Alt-Coin Traceability

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Abstract

Many alt-coins developed in recent years make strong privacy guarantees, claiming to be virtually untraceable. This paper explores the extent to which these claims are true after the first appraisals were made about these coins. In particular, we will investigate Monero (XMR) and Zcash (ZEC), competitors in the private cryptocurrency space. We will test how traceable these currencies are after the most recent security updates, and how they hold up against their claims. We run some traceability experiments based on previously published papers for each coin. Results show that, introducing strict security and anonymity requirements into the cryptocurrency ecosystem makes the coin effectively untraceable, as shown by Monero. On the other hand, Zcash still hesitates to introduce changes that alter user behavior. Despite its strong cryptographic features, transactions are overall more traceable.

1 Introduction

The popularization of digital money in the past few decades has introduced new motivations for cryptocurrency. "Private currency" became a hot topic, as many alt-coins boasting strong anonymity guarantees emerged all over the cryptocurrency space. The incentive for privacy is often tied to illicit activities, but many legal services and users find anonymity appealing if they, for example, want to hide their political donations. Thus, the search for anonymity began.

Firstly, cryptocurrency is almost always pseudonymous, but not anonymous. Pseudonymity is relatively built in to cryptocurrency at heart. Addresses are by default a pseudonym, one that is not linked to your name or any other information unless you choose to disclose it. The difficult part of the equation is anonymity, where users do not want to be associated with other addresses via their behavior or transactions. Untraceability is thus the privacy feature that is sought after. The first cryptocurrency, Bitcoin, is traceable by design. Transactions are validated only when the sender and the receiver addresses are verified, effectively linking the two and creating some sort of association between the two. Anyone who views that transaction is able to correctly identify the sender and the receiver. This is undesirable, because if one address is linked to certain behavior (like illegal trades), an address that regularly transacts with it might be flagged as potentially criminal. Blockchain analytics allow researchers who understand the ecosystem to put user behavior into concrete heuristics, and therefore link certain addresses to each other in a way that is undesirable for the user.

Alternative coins sprung out of Bitcoin in order to explore and reach the bounds of traceable currency. Many alt-coins are forks of Bitcoin, inheriting many of its familiar and well-loved characteristics while adding a twist, whether it be in the cryptography or validation process. These new currencies created distinct ecosystems where developers can introduce completely new procedures that alter the way users send and receive. These systems generated both academic and financial interest. In this paper, we will explore the extent to which alt-coins, which are created for the purpose of anonymity, fulfill their promise, and what that may mean for cryptocurrencies in the future. Specifically, we look at the traceability of two privacy-focused alt-coins, Monero and Zcash.

2 Background and Related Work

2.1 Monero

Monero is a privacy-focused cryptocurrency launched in April 2014. It has several features focused on enhancing unlinkability and untraceability. Unlinkability is not being able to link two addresses to the same person. Untraceability is not being able to link receiving money from having spent it. Monero promotes unlinkability by generating a one-time use address for every transaction output. Monero promotes untraceability by requiring each input in a transaction to be mixed with some decoy chaff inputs called mixins. An outside viewer only knows that one of the members of an input is the real transaction output (TXO) being spent, but they do not know which one.

Despite the use of one-time addresses and mixins, any node can still verify that each TXO is only spent one time. One-time ring signatures, a form of zero-knowledge proof, are utilized to solve this problem. The EdDSA algorithm, based on the elliptic curve discrete logarithm problem, is utilized for ring signatures. A one-time ring signature is composed of four algorithms, GEN, SIG, VER and LNK [Sab13]:

1. GEN: the signer picks a random secret key x and computes public key $P = xG$ and the key image $I = H_p(P)$, where H_p is a deterministic hash function.
2. SIG: the signer takes a message m, a set S' of public keys $\{P_i\}_{i \neq s}$ and outputs a signature σ and a subset $S = S' \bigcup \{P_s\}$.
3. VER: the verifier checks the signature.
4. LNK: the verifier checks if I has been used in past signatures.

Each transaction comes with a ring signature that can identify which mixin is the real one without revealing any information about it. Meanwhile, each mixin, as well as the real input, has a unique key image, and all nodes can check if any key image has been revealed before or not. Using this approach, double spending can be prevented easily [Mös+18].

Initially, Monero did not require transactions to use mixins. Thus, in the beginning, the majority of Monero transactions had zero mixins, which meant the real input was known and thus traceable. In March 2016, Monero started requiring a minimum of 2 mixins per input; this was increased to 4 in September 2017 and 6 in April 2018; and from October 2018, the number of mixins has been fixed at 10 for all transactions.

Though mixins make it harder to trace transactions, it is still possible to determine what the real input to a transaction is by doing some chain analysis as illustrated in Figure 1.

Prior work [Mös+18][Kum+17] has investigated the extent to which Monero transactions are traceable. Their analysis included doing chain analysis starting from those transactions with zero mixins. They also proposed several heuristics for guessing the real input and evaluated their effectiveness on the ground truth derived from the zero mixin chain analysis. Their heuristics include:

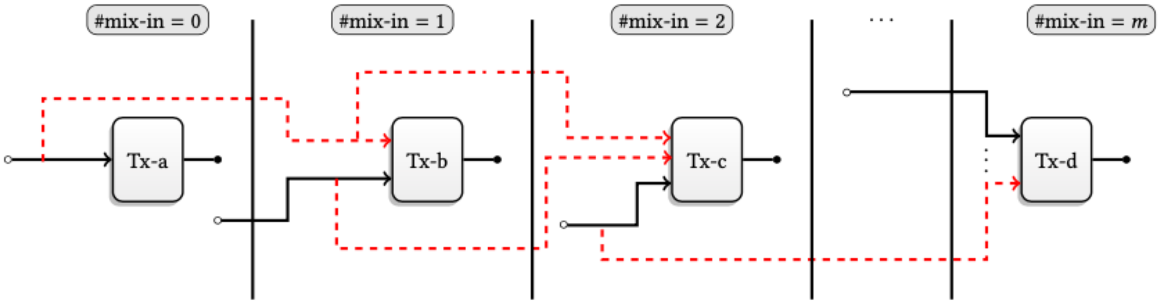
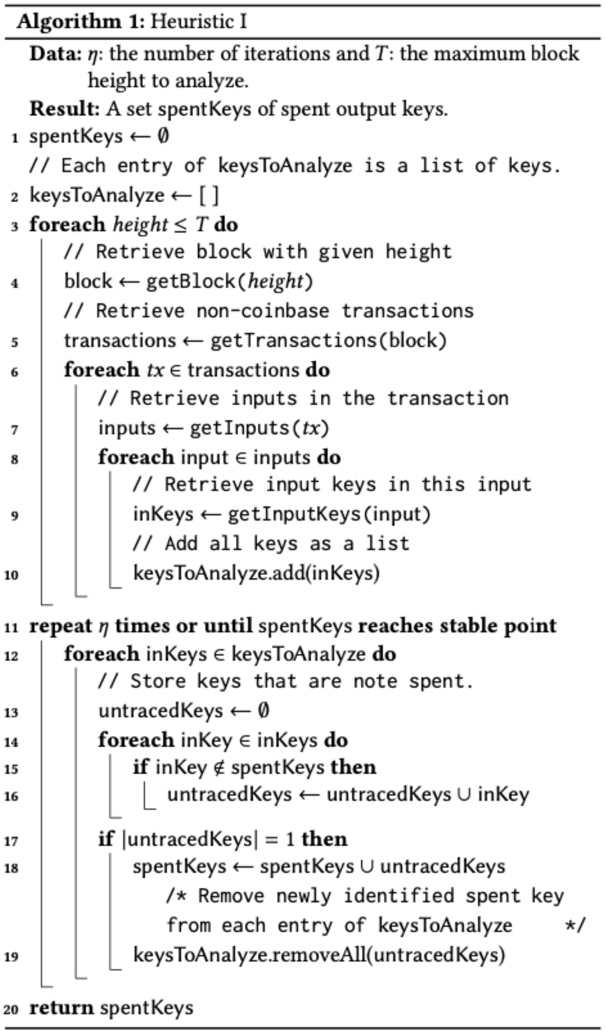


Figure 1: Figure 6 from [Kum+17] illustrating zero-mixin chain analysis. By iteratively marking spent outputs, one can deduce the real input for transactions with large numbers of mixins.

- **Zero mixin chain analysis:** Start with transactions that use zero mixins, where the real input TXOs are known. Remove those TXOs from all other transaction inputs. If any transaction inputs now only have one TXO member, then that is the real input. These deduced spent TXOs can then be removed from all other transactions. By iterating this process, one can deduce the real input for many transactions, even those that use a large number of mixins. The algorithm is described in [Kum+17] and shown in Figure 2.
- **Guess newest:** This temporal heuristic simply assumes the newest TXO included in a transaction input is the real input. This heuristic is based on analysis done on traceable transactions that shows people tend to spend Monero soon after receiving it. Möser et al. [Mös+18] and Kumar et al. [Kum+17] both achieved greater than 90% accuracy when applying this heuristic to ground truth for data prior to April 2017. Their results are shown in Figures 3 and 4. Several factors that contribute to the high accuracy of this heuristic include a large fraction of inputs having 0 mixins (2 mixins were not mandatory until March 2016) and a mixin sampling algorithm that does not mirror real spending patterns.
- **Merging outputs:** This heuristic was proposed in [Kum+17]. The idea is illustrated in Figure 5. When a transaction has two or more transaction outputs and two or more of those outputs are included in different inputs of another transaction, then those included outputs are assumed to be the real inputs. This heuristic is based on it being unlikely that multiple outputs of the same transaction would be included as different inputs in another transaction unless they were the real inputs. Since someone was able to spend two or more different outputs in the same transaction, it also suggests that those TXO addresses all belong to the same person, weakening unlinkability.

