Zcash Protocol Specification

Sean Bowe — Daira Hopwood — Taylor Hornby

January 29, 2016

1 Introduction

Zcash is an implementation of the *Decentralized Anonymous Payment* scheme **Zerocash** [2] with some adjustments to terminology, functionality and performance. It bridges the existing *transparent* payment scheme used by **Bitcoin** with a *confidential* payment scheme protected by zero-knowledge succinct non-interactive arguments of knowledge (*zk-SNARKs*).

2 Concepts

2.1 Integers, Bit Sequences, and Endianness

All integers visible in **Zcash**-specific encodings are unsigned, have a fixed bit length, and are encoded as big-endian.

In bit layout diagrams, each box of the diagram represents a sequence of bits. If the content of the box is a byte sequence, it is implicitly converted to a sequence of bits using big endian order. The bit sequences are then concatenated in the order shown from left to right, and the result is converted to a sequence of bytes, again using big-endian order.

Nathan: An example would help here. It would be illustrative if it had a few differently-sized fields.

$\text{Leading}_k(x)$, where k is an integer and x is a bit sequence, returns the leading (initial) k bits of its input.

$\text{Trailing}_k(x)$, where k is an integer and x is a bit sequence, returns the trailing (final) k bits of its input.

2.2 Cryptographic Functions

CRH is a collision-resistant hash function. In **Zcash**, the *SHA-256 compression* function is used which takes a 512-bit block and produces a 256-bit hash. This is different from the *SHA-256* function, which hashes arbitrary-length strings.

PRF_x is a pseudo-random function seeded by x. Three *independent* PRF_x are needed in our scheme: $\text{PRF}_x^{\text{addr}}$, PRF_x^{sn}, and PRF_x^{pk}. It is required that PRF_x^{sn} be collision-resistant across all x — i.e. it should not be feasible to find $(x, y) \neq (x', y')$ such that $\text{PRF}_x^{\text{sn}}(y) = \text{PRF}_{x'}^{\text{sn}}(y')$.

In **Zcash**, the *SHA-256 compression* function is used to construct all three of these functions. The bits 00, 01 and 10 are included (respectively) within the blocks that are hashed, ensuring that the functions are independent.

Nathan: Note: If we change input arity (i.e. N^{old}), we need to be aware of how it is associated with this bit-packing.

$$a_{pk} := PRF_{a_{sk}}^{addr}(0) \quad = CRH\left(\begin{array}{|c|c|c|c|} \hline \text{256 bit } a_{sk} & 0 & 0 & 0^{254} \\ \hline \end{array} \right)$$

$$sn := PRF_{a_{sk}}^{sn}(\rho) \quad = CRH\left(\begin{array}{|c|c|c|c|} \hline \text{256 bit } a_{sk} & 0 & 1 & \texttt{Trailing}_{254}(\rho) \\ \hline \end{array} \right)$$

$$h_i := PRF_{a_{sk}}^{pk}(i, h_{Sig}) \quad = CRH\left(\begin{array}{|c|c|c|c|c|} \hline \text{256 bit } a_{sk} & 1 & 0 & i & \texttt{Trailing}_{253}(h_{Sig}) \\ \hline \end{array} \right)$$

Daira: Should we instead define ρ to be 254 bits and h_{Sig} to be 253 bits?

2.3 Confidential Addresses and Private Keys

Nathan: This term, *confidential address*, may be confusing by comparison to a "private key". In the latter case the adjective is reminding a user of their responsibility to protect its privacy, but in the case of *confidential address* we want users to know "transfers to this address are confidential, but the address itself *may* be published or kept confidential depending on your needs. Two different people can compare addresses to know they have the same *confidential address*."

A key pair $(addr_{pk}, addr_{sk})$ is generated by users who wish to receive coins under this scheme. The tuple parts embody two distinct keypairs used for different purposes called the *spend authority* and the *key-private encryption* keypair. The *confidential address* $addr_{pk}$ is a tuple (a_{pk}, pk_{enc}), containing the public components of the *spend authority* and *key-private encryption* respectively. The $addr_{sk}$ is a tuple (a_{sk}, sk_{enc}), containing the secret components respectively.

Nathan: A diagram could really help here.

