Proof-of-Work Sidechains

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Abstract. During the last decade, the blockchain space has exploded with a plethora of new cryptocurrencies, covering a wide array of different features, performance and security characteristics. Nevertheless, each of these coins functions in a stand-alone manner, independently. Sidechains have been envisioned as a mechanism to allow blockchains to communicate with one another and, among other applications, allow the transfer of value from one chain to another, but so far there have been no decentralized constructions. In this paper, we put forth the first sidechains construction that allows communication between proof-of-work blockchains without trusted intermediaries. Our construction is generic in that it allows the passing of any information between blockchains. Using this construction, two blockchains can be connected in a "two-way peg" in which an asset can be transferred from one chain to another and back. We pinpoint the features needed for two chains to communicate: On the source side, a proof-of-work blockchain that has been *interlinked*, potentially with a velvet fork; on the destination side, a blockchain with smart contract support. We put forth the smart contracts needed to implement these sidechains and explain them in detail. In the heart of our construction, we use a recently introduced cryptographic primitive, Non-Interactive Proofs of Proof-of-Work (NIPoPoWs).

1 Introduction

Bitcoin [13] is the most successful *cryptocurrency* to date. It introduced *blockchains*, a of cryptographic consensus protocol in which *transactions* are organized into *blocks* which are put in a mutually agreed sequence despite the presence of adversaries. Consensus is achieved via *proof-of-work* [4] which is the precondition for block validity. Transactions moving value within blockchains have been proven to be secure and that consensus is eventually achieved, cf. [5,14,6].

Ethereum [3] extends Bitcoin's functionality introducing Turing-complete *smart contracts* programmed in languages like Solidity which run on top of the Ethereum Virtual Machine [18]. These contracts execute autonomously. The smart contracts are confined to access data only within

Research partially supported by H2020 project PRIVILEDGE # 780477

the blockchain itself, such as previous transactions and blocks. Access to external data requires a trusted third party or group thereof to vouch for the data validity [23].

Sidechains [1] are a mechanism for cross-chain communication in blockchains. They allow smart contracts on one blockchain to receive and react to *events* taking place on another blockchain without the need of trusted parties. Despite their widely agreed usefulness there exist no constructions that are decentralised and efficient at the same time.

Our contributions. In this paper, we introduce the first trustless construction for proof-of-work sidechains. We describe how to build generic communication between blockchains. As one application, we give the construction of a *two-way pegged* asset which can be moved from one blockchain to another while retaining its nature. We provide a high-level construction in Solidity. Our construction works across a broad range of blockchains requiring only two underlying properties. First, that the *source* blockchain is a proof-of-work blockchain supporting Non-Interactive Proofs of Proof-of-Work (NIPoPoWs), a cryptographic primitive which allows constructing succinct proofs *about* events which occur in a proof-of-work blockchain and which was recently introduced in [12]. Support for NIPoPoWs can be introduced to practically any work-based cryptocurrency such as Bitcoin and Ethereum without a hard or soft fork. Second, that the *target* blockchain is able to validate such proofs through smart contracts such as, e.g., Ethereum or Ethereum Classic. To our knowledge, we are the first to provide such a construction in full.

Related work. Sidechains were introduced as a Bitcoin upgrade mechanism by Back et al. [1]. They proposed introducing a new *child* blockchain which implements a new protocol version, with which assets are *2-way pegged*. The *firewall* property was articulated. No complete construction of the protocol was given. Their paper hints at the need for "*efficient SPV proofs*" (Appendix B) in future work, which we implemented here. We use the term *sidechains* in a more general notion than in their work. Our sidechains allow communication between *stand alone* blockchains and also convey *any* information, not just transfers of value. In our work, a blockchain is a sidechain of another chain if it can react to events on that chain, and so the relationship can be symmetric.