Both the Möser et al. [Mös+18] and Kumar et al. [Kum+17] analyses only analyze the Monero blockchain up to early 2017. Möser et al. do their analysis up through block 1288774 (from April 14, 2017) and Kumar et al. do their analysis up through block 1240503 (from February 6, 2017). For most of the periods analyzed by these papers, mixins were not required, and the majority of transactions used zero mixins. All these transactions are immediately traceable. From March 2016 onward, when a 2-mixin requirement went into effect, the number of fully-traceable transactions went down significantly.

It is also worth noting that information leakage of public mining pools can affect the deductibility of transactions. It is highly likely to be the real spend if an input in a pool's payout transaction



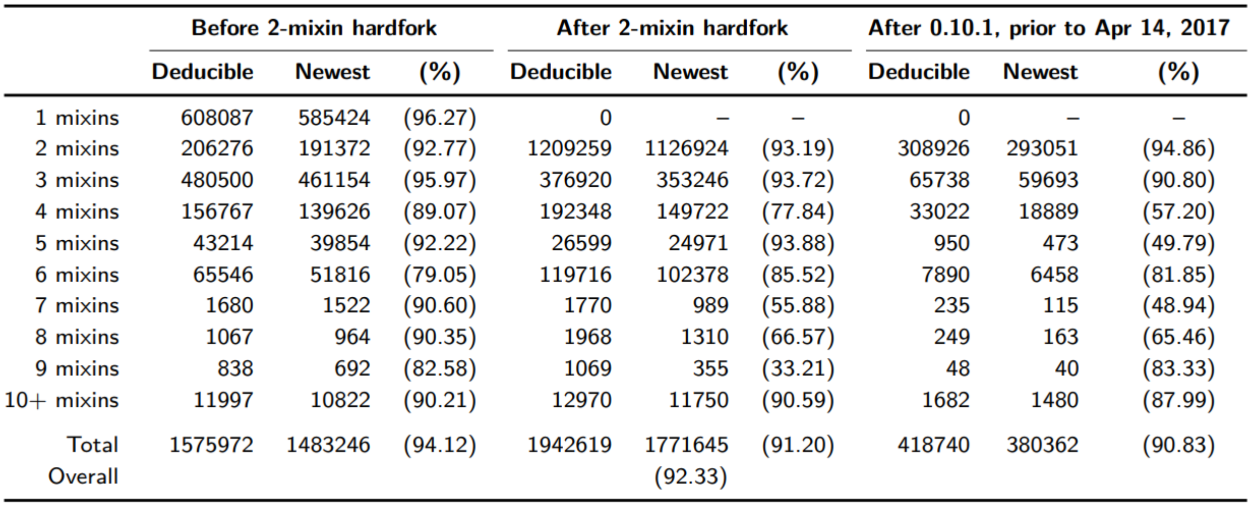
```
Algorithm 1: Heuristic I
Data: $\eta$: the number of iterations and $T$: the maximum block
      height to analyze.
Result: A set spentKeys of spent output keys.
spentKeys ← ∅
// Each entry of keysToAnalyze is a list of keys.
keysToAnalyze ← [ ]
foreach $height \leq T$ do
    // Retrieve block with given height
    block ← getBlock(height)
    // Retrieve non-coinbase transactions
    transactions ← getTransactions(block)
    foreach $tx \in$ transactions do
        // Retrieve inputs in the transaction
        inputs ← getInputs(tx)
        foreach input ∈ inputs do
            // Retrieve input keys in this input
            inKeys ← getInputKeys(input)
            // Add all keys as a list
            keysToAnalyze.add(inKeys)
repeat $\eta$ times or until spentKeys reaches stable point
    foreach inKeys ∈ keysToAnalyze do
        // Store keys that are note spent.
        untracedKeys ← ∅
        foreach inKey ∈ inKeys do
            if inKey ∉ spentKeys then
                untracedKeys ← untracedKeys ∪ inKey
        if |untracedKeys| = 1 then
            spentKeys ← spentKeys ∪ untracedKeys
                /* Remove newly identified spent key
                from each entry of keysToAnalyze     */
            keysToAnalyze.removeAll(untracedKeys)
return spentKeys
```

Figure 2: Algorithm 1 from [Kum+17] showing the zero-mixin chain analysis pseudocode.

is spent from a coinbase transaction of a block known to belong to the same pool. In the study of Möser et al. [Mös+18], the authors crawled 18 public mining pools and were able to detect mining pools' activities and deanonymize additional transactions.

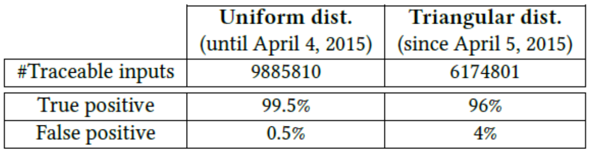
In January 2017 (toward the end of both of the previous analyses), Ring Confidential Transactions (or RingCT) was introduced as an experimental feature in Monero [Sun+17]. This feature hides input and output amounts. Previously, input and output amounts were public, so one could only choose TXOs with the same amount as the real input to include as mixin. This limited the choice of mixins and made traceability easier. With RingCT, any TXO can be included as a mixin and the input and output amounts of transactions are now hidden, which makes it harder to trace transactions.

RingCT was made required for all transactions in September 2017 and the minimum number of mixins was increased to 4. This minimum was increased to 6 in April 2018, and in October 2018, the number of mixins per transaction was fixed at 10. RingCT and the larger mixin requirements have made transactions much harder to trace. As can be seen from the graphs from [Mös+18] and [Kum+17] (Figure 6), there is a sharp drop in traceability after the introduction of RingCT.



	Before 2-mixin hardfork			After 2-mixin hardfork			After 0.10.1, prior to Apr 14, 2017		
	Deducible	Newest	(%)	Deducible	Newest	(%)	Deducible	Newest	(%)
1 mixins	608087	585424	(96.27)	0	–	–	0	–	–
2 mixins	206276	191372	(92.77)	1209259	1126924	(93.19)	308926	293051	(94.86)
3 mixins	480500	461154	(95.97)	376920	353246	(93.72)	65738	59693	(90.80)
4 mixins	156767	139626	(89.07)	192348	149722	(77.84)	33022	18889	(57.20)
5 mixins	43214	39854	(92.22)	26599	24971	(93.88)	950	473	(49.79)
6 mixins	65546	51816	(79.05)	119716	102378	(85.52)	7890	6458	(81.85)
7 mixins	1680	1522	(90.60)	1770	989	(55.88)	235	115	(48.94)
8 mixins	1067	964	(90.35)	1968	1310	(66.57)	249	163	(65.46)
9 mixins	838	692	(82.58)	1069	355	(33.21)	48	40	(83.33)
10+ mixins	11997	10822	(90.21)	12970	11750	(90.59)	1682	1480	(87.99)
Total	1575972	1483246	(94.12)	1942619	1771645	(91.20)	418740	380362	(90.83)
Overall					(92.33)				

Figure 3: Table 3 from [Mös+18] showing the accuracy of the guess-newest heuristic on inputs prior to April 14, 2017.



	Uniform dist. (until April 4, 2015)	Triangular dist. (since April 5, 2015)
#Traceable inputs	9885810	6174801
True positive	99.5%	96%
False positive	0.5%	4%

Figure 4: Table 5 from [Kum+17] showing the accuracy of the guess-newest heuristic on inputs up to February 2017.

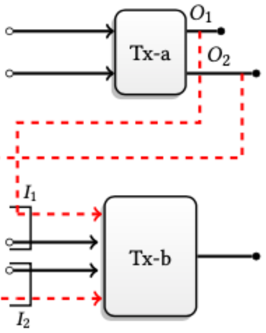


Figure 5: Figure 9 from [Kum+17] illustrating the merging outputs heuristic. Tx-a is called a ”source transaction” and Tx-b is called a ”destination transaction.”

In addition to the RingCT and mixin changes, Monero also changed their mixin sampling algorithm in response to these papers and their own research from Monero Research Labs [NNM14]. At first, mixins were sampled uniformly from all previous transactions. This was changed in April 2015 to a triangular distribution that favored more recent transactions[1]. Then, in response to evidence showing that real spending habits tended to spend recent TXOs, the sampling distribution

[1] https://github.com/monero-project/monero/commit/f2e8348be0c91c903e68ef582cee687c52411722

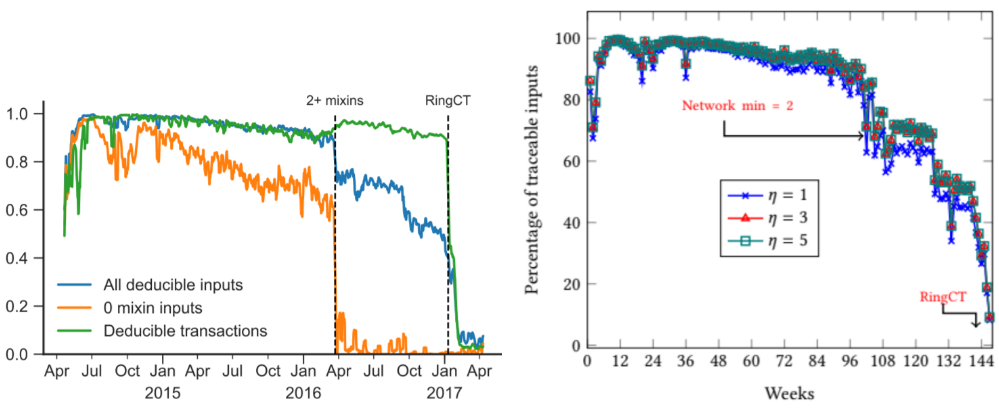


Figure 6: Figure 5 from [Mös+18] (left) and Figure 7c from [Kum+17] (right) showing the fraction of deducible inputs up to April 2017 and February 2017, respectively.

was changed in January 2017 to weigh recent transactions (past 5 days) more heavily. This ”recent zone” was further reduced to the past 3 days in September 2017. Finally, in response to [Mös+18], the mixin sampling distribution was changed to a gamma distribution with parameters hardcoded to the fitted gamma from Figure 11 of their paper[2] to better match the real spend-time distribution. This change first appeared in Monero 0.13.0 released in fall 2018.

