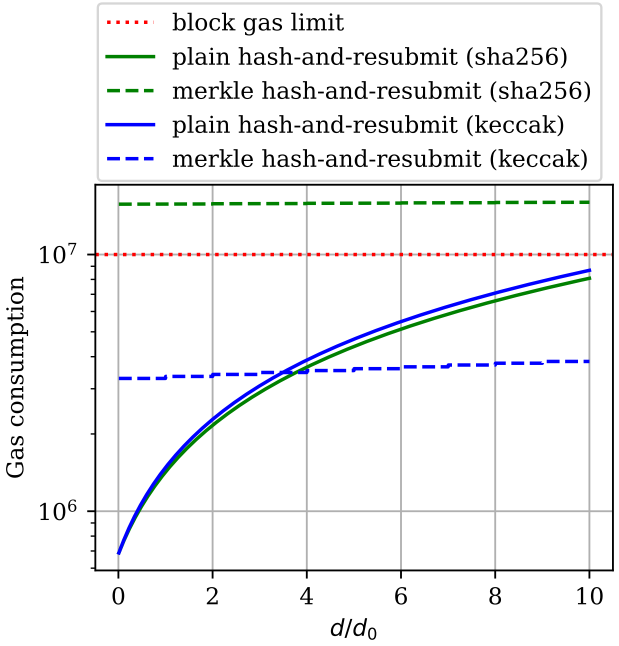


Figure 4: Trade-offs between *hash-and-resubmit* variations. In the vertical axis the gas consumption is displayed, and in vertical axis the size of d as a function of d₀. The size of d_0 is 10KB bytes, and the hash function we used is pre-compiled sha256.

blocks, respectively, as illustrated in Figure 5. Then, we use the smaller chain to create π_{subm}, , and the larger chain to create π_{cont}. By applying the protocol, π_{subm} is submitted, and a contest is initiated with π_{cont}. The contest is successful, since π_{subm} represents a chain consisting of fewer blocks than π_{cont}, therefore encapsulating less proof of work. We select this setting as it provides maximum code coverage, and it descries the most gas-heavy scenario.

In Algorithm 3 we show how *hash-and-resubmit* pattern is embedded into the NIPoPoW client.

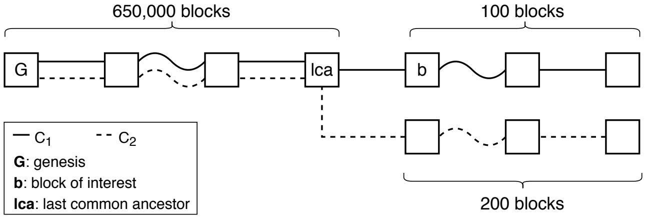


Figure 5: Forked chains for our gas analysis.

In Figure 6, we display how results of the *hash-and-resubmit* implementation differentiate from previous work for the aggregated cost of *submit* and *contest* phases. We observe that by using the *hash-and-resubmit* pattern, we achieve to increase the performance of the contract 50%. This is a decisive step towards creating a practical superlight client.

4 REMOVING LOOK-UP STRUCTURES

Now that we can freely retrieve large array structures, we can focus on other types of storage variables. A challenge we faced is that the protocol of NIPoPoWs dependents on a Directed Acyclic Graph (DAG) of blocks which is a mutable hashmap. This DAG is needed because interlink of superblocks can be adversarially defined. Using it, simple graph search extract the set of ancestor blocks of a block. In the final predicate evaluation, the set of ancestors of the best blockchain tip is passed to the predicate. The ancestors are included to avoid an adversary who presents an honest chain but skips the blocks of interest.

This logic is intuitive and efficient to implement in most traditional programming languages such as C++, JAVA, Python, JavaScript, etc. However, as our analysis demonstrates, such an implementation in Solidity is significantly