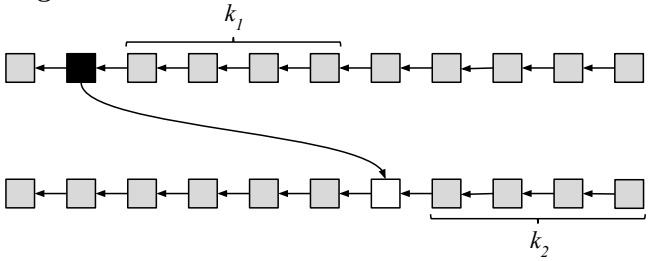
Polkadot [19], *Tendermint*, *Cosmos* [2], *Liquid* and *Interledger* [7] also build cross-chain transfers. Their validation relies on a trusted committees, federations or is left unspecified. *Drivechains* and *rootstock* are sidechain proposals which require miners of both chains to be aware of both networks. In our scheme, miners remain agnostic to the existence of

other chains and connect only to one network. *BTCRelay* is a trustless mechanism relaying information one-way from Bitcoin to Ethereum, in which miners are connected to their network only. BTCRelay requires the transmission of the entirety of the source blockchain headers into the target blockchain. Our proposal only requires data logarithmic in size of the source blockchain. This stems from the *succinctness* property of the NIPoPoW scheme. Other related work includes Plasma [15], XCLAIM [21], PeaceRelay, COMIT [9], and NOCUST [10] and Dogethereum.

2 Overview

We wish to transfer assets from one blockchain to another and then back. When assets can be transferred from one blockchain to another but not back, we call it a *one-way peg*. If assets can also be moved back, we call it a *two-way peg*. In each individual transfer of an asset, we have a particular *source blockchain*, from which the asset is moved, and a particular *target blockchain*, to which the asset is moved. In a sidechain setting of two blockchains that are two-way pegged, both blockchains can function as a source and a target blockchain for different transfers.

Fig. 1. Basic information transfer between two blockchains



While the motivation for the construction is to be able to move assets from one blockchain to another, we generalize the notion of sidechains from this strict setting. In general, we would like the target blockchain to be able to react to any *event* that occurs on the source blockchain. Such events can be the fact that a transaction with a particular TXID took place, that a certain account was paid a certain amount of money, or that a particular smart contract was instantiated. Our sidechain construction allows the target blockchain to react to events that took place on the source blockchain. This reaction can be implemented in its target blockchain smart contracts. We describe our construction in pseudocode similar to Ethereum' *Solidity*. In Solidity, *events* can be fired arbitrarily from within a smart contract and do not have a semantic interpretation.

In this setting, events are defined by Solidity using the event type and have an *event name*, a *contract address* which fired them, as well as certain parameter values. A contract can elect to fire an event with any name and any parameters of its choice by invoking the EMIT command.

A high-level overview of cross-chain event transmission is shown in Figure 1. The process is as follows. First, an event is fired in the source blockchain, shown at the top. This could be any event that can be emitted using Ethereum's EMIT command. This event firing is caused by a certain transaction which is included at a certain block, indicated in black at the top. This block is then buried under k_1 subsequent blocks within the source blockchain, where the k_1 parameter is a security parameter of the scheme depending on the specific parameters of the source blockchain [5]. As soon as this confirmation occurs, the target blockchain can react to the event, shown at the bottom. This reaction occurs in a transaction which is included in a block within the target blockchain, illustrated in white. As usual, the block needs to be confirmed by waiting for k_2 blocks to be mined on top of it. It is possible that $k_1 \neq k_2$ because of different blockchain parameters such as a difference in block generation time or network synchrony.

Using this basic functionality of event information exchange between blockchains, we can construct two-way pegged sidechains. In such a construction, an asset that exists on one blockchain will gain the ability to be *moved* to a different blockchain and back. We will use the example of moving ether, the native asset of the Ethereum blockchain, from the Ethereum blockchain into the Ethereum Classic blockchain and back. Such an action is different from *exchanging* ether (ETH), the native token of the Ethereum blockchain, with ether classic (ETC), the native token of the Ethereum Classic blockchain. Instead, the asset retains its nature; it maintains its price and its ability to be used for the same purposes, while being governed by the rules of the new blockchain, such as different performance, fees, features, or security guarantees. Furthermore, no counterparty or market is required to perform the exchange; the transfer is something a party can do on its own.