In our paper, we investigate the effectiveness of the changes to Monero since 2017 in mitigating the effectiveness of the above heuristics.

2.2 Zcash

Zcash is another alternative cryptocurrency that appeared as a competitor in the race to anonymity. A fork of Bitcoin, Zcash inherits most of its predecessor's characteristics. However, the motive behind its development is to completely break the link between the sender and the receiver.

Currently, Zcash is not widely used. It is unclear at the moment how much illicit or criminal activity is on Zcash, but a study as recent as May 6th, 2020 showed that it is by far not the preferred cryptocurrency on the dark web [Sil+20]. Many criminals do not understand Zcash's operating model and find it difficult to use, preferring Bitcoin and Monero [Sil+20].

One of Zcash's unique appeals is its method for proof-of-work. Using the novel form of zero-knowledge cryptography zk-SNARK (zero-knowledge succinct non-interactive argument of knowledge), Zcash allows zero interaction between the prover and the verifier, providing a barrier that further impedes efforts to link addresses together and thus potentially reveal information about the transaction or the address owner [Zks]. This novel technology is useful for cryptocurrency applications because it is succinct, meaning it is capable of completion within a matter of seconds [Zks].

The anatomy of a shielded transaction varies from that of a normal Bitcoin transaction. Under Bitcoin, each transaction is validated via linking the sender and receiver addresses, as well as the input and output values on the blockchain [Pet16]. zk-SNARKs allow nodes to validate transactions without actually revealing any information about the addresses or values involved. To do so, Zcash publishes a set of public parameters for all users to use for validating transactions. This process requires multiple parties to collaborate to create these parameters, which, if compromised, would result in counterfeiting of Zcash. The protocol is designed such that all members collaborating to

[2] https://github.com/monero-project/monero/commit/34d4b798d44250f64fdcac61439a86afa8607c3b

generate these parameters have to be dishonest in order for the final parameters to be compromised. Since these parameters have already been generated and are now readily available, users can now safely generate zk-SNARK proofs [Par].

In the Zcash ecosystem, there are two types of addresses - transparent and shielded - as illustrated in Figure 7. t-addr, as transparent addresses are known, are exactly like Bitcoin's addresses [Zte]. However, z-addr, their shielded counterparts, are the only addresses that really benefit from the additional anonymity features that Zcash is trying to implement.

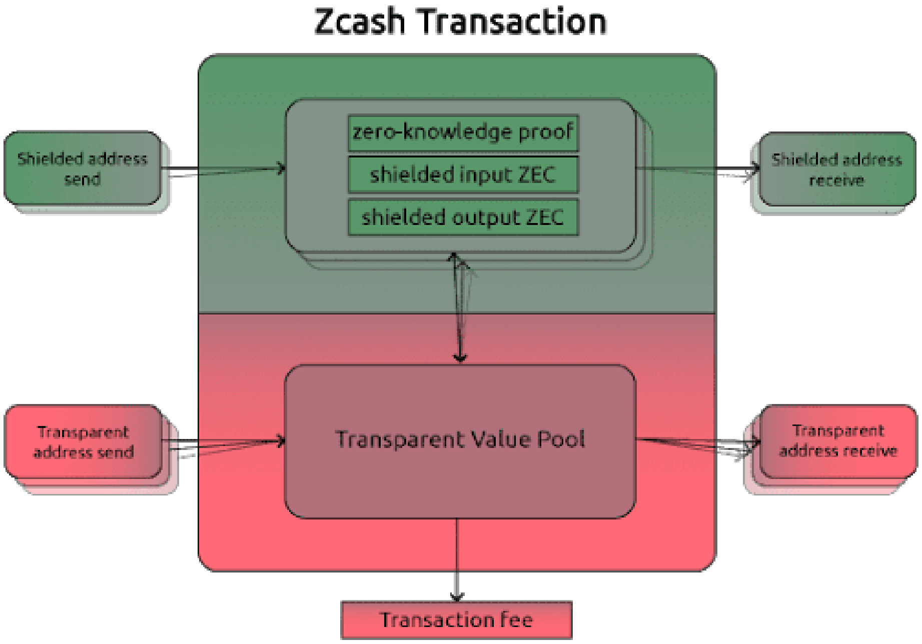


Figure 7: Figure from [Pet16]: High-level description of Zcash transactions. As seen, Zcash is divided between shielded and transparent pools, where shielded pools receive all the benefits of Zcash's anonymity guarantees.

Thus, it is evident that to take full advantage of Zcash, users should try to make transactions that utilize addresses in the shielded pool. Currently, there are four main types of transactions that can be made in Zcash, as shown in Figure 8: public (t-to-t), shielding (t-to-z), deshielding (z-to-t), and private (z-to-z) [Zte]. An example of each transaction type is given in Figure 9. Private transactions provide the most anonymity for the sender and receiver. However, unlike other altcoins in this anonymity space, Zcash does not require its users to make private transactions at all. In fact, there are completely no requirements on the types of transactions that take place in Zcash.

The function *vJoinSplit* determines the type of transaction it is. *vJoinSplit* takes in input and output t-addresses, also known as *zIn* and *zOut*. If *zIn* and *zOut* both have inputs, then the transaction is transparent, and if they are both empty, it is private. When *zIn* is populated but *zOut* is empty, the transaction is shielding. The vice versa is a deshielding transaction. These parameters are complemented by input double-spending tokens and output shielded addresses that provide additional information given the transaction type.

The overall Zcash ecosystem is not conducive towards achieving anonymity for its users. Historically, at any given time, only around 0.09% of ZEC transacted in a 30-day period is shielded [Zus]. There are 5 times more transparent transactions than shielded ones (t-to-z), and 13 times

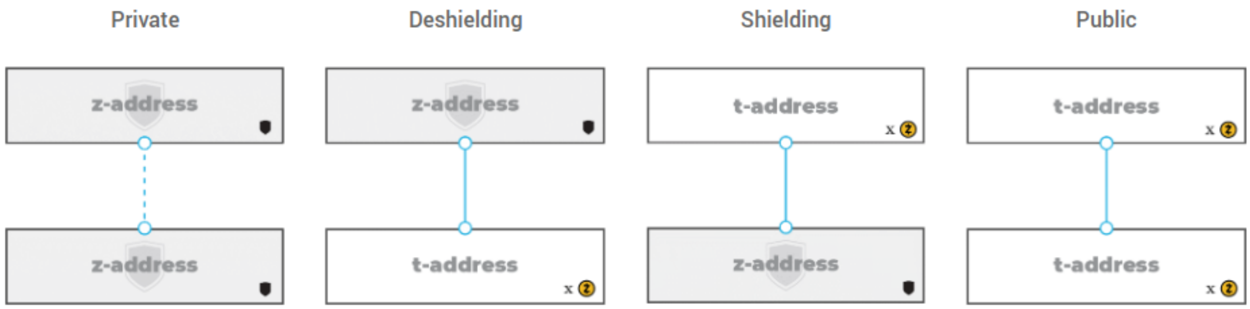


Figure 8: Figure from [Zte]: Four main types of transactions.

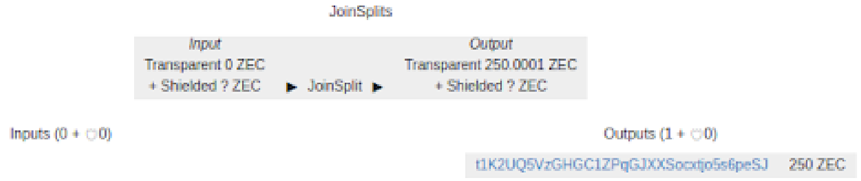
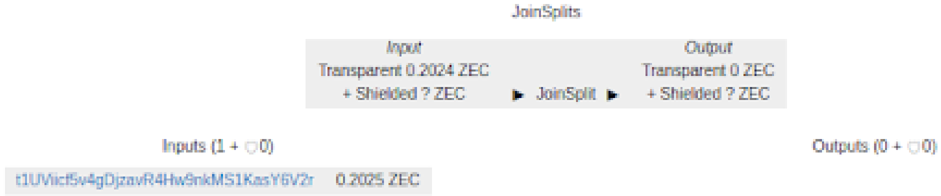
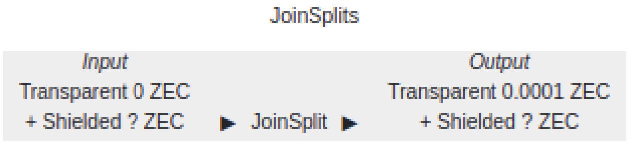
Txn type	Example
Public	 Inputs (1) t1KLGj3izuKveu1eFZUiwp3BEKHQA/Yv2Z7 99.14063 ZEC Outputs (2) t1RytpPXoGvevVECv5NsRVD2BTrz78xeiDQ 0.2 ZEC t1KLGj3izuKveu1eFZUiwp3BEKHQA/Yv2Z7 98.94053 ZEC
Deshielding	 JoinSplits Input Transparent 0 ZEC + Shielded ? ZEC ▶ JoinSplit ▶ Output Transparent 250.0001 ZEC + Shielded ? ZEC Inputs (0 + 🛡0) Outputs (1 + 🛡0) t1K2UQ5VzGHGC1ZPqGJXXSocxtjo5s6peSJ 250 ZEC
Shielding	 JoinSplits Input Transparent 0.2024 ZEC + Shielded ? ZEC ▶ JoinSplit ▶ Output Transparent 0 ZEC + Shielded ? ZEC Inputs (1 + 🛡0) t1UViicf5v4gDjzavR4Hw9nkMS1KasY6V2r 0.2025 ZEC Outputs (0 + 🛡0)
Private	 JoinSplits Input Transparent 0 ZEC + Shielded ? ZEC ▶ JoinSplit ▶ Output Transparent 0.0001 ZEC + Shielded ? ZEC

Figure 9: Table of examples for each type of transaction. [Zte]

more transparent transactions than “fully shielded” ones (i.e. z-to-z). Most third-parties for Zcash actually only allow transparent transactions. Given that Bitcoin can easily provide the same support as Zcash transparent transactions, it seems that the large majority of Zcash users do not yet understand Zcash’s operating model. Despite the demand for private digital money, Zcash is evidently still in the early stages of development.

