StrongChain: Transparent and Collaborative Proof-of-Work Consensus

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Abstract

Bitcoin is the most successful cryptocurrency so far. This is mainly due to its novel consensus algorithm, which is based on proof-of-work combined with a cryptographically-protected data structure and a rewarding scheme that incentivizes nodes to participate. However, despite its unprecedented success Bitcoin suffers from many inefficiencies. For instance, Bitcoin's consensus mechanism has been proved to be incentive-incompatible, its high reward variance causes centralization, and its hardcoded deflation raises questions about its long-term sustainability.

In this work, we revise the Bitcoin consensus mechanism by proposing StrongChain, a scheme that introduces transparency and incentivizes participants to collaborate rather than to compete. The core design of our protocol is to reflect and utilize the computing power aggregated on the blockchain which is invisible and "wasted" in Bitcoin today. Introducing relatively easy, although important changes to Bitcoin's design enables us to improve many crucial aspects of Bitcoin-like cryptocurrencies making it more secure, efficient, and profitable for participants. We thoroughly analyze our approach and we present an implementation of StrongChain. The obtained results confirm its efficiency, security, and deployability.

1 Introduction

One of the main novelties of Bitcoin [28] is Nakamoto consensus. This mechanism enabled the development of a permissionless, anonymous, and Internet-scale consensus protocol, and combined with incentive mechanisms allowed Bitcoin to emerge as the first decentralized cryptocurrency. Bitcoin is successful beyond all expectations, has inspired many other projects, and has started new research directions. Nakamoto consensus is based on proof-of-work (PoW) [8] in order to mitigate Sybil attacks [6]. To prevent modifications, a cryptographically-protected append-only list [2] is introduced. This list consists of transactions grouped into blocks and is usually referred to as a *blockchain*. Every active protocol participant (called a *miner*) collects transactions sent by users and tries to solve a computationally-hard puzzle in order to be able to write to the blockchain (the process of solving the puzzle is called *mining*). When a valid solution is found, it is disseminated along with the transactions that the miner wishes to append. Other miners verify this data and, if valid, append it to their replicated blockchains. The miner that has found a solution is awarded by a) the system, via a rewarding scheme programmed into the protocol, and b) fees paid by transaction senders. All monetary transfers in Bitcoin are expressed in its native currency (called bitcoin, abbreviated as BTC) whose supply is limited by the protocol.

Bitcoin has started an advent of decentralized cryptocurrency systems and as the first proposed and deployed system in this class is surprisingly robust. However, there are multiple drawbacks of Bitcoin that undermine its security promises and raise questions about its future. Bitcoin has been proved to be incentive-incompatible [9, 11, 39, 47]. Namely, in some circumstances, the miners' best strategy is to not announce their found solutions immediately, but instead withhold them for some time period. Another issue is that the increasing popularity of the system tends towards its centralization. Strong competition between miners resulted in a high reward variance, thus to stabilize their revenue miners started grouping their computing power by forming *mining pools*. Over time, mining pools have come to dominate the computing power of the system, and although they are beneficial for miners, large mining pools are risky for the system as they have multiple ways of abusing the protocol [9, 11, 18, 39]. Recently, researchers rigorously analyzed one of the impacts of Bitcoin's deflation [4, 27, 47]. Their results indicate that Bitcoin may be unsustainable in the long term, mainly due to decreasing miners' rewards that will eventually stop completely. Besides that, unusually for a transaction system, Bitcoin is designed to favor availability over consistency. This choice was motivated by its open and

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permissionless spirit, but in the case of inconsistencies (i.e., *forks* in the blockchain) the system can be slow to converge.

Motivated by these drawbacks, we propose StrongChain, a simple yet powerful revision of the Bitcoin consensus mechanism. Our main intuition is to design a system such that the mining process is more transparent and collaborative, i.e., miners get better knowledge about the mining power of the system and they are incentivized to solve puzzles together rather than compete. In order to achieve it, in the heart of the StrongChain's design we employ *weak solutions*, i.e., puzzle solutions with a PoW that is significant yet insufficient for a standard solution. We design our system, such that a) weak solutions are part of the consensus protocol, b) their finders are rewarded independently, and c) miners have incentives to announce own solutions and append solutions of others immediately. We thoroughly analyze our approach and show that with these changes, the mining process is becoming more transparent, collaborative, secure, efficient, and decentralized. Surprisingly, we also show how our approach can improve the freshness properties offered by Bitcoin. We present an implementation and evaluation of our scheme.

2 Background and Problem Definition

2.1 Nakamoto Consensus and Bitcoin

The Nakamoto consensus protocol allows decentralized and distributed network comprised of mutually distrusting participants to reach an agreement on the state of the global distributed ledger [28]. The distributed ledger can be regarded as a linked list of blocks, referred to as the *blockchain*, which serializes and confirms "transactions". To resolve any *forks* of the blockchain the protocol specifies to always accept the longest chain as the current one. Bitcoin is a peer-to-peer cryptocurrency that deploys Nakamoto consensus as its core mechanism to avoid double-spending. Transactions spending bitcoins are announced to the Bitcoin network, where miners validate, serialize all non-included transactions, and try to create (mine) a block of transactions with a PoW embedded into the block header. A valid block must fulfill the condition that for a cryptographic hash function H, the hash value of the block header is less than the target T.

Brute-forcing the nonce (together with some other changeable data fields) is virtually the only way to produce the PoW, which costs computational resources of the miners. To incentivize miners, the Bitcoin protocol allows the miner who finds a block to insert a special transaction (see below) minting a specified amount of new bitcoins and collecting transaction fees offered by the included transactions, which are transferred to an account chosen by the miner. Currently, every block mints 12.5 new bitcoins. This amount is halved every four years, upper-bounding the number of bitcoins that will be created to a fixed total of 21 million coins. It implies that after around the year 2140, no new coins will be created, and the transaction fees will be the only source of reward for miners. Because of its design, Bitcoin is a deflationary currency.

The overall hash rate of the Bitcoin network and the difficulty of the PoW determine how long it takes to generate a new block for the whole network (the block interval). To stabilize the block interval at about 10 minutes for the constantly changing total mining power, the Bitcoin network adjusts the target T every 2016 blocks (about two weeks, i.e., a *difficulty window*) according to the following formula

$$T_{new} = T_{old} \cdot \frac{\textit{Time of the last 2016 blocks}}{\textit{2016} \cdot \textit{10 minutes}}. \qquad (1)$$

In simple terms, the difficulty increases if the network is finding blocks faster than every 10 minutes, and decrease otherwise. With dynamic difficulty, Nakamoto's longest chain rule was considered as a bug,[1] as it is trivial to produce long chains that have low difficulty. The rule was replaced by the strongest-PoW chain rule where competing chains are measured in terms of PoW they aggregated. As long as there is one chain with the highest PoW, this chain is chosen as the current one.

Bitcoin introduced and uses the *unspent transaction output* model. The validity of a Bitcoin transaction is verified by executing a script proving that the transaction sender is authorized to redeem unspent coins. The only exception is the first transaction in the transaction list of a block, which implements how the newly minted bitcoins and transaction fees are distributed. It is called a *coinbase transaction* and it contains the amount of bitcoins (the sum of newly minted coins and the fees derived from all the transactions) and the beneficiary (typically the creator of the block). Also, the Bitcoin scripting language offers a mechanism (`OP_RETURN`) for recording data on the blockchain, which facilitates third-party applications built-on Bitcoin.

Bitcoin proposes the simplified payment verification (SPV) protocol, that allows resource-limited clients to verify that a transaction is indeed included in a block provided only with the block header and a short transaction's inclusion proof. The key advantage of the protocol is that SPV clients can verify the existence of a transaction without downloading or storing the whole block. SPV clients are provided only with block headers and on-demand request from the network inclusion proofs of the transactions they are interested in.

In the original white paper, Nakamoto heuristically argues that the consensus protocol remains secure as long as a majority ($> 50\%$) of the participants' computing power honestly follow the rule specified by the protocol, which is compatible with their own economic incentives.

[1] `https://goo.gl/thhusi`

2.2 Bitcoin Mining Issues

Despite its popularity, Nakamoto consensus and Bitcoin suffer from multiple issues. Bitcoin mining is not always incentive-compatible. By deviating from the protocol and strategically withholding found blocks, a miner in possession of a proportion α of the total computational power may occupy more than α portion of the blocks on the blockchain, and therefore gain disproportionally higher payoffs with respect to her share [1, 11, 39]. More specifically, an attacker tries to create a private chain by keeping found blocks secret as long as the chain is in an advantageous position with one or more blocks more than the public branch. She releases her private chain only when the public chain has almost caught up, hence invalidating the public branch and all the efforts made by the honest miners. This kind of attack, called *selfish mining*, can be more efficient when a well-connected selfish miner's computational power exceeds a certain threshold (around more than 30%). Thus, selfish mining does not pay off if the mining power is sufficiently decentralized.

Unfortunately, the miners have an impulse to centralize their computing resources due to Bitcoin's rewarding scheme. In Bitcoin, rewarding is a zero-sum game and only the lucky miner who manages to get her block accepted receives the reward, while others who indeed contributed computational resources to produce the PoW are completely invisible and ignored. Increasing mining competition leads to an extremely high variance of the payoffs of a miner with a limited computational power. A solo miner may need to wait months or years to receive any reward at all. As a consequence, miners are motivated to group their resources and form mining pools, that divide work among pool participants and share the rewards according to their contributions. As of November 2018, only five largest pools account for more than 65% of the mining power of the whole Bitcoin network.[2] Such mining pools not only undermine the decentralization property of the system but also raise various in-pool or cross-pool security issues [5, 9, 22, 37].