3 Construction

Cross-chain certificates

For our construction, we use a primitive called Non-Interactive Proofs of Proof-of-Work recently introduced in [12]. Non-Interactive Proofs of Proofs-of-Work are cryptographic protocols which implement a *prover*

and a *verifier*. The prover is a *full node* on the *source blockchain*. The verifier does not have access to that blockchain, but knows the source genesis block $\mathcal{G}$. The prover wants to convince the verifier that an *event* took place in the source blockchain; for instance, a smart contract method was called with certain parameters or that a payment was made into a particular address. Whether such an event took place can easily be determined if one inspects the whole blockchain. However, the prover wishes to convince the verifier by only sending a *succinct proof*, a short string which does not grow linearly with the size of the source blockchain, but, rather, *polylogarithmically*. The verifier must not be fooled by *adversarial provers* who provide incorrect proofs claiming that an event happened while in fact it didn't, or that it didn't while in fact it did. These adversaries can also mine blocks, but the honest parties are assumed to control the majority of computational power on both the source and the target blockchain networks. To withstand such attacks, the verifier accepts multiple proofs, at least one of which is assumed to have been honestly generated (this assumption is necessary in standard blockchain protocols in general [8,20]). Comparing these proofs against each other, the verifier extracts a reliable truth value corresponding to the same value it would deduce if it were to be running a full node on the blockchain itself. This property is the *security* of NIPoPoWs proven in [12].

The NIPoPoWs construction talks about *predicates* evaluated on blockchains, but we are interested in *events*. We can translate from events to predicates provable with NIPoPoWs. Specifically, given a genesis block $\mathcal{G}$, a smart contract address addr, an event name Event, and a series of event parameter values $(\mathsf{param}_1, \mathsf{param}_2, \cdots, \mathsf{param}_n)$, the predicate e we wish to check for truth is the following: *Has the event named* Event *been fired with parameters* $(\mathsf{param}_1, \mathsf{param}_2, \cdots, \mathsf{param}_n)$ *by the smart contract residing in address* addr *on the blockchain with genesis block* $\mathcal{G}$ *at least* k *blocks ago?* This predicate is (1) *monotonic*, meaning that it starts with the value false and, if it ever becomes true, it cannot ever change its value back as the blockchain grows; (2) *infix-sensitive*, meaning that its truth value can be deduced by inspecting a polylogarithmically-bound number of blocks on the blockchain (in our case one block, within which the event firing was confirmed); and (3) *stable*, meaning that, if one party deduces that its value is true, then soon enough *all* parties will deduce that its value is true. This last property stems from the requirement that the event be buried under k blocks ensuring a blockchain reorganization up to k blocks ago cannot affect the predicate's value.

In order to determine whether an event took place, the NIPoPoW verifier function $\mathsf{verify}_{k,m}^{\mathcal{G},e}(\mathcal{P})$ accepts the event description in the form of a blockchain predicate e, which we gave above, the genesis block of the remote chain $\mathcal{G}$, as well as two security parameters k and m. These security parameters can be constants specified when the sidechain system is created (concrete values for these are given in [12]). Subsequently, the NIPoPoW verifier accepts a set of *proofs* $\mathcal{P} = \{\pi_1, \pi_2, \cdots, \pi_n\}$ which it compares and extracts a truth value for the predicate: Whether the event has taken place in the remote blockchain or not. As long as at least one *honestly generated* proof π_i is provided, the verifier's security ensures that the output will correspond to whether the event actually occurred.

Our protocol works as follows. Whenever an event of interest occurs on the source blockchain, the occurence of this event is observed by a source blockchain honest node, who generates a NIPoPoW about it. The target blockchain contains a smart contract with a method to accept and verify the veracity of this proof. The node can then submit the proof to the smart contract by broadcasting a transaction on the target blockchain. As soon as the proof is validated by the smart contract, the target blockchain can elect to react to the event as desired.

Adoption considerations. Our construction has certain prerequisites for both the source and the target blockchain before it can be adopted. In the case of bidirectionally connected blockchains, both of them must satisfy the source and the target blockchain prerequisites.

- **The source blockchain** needs to support *proofs* about it, which requires augmenting it with an *interlink* vector, the details of which can be found in [11]. This interlink vector can be added to a blockchain using a *user-activated velvet fork* [12,22], which is performed without miner awareness and does not require a hard or soft fork. However, only events occuring *after* the velvet fork can be proven. New blockchains can adopt this from genesis.
- **The target blockchain** needs to be able to run the above verify function. This function can be programmed in a Turing-complete language such as Solidity. If the source blockchain proof-of-work hash function is available as an opcode or pre-compiled smart contract within the target blockchain's VM the way, e.g., Bitcoin's SHA256 hash function is available in Solidity, the implementation can be more gas-efficient.