The experiment we will be replicating the most closely is that of Kappos et al. [Kap+18]. This experiment was run before the Sapling upgrade in Zcash. By running some blockchain analytics and defining some heuristics (Figure 10) based on Zcash users’ behavior, the researchers were able to identify clusters and tag them to specific mining pools. Results (Figure 11) showed a good number of successful clustering, but it is impossible to verify how correct these clusters are. The researchers concede that there are definitely false positives within the successfully “traced” addresses. This paper showed that, even though cryptographically Zcash is very well-founded, the users behave in a way that does not take full advantage of the shielded pool, making them traceable. As each user in the shielded pool becomes linked to the transparent pool, the overall anonymity of the ZEC ecosystem reduces as the anonymity set shrinks drastically. On top of the already miniscule set of users even utilizing shielded transactions at all, Zcash is effectively traceable as of this study.

If two or more t-addresses are inputs in the same transaction (whether that transaction is transparent, shielded, or mixed), then they are controlled by the same entity.

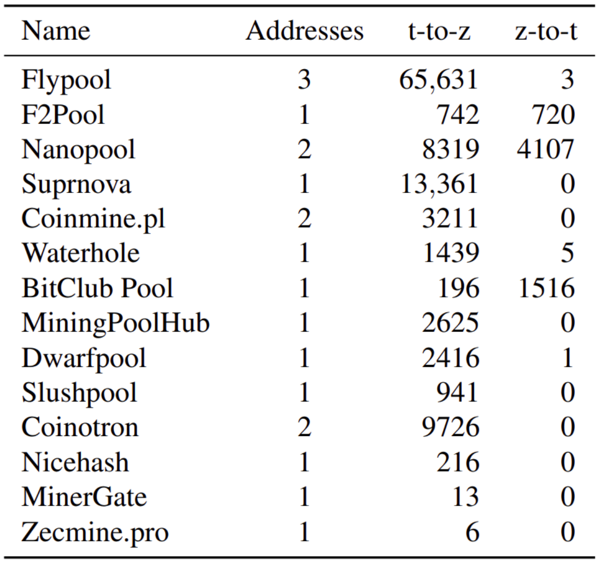
If one (or more) address is an input t-address in a vJoinSplit transaction and a second address is an output t-address in the same vJoinSplit transaction, then if the size of zOut is 1 (i.e., this is the only transparent output address), the second address belongs to the same user who controls the input addresses.

Any z-to-t transaction carrying 250.0001 ZEC in value is done by the founders.

If a z-to-t transaction has over 100 output t-addresses, one of which belongs to a known mining pool, then we label the transaction as a mining withdrawal (associated with that pool), and label all non-pool output t-addresses as belonging to miners.

For a value v, if there exists exactly one t-to-z transaction carrying value v and one z-to-t transaction carrying value v, where the z-to-t transaction happened after the t-to-z one and within some small number of blocks, then these transactions are linked.

Figure 10: Heuristics defined in Kappos et al. and used in our experiment [Kap+18].



Name	Addresses	t-to-z	z-to-t
Flypool	3	65,631	3
F2Pool	1	742	720
Nanopool	2	8319	4107
Suprnova	1	13,361	0
Coinmine.pl	2	3211	0
Waterhole	1	1439	5
BitClub Pool	1	196	1516
MiningPoolHub	1	2625	0
Dwarfpool	1	2416	1
Slushpool	1	941	0
Coinotron	2	9726	0
Nicehash	1	216	0
MinerGate	1	13	0
Zecmine.pro	1	6	0

Figure 11: Table 4 from [Kap+18]: Number of transactions linked to each pool given the number of addresses already tagged to each pool.

3 Experiments

3.1 Methodology

3.1.1 Monero

For the Monero experiments, we began by trying to reproduce the Möser et al. [Mös+18] experiments by trying their code provided at `https://github.com/maltemoeser/moneropaper`. We struggled getting the Neo4j setup queries (step 3 in the README) to run, hitting intermittent segfaults when running them on the Jeju machine (jeju.andrew.cmu.edu). Later, we were able to run the setup queries successfully on Anthony's personal Windows machine. However, when we then tried running some of Jupyter Notebook queries against our dataset, several queries (including the deducible_spends queries) yielded zero results. It was unclear whether this was due to bugs in the notebook queries or errors in importing and initializing the data in the Neo4j graph database.

Rather than spend more time debugging their code, we decided to parse the blockchain data ourselves and write our own analysis scripts. We first ran a Monero daemon on Jeju to download the entire blockchain up to block 2077094 (from April 15, 2020). We then downloaded a Monero blockchain explorer from `https://github.com/moneroexamples/onion-monero-blockchain-explorer`, compiled it, and deployed it on Jeju at `http://jeju.andrew.cmu.edu:8081/`. We then wrote Python and Java scripts that queried the local blockchain explorer using its REST JSON API to extract block and transaction info and do our traceability analysis. Our code is available at `https://github.com/erwa/monero-tracing`.

3.1.2 Zcash

To begin our traceability analysis of Zcash and its underlying elements we decided we wanted to replicate the results of Kappos et al. [Kap+18] and extend its analysis of the blockchain up to the current block height. Provided that the experiment from Kappos et al. required a well-provisioned machine and free storage space equivalent to triple the current Zcash blockchain size (26GiB). To do this we had the option of either using a machine used for academic research (jeju) that was provisioned with 32 cores, 256GB of RAM, and 45TB of disk space, or starting our own instance via cloud computing infrastructure. We decided to go with the latter mainly because we wanted more freedom in configuring the machine and did not want to do anything drastic to change the machine. The experiment required Docker virtualization, and many of the commands required root privileges. Given that we had some Amazon Web Services (AWS) credits, we launched Ubuntu AWS instances for the experiment and also created Elastic Block Store (EBS) volumes for persistent storage. After testing the experiment and various instance types, we found that the experiment required more compute and memory than initially believed. We concluded that a general-purpose t2.2xl Ubuntu instance (8 vCPUs, 32 GB RAM) attached to an EBS volume around 150GB in capacity was suitable for running the experiment most smoothly. One improvement to our setup could have been to automatically attach and mount the EBS volume to the instance on reboot. Although the experiment ran smoothly with the aforementioned specifications, we realize the experiment may have run faster with the more provisioned jeju machine.

While running the experiment, we encountered a few setbacks in which we had to edit the structure of the experiment in order to make progress. For one, we had to re-configure the allowed IP addresses and ports for the Zcash client to accept RPC commands from other containers in the Docker network, since the IP addresses provided did not work. In addition, we noticed that the extraction from blocks to a Postgres database made unnecessary calls to re-establish an RPC connection between the Zcash node and Postgres container for every block. This often led to the experiment hanging or the connection being lost before any significant progress could be made on the blockchain. Another issue with the experiment we encountered was the Zcash node running in its own container was being killed while the other container was processing, which sometimes led to the block index becoming out of sync. We suspected that this was due to the container limiting the amount of memory allocated to the Zcash process. This would require a reindexing of the entire 25 GB blockchain which also slowed progress. To address this issue we decided to run the Zcash client on the host system rather than running in the container. This significantly sped up the RPC calls from the Postgres container and made the Zcash client more stable. We also decided to move the blockchain to its own directory outside of the home directory and its own mounted volume mainly because we wanted the environment and experimental data to be encapsulated in EBS storage. These changes can all be found in our repository at `https://github.com/claiye/zcash-analysis-19733`. The sections most relevant to our replication of the experiment are "Troubleshooting" and "Updates from Past Experiment".

Another aspect of the experiment we had to familiarize ourselves with was the use of Spark, a framework used to process large amounts of data. The research analysis container came prebuilt with a version of PySpark that was to be used for the analysis portion of the experiment. However we found some incompatibilities with the Spark configurations and our host and Docker environment. In the Spark configuration settings, the runtime environment of the Spark process can be configured through the API, such as executor memory and worker threads. While the configuration settings provided in the repository worked smoothly for small sizes of the blockchain, when approaching the height used in the paper, the execution of the analysis became faulty with hidden errors. This and the aforementioned setbacks were a big hindrance to reaching the current day blockheight. In the next steps section we will discuss some ideas to speed up the overall experiment.

3.2 Results

3.2.1 Monero

Zero-Mixin Chain Analysis. We applied the zero mixin chain analysis on the entire blockchain from the beginning to block 2077094 (April 15, 2020). The chain analysis ran to completion (unable to deduce any more inputs) after 27 iterations of the algorithm. Though we found that some transactions as recent as April 9, 2020, are fully deducible, the percentage of partially or fully deducible transactions has been nearly zero for over two years, as seen in Figure 12. This suggests that the combination of RingCT and the increased number of mixins has been fairly successful at reducing the traceability of Monero transactions.

In addition to fully deduced inputs, we also looked at how much we reduced the anonymity set sizes of the non-fully deduced inputs. For comparison, first we show the results from Kumar et al. [Kum+17], which were done on blocks up to February 2017, in Figure 13. In their figure, η is the number of iterations they ran Algorithm 1 for.

