An Empirical Analysis of Anonymity in Zcash

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Abstract

Among the now numerous alternative cryptocurrencies derived from Bitcoin, Zcash is often touted as the one with the strongest anonymity guarantees, due to its basis in well-regarded cryptographic research. In this paper, we examine the extent to which anonymity is achieved in the deployed version of Zcash. We investigate all facets of anonymity in Zcash's transactions, ranging from its transparent transactions to the interactions with and within its main privacy feature, a *shielded pool* that acts as the anonymity set for users wishing to spend coins privately. We conclude that while it is possible to use Zcash in a private way, it is also possible to shrink its anonymity set considerably by developing simple heuristics based on identifiable patterns of usage.

1 Introduction

Since the introduction of Bitcoin in 2008 [34], cryptocurrencies have become increasingly popular to the point of reaching a near-mania, with thousands of deployed cryptocurrencies now collectively attracting trillions of dollars in investment. While the broader positive potential of "blockchain" (i.e., the public decentralized ledger underlying almost all cryptocurrencies) is still unclear, despite the growing number of legitimate users there are today still many people using these cryptocurrencies for less legitimate purposes. These range from the purchase of drugs or other illicit goods on so-called dark markets such as Dream Market, to the payments from victims in ransomware attacks such as WannaCry, with many other crimes in between. Criminals engaged in these activities may be drawn to Bitcoin due to the relatively low friction of making international payments using only pseudonyms as identifiers, but the public nature of its ledger of transactions raises the question of how much anonymity is actually being achieved.

Indeed, a long line of research [38, 39, 12, 27, 41] has by now demonstrated that the use of pseudonymous addresses in Bitcoin does not provide any meaningful level of anonymity. Beyond academic research, companies now provide analysis of the Bitcoin blockchain as a business [19]. This type of analysis was used in several arrests associated with the takedown of Silk Road [20], and to identify the attempts of the WannaCry hackers to move their ransom earnings from Bitcoin into Monero [17].

Perhaps in response to this growing awareness that most cryptocurrencies do not have strong anonymity guarantees, a number of alternative cryptocurrencies or other privacy-enhancing techniques have been deployed with the goal of improving on these guarantees. The most notable cryptocurrencies that fall into this former category are Dash [2] (launched in January 2014), Monero [3] (April 2014), and Zcash [7] (October 2016). At the time of this writing all have a market capitalization of over 1 billion USD [1], although this figure is notoriously volatile, so should be taken with a grain of salt.

Even within this category of privacy-enhanced cryptocurrencies, and despite its relative youth, Zcash stands somewhat on its own. From an academic perspective, Zcash is backed by highly regarded research [28, 13], and thus comes with seemingly strong anonymity guarantees. Indeed, the original papers cryptographically prove the security of the main privacy feature of Zcash (known as the *shielded pool*), in which users can spend shielded coins without revealing which coins they have spent. These strong guarantees have attracted at least some criminal attention to Zcash: the underground marketplace AlphaBay was on the verge of accepting it before their shutdown in July 2017 [11], and the Shadow Brokers hacking group started accepting Zcash in May 2017 (and in fact for their monthly dumps accepted exclusively Zcash in September 2017) [16].

Despite these theoretical privacy guarantees, the deployed version of Zcash does not require all transactions to take place within the shielded pool itself: it also supports so-called *transparent* transactions, which are essentially the same as transactions in Bitcoin in that they reveal the pseudonymous addresses of both the senders and recipients, and the amount being sent. It does require, however, that all newly generated coins pass through the shielded pool before being spent further, thus ensuring that all coins have been shielded at least once. This requirement led the Zcash developers to conclude that the anonymity set for users spending shielded coins is in fact all generated coins, and thus that "the mixing strategies that other cryptocurrencies use for anonymity provide a rather small [anonymity set] in comparison to Zcash" and that "Zcash has a distinct advantage in terms of transaction privacy" [9].