Blockchain agnosticism. We underline the remarkable property that miners and full nodes of the target blockchain do not need to be aware of the source blockchain at all. To them, all information about the source

blockchain is simply a string which is passed as a parameter to a smart contract and can remain *agnostic* to its semantics as a proof. Additionally, miners and full nodes of the source blockchain do not need to be aware of the target blockchain. Only the parties interested in facilitating cross-chain events must be aware of both. Those untrusted facilitators need to maintain an SPV node on the source blockchain about which they generate their NIPoPoW. To broadcast their proof on the target blockchain, they connect to target blockchain nodes and send the transaction containing the NIPoPoW. Blockchain agnosticism allows users to initiate cross-chain relationships between different blockchains *dynamically*, as long as the blockchains in question satisfy the above prerequisites.

Cross-chain events

We give our crosschain construction in Algorithm 1. Initially, our communication will be unidirectional. In the next section, we use two unidirectional channels to establish bidirectional communication. This smart contract runs on the target blockchain and informs it about events that took place in the source blockchain. It is parameterized by three parameters: k and m are the underlying security parameters of the NIPoPoW protocol. The value z is a *collateral* parameter, denominated in ether (or the native currency of the blockchain in which the execution takes place) and is used to incentivize honest participants to intervene in cases of false claims. The contract utilizes the NIPoPoW verify function parameterized by the event e, the remote genesis block $\mathcal{G}$ and the security parameters k and m. We do not give an explicit implementation of verify, as it can be implemented in a straightforward manner by translating the pseudocode listing of [12]. For our purposes, it suffices to treat it as a black box which, given a set of proofs, at least one of which is honestly generated, returns the truth value of the respective predicate.

The contract allows detecting remote blockchain events and can be *inherited* by other contracts that wish to adopt its functionality. It works as follows. First, the initialize method is called exactly once to configure the contract, passing the *hash* of the genesis block of the remote chain which this contract will handle. This method is internal and can only be called by the contract inheriting from it. Users of the contract can check it has been configured with the correct genesis block prior to using it. We note that, while our algorithm does not reflect this to keep complexity low, it is possible to have a contract interact with *multiple* remote chains by extending it to include multiple geneses.

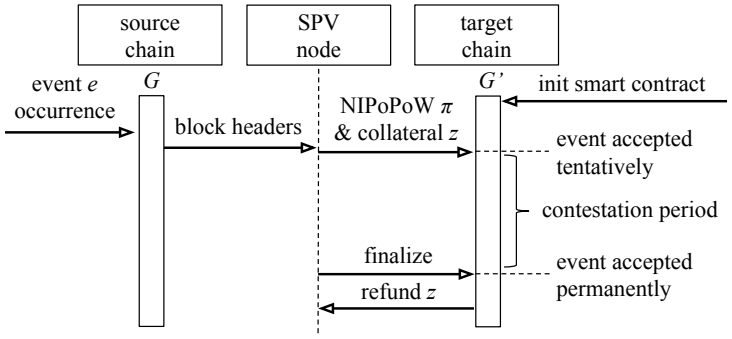
Algorithm 1 The smart contract skeleton that enables checking cross-chain proofs about events.

```
1: contract crosschain_{k,m,z}
2:     finalized-events ← ∅; events ← ∅
3:     internal function initialize(G_remote)
4:         G ← G_remote
5:     end function
6:     payable function submit-event-proof(π, e)
7:         if msg.value < z then                          ▷ Ensure sufficient collateral
8:             return ⊥
9:         end if
10:        if events[e] = ⊥ ∧ verify^{e,G}_{k,m}({π}) then
11:            events[e] ← {expire: block.number + k, proof: π, author: msg.sender}
12:        end if
13:    end function
14:    function finalize-event(e)
15:        if events[e] = ⊥ ∨ block.number < events[e].expire then
16:            return ⊥
17:        end if
18:        finalized-events ← finalized-events ∪ {e}
19:        author ← events[e].author
20:        events[e] ← ⊥
21:        author.send(z)                                 ▷ Return collateral
22:    end function
23:    function submit-contesting-proof(π*, e)
24:        if events[e] = ⊥ ∨ block.number ≥ events[e].expire then
25:            return ⊥
26:        end if
27:        if ¬verify^{e,G}_{k,m}({events[e].proof, π*}) then   ▷ Original proof was fraudulent
28:            events[e] ← ⊥
29:            msg.sender.send(z)                         ▷ Pay collateral to contester
30:        end if
31:    end function
32:    function event-exists(e)
33:        return e ∈ finalized-events
34:    end function
35: end contract
```