Users can accept payment from multiple parties with a single $addr_{pk}$ and the fact that these payments are destined to the same payee is not revealed on the blockchain, even to the paying parties. *However* if two parties collude to compare a $addr_{pk}$ they can trivially determine they are the same. In the case that a payee wishes to prevent this they should create a distinct *confidential address* for each payer.

2.4 Coins

A *coin* (denoted $\mathbf{c}$) is a tuple (a_{pk}, v, ρ, r) which represents that a value v is spendable by the recipient who holds the *spend authority* key pair (a_{pk}, a_{sk}) such that $a_{pk} = PRF_{a_{sk}}^{addr}(0)$. ρ and r are tokens randomly generated by the sender. Only a hash of these values is disclosed publicly, which allows these random tokens to blind the value and recipient *except* to those who possess these tokens.

In-band secret distribution In order to transmit the secret v, ρ and r to the recipient (necessary for the recipient to later spend) *without* requiring an out-of-band communication channel, the *key-private encryption* public key pk_{enc} is used to encrypt these secrets to form a *transmitted coin ciphertext*. The recipient's possession of the associated $(addr_{pk}, addr_{sk})$ (which contains both a_{pk} and sk_{enc}) is used to reconstruct the original *coin*.

Coin Commitments The underlying v and a_{pk} are blinded with ρ and r using the collision-resistant hash function CRH in a multi-layered process. The resulting hash $\texttt{cm} = \texttt{CoinCommitment}(\mathbf{c})$.

$$InternalH := CRH\left(\begin{array}{|c|c|} \hline \text{256 bit } a_{pk} & \text{256 bit } \rho \\ \hline \end{array} \right)$$

$$k := CRH\left(\begin{array}{|c|c|} \hline \text{384 bit } r & \texttt{Leading}_{128}(InternalH) \\ \hline \end{array} \right)$$

$$cm := CRH\left(\begin{array}{|c|c|c|} \hline \text{64 bit } v & \text{192 bit padding} & \text{256 bit } k \\ \hline \end{array} \right)$$

Serials A *serial number* (denoted sn) equals $PRF_{a_{sk}}^{sn}(\rho)$. A *coin* is spent by proving knowledge of ρ and a_{sk} in zero knowledge while disclosing sn, allowing sn to be used to prevent double-spending.

2.5 Coin Commitment Tree

rt

bm$_1$ bm$_2$ bm$_3$ bm$_4$ bm$_5$?   ?
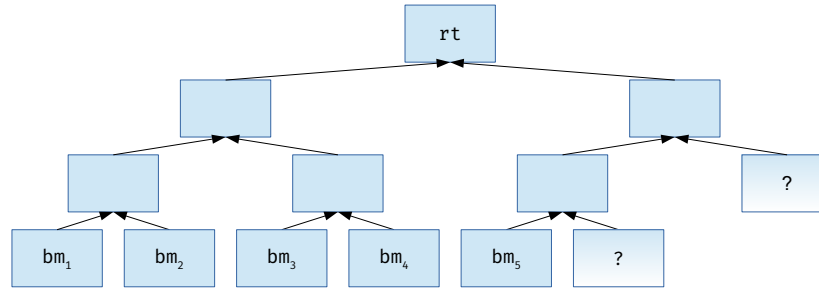
The *coin commitment tree* is an *incremental merkle tree* of depth d used to store *coin commitments* that *Pour transfers* produce. Just as the *unspent transaction output set* (UTXO) used in Bitcoin, it is used to express the existence of value and the capability to spend it. However, unlike the UTXO, it is *not* the job of this tree to protect against double-spending, as it is append-only.

Blocks in the blockchain are associated (by all nodes) with the root of this tree after all of its constituent *Pour descriptions' coin commitments* have been entered into the tree associated with the previous block.

2.6 Spent Serials Map

Transactions insert *serial numbers* into a *spent serial numbers map* which is maintained alongside the UTXO by all nodes.

Eli: a tx is just a string, so it doesn't insert anything. Rather, nodes process tx's and the "good" ones lead to the addition of serials to the spent serials map.

Transactions that attempt to insert a *serial number* into this map that already exists within it are invalid as they are attempting to double-spend.