Algorithm 3 The NIPoPoW client using hash-and-resubmit pattern

```
contract crosschain
    events $\leftarrow \bot$; G $\leftarrow \bot$
    function initialize($\mathsf{G}_{remote}$)
        G$\leftarrow$ $\mathsf{G}_{remote}$
    end function
    function submit($\pi_{\mathsf{subm}}$, $e$)
        require($\pi_{\mathsf{subm}}[0] = \mathsf{G}$)
        require(events$[e] = \bot$)
        require(valid-interlink($\pi$))
        DAG $\leftarrow$ DAG $\cup$ $\pi_{\mathsf{subm}}$
        events$[e]$.hash $\leftarrow$ H($\pi_{\mathsf{subm}}$)          ▷ enable pattern
        ancestors $\leftarrow$ find-ancestors()
        events$[e]$.pred $\leftarrow$ evaluate-predicate(ancestors, e)
        ancestors $= \bot$
    end function
    function contest($\pi^{*}_{\mathsf{subm}}$, $\pi_{\mathsf{cont}}$, $e$)          ▷ provide proofs
        require(events$[e]$.hash $=$ H($\pi^{*}_{\mathsf{subm}}$))     ▷ verify $\pi^{*}_{\mathsf{subm}}$
        require($\pi_{\mathsf{cont}}[0] = \mathsf{G}$)
        require(events$[e] \neq \bot$)
        require(valid-interlink($\pi_{cont}$))
        $lca$ $=$ find-lca($\pi^{*}_{\mathsf{subm}}$, $\pi_{\mathsf{cont}}$)
        require(score($\pi_{\mathsf{cont}}[: lca]$) $>$ score($\pi^{*}_{\mathsf{subm}}[: lca]$))
        DAG $\leftarrow$ DAG $\cup$ $\pi_{\mathsf{cont}}$
        ancestors $\leftarrow$ find-ancestors(DAG)
        events$[e]$.pred $\leftarrow$ evaluate-predicate(ancestors, $e$)
        ancestors $= \bot$
    end function
end contract
```

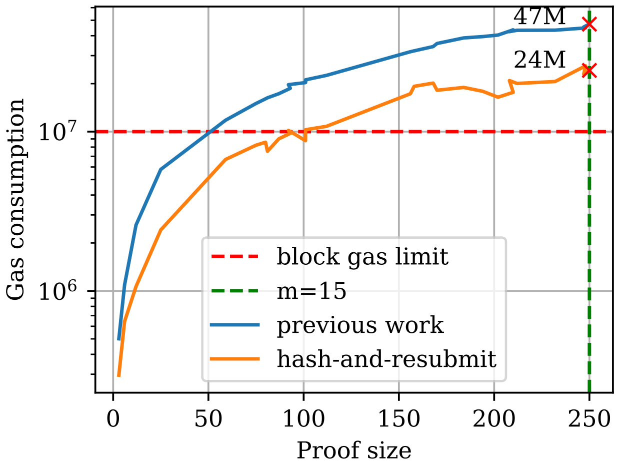


Figure 6: Performance improvement using hash-and-resubmit pattern in NIPoPoWs compared to previous work for a secure value of m. The gas consumption decreased by approximately 50%.

expensive. Albeit Solidity supports hashmap look-up structures, hashmaps can only be contained in storage. This affects performance, especially for large proofs.

We make a keen observation regarding potential positions of the *block of interest* in the proof which lead us to the construction of an architecture that does not require DAG, ancestors or other complementary structures. We adopt the notation from [15] to demonstrate our claims. Additionally, we denote the initially submitted proof as π_{subm} and the contesting proof as π_{cont}. In this context, we consider the predicate e to be of type ”block b exists inside a proof”, where b denotes the block of interest. The entity that initiates a submission is $\mathsf{E}_{\mathsf{subm}}$, and the entity that initiates a contest is $\mathsf{E}_{\mathsf{cont}}$.

Position of block of interest. NIPoPoWs are sets of sampled interlinked blocks, which means that they can be perceived as chains. If π_1 differs from π_2, then a fork is created at the index of the last common ancestor (lca). The block of interest lies at a certain index within π_{subm} and indicates a stable predicate [15, 17] that is true for π_{subm}. A submission in which b is absent from π_{subm} is aimless, because it automatically fails since no element of π_{subm} satisfies e. On the contrary, π_{cont}, tries to prove the falseness of the underlying predicate. This means that, if the block of interest is included in π_{cont}, then the contest is aimless. We refer to such aimless actions as *irrational* and components that are included in such actions as irrational components, i.e. irrational proof, blocks etc. We use the term *rational* to describe non-irrational actions and components.