Another seemingly harmless characteristic of Bitcoin is its finite monetary supply. However, researchers in their recent work [4, 27, 47] investigate the system dynamics when incentives coming from transaction fees are non-negligible compared with block rewards (in one extreme case the incentives come only from fees). They provide analysis and evidence, indicating an undesired system degradation due to the rational and self-interested participants. Firstly, such a system incentivizes large miner coalitions, increasing the system centralization even more. Secondly, it leads to a mining gap where miners would avoid mining when the available fees are insufficient. Even worse, rational miners tend to mine on chains that do not include available transactions (and their fees), rather than following the block selection rule specified by the protocol, resulting in a backlog of transactions. Finally, in the sole transaction fee regime, selfish mining attacks are efficient for miners with arbitrarily low mining power, regardless of their network connection qualities. These results suggest that making the block reward permanent and accepting the monetary inflation may be a wise design choice to ensure the stability of the cryptocurrency in the long run.

Moreover, the chain selection rule (i.e., the strongest chain is accepted), together with the network delay, occasionally lead to forks, where two or more blocks pointing to the same block are created around the same time, causing the participants to have different views of the current system state. Such conflicting views will eventually be resolved since with a high probability one branch will finally beat the others (then the blocks from the "losing" chain become *stale blocks*). The process of fork resolution is quite slow, as blocks have the same PoW weight and they arrive in 10-minutes intervals (on average).

Finally, the freshness properties provided by Bitcoin are questionable. By design, the Bitcoin blockchain preserves the order of blocks and transactions, however, the accurate estimation of time of these events is challenging [43], despite the fact that each block has an associated timestamp. A block's timestamp is accepted if a) it is greater than the median timestamp of the previous eleven blocks, and b) it is less than the network time plus two hours.[3] This gives significant room for manipulation — in theory, a timestamp can differ in hours from the actual time since it is largely determined by a single block creator. In fact, as time cannot be accurately determined from the timestamps, the capabilities of the Bitcoin protocol as a timestamping service are limited, which may lead to severe attacks by itself [3, 17].

2.3 Requirements

For the purpose of revising a consensus protocol of PoW blockchains in a secure, well-incentivized, and seamless way, we define the following respective requirements:

- **Security** – the scheme should improve the security of Nakamoto consensus by mitigating known attack vectors and preventing new ones. In essence, the scheme should be incentive-compatible, such that miners benefit from following the consensus rules and have no gain from violating them.
- **Reward Variance** – another objective is to minimize the variance in rewards. This requirement is crucial for decentralization since a high reward variance is the main motivation of individual miners to join centralized mining pools. Centralization is undesirable as large-enough mining pools can attack the Bitcoin protocol.
- **Chain Quality** – the scheme should provide a high chain quality, which usually is described using the two following properties.

[2] `https://btc.com/stats/pool?pool_mode=month`

[3] `https://en.bitcoin.it/wiki/Block_timestamp`

  - **Mining Power Utilization** – the ratio between the mining power on the main chain and the mining power of the entire blockchain network. This property describes the performance of mining and its ideal value is 1, which denotes that all mining power of the system contributes to the "official" or "canonical" chain. A high mining power utilization implies a low stale block rate.
  - **Fairness** – the protocol should be fair, i.e., a miner should earn rewards proportionally to the resources invested by her in mining. We denote a miner with α of the global mining power as an *α-strong miner*.
- **Efficiency and Practicality** – the scheme should not introduce any significant computational, storage, or bandwidth overheads. This is especially important since Bitcoin works as a replicated state machine, therefore all full nodes replicate data and the validation process. In particular, the block validation time, its size, and overheads of SPV clients should be at least similar as today. Moreover, the protocol should not introduce any assumptions that would be misaligned with Bitcoin's spirit and perceived as unacceptable by the community. In particular, the scheme should not introduce any trusted parties and should not assume strong synchronization of nodes (like global and reliable timestamps).

3 High-level Overview

3.1 Design Rationale

Our first observation is that Bitcoin mining is not transparent. It is difficult to quickly estimate the computing power of the different participants, because the only indicator is the found blocks. After all, blocks arrive with a low frequency, and each block is equal in terms of its implied computational power. Consequently, the only way of resolving forks is to wait for a stronger chain to emerge, which can be a time-consuming process. A related issue is block-withholding-like attacks (e.g., selfish mining) which are based on the observation that sometimes it is profitable for an attacker to deviate from the protocol by postponing the announcement of new solutions. We see transparency as a helpful property also in this context. Ideally, non-visible (hidden) solutions should be penalized, however, in practice it is challenging to detect and prove that a solution was hidden. We observe that an alternative way of mitigating these attacks would be to promote visible solutions, such that with more computing power aggregated around them they get stronger. This would incentivize miners to publish their solutions immediately, since keeping it secret may be too risky as other miners could strengthen a competing potential (future) solution over time. Finally, supported by recent research results [4, 11, 27, 39, 47], we envision that redesigning the Bitcoin reward scheme is unavoidable to keep the system sustainable and more secure. Beside the deflation issues (see Section 2.2), the reward scheme in Bitcoin is a zero-sum game rewarding only lucky miners and ignoring all effort of other participants. That causes fierce competition between miners and a high reward variance, which stimulates miners to collaborate, but within mining pools, introducing more risk to the system. We aim to design a system where miners can benefit from collaboration but without introducing centralization risks.

3.2 Overview

Motivated by these observations, we see weak puzzle solutions, currently invisible and "wasted" in Bitcoin, as a promising direction. Miners exchanging them could make the protocol more transparent as announcing them could reflect the current distribution of computational efforts on the network. Furthermore, if included in consensus rules, they could give blocks a better granularity in terms of PoW, and incentivize miners to collaborate. In our scheme, miners solve a puzzle as today but in addition to publishing solutions, they exchange weak solutions too (i.e., almost-solved puzzles). The lucky miner publishes her solution that embeds gathered weak solutions (pointing to the same previous block) of other miners. Such a published block better reflects the aggregated PoW of a block, which in the case of a fork can indicate that more mining power is focused on a given branch (i.e., actually it proves that more computing power "believes" that the given branch is correct). Another crucial change is to redesign the Bitcoin reward system, such that the finders of weak solutions are also rewarded. Following lessons learned from mining pool attacks, instead of sharing rewards among miners, our scheme rewards weak solutions proportionally to their PoW contributed to a given block and all rewards are independent of other solutions of the block. (Note, that this change requires a Bitcoin *hard fork*.)

There are a few intuitions behind these design choices. First, a selfish miner finding a new block takes a high risk by keeping this block secret. This is because blocks have a better granularity due to honest miners exchanging partial solutions and strengthening their prospective block, which in the case of a fork would be stronger than the older block kept secret (i.e., the block of the selfish miner). Secondly, miners are actually incentivized to collaborate by a) exchanging their weak solutions, and b) by appending weak solutions submitted by other miners. For the former case, miners are rewarded whenever their solutions are appended, hence keeping them secret can be unprofitable for them. For the latter case, a miner appending weak solutions of others only increases the strength of her potential block, and moreover, appending these solutions does not negatively influence the miner's potential reward. Finally, our approach comes with another benefit. Proportional rewarding of weak solutions

decreases the reward variance, thus miners do not have to join large mining pools in order to stabilize their revenue. This could lead to a higher decentralization of mining power on the network.

In the following sections, we describe details of our system, show its analysis, and report on its implementation.

4 StrongChain Details

4.1 Mining

As in Bitcoin, in StrongChain miners authenticate transactions by collecting them into blocks whose headers are protected by a certain amount of PoW. A simplified description of a block mining procedure in StrongChain is presented as the *mineBlock()* function in Algorithm 1. Namely, every miner tries to solve a PoW puzzle by computing the hash function over a newly created header. The header is constantly being changed by modifying its nonce field,[4] until a valid hash value is found. Whenever a miner finds a header hdr whose hash value $h = H(hdr)$ is smaller than the *strong target* T_s, i.e., a h that satisfies the following:

$$h < T_s,$$

then the corresponding block is announced to the network and becomes, with all its transactions and metadata, part of the blockchain. We refer to headers of included blocks as *strong headers*.

One of the main differences with Bitcoin is that our mining protocol handles also headers whose hash values do not meet the strong target T_s, but still are low enough to prove a significant PoW. We call such a header a *weak header* and its hash value h has to satisfy the following:

$$T_s \leq h < T_w, \tag{2}$$

where $T_w > T_s$ and T_w is called the *weak target*.

Whenever a miner finds such a block header, she adds it to her local list of weak headers (i.e., *weakHdrsTmp*) and she propagates the header among all miners. Then every miner that receives this information first validates it (see *onRecvWeakHdr()*) by checking whether

- the header points to the last strong header,
- its other fields are correct (see Section 4.2),
- and Equation 2 is satisfied.

Afterward, miners append the header to their lists of weak headers. We do not limit the number of weak headers appended, although this number is correlated with the T_w/T_s ratio (see Section 5).

Finally, miners continue the mining process in order to find a strong header. In this process, a miner keeps creating candidate headers by computing hash values and checking whether the strong target is met. Every candidate header

[4] In fact, other fields can be modified too if needed.