Eli: After defining *transaction*, one should define what a *legal tx* is (this definition depends on a particular blockchain [view]) and only then can one talk about "attempts" of transactions, and insertions of serial numbers into the spent serials map.

2.7 The Blockchain

At a given point in time, the *blockchain view* of each *full node* consists of a sequence of one or more valid *blocks*. Each *block* consists of a sequence of one or more *transactions*. In a given node's *blockchain view*, *treestates* are chained in an obvious way:

- The input *treestate* of the first *block* is the empty *treestate*.

- The input *treestate* of the first *transaction* of a *block* is the final *treestate* of the immediately preceding *block*.

- The input *treestate* of each subsequent *transaction* in a *block* is the output *treestate* of the immediately preceding *transaction*.

- The final *treestate* of a *block* is the output *treestate* of its last *transaction*.

An *anchor* is a Merkle tree root of a *treestate*, and uniquely identifies that *treestate* given the assumed security properties of the Merkle tree's hash function.

Each *transaction* is associated with a sequence of *Pour descriptions*. TODO They also have a transparent value flow that interacts with the Pour v_{pub}^{old} and v_{pub}^{new}. Inputs and outputs are associated with a value.

The total value of the outputs must not exceed the total value of the inputs.

The *anchor* of the first *Pour description* in a *transaction* must refer to some earlier *block*'s final *treestate*.

The *anchor* of each subsequent *Pour description* may refer either to some earlier *block*'s final *treestate*, or to the output *treestate* of the immediately preceding *Pour description*.

These conditions act as constraints on the blocks that a *full node* will accept into its *blockchain view*.

We rely on Bitcoin-style consensus for *full nodes* to eventually converge on their views of valid *blocks*, and therefore of the sequence of *treestates* in those *blocks*.

Value pool   Transaction inputs insert value into a *value pool*, and transaction outputs remove value from this pool. The remaining value in the pool is available to miners as a fee.

3   Pour Transfers and Descriptions

A *Pour description* is data included in a *block* that describes a *Pour transfer*, i.e. a confidential value transfer. This kind of value transfer is the primary **Zerocash**-specific operation performed by transactions; it uses, but should not be confused with, the `POUR` *circuit* used for the *zk-SNARK* proof and verification.

A *Pour transfer* spends N^{old} *coins* $\mathbf{c}_{1..N^{old}}^{old}$ and creates N^{new} *coins* $\mathbf{c}_{1..N^{new}}^{new}$. **Zcash** transactions have an additional field `vpour`, which is a sequence of *Pour descriptions*.

Each *Pour description* consists of:

> `vpub_old` which is a value v_{pub}^{old} that the *Pour transfer* removes from the value pool.
>
> `vpub_new` which is a value v_{pub}^{new} that the *Pour transfer* inserts into the value pool.
>
> `anchor` which is a merkle root rt of the *coin commitment tree* at some block height in the past, or the merkle root produced by a previous pour in this transaction. Sean: We need to be more specific here.
>
> `scriptSig` which is a *script* that creates conditions for acceptance of a *Pour description* in a transaction. The `SHA256Compress` hash of this value is h_{Sig}.
>
> Daira: Why `SHA256Compress` and not *SHA-256*? The script is variable-length.
>
> `scriptPubKey` which is a *script* used to satisfy the conditions of the `scriptSig`.
>
> `serials` which is an N^{old} size sequence of serials $sn_{1..N^{old}}^{old}$.
>
> `commitments` which is a N^{new} size sequence of *coin commitments* $cm_{1..N^{new}}^{new}$.
>
> `ciphertexts` which is a N^{new} size sequence each element of which is a *transmitted coin ciphertext*.
>
> `vmacs` which is a N^{old} size sequence of message authentication tags $h_{1..N^{old}}$ that bind h_{Sig} to each a_{sk} of the *Pour description*.
>
> `zkproof` which is the zero-knowledge proof π_{POUR}.

Merkle root validity   A *Pour description* is valid if rt is a Coin commitment tree root found in either the blockchain or a merkle root produced by inserting the Coin commitments of a previous *Pour description* in the transaction to the Coin commitment tree identified by that previous *Pour description*'s *anchor*.