In the NIPoPoW protocol, proofs' segments $\pi_{\mathsf{subm}}\{:\mathsf{lca}\}$ and $\pi_{\mathsf{cont}}\{:\mathsf{lca}\}$ are merged to prevent adversaries from skipping or adding blocks, and the predicate is evaluated against $\pi_{\mathsf{subm}}\{:\mathsf{lca}\} \cup \pi_{\mathsf{cont}}\{:\mathsf{lca}\}$. We observe that $\pi_{\mathsf{cont}}\{:\mathsf{lca}\}$ can be omitted, because no block B exists such that $\{\mathsf{B} : \mathsf{B} \notin \pi_{\mathsf{subm}}\{:\mathsf{lca}\} \land \mathsf{B} \in \pi_{\mathsf{cont}}\{:\mathsf{lca}\}\}$ where B results into positive evaluation of the predicate. This is due to the fact that, in a rational contest, b is not included in π_{cont}. Consequently, π_{cont} is only rational if it forks π_{subm} in a block is prior to b.

In Figure 7 we display a fork of two proofs. Solid lines connect blocks of π_{subm} and dashed lines connect blocks of π_{cont}. Examining which scenarios are rational depending on different positions of the block of interest, we observe that blocks `B`, `C` and `E` do not qualify, because they are included only in π_{cont}. Block `A` is included in $\pi_{\mathsf{subm}}\{:\mathsf{lca}\}$, which means that π_{cont} is an irrational contest because the lca comes after b. Therefore A is an irrational block as a component of an irrational contest. Given this configuration, the only rational block of interest is `D` and its predecessors (which we do not display in the figure).

Minimal forks. By combining the above observations, we derive that, π_{cont} can be truncated into $\pi_{\mathsf{cont}}\{:\mathsf{lca}\}$ without affecting the correctness of the protocol. We will term this truncated proof $\pi^{\mathsf{tr}}_{\mathsf{cont}}$[5]. Security is preserved if we require $\pi^{\mathsf{tr}}_{\mathsf{cont}}$ to be a *minimal fork* of π_{subm}. A minimal fork is a fork

[5] We cannot proceed to further truncation of $\pi^{\mathsf{tr}}_{\mathsf{cont}}$, because in the NIPoPoW protocol blocks within segment $\pi\{:\mathsf{lca}\}$ of each proof are required for the score calculation.

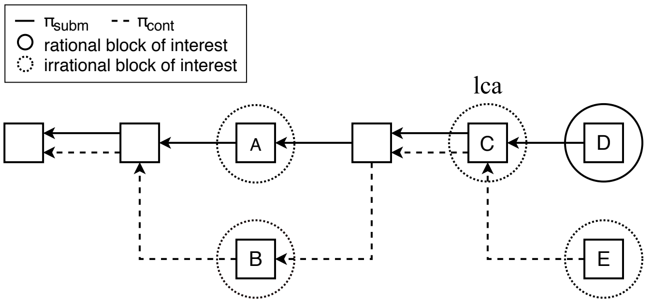


Figure 7: Fork of two chains. Solid lines connect blocks of π_{subm} and dashed lines connect blocks of π_{cont}. In this configuration, blocks in dashed circles are irrational blocks of interest, and the block in the solid circle is a rational block of interest. Blocks B, C and E are irrational because they exist in π_{cont}. Block A is irrational because it belongs to the subchain $\pi_{\mathsf{subm}}\{\text{:lca}\}$

chain that shares exactly one common block with the main chain. A proof $\tilde{\pi}$, which is minimal fork of π, has the following attributes:

(1) $\pi\{lca\} = \tilde{\pi}[0]$
(2) $\pi\{lca{:}\} \cap \tilde{\pi}[1{:}] = \emptyset$

By requiring $\pi^{\mathsf{tr}}_{\mathsf{cont}}$ to be a minimal fork of π_{subm}, we prevent adversaries from dispatching an augmented $\pi^{\mathsf{tr}}_{\mathsf{cont}}$ to claim better score against π_{subm}. Such an attempt is displayed in Figure 8.