In this paper, we provide the first in-depth empirical analysis of anonymity in Zcash, in order to examine these claims and more generally provide a longitudinal study of how Zcash has evolved and who its main participants are. We begin in Section 4 by providing a general examination of the Zcash blockchain, from which we observe that the vast majority of Zcash activity is in the transparent part of the blockchain, meaning it does not engage with the shielded pool at all. In Section 5, we explore this aspect of Zcash by adapting the analysis that has already been developed for Bitcoin, and find that exchanges typically dominate this part of the blockchain.

We then move in Section 6 to examining interactions with the shielded pool. We find that, unsurprisingly, the main actors doing so are the founders and miners, who are required to put all newly generated coins directly into it. Using newly developed heuristics for attributing transactions to founders and miners, we find that 65.6% of the value withdrawn from the pool can be linked back to deposits made by either founders or miners. We also implement a general heuristic for linking together other types of transactions, and capture an additional 3.5% of the value using this. Our relatively simple heuristics thus reduce the size of the overall anonymity set by 69.1%.

In Section 7, we then look at the relatively small percentage of transactions that have taken place within the shielded pool. Here, we find (perhaps unsurprisingly) that relatively little information can be inferred, although we do identify certain patterns that may warrant further investigation. Finally, we perform a small case study of the activities of the Shadow Brokers within Zcash in Section 8, and in Section 9 we conclude.

All of our results have been disclosed, at the time of the paper's submission, to the creators of Zcash, and discussed extensively with them since. This has resulted in changes to both their public communication about Zcash's anonymity as well as the transactional behavior of the founders. Additionally, all the code for our analysis is available as an open-source repository.[1]

[1] `https://github.com/manganese/zcash-empirical-analysis`

2 Related work

We consider as related all work that has focused on the anonymity of cryptocurrencies, either by building solutions to achieve stronger anonymity guarantees or by demonstrating its limits.

In terms of the former, there has been a significant volume of research in providing solutions for existing cryptocurrencies that allow interested users to mix their coins in a way that achieves better anonymity than regular transactions [15, 42, 21, 24, 40, 14, 22, 25]. Another line of research has focused on producing alternative privacy-enhanced cryptocurrencies. Most notably, Dash [2] incorporates the techniques of CoinJoin [24] in its PrivateSpend transactions; Monero [3, 35] uses ring signatures to allow users to create "mix-ins" (i.e., include the keys of other users in their own transactions as a way of providing a larger anonymity set); and Zcash [7, 13] uses zero-knowledge proofs to allow users to spend coins without revealing which coins are being spent.

In terms of the latter, there has also been a significant volume of research on de-anonymizing Bitcoin [38, 39, 12, 27, 41]. Almost all of these attacks follow the same pattern: they first apply so-called clustering heuristics that associate multiple different addresses with one single entity, based on some evidence of shared ownership. The most common assumption is that all input addresses in a transaction belong to the same entity, with some papers [12, 27] also incorporating an additional heuristic in which output addresses receiving change are also linked. Once these clusters are formed, a "re-identification attack" [27] then tags specific addresses and thus the clusters in which they are contained. These techniques have also been applied to alternative cryptocurrencies with similar types of transactions, such as Ripple [30].

The work that is perhaps closest to our own focuses on de-anonymizing the privacy solutions described above, rather than just on Bitcoin. Here, several papers have focused on analyzing so-called privacy overlays or mixing services for Bitcoin [33, 26, 31, 32], and considered both their level of anonymity and the extent to which participants must trust each other. Some of this analysis [32, 26] also has implications for anonymity in Dash, due to its focus on CoinJoin. More recently, Miller et al. [29] and Kumar et al. [23] looked at Monero. They both found that it was possible to link together transactions based on temporal patterns, and also based on certain patterns of usage, such as users who choose to do transactions with 0 mix-ins (in which case their ring signature provides no anonymity, which in turns affects other users who may have included their key in their own mix-ins). Finally, we are aware of one effort to de-anonymize Zcash, by Quesnelle [37]. This article focuses on linking together the transactions used to shield