The lifecycle of an event submission is illustrated in Figure 2. When an event has taken place in the source blockchain, any source blockchain SPV node, the *author*, can inform the crosschain contract about this fact by generating a NIPoPoW π claiming that the event took place based on their current view of the source blockchain. This proof can then be submitted to the target blockchain by calling the submit-event-proof function and passing it the proof π and the event predicate e. The submission is

accompanied by a collateral payment z. If the author is honest, this collateral will be returned to her later. The submit-event-proof function runs the NIPoPoW verify algorithm to check that the proof π is well-formed and that it claims that the predicate is true. It then stores the proof for later use. It also stores the address of the *author* and an *expiration block number*.

Fig. 2. A sequence diagram showing the actions of the untrusted SPV node when communicating with both blockchain networks and the lifecycle of an event submission

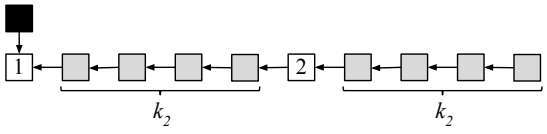


Upon submission of a proof to the submit-event-proof function, the event is *tentatively accepted* for a *contestation period* of k blocks, during which any other party, the *contester*, can provide a counter-proof showing that the original proof was fraudulent. The contester can call the submit-contesting-proof function passing it the contesting proof π^* and the event predicate e. The function runs the NIPoPoW verify algorithm to compare the original proof events$[e]$.proof against the contesting proof π^*. If the verification algorithm concludes that the original proof was fraudulent, the tentatively accepted event is abandoned and the collateral is paid to the contester.

Otherwise, when the contestation period has expired without any valid contestations, the author can call the finalize-event function. This function changes the acceptance of the event from tentative to *permanent* by including it in the finalized-events set and returns the collateral to the author. Finally, the event-exists function can be used by the inheriting contract to check if an event has been permanently accepted. The target blockchain state during this execution is shown in Figure 3. The source blockchain's event included in the black box, upon sufficient confirmation by k_1 blocks (not shown), is transmitted to the target blockchain

at the bottom. The target blockchain includes the event *tentatively* in block 1 until a contestation period of k_2 has passed; the event is included *permanently* in block 2; subsequently, permanent inclusion needs to be confirmed with k_2 further blocks.

Fig. 3. The target blockchain state during event submission



Two-way pegged sidechains

Having created the generic crosschain contract, we now build two-way pegged sidechains on top. For concreteness, we use the example of transferring ether (ETH), the native currency of the Ethereum blockchain, to the Ethereum Classic blockchain, and back. We note that this example is arbitrary and for illustration. Our construction can be used between any work-based blockchains satisfying the prerequisites detailed above.

When ether is moved to the Ethereum Classic blockchain, it will be represented as an ERC20 token[3] within Ethereum Classic. Let this custom token be called ETH20. The asset retains its nature as it moves from one blockchain to another if it is always possible to move ETH into ETH20 and back at a one-to-one rate. The economic reason is that the price of ETH and ETH20 on the market will necessarily be the same. If the price of ETH were to ever be significantly above the price of ETH20 in the market, then a rational participant would exchange their ETH20 for ETH using sidechains and sell their ETH on the market instead, and vice versa. There can be a small discrepancy in the two prices which stems from two different factors: First, the fees needed for a cross-chain transfer; and second, the temporary market fluctuations that can occur during the limited time needed to perform the cross chain transfer ($k_1 + 2k_2$). If we assume the price fluctuation (of ETH20 denominated in ETH) per unit of time is bounded, then the market price difference between ETH and ETH20 at any moment in time can be bounded by the sum of these two factors.

[3] The ERC20 standard [17] defines an interface implementable by smart contracts that enables holding and transferring custom fungible tokens such as ICO tokens.

The sidechain smart contracts are presented in Algorithm 2. These smart contracts both extend the crosschain smart contract of Algorithm 1. Furthermore, $\mathsf{sidechain}_2$ also inherits basic ERC20 functionality which allows token owners to transfer the token [16]. The $\mathsf{sidechain}_1$ contract will be instantiated on Ethereum, while the $\mathsf{sidechain}_2$ contract will be instantiated on Ethereum Classic. Suppose the genesis block hash of Ethereum is $\mathcal{G}_1$ and of Ethereum Classic is $\mathcal{G}_2$. We will use the genesis block hash of each blockchain as its unique identifier.