Algorithm 1: Pseudocode of StrongChain functions.

```
function mineBlock()
    weakHdrsTmp ← ∅;
    for nonce ∈ {0,1,2,...} do
        hdr ← createHeader(nonce);
        /* check if the header meets the strong target */
        h_tmp ← H(hdr);
        if h_tmp < T_s then
            B ← createBlock(hdr, weakHdrsTmp, Txs);
            broadcast(B);
            return; /* signal to mine with the new block */
        /* check if the header meets the weak target */
        if h_tmp < T_w then
            weakHdrsTmp.add(hdr);
            broadcast(hdr);
function onRecvWeakHdr(hdr)
    h_w ← H(hdr);
    assert(T_s ≤ h_w < T_w and validHeader(hdr));
    assert(hdr.PrevHash == H(lastBlock.hdr)) ;
    weakHdrsTmp.add(hdr);
function rewardBlock(B)
    /* reward block finder with R */
    reward(B.hdr.Coinbase, R + B.TxFees);
    w ← γ * T_s/T_w; /* reward weak headers proportionally */
    for hdr ∈ B.weakHdrSet do
        reward(hdr.Coinbase, w * c * R);
function validateBlock(B)
    assert(H(B.hdr) < T_s and validHeader(B.hdr));
    assert(B.hdr.PrevHash == H(lastBlock.hdr)) ;
    assert(validTransactions(B));
    for hdr ∈ B.weakHdrSet do
        assert(T_s ≤ H(hdr) < T_w and validHeader(hdr));
        assert(hdr.PrevHash == H(lastBlock.hdr));
function chainPoW(chain)
    sum ← 0;
    for B ∈ chain do
        /* for each block compute its aggregated PoW */
        T_s ← B.hdr.Target;
        sum ← sum + T_max/T_s;
        for hdr ∈ B.weakHdrSet do
            sum ← sum + T_max/T_w;
    return sum;
function getTimestamp(B)
    sumT ← B.hdr.Timestamp;
    sumW ← 1.0;
    /* average timestamp by the aggregated PoW */
    w ← T_s/T_w;
    for hdr ∈ B.weakHdrSet do
        sumT ← sumT + w * hdr.Timestamp;
        sumW ← sumW + w;
    return sumT/sumW;
```

"protects" all collected weak headers (note that all of these weak headers point to the same previous strong header).

In order to keep the number of found weak headers close to a constant value, StrongChain adjusts the difficulty T_w of weak headers every 2016 blocks immediately following the adjustment of the difficulty T_s of the strong headers according to Equation 1, such that the ratio T_w/T_s is kept at a constant (we discuss its value in Section 5).

4.2 Block Layout and Validation

A block in our scheme consists of transactions, a list of weak headers, and a strong header that authenticates these transactions and weak headers. Strong and weak headers in our system inherit the fields from Bitcoin headers and additionally enrich it by a new field. A block header consists of the following fields:

PrevHash: is a hash of the previous block header,

Target: is the value encoding the current target defining the difficulty of finding new blocks,

Nonce: is a nonce, used to generate PoW,

Timestamp: is a Unix timestamp,

TxRoot: is the root of the Merkle tree [24] aggregating all transactions of the block, and

Coinbase: represents an address of the miner that will receive a reward.

As our protocol rewards finders of weak headers (see details in Section 4.4), every weak header has to be accompanied with the information necessary to identify its finder. Otherwise, a finder of a strong block could maliciously claim that some (or all) weak headers were found by her and get rewards for them. For this purpose and for efficiency, we introduced a new 20B-long header field named *Coinbase*. With the introduction of this field, StrongChain headers are 100B long. But on the other hand, there is no longer any need for Bitcoin coinbase transactions (see Section 2.1), as all rewards are determined from headers.

In our scheme, weak headers are exchanged among nodes as part of a block, hence it is necessary to protect the integrity of all weak headers associated with the block. To realize it, we introduce a special transaction, called a *binding transaction*, which contains a hash value computed over the weak headers. This transaction is the first transaction of each block and it protects the collected weak headers. Whenever a strong header is found, it is announced together with all its transactions and collected weak headers, therefore, this field protects all associated weak headers. To encode this field we utilize the `OP_RETURN` operation as follows:

$$\texttt{OP\_RETURN} \quad H(hdr_0 \| hdr_1 \| ... \| hdr_n), \tag{3}$$

where hdr_i is a weak header pointing to the previous strong header. Since weak headers have redundant fields (the *PrevHash*, *Target*, and *Version* fields have the same values as the strong header), we propose to save bandwidth and storage by not including these fields into the data of a block. This modification reduces the size of a weak header from 100B to 60B only, which is especially important for SPV clients who keep downloading new block headers.

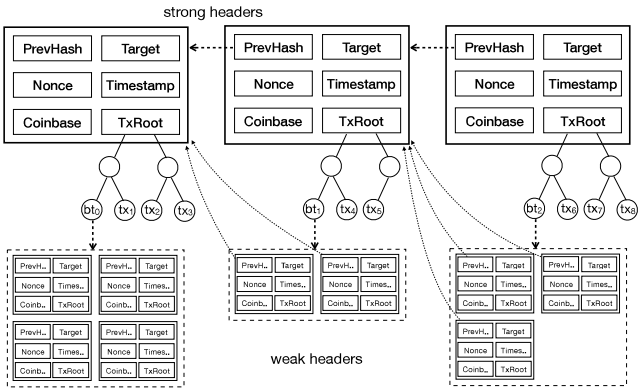


Figure 1: An example of a blockchain fragment with strong headers, weak headers, and binding and regular transactions.

With our approach, a newly mined and announced block can encompass multiple weak headers. Weak headers, in contrast to strong headers, are not used to authenticate transactions, and they are even stored and exchanged *without* their corresponding transactions. Instead, the main purpose of including weak headers it to contribute and reflect the aggregated mining power concentrated on a given branch of the blockchain. We present a fragment of a blockchain of StrongChain in Figure 1. As depicted in the figure, each block contains a single strong header, transactions, and a set of weak headers aggregated via a binding transaction.

On receiving a new block, miners validate the block by checking the following (see *validateBlock()* in Algorithm 1):

1. The strong header is protected by the PoW and points to the previous strong header.
2. Header fields have correct values (i.e., the version, target, and timestamp are set correctly).
3. All included transactions are correct and protected by the strong header. This check also includes checking that all weak headers collected are protected by a binding transaction included in the block.
4. All included weak headers are correct: a) they meet the targets as specified in Equation 2, b) their *PrevHash* fields point to the previous strong header, and c) their version, targets, and timestamps have correct values.

If the validation is successful, the block is accepted as part of the blockchain.

4.3 Forks

One of the main advantages of our approach is that blocks reflect their aggregated mining power more precisely. Each block beside its strong header contains multiple weak head-

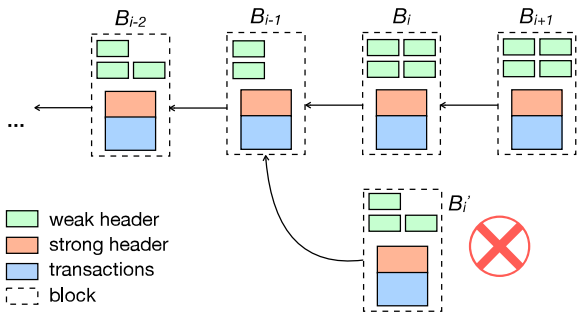


Figure 2: An example of a forked blockchain in StrongChain.

ers that contribute to the block's PoW. In the case of a fork, our scheme relies on the strongest chain rule, however, the PoW is computed differently than in Bitcoin. For every chain its PoW is calculated as presented by the *chainPoW()* procedure in Algorithm 1. Every chain is parsed and for each of its blocks the PoW is calculated by adding:

1. the PoW of the strong header, computed as T_{max}/T_s, where T_{max} is the maximum target value, and
2. the accumulated PoW of all associated weak headers, counting each weak header equally as T_{max}/T_w.

Then the chain's PoW is expressed as just the sum of all its blocks' PoW. Such an aggregated chain's PoW is compared with the competing chain(s). The chain with the largest aggregated PoW is determined as the current one. As difficulty in our protocol changes over time, the strong target T_s and PoW of weak headers are relative to the maximum target value T_{max}. We assume that nodes of the network check whether every difficulty window is computed correctly (we skipped this check in our algorithms for easy description).

Including and empowering weak headers in our protocol moves away from Bitcoin's "binary" granularity and gives blocks better expression of the PoW they convey. An example is presented in Figure 2. For instance, nodes having the blocks B_i and B_i' can immediately decide to follow the block B_i as it has more weak headers associated, thus it has accumulated more PoW than the block B_i'.

An exception to this rule is when miners solve conflicts. Namely, on receiving a new block, miners run the algorithm as presented, however, they also take into consideration PoW contributions of known weak headers that point to the last blocks. For instance, for a one-block-long fork within the same difficulty window, if a block B includes l weak headers and a miner knows of k weak headers pointing to B, then that miner will select B over any competing block B' that includes l' weak and has k' known weak headers pointing to it if $l+k > l'+k'$. Note that this rule incentivizes miners to propagate their solutions as quickly as possible as competing blocks become "stronger" over time.