Non-malleability A *Pour description* is valid if the script formed by appending `scriptPubKey` to `scriptSig` returns *true*. The `scriptSig` is cryptographically bound to π_{POUR}.

Balance A *Pour transfer* can be seen, from the perspective of the transaction, as an input and an output simultaneously. $v^{\text{old}}_{\text{pub}}$ takes value from the value pool and $v^{\text{new}}_{\text{pub}}$ adds value to the value pool. As a result, $v^{\text{old}}_{\text{pub}}$ is treated like an *output* value, whereas $v^{\text{new}}_{\text{pub}}$ is treated like an *input* value.

Commitments and Serials A *transaction* that contains one or more *Pour descriptions*, when entered into the blockchain, appends to the *coin commitment tree* with all constituent *coin commitments*. All of the constituent *serial numbers* are also entered into the *spent serial numbers map* of the *blockchain view and mempool*. A *transaction* is not valid if it attempts to add a *serial number* to the *spent serial numbers map* that already exists in the map.

3.1   Pour Circuit and Proofs

In **Zcash**, N^{old} and N^{new} are both 2.

A valid instance of π_{POUR} assures that given a *primary input* $(\text{rt}, \text{sn}^{\text{old}}_{1..N^{\text{old}}}, \text{cm}^{\text{new}}_{1..N^{\text{new}}}, v^{\text{old}}_{\text{pub}}, v^{\text{new}}_{\text{pub}}, h_{\text{Sig}}, h_{1..N^{\text{old}}})$, a witness of *auxiliary input* $(\text{path}_{1..N^{\text{old}}}, \mathbf{c}^{\text{old}}_{1..N^{\text{old}}}, a^{\text{old}}_{\text{sk},1..N^{\text{old}}}, \mathbf{c}^{\text{new}}_{1..N^{\text{new}}})$ exists, where:

for each $i \in \{1..N^{\text{old}}\}$: $\mathbf{c}^{\text{old}}_i = (a^{\text{old}}_{\text{pk},i}, v^{\text{old}}_i, \rho^{\text{old}}_i, r^{\text{old}}_i)$

for each $i \in \{1..N^{\text{new}}\}$: $\mathbf{c}^{\text{new}}_i = (a^{\text{new}}_{\text{pk},i}, v^{\text{new}}_i, \rho^{\text{new}}_i, r^{\text{new}}_i)$

The following conditions hold:

Merkle path validity for each $i \in \{1..N^{\text{old}}\} \mid v^{\text{old}}_i \neq 0$: path_i must be a valid path of depth d from $\texttt{CoinCommitment}(\mathbf{c}^{\text{old}}_i)$ to Coin commitment merkle tree root rt.

Balance $v^{\text{old}}_{\text{pub}} + \sum_{i=1}^{N^{\text{old}}} v^{\text{old}}_i = v^{\text{new}}_{\text{pub}} + \sum_{i=1}^{N^{\text{new}}} v^{\text{new}}_i$.

Serial integrity for each $i \in \{1..N^{\text{new}}\}$: $\text{sn}^{\text{old}}_i = \text{PRF}^{\text{sn}}_{a^{\text{old}}_{\text{sk},i}}(\rho^{\text{old}}_i)$.

Spend authority for each $i \in \{1..N^{\text{old}}\}$: $a^{\text{old}}_{\text{pk},i} = \text{PRF}^{\text{addr}}_{a^{\text{old}}_{\text{sk},i}}(0)$.

Non-malleability for each $i \in \{1..N^{\text{old}}\}$: $h_i = \text{PRF}^{\text{pk}}_{a^{\text{old}}_{\text{sk},i}}(i, h_{\text{Sig}})$

Commitment integrity for each $i \in \{1..N^{\text{new}}\}$: $\text{cm}^{\text{new}}_i = \texttt{CoinCommitment}(\mathbf{c}^{\text{new}}_i)$

4   Encoding Addresses, Private keys, Coins, and Pour descriptions

This section describes how **Zcash** encodes public addresses, private keys, coins, and *Pour descriptions*.

Addresses, keys, and coins, can be encoded as a byte string; this is called the *raw encoding*. This byte string can then be further encoded using Base58Check. The Base58Check layer is the same as for upstream **Bitcoin** addresses [1].