The two smart contracts both contain an initialize method which accepts the hash of the remote blockchain as well as the address of the remote smart contract it will interface with. Note that, while the two genesis hashes can be hard-coded into the respective smart contract code itself, the remote contract address cannot be built-in as a constant into the smart contract, but must be later specified by calling the initialize function. The reason is that, if $\mathsf{sidechain}_1$ were to be created on $\mathcal{G}_1$, it would require the address of $\mathsf{sidechain}_2$ to exist prior to its creation, and vice versa in a circular dependency. Therefore, the two contracts must first be created on their respective blockchain to obtain addresses, and then their initialize methods can be called to inform each contract about the address of the other. Specifically, first the contract $\mathsf{sidechain}_1$ is created on $\mathcal{G}_1$ to obtain its instance address which we also denote $\mathsf{sidechain}_1$. Then the second contract, $\mathsf{sidechain}_2$, is created on $\mathcal{G}_2$ to obtain its address $\mathsf{sidechain}_2$. Subsequently, the initialize function of $\mathsf{sidechain}_1$ is called, passing it $\mathcal{G}_2$ and the address $\mathsf{sidechain}_2$. Finally, initialize is called on $\mathsf{sidechain}_2$, passing it $\mathcal{G}_1$ and the address $\mathsf{sidechain}_1$. These initialization parameters are stored by the respective smart contracts for future use. As the crosschain contract requires, the initialize method can only be called once. Any user wishing to utilize this sidechain is expected to validate that the contracts have been set up correctly and that initialize has been called with the appropriate parameters.

$\mathsf{sidechain}_1$ contains a deposit function which is *payable* in the native asset of Ethereum, ETH. When a user pays ETH into the deposit function, the funds are held by the smart contract and can later be used to pay parties who wish to *withdraw*, an operation performed by calling the withdraw function. $\mathsf{sidechain}_2$ contains similar deposit and withdraw functions which, however, do not pay in the native currency of Ethereum Classic, but instead maintain a balance mapping akin to a typical ERC20 implementation. The balance is updated when a user deposits or withdraws.

Algorithm 2 An asset transferring contract between $\mathcal{G}_1$ and $\mathcal{G}_2$

```
1: contract sidechain_1 extends crosschain_{k,m,z}
2:     initialized ← false; ctr ← 0
3:     function initialize(G_2, sidechain_2)
4:         if ¬initialized then
5:             crosschain.initialize(G_2)   ▷ Initialize with the remote chain genesis block
6:             initialized ← true
7:             this.sidechain_2 ← sidechain_2
8:         end if
9:     end function
10:    payable function deposit(target)
11:        ▷ Emit an event to be picked up by remote contract
12:        ctr += 1
13:        emit Deposited_1(target, msg.value, ctr)
14:    end function
15:    function withdraw(amount, target, ctr)
16:        ▷ Validate that event took place on remote chain
17:        if ¬event-exists((sidechain_2, Deposited_2, (amount, target, ctr))) then
18:            return ⊥
19:        end if
20:        msg.sender.send(amount)
21:    end function
22: end contract
23: contract sidechain_2 extends crosschain_{k,m,z}; ERC20
24:    mapping(address ⇒ int) balances
25:    initialized ← false; ctr ← 0
26:    function initialize(G_1, sidechain_1)
27:        if ¬initialized then
28:            crosschain.initialize(G_1)
29:            initialized ← true
30:            this.sidechain_1 ← sidechain_1
31:        end if
32:    end function
33:    function deposit(target, amount)
34:        if balances[msg.sender] < amount then
35:            return ⊥
36:        end if
37:        balances[msg.sender] −= amount                    ▷ Charge account of sender
38:        ctr += 1
39:        emit Deposited_2(target, amount, ctr)
40:    end function
41:    function withdraw(amount, target, ctr)
42:        if ¬event-exists((sidechain_1, Deposited_1, (amount, target, ctr))) then
43:            return ⊥
44:        end if
45:        balances[target] += amount                        ▷ Credit target account
46:    end function
47: end contract
```