We did a similar effective anonymity-set size analysis on all inputs with 10 or fewer mixins up to April 2020, but instead of just running Algorithm 1 for a fixed number of iterations, we ran it until it converged (no more inputs were deducible), which required 27 iterations. The results are shown in Figure 14.

RingCT was introduced in January 2017 and since fall 2018, all transactions require exactly 10 mixins. Our results show that for inputs with 10 mixins (which include all transactions since fall 2018), despite running zero-mixin chain analysis to convergence, the large majority of 10-mixin transactions still retain their original anonymity set size of 11. For most other mixin amounts, the effective anonymity set sizes are also significantly larger on average than in the Kumar et al.

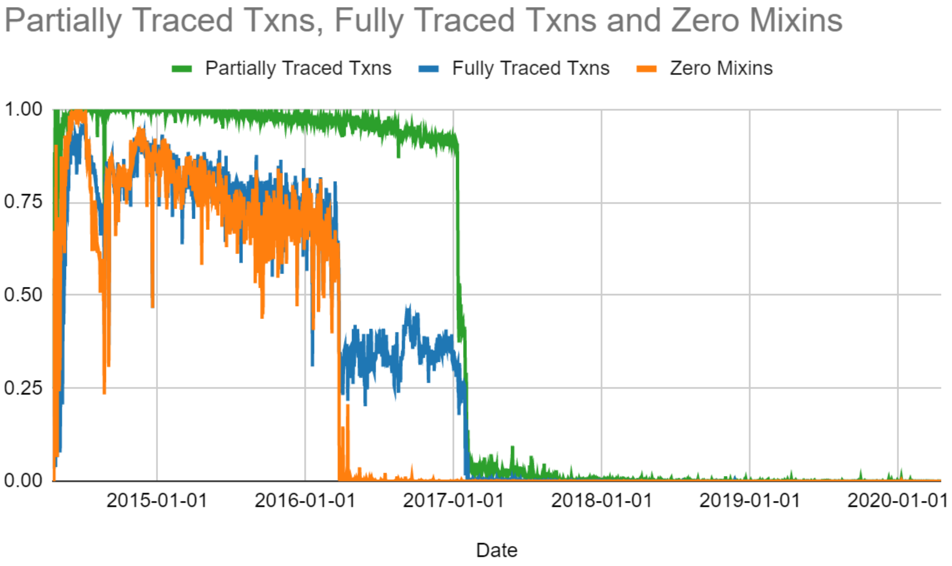


Figure 12: Daily fraction of transactions with zero mixins, at least one traceable input, and all inputs deducible from the beginning of Monero to April 15, 2020.

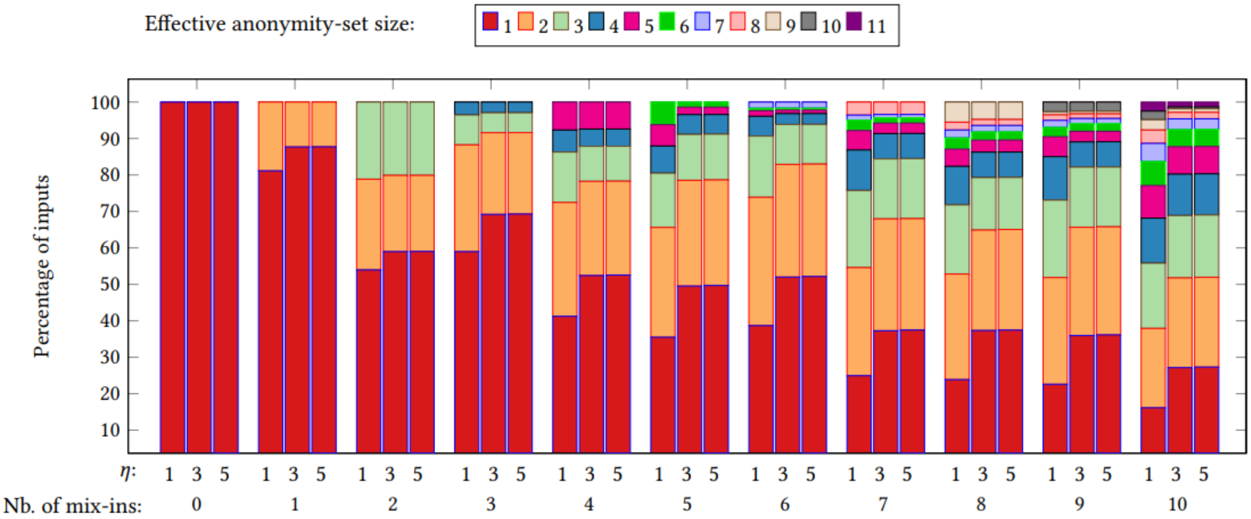


Figure 13: Figure 8 from [Kum+17] illustrating the effective anonymity-set size after running zero-mixin chain analysis for inputs up to February 2017.

results. This suggests that the RingCT feature and fixed 10-mixin requirement have been fairly effective at reducing the traceability of Monero transactions.

We also investigated what would happen if a significant fraction of non-deduced inputs were somehow traced (e.g.: a data breach that exposed secret keys). We did this simulation by choosing X% of non-deduced inputs and then "guessing" the newest TXO included in each of these inputs as the real input, and then running zero-mixin chain analysis again. We tried this for X = 15, 30, and 60. Our results are shown in Figure 15. We see that even after a 30% breach, over half

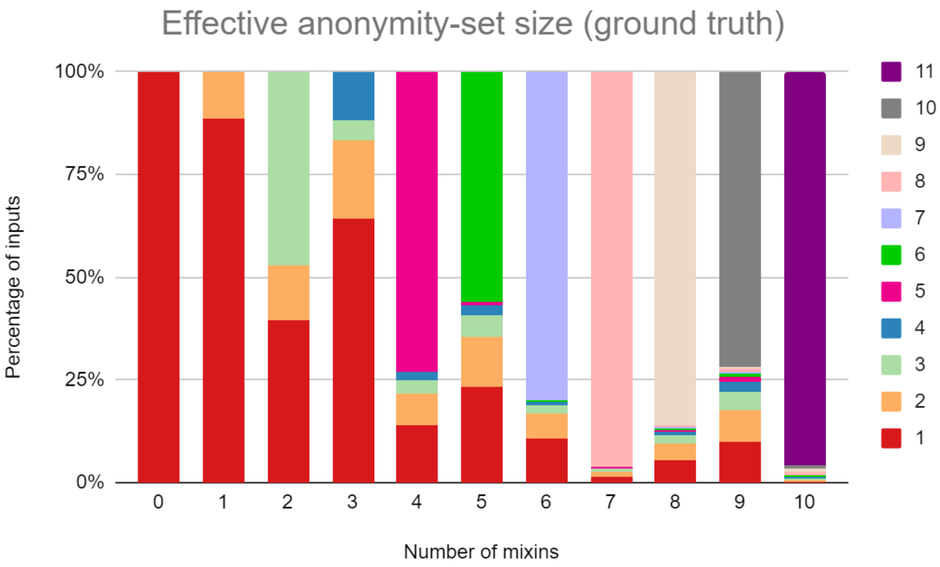
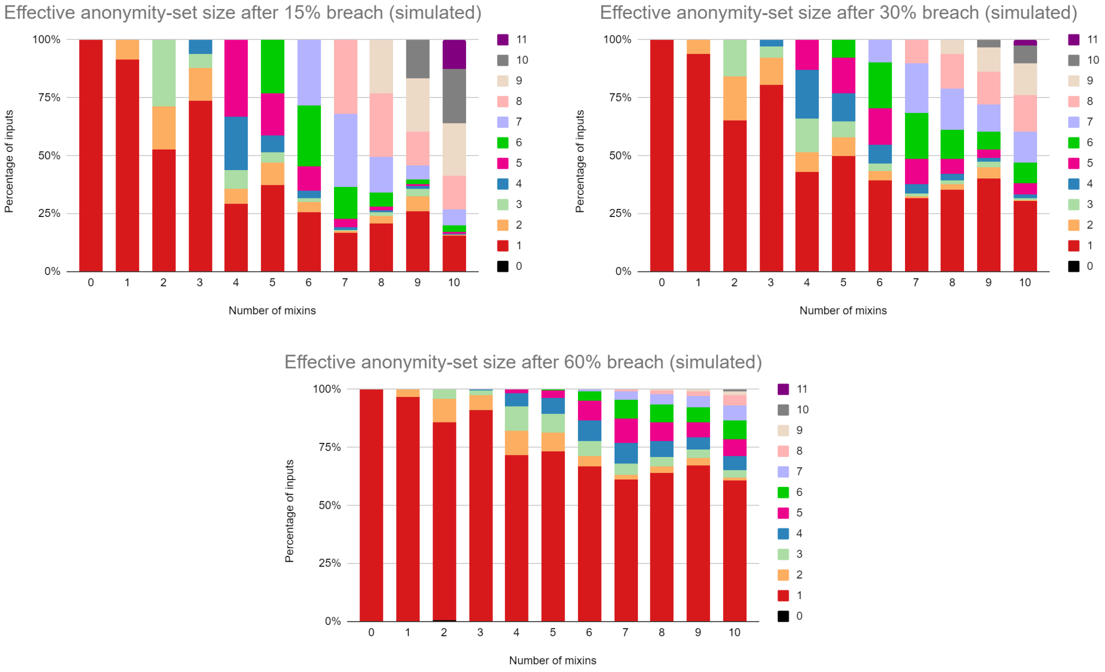

Effective anonymity-set size (ground truth)

Figure 14: Effective anonymity-set size of inputs up to April 2020 after applying zero-mixin chain analysis.