4.4 Rewarding Scheme

The rewards distribution is another crucial aspect of StrongChain and it is presented by the *rewardBlock()* procedure from Algorithm 1. The miner that found the strong header receives the full reward R. Moreover, in contrast to Bitcoin, where only the "lucky" miner is paid the full reward, in our scheme all miners that have contributed to the block's PoW (i.e., whose weak headers are included) are paid by commensurate rewards to the provided PoW. A weak header finder receive a fraction of R, i.e., $\gamma * c * R * T_s/T_w$, as a reward for its corresponding solution contributing to the total PoW of a particular branch, where the γ parameter influences the relative impact of weak header rewards and c is just a scaling constant (we discuss their potential values and implications in Section 5). Moreover, we do not limit weak header rewards and miners can get multiple rewards for their weak headers within a single block. Similar reward mechanisms are present in today's mining pools (see Section 8), but unlike them, weak header rewards in StrongChain are independent of each other. Therefore, the reward scheme is not a zero-sum game and miners cannot increase their own rewards by dropping weak headers of others (actually, as we discuss in Section 5, they can only lose since their potential solutions would have less PoW without others' weak headers). Furthermore, weak header rewards decrease significantly the mining variance as miners can get steady revenue, making the system more decentralized and collaborative.

As mentioned before, the number of weak headers of a block is unlimited, they are rewarded independently (i.e., do not share any reward), and all block rewards in our system are proportional to the PoW contributed. In such a setting, a mechanism incentivizing miners to terminate a block creation is needed (without such a mechanism, miners could keep creating huge blocks with weak headers only). In order to achieve this, StrongChain always attributes block transaction fees ($B.TxFees$) to the finder of the strong header (who also receives the full reward R).

Note that in our rewarding scheme, the amount of newly minted coins is always at least R, and consequently, unlike Bitcoin or Ethereum [48], the total supply of the currency in our protocol is not upper-bounded. This design decision is made in accordance with recent results on the long-term instability of deflationary cryptocurrencies [4, 27, 47].

4.5 Timestamps

In StrongChain, we follow the Bitcoin rules on constraining timestamps (see Section 2.1), however, we redefine how block timestamps are interpreted. Instead of solely relying on a timestamp put by the miner who mined the block, block timestamps in our system are derived from the strong header and all weak headers included in the corresponding block. The algorithm to derive a block's timestamp is presented as

getTimestamp() in Algorithm 1. A block's timestamp is determined as a weighted average timestamp over the strong header's timestamp and all timestamps of the weak headers included in the block. The strong header's timestamp has a weight of 1, while weights of weak header timestamps are determined as their PoW contributed (namely, a weak header's timestamp has a weight of the ratio between the strong target and the weak target). Therefore, the timestamp value is adjusted proportionally to the mining power associated with a given block. That change reflects an average time of the block creation and mitigates miners that intentionally or misconfigured put incorrect timestamps into the blockchain. We show the effectiveness of this approach in Section 5.5.

4.6 SPV Clients

Our protocol supports light SPV clients. With every new block, an SPV client is updated with the following information:

$$hdr, hdr_0, hdr_1, ..., hdr_n, BTproof, \tag{4}$$

where *hdr* is a strong header, hdr_i are associated weak headers, and *BTproof* is an inclusion proof of a binding transaction that contains a hash over the weak headers (see Equation 3). Note that headers contain redundant fields, thus as described in Section 4.2, they can be provided to SPV clients efficiently.

With this data, the client verifies fields of all headers, computes the PoW of the block (analogous, as in *chainPoW()* from Algorithm 1), and validates the *BTproof* proof to check whether all weak headers are correct, and whether the transaction is part of the blockchain (the proof is validated against *TxRoot* of *hdr*). Afterward, the client saves the strong header *hdr* and its computed PoW, while other messages (the weak headers and the proof) can be dropped.

5 Analysis

In this section, we evaluate the requirements discussed in Section 2.3. We start with analyzing StrongChain's efficiency and practicality. Next, we study how our design helps with reward variance, chain quality, and security.

5.1 Efficiency and Practicality

For the efficiency, it is important to consider the main source of additional load on the bandwidth, storage, and processing power of the nodes: the weak headers. Hence, in the following section we analyze the probability distribution of the number of weak headers. Next, we discuss the value of the impact of the parametrization on the average block rewards.

5.1.1 Number of Weak Headers

In Bitcoin, we assume that hashes are drawn randomly between 0 and $T_{max} = 2^{256} - 1$. Hence, a single hash being smaller than T_w is a *Bernoulli trial* with parameter $p_w = T_w/2^{256}$. The number of hashes tried until a weak header is found is therefore *geometrically* distributed, and the time in seconds between two weak headers is approximately *exponentially* distributed with rate ηp_w, where η is the total hash rate per second and p_w is chosen such that $\eta p_w \approx 1/600$. When a weak header is found, it is also a strong block with probability p_s/p_w (where $p_s = T_s/2^{256}$), which is again a Bernoulli trial. Hence, the probability distribution of the number of weak headers found between two strong blocks is that of the number of trials before the first successful trial — as such, it also follows a geometric distribution, but with mean $p_w/p_s - 1$.[5] For example, for $T_w/T_s = 2^{10}$ this means that the average number of weak headers per block equals 1023. With 60 bytes per weak header (see Section 4.2) and 1MB per Bitcoin block, this would mean that the load increases by little over 6% on average with a small computational overhead introduced (see details in Section 7). The probability of having more than 16667 headers (or 1MB) in a block would equal.[6]

$$\left(1 - \frac{p_s}{p_w}\right)^{16668} = \left(1 - 2^{-10}\right)^{16668} \approx 8.4603 \cdot 10^{-8}.$$

Since around 51,000 Bitcoin blocks are found per year, this is expected to happen roughly once every 230 years.

5.1.2 Total Rewards

To ease the comparison to the Bitcoin protocol, we can enforce the same average mining reward per block (currently 12.5 BTC). Let R denote Bitcoin's mining reward. Since we reward weak headers as well as strong blocks, we need to scale all mining rewards by a constant c to ensure that the total reward remains unchanged — this is done in the *rewardBlock* function in Algorithm 1. As argued previously, we reward all weak headers equally by $\gamma R T_s/T_w$. Since the average number of weak headers per strong block is $T_w/T_s - 1$, this means that the expected total reward per block (i.e., strong block and weak header rewards) equals $cR + cR\gamma T_s/T_w \cdot (T_w/T_s - 1)$. Hence, we find that

$$c = \frac{1}{1 + \gamma(T_w/T_s - 1)T_s/T_w},$$

[5] Another way to reach this conclusion is as follows: the number of weak headers found in a fixed time interval is Poisson distributed, and it can be shown that the number of Poisson arrivals in an interval with exponentially distributed length is geometrically distributed.

[6] For an actual block implementation, we advice to introduce separate spaces for weak headers and transactions. With such a design, miners do not have incentives and trade-offs between including more transactions instead of weak headers.

which for large values of T_w/T_s is close to $1/(1+\gamma)$. This means that if $\gamma = 1$, the strong block and weak header rewards contribute almost equally to a miner's total reward.

5.2 Reward Variance of Solo Mining

The tendency towards centralization in Bitcoin caused by powerful mining pools can largely be attributed to the high reward variance of solo mining [15, 37]. Therefore, keeping the reward variance of a solo miner at a low level is a central design goal.

Let $\mathbf{R}^{BC}$ and $\mathbf{R}^{SC}$ be the random variables representing the per-block rewards for an α-strong solo miner in Bitcoin and in StrongChain, respectively. For any given strong block in both protocols, we define the random variable $\mathbf{I}$ as follows:

$$\mathbf{I} = \begin{cases} 1 & \text{the block is mined by the solo miner,} \\ 0 & \text{otherwise.} \end{cases}$$

By definition, $\mathbf{I}$ has a Bernoulli distribution, which means that $\mathbb{E}(\mathbf{I}) = \alpha$ and $\mathrm{Var}(\mathbf{I}) = \alpha(1-\alpha)$, where $\mathbb{E}$ and Var are the mean and variance of a random variable respectively. The following technical lemma will aid our analysis of the reward variances of solo miners:

Lemma 1. *Let $X_1, X_2, \ldots$ be independent and identically distributed random variables. Let N be defined on $\{0,1,\ldots\}$ and independent of $X_1, X_2, \ldots$. Let N and all X_i have finite mean and variance. Then*

$$\mathrm{Var}\left(\sum_{i=1}^{N} X_i\right) = \mathbb{E}(N)\mathrm{Var}(X) + \mathrm{Var}(N)(\mathbb{E}(X))^2.$$

Proof. See [7]. □

Reward Variance of Solo Mining in Bitcoin. Bitcoin rewards the miner of a block creator with the fixed block reward R and the variable (total) mining fees, which we denote by the random variable $\mathbf{F}$. Therefore, we have

$$\mathbf{R}^{BC} = \mathbf{I}(R + \mathbf{F}),$$

which implies that

$$\mathrm{Var}(\mathbf{R}^{BC}) = R^2\mathrm{Var}(\mathbf{I}) + \mathrm{Var}(\mathbf{IF}). \tag{5}$$

Since $\mathbf{IF} = \sum_{i=0}^{\mathbf{I}} \mathbf{F}$, we can use Lemma 1 (substituting $\mathbf{I}$ for N and $\mathbf{F}$ for X) to obtain

$$\mathrm{Var}(\mathbf{IF}) = \mathbb{E}(\mathbf{I})\mathrm{Var}(\mathbf{F}) + \mathrm{Var}(\mathbf{I})\mathbb{E}^2(\mathbf{F}). \tag{6}$$

Combining (5) and (6) gives

$$\begin{aligned} \mathrm{Var}(\mathbf{R}^{BC}) &= \mathbb{E}(\mathbf{I})\mathrm{Var}(\mathbf{F}) + \mathrm{Var}(\mathbf{I})\left(\mathbb{E}^2(\mathbf{F}) + R^2\right) \\ &= \alpha\mathrm{Var}(\mathbf{F}) + \alpha(1-\alpha)\left(\mathbb{E}^2(\mathbf{F}) + R^2\right). \end{aligned} \tag{7}$$

When the fees are small compared to the mining reward, this simplifies to $\alpha(1-\alpha)R^2$. By comparison, in [37] the variance of the block rewards (without fees) earned by a solo miner across a time period of t seconds is studied, and found to equal $\alpha R^2 t/600$.[7] The same quantity can be obtained by using (7), Lemma 1, and the total number of strong blocks found (by any miner) after t seconds of mining (which has a Poisson distribution with mean $t/600$).