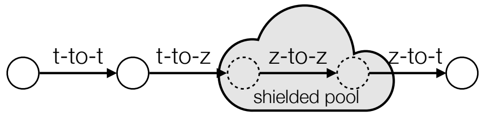


Figure 1: A simple diagram illustrating the different types of Zcash transactions. All transaction types are depicted and described with respect to a single input and output, but can be generalized to handle multiple inputs and outputs. In a t-to-t transaction, visible quantities of ZEC move between visible t-addresses (zIn,zOut $\neq \emptyset$). In a t-to-z transaction, a visible amount of ZEC moves from a visible t-address into the shielded pool, at which point it belongs to a hidden z-address (zOut $= \emptyset$). In a z-to-z transaction, a hidden quantity of ZEC moves between hidden z-addresses (zIn,zOut $= \emptyset$). Finally, in a z-to-t transaction, a hidden quantity of ZEC moves from a hidden z-address out of the shielded pool, at which point a visible quantity of it belongs to a visible t-address (zIn $= \emptyset$).

and deshield coins, based on their timing and the amount sent in the transactions. In comparison, our paper implements this heuristic but also provides a broader perspective on the entire Zcash ecosystem, as well as a more in-depth analysis of all interactions with (and within) the shielded pool.

3 Background

3.1 How Zcash works

Zcash (ZEC) is an alternative cryptocurrency developed as a (code) fork of Bitcoin that aims to break the link between senders and recipients in a transaction. In Bitcoin, recipients receive funds into addresses (referred to as the vOut in a transaction), and when they spend them they do so from these addresses (referred to as the vIn in a transaction). The act of spending bitcoins thus creates a link between the sender and recipient, and these links can be followed as bitcoins continue to change hands. It is thus possible to track any given bitcoin from its creation to its current owner.

Any transaction which interacts with the so-called shielded pool in Zcash does so through the inclusion of a *vJoinSplit*, which specifies where the coins are coming from and where they are going. To receive funds, users can provide either a transparent address (t-address) or a shielded address (z-address). Coins that are held in z-addresses are said to be in the shielded pool.

To specify where the funds are going, a vJoinSplit contains (1) a list of output t-addresses with funds assigned to them (called *zOut*), (2) two shielded outputs, and (3) an encrypted memo field. The zOut can be empty, in which case the transaction is either *shielded* (t-to-z) or *private* (z-to-z), depending on the inputs. If the zOut list contains a quantity of ZEC not assigned to any address, then we still consider it to be empty (as this is simply the allocation of the miner's fee). Each shielded output contains an unknown quantity of ZEC as well as a hidden double-spending token. The shielded output can be a dummy output (i.e., it contains zero ZEC) to hide the fact that there is no shielded output. The encrypted memo field can be used to send private messages to the recipients of the shielded outputs.

To specify where the funds are coming from, a vJoinSplit also contains (1) a list of input t-addresses (called *zIn*), (2) two double-spending tokens, and (3) a zero-knowledge proof. The zIn can be empty, in which case the transaction is either *deshielded* (z-to-t) if zOut is not empty, or private (z-to-z) if it is. Each double-spending token is either a unique token belonging to some previous shielded output, or a dummy value used to hide the fact that there is no shielded input. The double-spending token does not reveal to which shielded output it belongs. The zero-knowledge proof guarantees two things. First, it proves that the double-spending token genuinely belongs to some previous shielded output. Second, it proves that the sum of (1) the values in the addresses in zIn plus (2) the values represented by the double-spending tokens is equal to the sum of (1) the values assigned to the addresses in zOut plus (2) the values in the shielded outputs plus (3) the miner's fee. A summary of the different types of transactions is in Figure 1.

3.2 Participants in the Zcash ecosystem

In this section we describe four types of participants who interact in the Zcash network.