Effective anonymity-set size after 15% breach (simulated)

Effective anonymity-set size after 30% breach (simulated)

Effective anonymity-set size after 60% breach (simulated)

Figure 15: Effective anonymity-set sizes for inputs with up to 10 mixins after simulating a breach of X% of non-deduced inputs. Note that an anonymity-set size of 0 means we must have guessed wrong for one of the inputs we simulated a breach for, leading to a contradiction, but this was a negligible percentage of inputs.

of 10-mixin inputs still maintain an anonymity set size of 7 or more. Such a breach is already an unlikely scenario given that secret keys for many different users are not usually aggregated on one machine, but instead, each user's secret key generally resides only on their own personal device.

Guess-Newest Heuristic. Using the deduced inputs from the zero mixin chain analysis as our ground truth, we then investigated the effectiveness of the temporal heuristic that guesses the newest TXO included in an input as the real input. Since many security changes have been made to Monero since the introduction of RingCT (January 2017), we compared how effective the guess-newest heuristic was before RingCT and after RingCT (Figure 16).

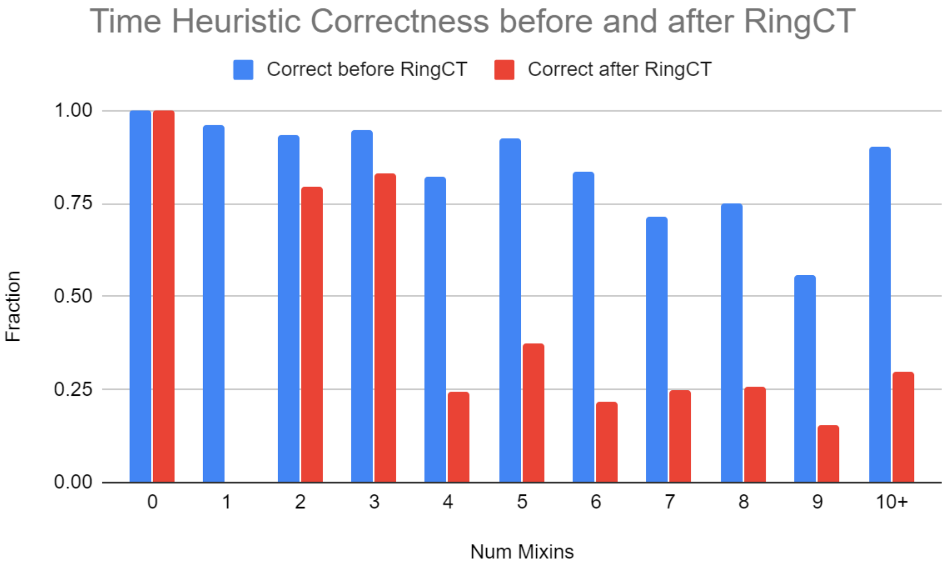


Figure 16: The accuracy of the guess-newest heuristic for inputs before and after RingCT (January 2017).

Whereas Möser et al. [Mös+18] and Kumar et al. [Kum+17] reported 90%+ accuracy when analyzing inputs prior to April 2017 and February 2017, respectively, we find that for transactions post-RingCT (January 2017), the accuracy of the guess-newest heuristic drops dramatically. For inputs with 10+ mixins (which includes all inputs since fall 2018 when the number of mixins per transaction was fixed at 10), we see that the accuracy of the heuristic has decreased about 3x, going from about 90% pre-RingCT to about 30% post-RingCT.

Several factors contributed to the decrease in accuracy of the guess-newest heuristic. First, with RingCT, input and output amounts are now hidden. This means that you can now use any RingCT output as a mixin. Prior to RingCT, you could only use TXOs that had the same amount as the real TXO, which significantly reduced the set of TXOs you could choose mixins from. Next, as shown in [Mös+18] and [Kum+17], users tend to spend TXOs soon after they are created. Thus, it makes sense to choose mixins form a distribution that more closely resembles real spending patterns. Since RingCT was introduced, some mixins were chosen from a ”recent zone,” which was originally 5 days and then reduced to 3 days. The mixin sampling distribution has since been replaced with a gamma distribution (from [Mös+18]) fitted to the empirical spend-time distribution.

We also analyzed transactions between our group members to further test the accuracy of the time heuristic on recent Monero transactions. The time distribution of the real input is shown in

Figure 17. We conducted 76 transactions between us, 52 of which we have ground truth for the real input. The following figure indexes the real inputs from 0-10, with a higher index meaning a newer input, so the newest inputs have index 10. From the figure it is shown that only approximately 38.5% of the real inputs are the newest. Considering all current Monero transactions have 10 mixins, the accuracy of time heuristic is consistent with the previous analysis.

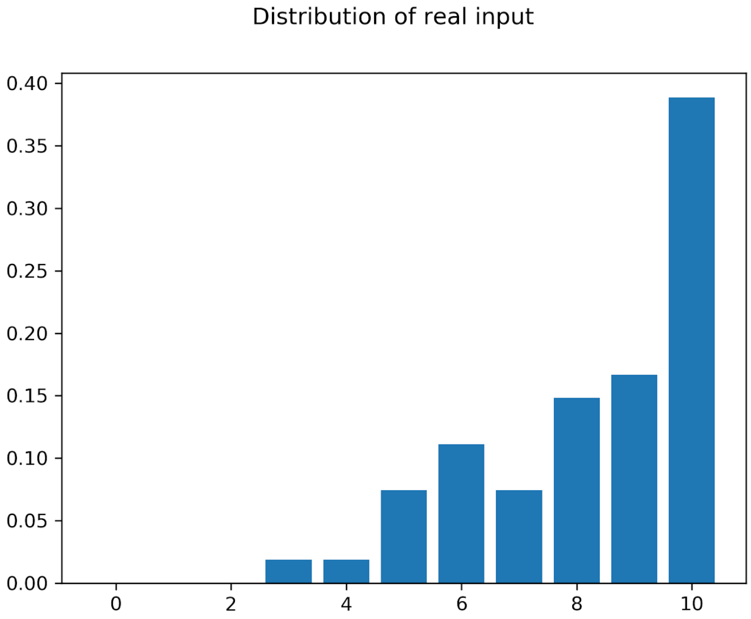


Figure 17: Distribution showing the probability that each ring member is the real input for the 52 traceable inputs from transactions between Anthony and Ruiqi.

Merging Outputs Heuristic. Finally, we empirically validate the accuracy of the Merging Outputs heuristic from section 5.2 of Kumar et al. [Kum+17]. In their paper, they ran this heuristic on pre-RingCT inputs and obtained the results shown in Figure 18.

We ran this heuristic for post-RingCT inputs for which we had ground truth for. This was only 6783 destination inputs, 0.7% of all destination inputs, but the results (Figure 19) show that when the merging outputs heuristic is applicable (this is the case for about 5% of RingCT transactions), it is fairly accurate (e.g.: for RingCT inputs with 10+ mixins, the accuracy is over 80%). It makes sense that the accuracy of the merging outputs heuristic is about the same pre- and post-RingCT as this heuristic is unaffected by the number of mixins or the mixin sampling distribution. However, as mentioned above, it can only be applied to a small fraction of transactions.

3.2.2 Zcash

Our initial results include an overall analysis of the Zcash ecosystem up the blockheight of 300,000 blocks, which is a bit greater than the number of blocks experimented on in [Kap+18]. We also ran analysis at heights of 50K and 240K, and the results from the two are similar to that of our most recent block height. The blockchain at this point contains 2,781,533 total transactions, and Figures 20 and 21 show the breakdown in transaction types.

From these two figures we can see how in the Zcash ecosystem, the majority of participants are not taking advantage of the privacy benefits of the protocol that implement zero-knowledge proofs

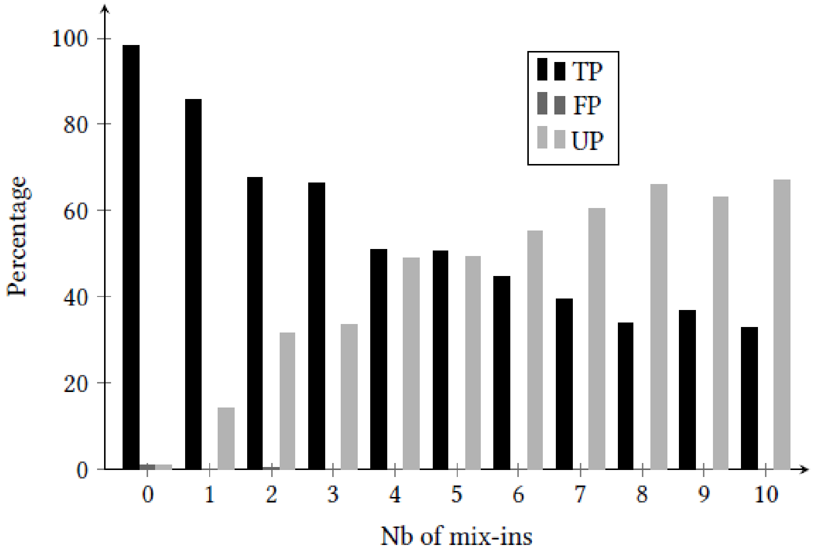


Figure 18: Figure 11 from [Kum+17] illustrating the accuracy of the merging outputs heuristic for non-RingCT inputs. TP means true positive, FP means false positive, and UP means unknown positive. The TPs and FPs are the inputs for which they had ground truth, and the UPs are those inputs that were not fully traceable using zero-mixin chain analysis.