Reward Variance of Solo Mining in StrongChain. For $\mathbf{R}^{SC}$, we assume that the solo miner has $\mathbf{N}$ weak headers included in the strong block, and that she obtains $c\gamma RT_s/T_w$ reward per weak header. Then the variance equals

$$\mathbf{R}^{SC} = \mathbf{I}(cR + \mathbf{F}) + c\gamma RT_s/T_w\mathbf{N},$$

where c is the scaling constant derived in Section 5.1.2. Hence, by applying Lemma 1, we compute the variance of $\mathbf{R}^{SC}$ as

$$\begin{aligned} \mathrm{Var}(\mathbf{R}^{SC}) = (cR)^2\mathrm{Var}(\mathbf{I}) + \mathrm{Var}(\mathbf{IF}) \\ + (c\gamma RT_s/T_w)^2\mathrm{Var}(\mathbf{N}). \end{aligned} \tag{8}$$

The first term, which represents the variance of the strong block rewards, is similar to Bitcoin but multiplied by c^2. If we choose $T_w/T_s = 1024$ and $\gamma = 10$ (this choice is motivated later in this section), c^2 roughly equals 0.0083, which is quite small. Hence, the strong block rewards have a much smaller impact on the reward variance in our setting than in Bitcoin. The second term, which represents the variance of the fees, is precisely the same as for Bitcoin. The third term represents the variance of the weak header rewards, which in turn completely depends on $\mathrm{Var}(\mathbf{N})$.

To evaluate $\mathrm{Var}(\mathbf{N})$, we again use Lemma 1: let, for any weak header, $\mathbf{J}$ equal 1 if it is found by the solo miner, and 0 otherwise. Also, let $\mathbf{L}$ be the total number of weak headers found in the block, so including those not found by the solo miner. Then $\mathbf{N}$ is the sum of $\mathbf{L}$ instances of $\mathbf{J}$, where $\mathbf{J}$ has a Bernoulli distribution with success probability α (and therefore $\mathbb{E}(\mathbf{J}) = \alpha$ and $\mathrm{Var}(\mathbf{J}) = \alpha(1-\alpha)$), and $\mathbf{L}$ has a geometric distribution with success probability T_s/T_w (and therefore $\mathbb{E}(\mathbf{L}) = T_w/T_s - 1$ and $\mathrm{Var}(\mathbf{L}) = (T_w/T_s)^2 - T_w/T_s$. By substituting this into (8), we obtain:

$$\begin{aligned} \mathrm{Var}(\mathbf{N}) &= \mathbb{E}(\mathbf{L})\mathrm{Var}(\mathbf{J}) + \mathrm{Var}(\mathbf{L})(\mathbb{E}(\mathbf{J}))^2 \\ &= (T_w/T_s - 1)\alpha(1-\alpha) \\ &\quad + ((T_w/T_s)^2 - T_w/T_s)\alpha^2 \end{aligned} \tag{9}$$

Substituting (9) for $\mathrm{Var}(\mathbf{N})$ and $\alpha(1-\alpha)$ for $\mathrm{Var}(\mathbf{I})$ into (8) then yields an expression that can be evaluated for different values of T_w/T_s, γ, and α, as we discuss in the following.

[7] In particular, it is found to be $htR^2/(2^{32}D)$, where $h = \alpha\eta$ and $\eta/(2^{32}D) \approx 1/600$.

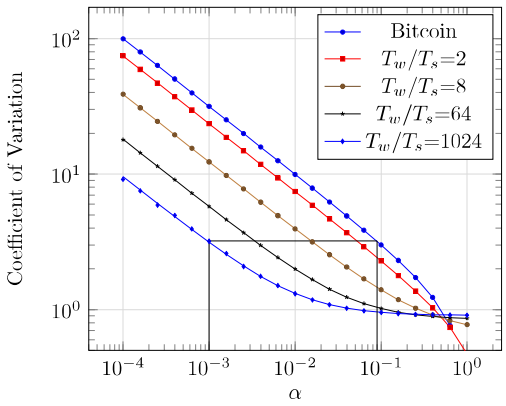


Figure 3: *Coefficients of variation* for the total rewards of α-strong miners for different strong/weak header difficulty ratios ($T_w/T_s = 1$ corresponds to Bitcoin). The lines indicate the exact results obtained using our analysis, whereas the markers indicate simulation results. We used $\gamma = \log_2(T_w/T_s)$. The black lines indicate that for $T_w/T_s = 1024$, a 0.1%-strong miner has a coefficient of variation that is comparable to a 9%-strong miner's in Bitcoin.

Comparison The difference between between (7) and (8) in practice is illustrated in Figure 3. This is done by comparing for a range of different values of α the block rewards' *coefficient of variation*, which is the ratio of the square root of the variance to the mean.

To empirically validate the results, we have also implemented a simulator in Java that can evaluate Bitcoin as well as StrongChain. We use two nodes, one of which controls a share α of the hash rate, and another controls a share $1-\alpha$. The nodes can broadcast information about blocks, although we abstract away from most of the other network behavior. We do not consider transactions (i.e., we mine empty blocks), and we use a simplified model for the propagation delays: delays are drawn from a Weibull distribution with shape parameter 0.6 [31], although for Figure 3 the mean was chosen to be negligible (more realistic values are chosen for Table 1).

The black lines in Figure 3 demonstrate that when $T_w/T_s = 1024$, a miner with share 0.1% of the mining power has the same coefficient of reward variation as a miner with stake 9% in Bitcoin. Also note that for $T_w/T_s = 1024$ and $\alpha \geq 1\%$, the coefficient of variation does not substantially decrease anymore, because nearly all of the reward variance is due to the number of weak headers. Hence, there would be fewer reasons for miners in our system to join large and cooperative mining pools, which has a positive effect on the decentralization of the system.

5.3 Chain Quality

One measure for the 'quality' of a blockchain is the stale rate of blocks [16], i.e., the percentage of blocks that appear during forks and do not make it onto the main chain. This is closely related to the notion of mining power utilization [10], which is the fraction of mining power used for non-stale blocks. In StrongChain, the stale rate of strong blocks may increase due to high latency. After all, while a new block is being propagated through the network, weak headers that strengthen the previous block that are found will be included by miners in their PoW calculation. As a result, some miners may refuse to switch to the new block when it arrives. However, the probability of this happening is very low: because each weak header only contributes T_s/T_w to the difficulty of a block, it would take on average 10 minutes to find enough weak headers to outweigh a block. As we can see in Table 1, the effect on the stale rate is negligible even for very high network latencies (i.e., 53 seconds). We also emphasize that the strong block stale rate is less important in our setting, as the losing miner still would benefit from her weak headers appended to the winning block.

Regarding the fairness, defined as the ratio between the observed share of the rewards (we simulate using one 10%-strong miner and a 90%-strong one) and the share of the mining power, we see that StrongChain does slightly worse than Bitcoin for high network latencies. The most likely cause is that due to the delay in the network, the 10%-strong miner keeps mining on a chain that has already been extended for longer than necessary. This gives the miner a slight disadvantage compared to the 90%-strong miner.

5.4 Security

One of the main advantages of StrongChain is the added robustness to selfish mining strategies akin to those discussed in [11] and [39]. In selfish mining, attackers aim to increase their share of the earned rewards by tricking other nodes into mining on top of a block that is unlikely to make it onto the main chain, thus wasting their mining power. This may come at a short-term cost, as the chance of the attacker's blocks going stale is increased — however, the difficulty rescale that occurs every 2016 blocks means that if the losses to the honest nodes are structural, the difficulty will go down and the gains of the attacker will increase.

In the following, we will consider the selfish mining strategy of [11],[8] described as follows:

- The attacker does not propagate a newly found block until she finds at least a second block on top of it, and then only if the difference in difficulty between her chain and the strongest known alternative chain is between zero and R.
- The attacker adopts the strongest known alternative chain if its difficulty is at least greater than her own by R.

[8] The 'stubborn mining' strategy of [39] offers mild improvements over [11] for powerful miners, but the comparison with StrongChain is similar. We have also modeled StrongChain using a Markov decision process, in a way that is similar to the recently proposed framework of [51]. Due to the state space explosion problem, we could only investigate the protocol with a small number of expected weak headers, but we have not found any strategies noticeably that are better than those presented.