SHA-256 compression function outputs are always represented as strings of 32 bytes.

The language consisting of the following encoding possibilities is prefix-free.

4.1 Transparent Public Addresses

These are encoded in the same way as in **Bitcoin** [1].

4.2 Transparent Private Keys

These are encoded in the same way as in **Bitcoin** [1].

4.3 Confidential Public Addresses

A *confidential address* consists of a_{pk} and pk_{enc}. a_{pk} is a SHA-256 compression function output. pk_{enc} is an encryption public key (currently ECIES, but this may change to Curve25519/crypto_box_seal), which represents an equivalence class of two points sharing an x coordinate on an elliptic curve.

4.3.1 Raw Encoding

The raw encoding of a confidential address consists of:

0x92	a_{pk} (32 bytes)	A 33-byte encoding of pk_{enc}

- A byte, **0x92**, indicating this version of the raw encoding of a **Zcash** public address.

- 32 bytes specifying a_{pk}.

- An encoding of pk_{enc}: The byte **0x01**, followed by 32 bytes representing the x coordinate of an elliptic curve point according to the **FE2OSP** primitive specified in section 5.5.4 of IEEE Std 1363-2000. [Non-normative note: Since the curve is over a prime field, this is just the 32-byte big-endian representation of the x coordinate. The overall encoding matches the **EC2OSP-X** primitive specified in section 5.5.6.3 of IEEE Std 1363a-2004. It does not matter which of the two points with the same x coordinate is used.]

Daira: check that this lead byte is distinct from other Bitcoin stuff, and produces 'z' as the Base58Check leading character.

Nathan: what about the network version byte?

Daira: add bibliographic references for the IEEE standards.

4.4 Confidential Address Secrets

A confidential address secret consists of a_{sk} and sk_{enc}. a_{sk} is a SHA-256 compression function output. sk_{enc} is an encryption private key (currently ECIES), which is an integer.

4.4.1 Raw Encoding

The raw encoding of a confidential address secret consists of, in order:

0x93	a_{sk} (32 bytes)	sk_{enc} (32 bytes)

- A byte **0x93** indicating this version of the raw encoding of a **Zcash** private key.

- 32 bytes specifying a_{sk}.

- 32 bytes specifying a big-endian encoding of sk_{enc}.

Daira: check that this lead byte is distinct from other Bitcoin stuff, and produces 'z' as the Base58Check leading character.

Nathan: what about the network version byte?

4.5 Coins

Transmitted coins are stored on the blockchain in encrypted form, together with a *coin commitment* cm.

A *transmitted coin ciphertext* is an ECIES encryption of a *transmitted coin plaintext* to a *key-private encryption key* pk_{enc}.

A *transmitted coin plaintext* consists of (v, ρ, r), where:

- v is a 64-bit unsigned integer representing the value of the *coin* in *zatoshi* ($1\ \mathbf{ZEC} = 10^8\ zatoshi$).

- ρ is a 32-byte $\mathsf{PRF}^{sn}_{a_{sk}}$ preimage.

- r is a 48-byte *COMM* trapdoor.

Note that the value s described as being part of a coin in the **Zerocash** paper is not encoded because it is fixed to zero.

4.6 Raw Encoding

The raw encoding of a *transmitted coin plaintext* consists of, in order:

0x00	v (8 bytes)	ρ (32 bytes)	r (48 bytes)

- A byte **0x00** indicating this version of the raw encoding of a *transmitted coin plaintext*.

- 8 bytes specifying a big-endian encoding of v.

- 32 bytes specifying ρ.

- 48 bytes specifying r.

5 Pours (within a transaction on the blockchain)

TBD.

6 Transactions

TBD.

7 References

[1] Base58Check encoding. `https://en.bitcoin.it/wiki/Base58Check_encoding`. Accessed: 2016-01-26.

[2] Eli Ben-Sasson, Alessandro Chiesa, Christina Garman, Matthew Green, Ian Miers, Eran Tromer, and Madars Virza. Zerocash: Decentralized Anonymous Payments from Bitcoin. In *Proceedings of the IEEE Symposium on Security and Privacy (Oakland) 2014*, pages 459–474. IEEE, 2014.