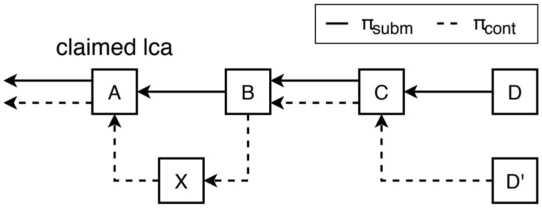


Figure 8: An adversary attests to contest with a malformed proof. Adversary proof consists of blocks {A, X, B, C, D'} that achieves better score against submit proof {A, B, C, D}. This attempt is rejected due to the minimal-fork requirement.

In Algorithm 4, we show how minimal fork technique is incorporated into our client replacing the DAG and ancestors. In Figure 9 we show how the performance of the client improves. We use the same test case as in *hash-and-resubmit*.

TODO: comment results

5 LEVERAGING AN OPTIMISTIC SCHEMA

We discussed how the verification in the NIPoPoW protocol is realized in two phases. In *submit* phase, the verification of the π_{subm} is realized. This is necessary in order to prevent adversaries from injecting blocks that do not belong to the chain, or changing existing blocks. A proof is valid if it is

Algorithm 4 The NIPoPoW client using the minimal fork technique

```
contract crosschain
    events ← ⊥; G ← ⊥
    function initialize($G_{remote}$)
        G← $G_{remote}$
    end function
    function submit($\pi_{\mathsf{subm}}$, $e$)
        require($\pi_{\mathsf{subm}}[0]$ = G)
        require(events[$e$] = ⊥)
        require(valid-interlink($\pi_{\mathsf{subm}}$))
        events[$e$].hash ← H($\pi_{\mathsf{subm}}$)
        events[$e$].pred ← evaluate-predicate($\pi_{\mathsf{subm}}$, $e$)
    end function
    function contest($\pi^*_{\mathsf{subm}}$, $\pi^{\mathsf{tr}}_{\mathsf{cont}}$, $e$, $f$)      ▷ $f$: fork index
        require($\pi^{\mathsf{tr}}_{\mathsf{cont}}[0] = \pi^*_{\mathsf{subm}}[f]$)      ▷ check fork head
        require(events[$e$] ≠ ⊥)
        require(events[$e$].hash = H($\pi^*_{\mathsf{subm}}$))
        require(valid-interlink($\pi^{\mathsf{tr}}_{\mathsf{cont}}$))
        require(minimal-fork($\pi^*_{\mathsf{subm}}$, $\pi^{\mathsf{tr}}_{\mathsf{cont}}$, $f$))
        require(score($\pi^{\mathsf{tr}}_{\mathsf{cont}}$) > score($\pi^*_{\mathsf{subm}}[f{:}]$))
        events[$e$].pred ← evaluate-predicate($\pi^{\mathsf{tr}}_{\mathsf{cont}}$, $e$)
    end function
    function minimal-fork($\pi_1$, $\pi_2$, $f$)
        for $p$ in $\pi_1$ do
            if $p \in \pi_2$ then
                return false
            end if
        end for
    end function
end contract
```

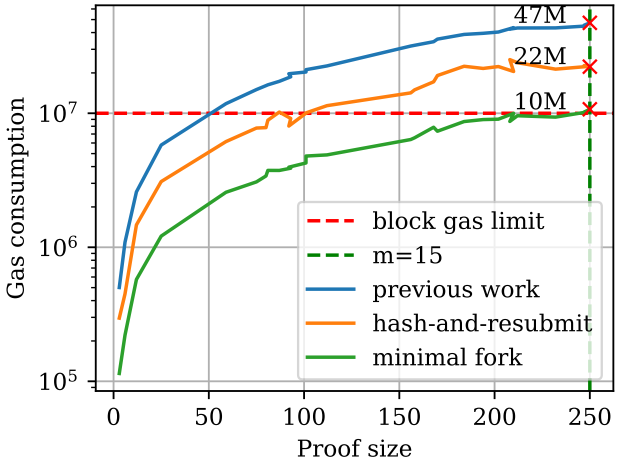


Figure 9

structurally correct. The correctly structured NIPoPoW has the following requirements:

(1) the first block of the proof is the genesis block of the underlying blockchain.
(2) every block has a valid interlink.

Asserting the existence of genesis is an inexpensive operation of constant complexity. However, confirming the interlink correctness of all blocks is a process of linear complexity to size of the proof. Albeit the verification is performed in memory, sufficiently large proofs result in costly submissions, and it consists the most demanding function of *submit* phase. In Table 3 we display the cost of valid-interlink function which determines the structural correctness of a proof in comparison with the overall gas used in submit.