	Latency	Bitcoin	StrongChain						
			$T_w/T_s = 2$	$T_w/T_s = 64$			$T_w/T_s = 1024$		
			$\gamma = 1$	$\gamma = 1$	$\gamma = 7$	$\gamma = 63$	$\gamma = 1$	$\gamma = 10$	$\gamma = 1023$
strong stale rate	low	.0023	.0025	.0021	.0026	.0028	.0023	.0025	.0019
	medium	.0073	.0082	.0087	.0077	.0078	.0084	.0067	.0081
	high	.0243	.0297	.0242	.0263	.0247	.0274	.0249	.0263
weak stale rate	low	—	.0043	.0047	.0049	.0046	.0049	.0047	.0047
	medium	—	.0142	.0151	.0154	.0149	.0145	.0147	.0149
	high	—	.0400	.0459	.0474	.0452	.0469	.0455	.0463
fairness	low	.9966	.9814	.9749	.9747	.9838	.9645	.9809	.9812
	medium	.9276	.9384	.9570	.9360	.9364	.9329	.9400	.9385
	high	.7951	.7640	.7978	.7820	.7757	.7756	.7766	.7775

Table 1: For several different protocols, the strong block stale rate, weak header rate, and the 'fairness' for an α-strong honest miner with $\alpha = 0.1$. Here, fairness is defined as the ratio between the observed share of the reward and the 'fair' share of the rewards (i.e, 0.1). 'Low', 'medium', and 'high' latencies refer to the mean of the delay distribution in the simulator; these are roughly 0.53 seconds, 5.3 seconds, and 53 seconds respectively. The simulations are based on a time period corresponding to roughly 20 000 blocks.

In Figure 4a, we have depicted the profitability of this selfish mining strategy for different choices of T_w/T_s. As we can see, for $T_w/T_s = 1024$ the probability of being 'ahead' after two strong blocks is so low that the strategy only begins to pay off when the attackers' mining power share is close to 45% — this is an improvement over Bitcoin, where the threshold is closer to 33%.

StrongChain does introduce new adversarial strategies based on the mining of new weak headers. Some examples include not broadcasting any newly found weak blocks ("reclusive" mining), refusing to include the weak headers of other miners ("spiteful" mining), and postponing the publication of a new strong block and wasting the weak headers found by other miners in the meantime. In the former case, the attacker risks losing their weak blocks, whereas in both of the latter two cases, the attacker risks their strong block going stale as other blocks and weak headers are found. Hence, these are not cost-free strategies. Furthermore, because the number of weak headers does not affect the difficulty rescale, the attacker's motive for increasing the stale rate of other miners' weak headers is less obvious (although in the long run, an adversarial miner could push other miners out of the market entirely, thus affecting the difficulty rescale).

In Figure 4b, we have displayed the relative payout (with respect to the total rewards) of a reclusive α-strong miner — this strategy does not pay for any $\alpha < 0.5$. In Figure 4c, we have depicted the relative payoff of a spiteful mine who does not include other miners' weak blocks unless necessary (i.e., unless others' weak blocks together contribute more than R to the difficulty, which would mean that any single block found by the spiteful miner would always go stale). For low latencies (the graphs were generated with an average latency of 0.53 seconds), the strategy is almost risk-free, and the attacker does manage to hurt other miners more than herself, leading to an increased relative payout. However, as displayed in Figure 4d, there are no absolute gains, even mild

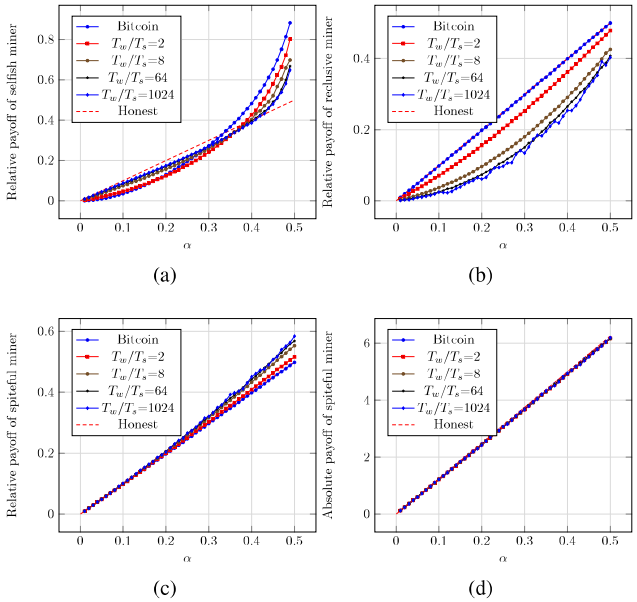
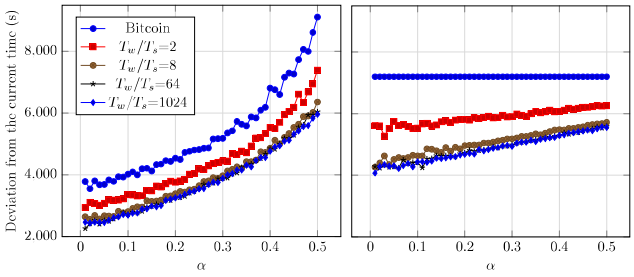


Figure 4: Payoffs of an α-strong adversarial miner for different strategies. Figure (a): relative payoff of a *selfish* miner following the strategy of [11], compared to an $(1-\alpha)$-strong honest miner. Figure (b): relative payoff of a *reclusive* miner who does not broadcast her weak blocks. Figure (c): *relative* payoff (with respect to the rewards of all miners combined) of a *spiteful* miner, who does not include other miners' weak blocks unless necessary. Figure (d): *absolute* payoff of a *spiteful* miner, with 12.5 BTC on average awarded per block. We consider Bitcoin and StrongChain with different choices of T_w/T_s, with $\gamma = \log_2(T_w/T_s)$.

losses. As mentioned earlier, the weak headers do not affect the difficulty rescale so there is no short-term incentive to engage in this behavior — additionally there is little gain in computational overhead as the attacker still needs to process her own weak headers. In Section 6.1 we will discuss protocol updates that can mitigate these strategies regardless.



(a) (b)

Figure 5: The deviation from the network time that an α-strong adversary can introduce for its mined blocks by slowing (the left graph) and accelerating (the right graph) timestamps.

5.5 More Reliable Timestamps

Finally, we conducted a series of simulations to investigate how the introduced redefinition of timestamps interpretation (see *getTimestamp()* in Algorithm 1 and Section 4.5) influences the timestamp reliability in an adversarial setting. We assume that an adversary wants to deviate blockchain timestamps by as much as possible. There are two strategies for such an attack, i.e., an adversary can either "slow down" timestamps or "accelerate" them. In the former attack, the best adversary's strategy is to use the minimum acceptable timestamp in every header created by the adversary. Namely, the adversary sets its timestamps to the median value of the last eleven blocks (a header with a lower timestamp would not be accepted by the network – see Section 2.2). As for the latter attack, the adversary can analogously bias timestamps towards the future by putting the maximum acceptable value in all her created headers. The maximum timestamp value accepted by network nodes is two hours in the future with respect to the nodes' internal clocks (any header with a higher timestamp would be rejected).

In our study, we assume that honest nodes maintain the network time which the adversary tries to deviate from. We consider the worst-case scenario, which is when the adversary, who also biases all her header timestamps, mines the strong block. We measure (over 10000 runs) how such a malicious timestamp can be mitigated by our redefinition of the block timestamps interpretation. We present the obtained results in Figure 5, and as shown in the slow-down case our protocol achieves much more precise timestamps than Bitcoin (the difference is around 2000 seconds). Similarly, when the adversary accelerates timestamps, our protocol can mitigate it effectively, adjusting the adversarial timestamps by 2000-3500 seconds towards the correct time. This effect is achieved due to the block's timestamp calculation as a weighted average of all block headers. The adversary could try to remove honest participants' weak headers in order to give a stronger weight to its malicious timestamps, but in Section 6.1 we discuss ways to mitigate it.

6 Discussion

6.1 Impact of the Parameter Choice

The results presented in Section 5 required several parameters to be fixed. First of all, we had to choose γ, which determines the relative contribution of the weak headers to the total mining rewards. Second, there is the contribution of the weak blocks to the chain difficulty, which in the *chainPoW()* function in Algorithm 1 was set to be only T_{max}/T_w. This means that the PoW of a weak header relative to a strong block's PoW — we call this the *difficulty factor* — is fixed to be T_s/T_w. In the following, we first discuss the relevant trade-offs and then motivate our choice.

When both γ and the difficulty factor are low, the impact on the reward variance of the miners (as per Figure 3) will be mild as the strong block rewards still constitute about 50% of the mining rewards. This reliance on the block rewards also means that 'spiteful' mining as discussed in Section 5.4 is disincentivized as the risk of strong blocks going stale still has a considerable impact on total rewards. However, selfish mining as proposed in [11] relies on several blocks in a row being mined in secret, and even for a low difficulty factor it becomes much harder for the attacker's chain to stay 'ahead' of the honest chain, as the latter accumulates strength from the weak headers at a faster rate. Hence, in this setting we only gain protection against selfish mining.

When γ is high but the difficulty factor is not (which is the setting of Section 5), then in addition to disincentivizing selfish mining, the reward variances become much less dependent on the irregular strong block rewards. This benefits small miners and reduces centralization, as we also discuss in Section 6.2. However, spiteful mining will have more of an impact as the possible downside (i.e., a latency-dependent increase in the strong block stale rate) will have less of an effect on the total rewards.