Founders took part in the initial creation and release of Zcash, and will receive 20% of all newly generated coins (currently 2.5 ZEC out of the 12.5 ZEC block reward). The founder addresses are specified in the Zcash chain parameters [8].

Miners take part in the maintenance of the ledger, and in doing so receive newly generated coins (10 out of the 12.5 ZEC block reward), as well as any fees from the transactions included in the blocks they mine. Many miners choose not to mine on their own, but join a mining pool; a list of mining pools can be found in Table 4. One or many miners win each block, and the first transaction in the block is a *coin generation* (coingen) that assigns newly generated coins to their address(es), as well as to the address(es) of the founders.

Services are entities that accept ZEC as some form of payment. These include exchanges like Bitfinex, which allow users to trade fiat currencies and other cryptocurrencies for ZEC (and vice versa), and platforms like ShapeShift [4], which allow users to trade within cryptocurrencies and other digital assets without requiring registration.

Finally, users are participants who hold and transact in ZEC at a more individual level. In addition to regu-

Type	Number	Percentage
Transparent	1,648,745	73.5
Coingen	258,472	11.5
Deshielded	177,009	7.9
Shielded	140,796	6.3
Mixed	10,891	0.5
Private	6934	0.3

Table 1: The total number of each transaction type.

lar individuals, this category includes charities and other organizations that may choose to accept donations in Zcash. A notable user is the Shadow Brokers, a hacker group who have published several leaks containing hacking tools from the NSA and accept payment in Zcash. We explore their usage of Zcash in Section 8.

4 General Blockchain Statistics

We used the `zcashd` client to download the Zcash blockchain, and loaded a database representation of it into Apache Spark. We then performed our analysis using a custom set of Python scripts equipped with PySpark. We last parsed the block chain on January 21 2018, at which point 258,472 blocks had been mined. Overall, 3,106,643 ZEC had been generated since the genesis block, out of which 2,485,461 ZEC went to the miners and the rest (621,182 ZEC) went to the founders.

4.1 Transactions

Across all blocks, there were 2,242,847 transactions. A complete breakdown of the transaction types is in Table 1, and graphs depicting the growth of each transaction type over time are in Figures 2 and 3.[2] The vast majority of transactions are public (i.e., either transparent or a coin generation). Of the transactions that do interact with the pool (335,630, or 14.96%, in total), only a very small percentage are private transactions; i.e., transactions within the pool. Looking at the types of transactions over time in Figure 2, we can see that the number of coingen, shielded, and deshielded transactions all grow in an approximately linear fashion. As we explore in Section 6.2, this correlation is due largely to the habits of the miners. Looking at both this figure and Figure 3, we can see that while the number of transactions interacting with the pool has grown in a relatively linear fashion, the value they carry has over time become a very small percentage of all blocks, as more mainstream (and thus transparent) usage of Zcash has increased.

[2] We use the term 'mixed' to mean transactions that have both a vIn and a vOut, and a vJoinSplit.

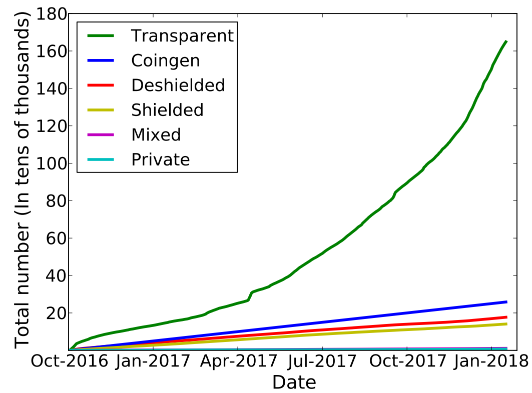


Figure 2: The total number of each of the different types of transactions over time.