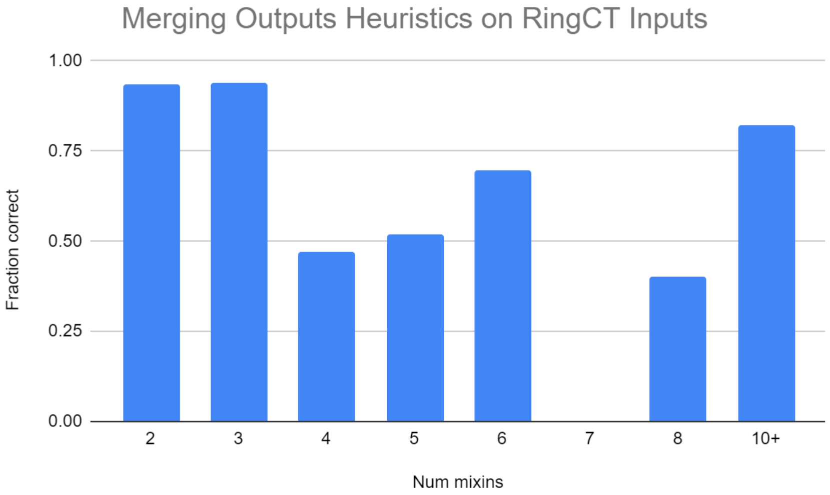


Figure 19: Accuracy of Merging Outputs heuristic on RingCT destination inputs for which we had ground truth from the zero-mixin chain analysis.

aimed to increase anonymity. The majority of participants in the system are using Zcash public t-to-t transaction, which mirrors the Bitcoin ecosystem and its anonymity issues.

We also were able to analyze the top Zcash addresses in terms of value sent, received and currently holding. We found that a single address had the highest send and receive, of 162,645,413 and 162,707,356 ZEC respectively. The highest wallet value was found to be 145,722 ZEC which is equivalent to ∼6,092,636.00 USD. We observed that Flypool and F2 Pool were in the top 10

Type	Amount	Percentage
coingen	30000	10.79
mixed	13070	0.47
deshielded	212496	7.64
shielded	168600	6.06
private	8508	0.31
public	2078859	74.74

Figure 20: Types of transactions included in our experiment, up to 300,000 block height.

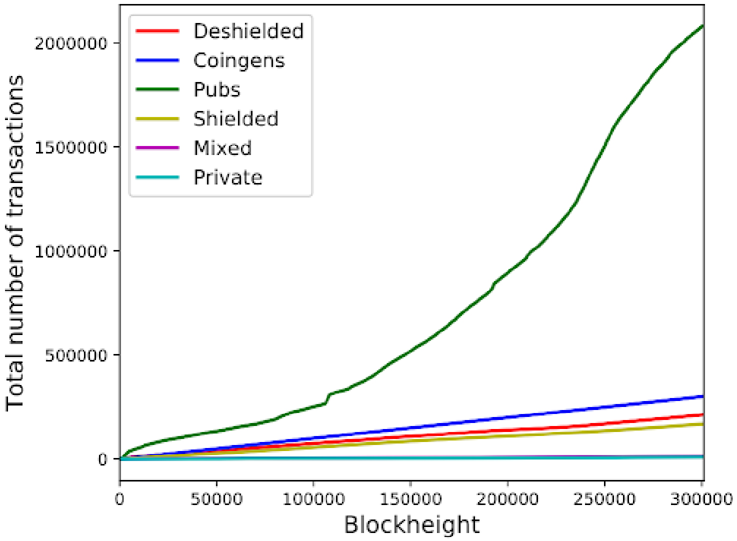


Figure 21: Types of transactions up to 300,000 block height.

addresses for all three categories of total send, received, and in wallet. Next we analyzed the shielded pool itself, which is the collection of shielded addresses that use zero-knowledge proofs for transaction verification. Since Zcash has this additional layer of obfuscation that Bitcoin does not in the form of shielded addresses, the use patterns of individuals within the shielded pool can go lengths to decreasing the anonymity of Zcash.

Figures 22 and 23 provide some key heuristics regarding the shielded pool which are applied in the later portions of the analysis. For one, in Figure 22 we can observe the total value of the shielded pool increasing generally, but doing so with a pattern of recurring spikes of deposits and withdrawals. Because miners and founders are members of the ecosystem that behave in a scheduled manner due to coingen and founder rewards, we can use this to link their transactions involving the shielded pool. In addition, Figure 23, which shows the ratio between deposits and withdrawals into the shielded pool, shows that the two transactions usually happen in close proximity with each other. For the general shielded pool withdrawals come shortly after deposits which forms an equilibrium. For the founders specifically, the deposits and withdrawals followed a step function where the withdrawals climbed in small increments came in relation to the deposits that came in bigger batches. This again reflects miner and founder behavior occurring on a recurring schedule based on the solution rate, and a well chosen heuristic can deanonymize activity with the shielded pool.

Using the miner addresses sent by the [Kap+18] project team and the founder address that are

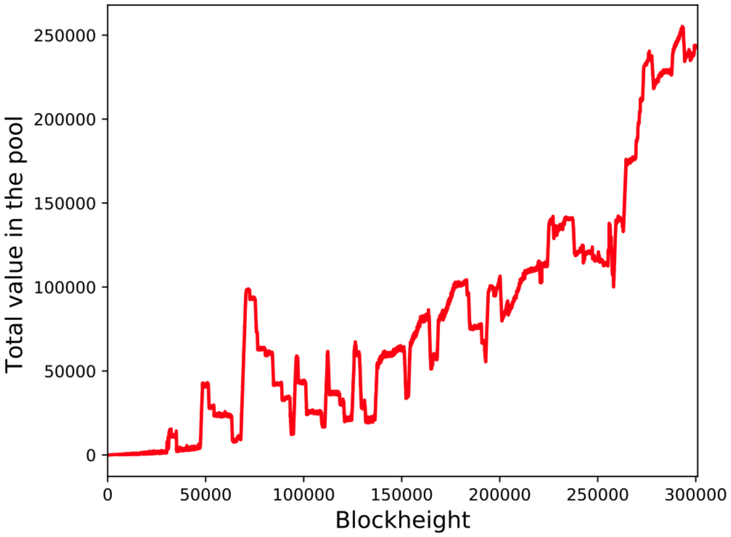


Figure 22: The total amount of Zcash value in the shielded pool at various block heights.

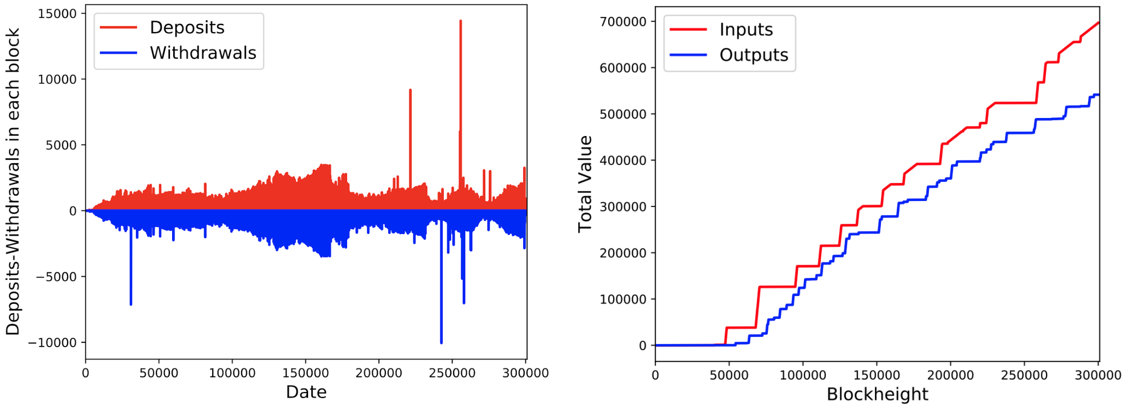


Figure 23: Deposits and withdrawals into the shielded pool over time for the entire shielded pool and specifically for founders, respectively.

available in the Zcash white-paper, we were able to analyze the amounts in which various entities made deposits into the shielded pool. Our results from running the heuristic are provided in Figure 24. We observe that the majority of people making deposits into the shielded pools are miners and founders, which follows the assumption that the general user is seldom taking advantage of the ecosystem.

Next we applied heuristics 3 and 4 from [Kap+18] that state: Any z-to-t transaction carrying 250.0001 ZEC in value is done by the founders and If a z-to-t transaction has over 100 output t-addresses, one of which belongs to a known mining pool, then we label the transaction as a mining withdrawal (associated with that pool), and label all non-pool output t-addresses as belonging to miners. These two heuristics when applied can differentiate between miners and founders who make deshielded transactions, which are transactions leaving the shielded pool. Figure 25 shows that the founder and miner withdrawals are distinguishable from other withdrawals from the shielded pool, which goes to show that a factor of traceability exists for deshielded transactions in Zcash. We were

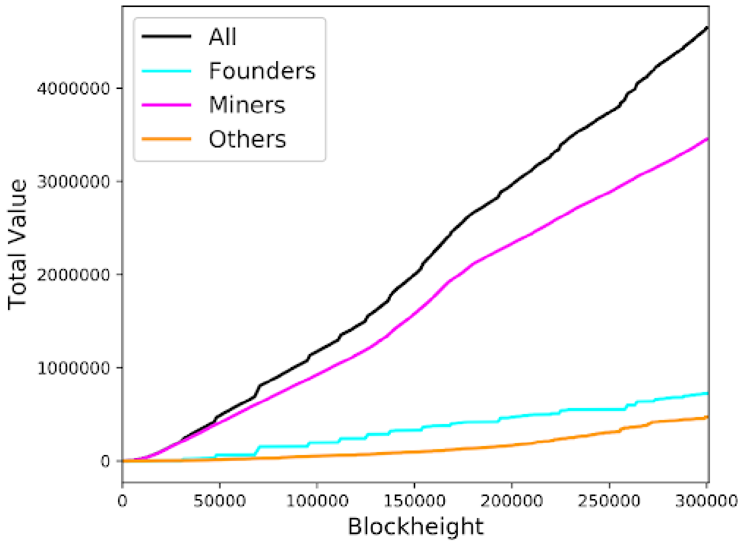


Figure 24: Value deposited in shielded pool over time by various Zcash entities.