When both γ and the difficulty factor are high, the impact of spiteful mining is mitigated. The reason is that blocks quickly accumulate enough weak headers to outweigh a strong block, and in this case spiteful miners need to adopt the other weak blocks or risk their strong block becoming stale with certainty. The downside in this setting is that the system-wide block stale rate is increased. For example, if each weak header contributes $\gamma T_s/T_w$ to the difficulty and $\gamma = 10$, then after (on average) one minute enough weak headers are found to outweigh a strong block, and if propagation of the block takes longer than one minute then some miners will not adopt the block, increasing the likelihood of a fork.

In this paper, we have chosen the second of the three approaches — a moderately high γ, yet a minor difficulty factor. The reason is that the only downside (spiteful mining) was considered less of a concern than the other downsides (namely a low impact on reward variances and a higher block

stale rate respectively) for two reasons: a) because spiteful mining does not lead to clear gains for the attacker, and b) because it only has a large impact on other miners' profits if the attacker controls a large share of the mining power, whereas the emergence of large mining pools is exactly what StrongChain discourages. The specific value of $\gamma = 10$ for $T_w/T_s = 1024$ (or $\gamma = \log_2(T_w/T_s)$ in general) was chosen to sufficiently reduce mining reward variances, yet leaving some incentive to discourage spiteful mining.

The protocol can be further extended to disincentivize spiteful mining, e.g., by additionally awarding strong block finders a reward that is proportional to the number of weak headers included. This would make StrongChain more similar to Ethereum, where stale block ('uncle') rewards are paid both to the miner of a stale block and the miner of the successful block that included it (see Section 8 for additional discussion of Ethereum's protocol). However, we leave such modifications and their consequences as future work.

6.2 StrongChain and Centralized Mining

Decentralized mining pools aim to reduce variance while providing benefits for the system (i.e., trust minimization for pools, and a higher number of validating nodes). However, mining in Bitcoin is in fact dominated by centralized mining pools whose value proposition, over decentralized pools, is an easy setup and participation. Therefore, rational miners motivated by their own benefit, instead of joining decentralized pools prefer centralized "plug-and-play" mining. It is still debatable whether centralized mining pools are beneficial or harmful to the system. However, it has been proved multiple times, that the concentration of significant computing power caused by centralized mining is risky and should be avoided, as such a strong pool has multiple ways of misbehaving and becomes a single point of failure in the system. One example is the pool GHash.IO, which in 2014 achieved more than 51% of the mining power. This undermined trust in the Bitcoin network to the extent that the pool was forced to actively ask miners to join other pools [12].

In order to follow incentives of rational miners, StrongChain does not require any radical changes from them and is compatible with centralized mining pools; however, it is specifically designed to mitigate their main security risk (i.e., power centralization). In StrongChain such pools could be much smaller than in Bitcoin (due to minimized variance) and to support this argument we conducted a study. We listed the largest Bitcoin mining pools and their shares in the global mining power (according to `https://www.blockchain.com/en/pools` as for the time of writing). Then for each pool, we calculated what would be the pool size in StrongChain to offer the miner the same payout variance experience, and the variance reduction factor in that case. As shown in Table 2, for the Bitcoin largest mining pool with 18.1% of the global hash rate, an equivalent pool in StrongChain (to provide miners the same reward experience) could be as small as 0.245% of the hash rate – around 74 times smaller. Even better reduction factors are achieved for smaller pools. Therefore, our study indicates that StrongChain makes the size of a pool almost an irrelevant factor for miners' benefits (i.e., there is no objective advantage of joining a large pool over a medium or a small one). Therefore we envision that with StrongChain, centralized mining pools will naturally be much more distributed.

Mining Pool	Pool Size		Size
	Bitcoin	StrongChain	Reduction
BTC.com	18.1%	0.245%	74×
F2Pool	14.1%	0.172%	82×
AntPool	11.7%	0.135%	87×
SlushPool	9.1%	0.099%	92×
ViaBTC	7.5%	0.079%	95×
BTC.TOP	7.1%	0.074%	96×
BitClub	3.1%	0.030%	103×
DPOOL	2.6%	0.025%	104×
Bitcoin.com	1.9%	0.018%	106×
BitFury	1.7%	0.016%	106×

Table 2: Largest Bitcoin mining pools and the corresponding pool sizes in StrongChain offering the same relative reward variance ($T_w/T_s = 1024$ and $\gamma = 10$).

Limitations

As discussed, it is beneficial for the system if as many participants as possible independently run full nodes; however, miners join large centralized pools not only due to high reward variance. Other potential reasons include the minimization of operational expenses as running a full node is a large overhead, higher efficiency since large pools may use high-performance hardware and network, better ability to earn extra income from merge mining [29], better protection against various attacks, anonymity benefits, etc. This work focuses on removing the reward variance reason. Although we believe that StrongChain would produce a larger number of small pools in a natural way, it does not eliminate the other reasons, so some large centralized pools may still remain. Luckily, our system is orthogonal to multiple concurrent solutions. For instance, StrongChain could be easily combined with non-outsourceable puzzle schemes (see Section 8) to increase the number of full nodes by explicitly disincentivizing miners from outsourcing their computing power. We leave such a combination as interesting future work.

7 Realization in Practice

We implemented our system in order to investigate its feasibility and confirm the stated properties. We implemented a StrongChain full node with interactive client in Python, and

our implementation includes the complete logic from Algorithm 1 and all functionalities required to have a fully operational system (communication modules, message types, validation logic, etc...).[9] As described before, the main changes in our implementation to the Bitcoin's block layout are:

- a new (20B-long) *Coinbase* header field,
- a new binding transaction protecting all weak headers of the block,
- removed original coinbase transaction,

where a binding transaction has a single (32B-long) output as presented in Equation 3.[10]

Weak headers introduced by our system impact the bandwidth and storage overhead (when compared with Bitcoin). Due to compressing them (see Section 4.2), the size of a single weak header in a block is 60B. For example, with an average number of weak headers equal 1024, the storage and bandwidth overhead increases by about 61.5KB per block (e.g., with 64 weak headers, the overhead is only 3.8KB). Taking into account the average Bitcoin block size of about 1MB (the average between 15 Oct and 15 Nov 2018[11]), 1024 weak headers constitute around 6.1% of today's blocks, while 64 headers only 0.4%. The same overhead is introduced to SPV clients, that besides a strong header need to obtain weak headers and a proof for their corresponding binding transaction. Thus, an SPV update (every 10 minutes) would be 61.5KB or 3.8KB on average for 1024 or 64 weak headers, respectively. However, since only strong headers authenticate transactions, SPV clients do not need to store weak headers and after they are validated, they can remove them (they need to just calculate and associate their aggregated PoW with the strong header). Such an approach would not introduce any noticeable storage overhead on SPV clients.

Nodes validate all incoming weak headers; however, this overhead is a single hash computation and simple sanity checks per header. Even with our unoptimized implementation running on a commodity PC the total validation of a single weak header takes around 50μs on average (i.e., 51ms per 1024 headers on a single core). Given that we do not believe this overhead can lead to more serious denial-of-service attacks than ones already known and existing in Bitcoin (e.g., spamming with large invalid blocks). Additionally, StrongChain can adopt prevention techniques present in Bitcoin, like blacklisting misbehaving peers.

[9] Our implementation is available at `https://github.com/ivan-homoliak-sutd/strongchain-demo/`.

[10] An alternative choice is to store a hash of weak headers in a header itself. Although simpler, that option would incur a higher overhead if the number of weak headers is greater than several.

[11] `https://www.blockchain.com/en/charts/avg-block-size`

8 Related work

Employing weak solutions (and their variations) in Bitcoin is an idea [36,38] circulating on Bitcoin forums for many years. Initial proposals leverage weak solutions (i.e., *weak blocks*) for faster transaction confirmations [45,46], for signaling the current working branch of particular miners [13,14,30]. Unfortunately, most of these proposals come without necessary details or lack rigorous analysis. Below, we discuss the most related attempts that have been made to utilize weak or stale blocks in PoW-based decentralized consensus protocols. We compare these systems in Table 3 according to their reward and PoW calculation schemes.

Subchains. Rizun proposes Subchains [35], where a chain of weak blocks (a so-called subchain) bridging each pair of subsequent strong blocks is created. The design of Subchain puts a special focus on increasing the transaction throughput and the double-spend security for unconfirmed transactions. Rizun argues that since the (weak) block interval of subchains is much smaller than the strong block interval, it allows for faster (weak) transaction confirmations. Another claimed advantage of such an approach is that during the process of building subchains, the miners can detect forks earlier, and take actions accordingly to avoid wasting computational power. However, the design of Subchain sidesteps a concrete security analysis at the subchain level. In detail, by using a chaining data structure where one weak header referencing the previous weak header in a subchain, it introduces high stale rate on a subchain. More importantly, due to applying a Bitcoin-like subchain selection policy in case of conflicts, this approach is vulnerable to the selfish mining attack launched on a subchain.