Process	Gas cost	Total %
verify-interlink	2,200,000	53%
submit	4,700,000	100%

Table 3: Gas usage of function verify-interlink compared to overall gas consumption of submit.

Dispute phase. We observe that an additional phase in our protocol alleviates the burden of verifying all elements of the proof by enabling the indication of an incorrect block. This phase, which we term *dispute* phase leverages selective verification of the submitted proof at a certain index, which, as a constant operation, significantly reduces the gas cost of the verification process.

In the protocol where *dispute* is incorporated, when an invalid proof π_{subm} is submitted by $\mathsf{E_{subm}}$, a node, $\mathsf{E_{cont}}$, retrieves the proof from the calldata. Then, the proof is checked for it validity *off-chain.* In order to prove that π_{subm} is invalid, $\mathsf{E_{cont}}$ only needs to indicate the index in which π_{subm} fails the verification. In turn, π_{cont} calls dispute(π^*_{subm}, i), where i indicates the disputing index of π^*_{subm}. Note that, the this additional phase phase does not imply more rounds of interactions between $\mathsf{E_{subm}}$ and $\mathsf{E_{cont}}$. In the case where π_{subm} is invalidated in *dispute* phase, the contest function is not needed. Similarly, in the case in which *pis* is structurally correct, but represents a chain that is not valid, then the call of contest is sufficient.

In Table 4 we display the gas consumption with of a cycle of interactions *submit* + *dispute* for a case where π_{subm} is structurally incorrect, and *submit* + *contest* for a case where π_{subm} is structurally correct, but represents a dishonest chain. In Algorithm 5, we show the implementation of *dispute* phase. In Figure 10, we illustrate the performance gain of the client using *dispute* phase. The contest function remains unchanged.

6 CRYPTOECONOMICS

Function	Gas cost
submit	2,500,000
dispute	1,300,000
Total	3,800,000

Table 4: Gas usage after removing linear block validation using dispute phase.

Algorithm 5 The NIPoPoW client using dispute phase

```
contract crosschain
    events ← ⊥; G ← ⊥
    function initialize($G_{remote}$)
        G← $G_{remote}$
    end function
    function submit($\pi_{\mathsf{subm}}$, $e$)
        require($\pi_{\mathsf{subm}}[0] = G$)
        require(events[$e$] = ⊥)
        events[$e$].hash ← H($\pi_{\mathsf{subm}}$)
        events[$e$].pred ← evaluate-predicate($\pi_{\mathsf{subm}}$, $e$)
    end function
    function dispute($\pi^*_{\mathsf{subm}}$, $e$, $i$)                ▷ $i$: dispute index
        require(events[$e$] ≠ ⊥)
        require(events[$e$].hash = H($\pi^*_{\mathsf{subm}}$))
        require(¬valid-block($\pi_{\mathsf{subm}}$, $i$))
        events[$e$] ← ⊥
    end function
    function valid-block($\pi$, $i$)
        $l$ ← $\pi[i]$.level
        if $\pi[i+1]$.intelink[$l$] = $\pi[i]$ then
            return true
        end if
        return false
    end function
end contract
```

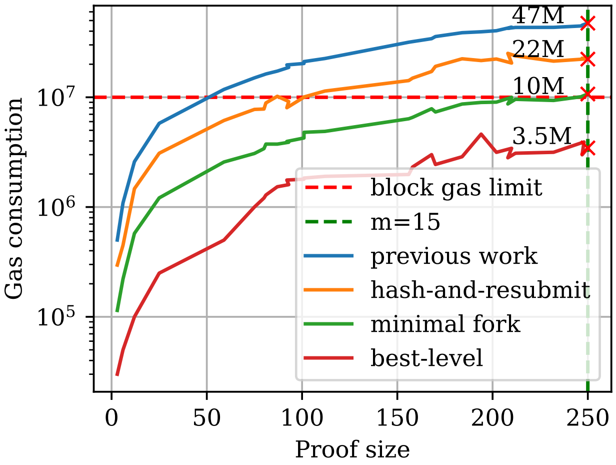


Figure 10: Caption

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