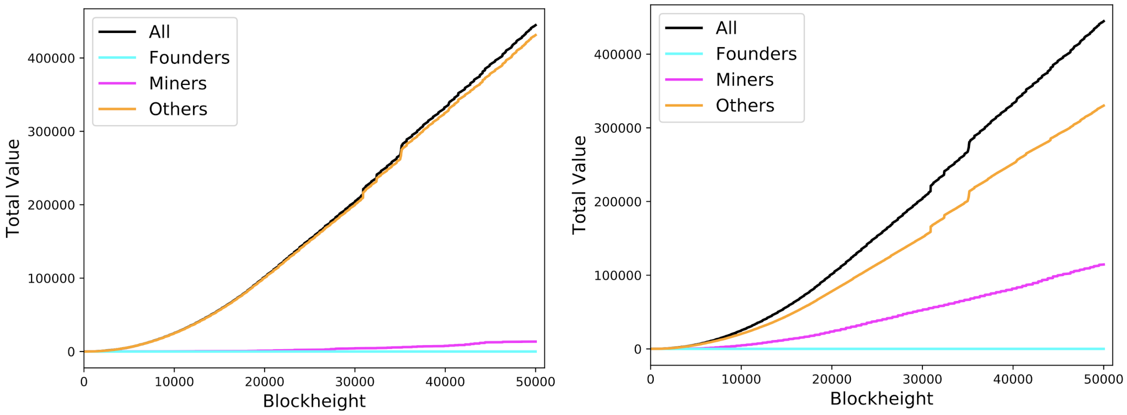


Figure 25: The amount of value withdrawn from the shielded pool over time by different entities.

only able to observe this trend up to a block height of 50,000, as we encountered errors creating this graph for larger datasets. However, since we corroborated the paper's previous findings, it is safe to say the current Zcash ecosystem reflects this.

The Zcash clustering analysis involved using our own provided founder and pool address tags, on top of the heuristics defined in the paper. After conducting the analysis, we found 121,530 distinct clusters, the top 10 of which contained 541,922 distinct addresses. A total of 790,516 transaction addresses have sent transactions. Figure 26 showcases the top clusters at block height 300,000. We can observe that the top two clusters contain a good amount of the overall addresses analyzed. In the largest cluster that contained 77,095 addresses, 9 miners and 4 founders we tagged beforehand were encapsulated in the cluster. Figure 27 contains important statistics related to the cluster C0. The statistics that are calculated on clusters of addresses and the heuristics that link addresses together go to show that even though Zcash offers strong privacy primitives, the vast majority of actors within the ecosystem are subject to a degree of traceability and linkability.

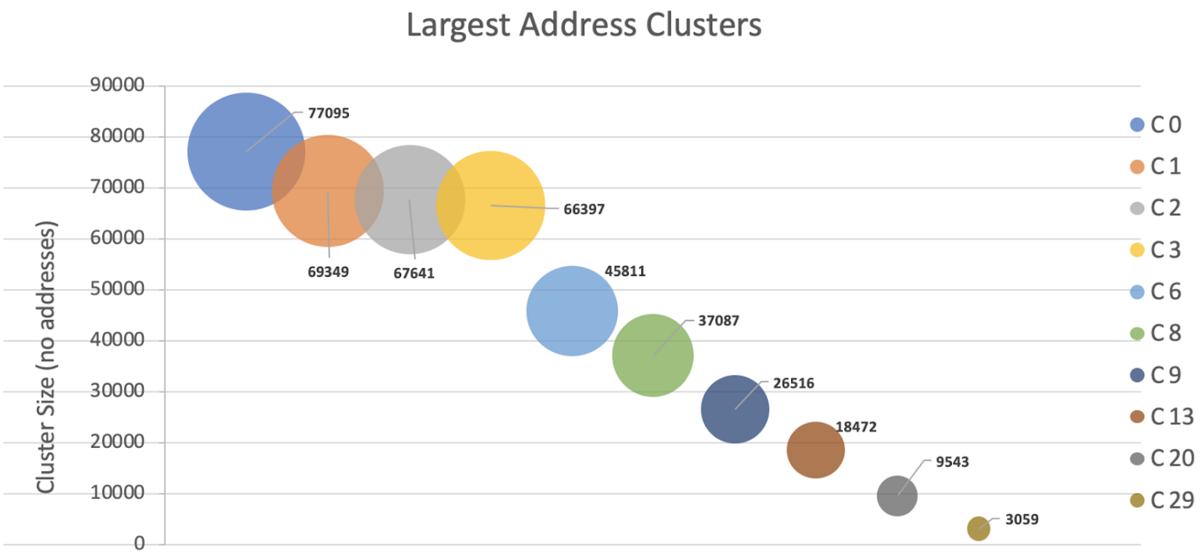


Figure 26: The largest 10 address clusters by size in descending order.

total_coingens_recv	49
total_current_value	254552.676835
total_no_txs_total	37275162
distinct_total_no_txs	112662
total_pool_recv	835851.51
total_pool_sent	0.0
total_recv	1.6538204E+8
total_sent	1.6512974E+8
total_txs_recv	24893931
total_txs_sent	12381231
total_vins_count	14058267
total_vouts_count	24893943

Figure 27: Statistics regarding largest cluster C0 (65,255 addresses).

4 Future Work

4.1 Monero

We have investigated the traceability of transactions made using recent versions of Monero with three heuristics that were successful for tracing transactions made using previous versions. Much more work could be conducted, however, in future work. We could possibly integrate our traced results into the Monero blackball database or blackballing tool (`https://moneroblackball.com/`) and compare our traced transactions with what the blackballing tool traces. It would also be interesting to study the amount of money that is traceable. In addition, mining pool transactions were shown by Möser et al. [Mös+18] to be a great source of information leakage based on the characteristics of a transaction from a mining pool. By incorporating the public data of mining pools, we may be able to trace more transactions. Additionally, we could conduct more sophisticated chain analysis on the transaction inputs by implementing a Sudoku-like solver like the one by Möser et al. [Mös+18]. Such a solver could make deductions on the following: Suppose we have 3 transactions: transaction 1 and 2 both have TXO 1 and TXO 2 as their anonymity sets, and transaction 3 has TXO 1, 2, and 3 in its anonymity set. Then TXO 3 must be the real input of transaction 3. We expect these future studies will provide new insight into the traceability of Monero.

4.2 Zcash

The most immediate future work would be to parse the blockchain to the current day state to further analyze how the Zcash ecosystem has evolved over time. However with the few setbacks we encountered we believe some work done to change some parts of the experiment could be done. For starters, parsing the blockchain directly from the binary files could prove to be much faster than using an RPC to call the Zcash client for every block. The network overhead even after some changes to the extraction networking still proved to be significant. In addition, work can be done to improve the process in which the downloaded Postgres data is first exported to CSV, then Parquet, then loaded to Spark for analysis, all of which take hours to run for high loads. This made the integration process we desired difficult to achieve at a high blockheight. One solution could be to do the raw parsing inside the Spark application followed by the analysis. This way inter-container communication and file writing would not be needed, which would also save disk space. Lastly, another avenue of further work could be discovering further heuristics that can be used to increase the linkability of pools and clusters based on the various stakeholder tendencies within the ecosystem. This experiment also showed that there is currently no intuitive and efficient way to parse the Zcash blockchain such that these experiments can be run. A locally-run ZEC blockchain explorer (like the one for Monero, but not like the web applications) could be useful for any future academic research into this cryptocurrency that requires access to over 26 GB of the blockchain.

More academic research is needed in Zcash overall. Illicit activities, namely money laundering, trading illegal substances, and terrorism funding, only seem to be low in Zcash because there is not enough investigation in that space to reveal the crimes. Ironically, the current research around Zcash's claimed anonymity, which has mostly proved it to be much more traceable than Monero, makes it less appealing to criminals. With a ranking of 26 out of all cryptocurrencies in terms of market capitalizations, ZEC is simply not "where the money is," thus not enticing to criminals to use if they want to be more accessible to a broader market. All of these factors conclude that academic rigor in Zcash as a cryptocurrency, not just its novel cryptography technology, is needed in order for it to become a more prominent alt-coin.

5 Conclusion

5.1 Monero

The anonymity of Monero has evolved to a large extent in the recent few years. With the introduction of RingCT and the increase of mandatory mixins to 10, it is much harder to trace the transactions. We investigated the effectiveness of three successful heuristics from the pre-RingCT era (i.e. before January 2017). The percentage of deducible transactions through zero chain analysis decreased to nearly 0% after the implementation of RingCT. The accuracy of the time heuristic has also reduced considerably to less than 40% with 10 mixins with a more realistic time distribution of mixins. The merging outputs heuristic still has good performance, but it can only be applied to a small portion of all transactions. We thus came to the conclusion that compared to the version three years ago, current Monero transactions can be conducted with superior anonymity with the introduction of new techniques like RingCT.

5.2 Zcash

As we expected, Zcash's privacy guarantees are questionable, despite continued cryptographic advancements in the new releases. As the volume of public transactions increase at a much faster rate than that of shielded and private transactions, the overall anonymity of ZEC users, even if they are fully utilizing the features of the shielded pools, is decreased. Observing the ZEC public blockchain at various block heights from a smaller 50,000 to past 300,000 block heights, it is noticeably easier to identify more clusters and more addresses associated with each cluster. Heuristics defined by Kappos et al. in 2018 [Kap+18] still correctly characterize user behavior and thus make ZEC more traceable and therefore less anonymous. Incentivizing current users to at least partially engage in shielded pools would significantly reduce the current flaw in its privacy guarantees.

6 Acknowledgments

We thank Professor Nicolas Christin and his Ph.D. student Kyle Soska for providing us access to the Jeju machine for running our Monero experiments and for installing needed libraries. We also thank them for pointing us to related work and suggesting the Monero breach simulation analysis.

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