Flux. Based on similar ideas as Subchain, Zamyatin et al. propose Flux [49]. In contrast to Subchain, Flux shares rewards (from newly minted coins and transaction fees) evenly among the finders of weak and strong blocks according to the computational resources they invested. This approach reduces the reward variance of miners, and therefore mitigates the need for large mining pools, which is beneficial for the system's decentralization. In addition, simulation experiments show that Flux renders selfish mining on the main chain less profitable. However, alike Subchains, Flux employs a chain structure for weak blocks, which inevitably introduces race conditions, increasing the stale rate of weak blocks and making it more susceptible to selfish mining attacks at the subchain level. The designers of Flux let both of these issues open and discuss the potential application of GHOST [41] to subchains. Another limitation of this work is that the authors do not analyze the requirements on space consumption when putting possibly a high number of overlapping transactions into Flux subchains, which could negatively influence network, storage, and processing resources.

Remarks on Subchain and Flux. One important difference between our approach and the above two designs is that we

	Bitcoin v0.1	Bitcoin	Fruitchains	Flux	StrongChain
Reward (strong)	$R+F$	$R+F$	0	$(R+F)/(E+1)$	$cR+F$
Reward (weak)	0	0	$(R+F)/E$	$(R+F)/(E+1)$	$c\gamma RT_s/T_w$
Chain weight contrib. (strong)	1	T_{max}/T_s	T_{max}/T_s	T_{max}/T_s	T_{max}/T_s
Chain weight contrib. (weak)	0	0	0	0	T_{max}/T_w

Table 3: The comparison of reward and PoW computation schemes of StrongChain and the related systems. (F: block transaction fees, E: expected number of weak headers per block. The entries for Flux are approximations for the PPLNS scheme in P2Pool, on which it is based.)

adopt a flat hierarchy for the weak blocks, which not only eliminates the possibility of selfish mining in a set of weak solutions, but also avoids the issue of stale rate of weak blocks. In contrast, both Subchain and Flux employ a chain structure for weak blocks, inevitably making them more susceptible to selfish mining attacks at the subchain level. Moreover, in our approach rewards are not shared, therefore miners can only benefit from appending received weak solutions. In addition, none of Subchain and Flux provide a concrete implementation demonstrating their applicability.

FruitChains. Another approach to address the mining variance and selfish mining issues is the FruitChains protocol proposed by Pass and Shi [32]. In FruitChains, instead of directly storing the records inside blocks, the records or transactions are put inside "fruits" with relatively low mining difficulties. Fruits then are appended to a blockchain via blocks which are mined with a higher difficulty. Mined fruits and blocks yield rewards, hence, miners can be paid more often and there is no need to form a mining pool.

However, some practical and technical details of FruitChains lead to undesired side effects. First, the scheme allows fruits with small difficulties to be announced and accepted by other miners. With too small difficulty it could render high transmission overheads or even potential denial-of-service attacks and its effects on the network are not investigated. On the other hand, too high fruit difficulty could result in a low transaction throughput and a high reward variance. Second, duplicate fruits are discarded, even though they might be found by different miners – this naturally implies some stale fruit rate (uninvestigated in the paper). Similarly, it is unclear would a block finder have an incentive to treat all fruits equally and to not prioritize her mined fruits (especially when fruits are associated with transaction fees). Moreover, fruits that are not appended to the blockchain quickly enough have to be mined and broadcast again, rendering additional overheads. Finally, the description of FruitChains lacks important details (e.g., the size of the fruits or the overheads introduced) as well as an actual implementation.

GHOST and Ethereum. An alternative approach for decreasing a high reward variance of miners is to shorten the block creation rate to the extent that does not hurt the overall system security – such an approach increases transaction throughput as well. The Greedy Heaviest-Observed Sub-Tree (GHOST) chain selection rule [41] makes use of stale blocks to increase the weight of their ancestors, which achieves a 600 fold speedup for the block generation compared to Bitcoin, while preserving its security strength. Despite the inclusion of stale blocks in the blockchain, only the miners of the main chain get rewards for the inclusion of the stale blocks.

In contrast to the original GHOST, the white and yellow papers of Ethereum [44, 48] propose to reward also miners of stale blocks in order to further increase the security – not wasting with the consumed resources for mining of stale blocks. However, Ritz and Zugenmaier shows that rewarding so called "uncle blocks" lowers the threshold at which selfish mining is profitable [34] – a selfish miner can built-up the "heaviest" chain, as she can reference blocks previously not broadcast to the honest network. Likewise, the inclusive blockchain protocol [20], which increases the transaction throughput, but leaves the selfish mining issue unsolved.

DAG-based Protocols. SPECTRE [40] is an example of the protocols family that leverages a directed acyclic graph (DAG). This family proposed more radical design changes motivated by the observation that one essential throughput limitation of Nakamoto consensus is the data structure leveraged which can be maintained only sequentially. SPECTRE generalizes the Nakamoto's blockchain into a DAG of blocks, while allowing miners to add blocks concurrently with a high frequency, just basing on their individual current views of the DAG. Such a design provides multiple advantages over chain-based protocols including StrongChain. Frequently published blocks increase transaction throughput and provide fast confirmation times while relaxed consistency requirements allow to tolerate propagation delays. Like StrongChain, SPECTRE also aims to decrease mining reward variance, but achieves it again via frequent blocks. However, frequent blocks have a side effect of transaction redundancy which negatively impacts the storage and transmission overheads, and this aspect was not investigated. Moreover, SPECTRE provides a weaker property than chain-based consensus protocols as simultaneously added transactions cannot be ordered. This and schemes following a similar design are payments oriented and to support order-specific applications, like smart contracts, they need to be enhanced with an additional ordering logic.

More recently, Sompolinsky and Zohar [42] proposed two DAG-based protocols improving the prior work. PHANTOM introduces and uses a greedy algorithm (called the

GHOSTDAG protocol) to determine the order of transactions. This eliminates the applicability issues of SPECTRE, but for the cost of slowing down transaction confirmation times. Combining advantages of PHANTOM and SPECTRE into a full system was left by the authors as a future work.

Decentralization-oriented Schemes. Mining decentralization was a goal of multiple previous proposals. One direction is to design mining such that miners do not have incentive to outsource resources or forming coalitions. Permacoin [25] is an early attempt to achieve it where miners instead of proving their work prove that their store (fragments of) a globally-agreed file. Permacoin is designed such that: a) payment private keys are bound to puzzle solutions – outsourcing private keys is risky for miners, b) sequential and random storage access is critical for the mining efficiency, thus it disincentives miners from outsourcing data. If the file is valuable, then a side-effect of Permacoin is its usefulness, as miners replicate the file.

The notion of non-outsourceable mining was further extended and other schemes were proposed [26, 50]. Miller et al. [26] introduces "strongly non-outsourceable puzzles" that aim to disincentivize pool creation by requiring all pool participants to remain honest. In short, with these puzzles any pool participant can steal the pool reward without revealing its identity. The scheme relies on zero knowledge proofs requiring a trusted setup and introducing significant computational overheads. The scheme is orthogonal to StrongChain and could be integrated with easily integrated with StrongChain, however, after a few years of their introduction no system of this class was actually deployed at scale; thus, we do not have any empirical results confirming their promised benefits.

SmartPool is a different approach that was proposed by Luu et al. [23]. In SmartPool, the functionality of mining pools was implemented as a smart contract. Such an approach runs natively only on smart-contract platforms but it allows to eliminate actual mining pools and their managers (note that SmartPool still imposes fees for running smart contracts), while preserving most benefits of pool mining.

Rewarding Schemes for Mining Pools. Mining pools divide the block reward (together with the transaction fees) in such a way that each miner joining the pool is paid his fair share in proportion to his contribution. Typically, the contribution of an individual miner in the pool is witnessed by showing weak solutions called *shares*.

There are various rewarding schemes that mining pools employ. The simplest and most natural method is the proportional scheme where the reward of a strong block is divided in proportion to the numbers of shares submitted by the miners. However, this scheme leads to pool hopping attacks [33]. To avoid this security issue, many other rewarding systems are developed, including the Pay-per-last-N-shares (PPLNS) scheme and its variants. We refer the reader to [37] for a systematic analysis of different pool rewarding systems.

The reward mechanisms in StrongChain can be seen conceptually as a mining pool built-in into the protocol. However, there are important differences between our design and the mining pools. The most contrasting one is that in StrongChain rewarding is not a zero-sum game and miners do not share rewards. In mining pools, all rewards are shared and this characteristic causes multiple in- and cross-pool attacks that cannot be launched against our scheme. Furthermore, the miner collaboration within Bitcoin mining pools is a "necessary evil", while in StrongChain the collaboration is beneficial for miners and the overall system. We discuss StrongChain and mining pools further in Section 6.2.

9 Conclusions

In this paper, we proposed a transparent and collaborative proof-of-work protocol. Our approach is based on Nakamoto consensus and Bitcoin, however, we modified their core designs. In particular, in contrast to them, we take advantage of weak solutions, which although they do not finalize a block creation positively contribute to the blockchain properties. We also proposed a rewarding scheme such that miners can benefit from exchanging and appending weak solutions. These modifications lead to a more secure, fair, and efficient system. Surprisingly, we show that our approach helps with seemingly unrelated issues like the freshness property. Finally, our implementation indicates the efficiency and deployability of our approach.

Incentives-oriented analysis of consensus protocols is a relatively new topic and in the future we would like to extend our work by modeling our protocol with novel frameworks and tools. Another topic worth investigating in future is how to combine StrongChain with systems solving other drawbacks of Nakamoto consensus [10, 19, 21], or how to mimic the protocol in the proof-of-stake setting.

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