Moving funds from the Ethereum blockchain into the Ethereum Classic blockchain works as follows. First, the user pays with ETH to call the deposit function of $\mathsf{sidechain}_1$ which resides on $\mathcal{G}_1$, passing the target parameter which indicates their address in the Ethereum Classic blockchain that they wish to receive the money into. This call emits an event, $\mathsf{Deposited}_1$ which contains the necessary data: the target, the amount paid, as well as a nonce ctr to allow for future payments of the same amount to the same target. When the event has been emitted and buried under k_1 blocks within the Ethereum blockchain, the user produces an Ethereum NIPoPoW π_1 about the predicate e_1 which claims that the event $\mathsf{Deposited}_1$ has been emitted in blockchain $\mathcal{G}_1$ with the particular parameters by the contract residing at address $\mathsf{sidechain}_1$.

Subsequently, the user calls the submit-event-proof function of $\mathsf{sidechain}_2$ (which is inherited from the crosschain contract), passing the NIPoPoW π_1 and the event predicate e_1 and paying collateral z, which registers e_1 on $\mathsf{sidechain}_2$ as tentative. Because the user is honest, no adversary can produce a π_1^* which disproves their claim during the dispute period, and therefore the user waits for k_2 blocks for the contestation period to expire without any successful contestations. She then calls the finalize-event function for e_1 and receives back the collateral z, marking the event permanent. Finally, she calls the function withdraw of $\mathsf{sidechain}_2$, passing it the same parameters that e_1 was issued with. The withdraw function checks that e_1 exists using the event-exists method, which will return true. The user is then credited with amount in their ETH20 balance stored in balances[target]. This increment in balance creates brand new ETH20 tokens. The withdraw function also stores the signature of the event parameters that have been spent to avoid replay attacks, which is not shown here for algorithm brevity.

The user can then transfer their ETH20 tokens by utilizing the functionality inherited from the ERC20 contract. When some (not necessarily the same) user is ready to move some (not necessarily the same) amount of ETH20 from the Ethereum Classic blockchain back into ETH on the Ethereum blockchain, they follow the reverse procedure: They call the withdraw function of $\mathsf{sidechain}_2$ which ensures their ERC20 balance is sufficient, deduces the requested amount, and fires an event e_2 as before. At this point, these particular ETH20 tokens are destroyed by the balance deduction. Once e_2 is confirmed in $\mathcal{G}_2$, the user produces the NIPoPoW π_2 about e_2 which claims a payment was made within $\mathcal{G}_2$. That proof is then submitted to $\mathsf{sidechain}_1$ by calling the submit-event-proof and finalize-event functions as before. Last, the user calls the withdraw func-

tion of $\mathsf{sidechain}_1$, which uses the event-exists function which will return true, finally paying back the user the respective amount of ETH. Because the only way to create ETH20 tokens in $\mathsf{sidechain}_2$ is by depositing ETH into $\mathsf{sidechain}_1$, there will always exist a sufficient balance of ETH owned by the $\mathsf{sidechains}_1$ smart contract to pay for any requested withdrawals.

Suppose now that an adversarial user makes a false claim that an event e took place in $\mathcal{G}_1$ and posts a relevant NIPoPoW π in $\mathcal{G}_2$. If an honest party is monitoring the chain $\mathcal{G}_2$ for the appearance of NIPoPoWs and the chain $\mathcal{G}_1$ for the firing of events, the fraudulence of π will be immediately obvious to them. They can subsequently generate a contesting NIPoPoW π^* providing a counter-claim that e did not occur. The honest party will broadcast this transaction at the beginning of the contestation period. Due to the *liveness* property of $\mathcal{G}_2$, the honest party will manage to include this transaction into $\mathcal{G}_2$ within one of the blocks before the end of the contestation period. The collateral z must be sufficient to incentivize an honest party to monitor $\mathcal{G}_1$ and $\mathcal{G}_2$ simultaneously, pay for transaction fees and ensure the time needed to generate a NIPoPoW π^* is small as compared to block generation time. The argument for $\mathcal{G}_2$ is analogous.

Conclusion. We gave the first trustless Proof-of-Work sidechain construction based on the NIPoPoWs primitive. We detailed the implementation of the verifier in the form of a Solidity smart contract. We described how cross-chain events can be used to give rise to two-way pegging, the original sidechains vision, and argued for the need of cryptoeconomic collateral to disincentivise dishonest behavior. Finally, we argued about the feasibility of our proposal and gave the prerequisites for its adoption.

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