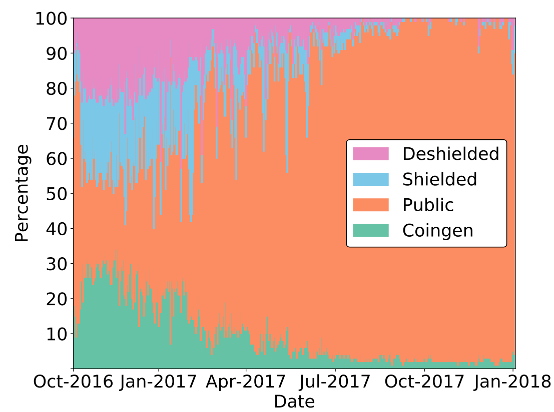


Figure 3: The fraction of the value in each block representing each different type of transaction over time, averaged daily. Here, 'public' captures both transparent transactions and the visible components of mixed transactions.

4.2 Addresses

Across all transactions, there have been 1,740,378 distinct t-addresses used. Of these, 8,727 have ever acted as inputs in a t-to-z transaction and 330,780 have ever acted as outputs in a z-to-t transaction. As we explore in Section 6.2, much of this asymmetry is due to the behavior of mining pools, which use a small number of addresses to collect the block reward, but a large number of addresses (representing all the individual miners) to pay out of the pool. Given the nature of the shielded pool, it is not possible to know the total number of z-addresses used.

Figure 4 shows the total value in the pool over time. Although the overall value is increasing over time, there are certain shielding and de-shielding patterns that create spikes. As we explore in Section 6, these spikes are due largely to the habits of the miners and founders. At the time of writing, there are 112,235 ZEC in the pool, or 3.6% of the total monetary supply.

If we rank addresses by their wealth, we first observe that only 25% of all t-addresses have a non-zero bal-

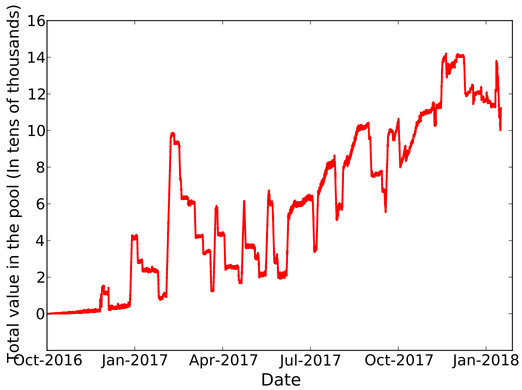


Figure 4: The total value in the shielded pool over time.

ance. Of these, the top 1% hold 78% of all ZEC. The address with the highest balance had 118,257.75 ZEC, which means the richest address has a higher balance than the entire shielded pool.

5 T-Address Clustering

As discussed in Section 4, a large proportion of the activity on Zcash does not use the shielded pool. This means it is essentially identical to Bitcoin, and thus can be deanonymized using the same techniques discussed for Bitcoin in Section 2.

5.1 Clustering addresses

To identify the usage of transparent addresses, we begin by recalling the "multi-input" heuristic for clustering Bitcoin addresses. In this heuristic, addresses that are used as inputs to the same transaction are assigned to the same cluster. In Bitcoin, this heuristic can be applied to all transactions, as they are all transparent. In Zcash, we perform this clustering as long as there are multiple input t-addresses.

Heuristic 1. 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.

In terms of false positives, we believe that these are at least as unlikely for Zcash as they are for Bitcoin, as Zcash is a direct fork of Bitcoin and the standard client has the same behavior. In fact, we are not aware of any input-mixing techniques like CoinJoin [24] for Zcash, so could argue that the risk of false positives is even lower than it is for Bitcoin. As this heuristic has already been used extensively in Bitcoin, we thus believe it to be realistic for use in Zcash.

We implemented this heuristic by defining each t-address as a node in a graph, and adding an (undirected) edge in the graph between addresses that had been input to the same transaction. The connected components of the graph then formed the clusters, which represent distinct entities controlling potentially many addresses. The result was a set of 560,319 clusters, of which 97,539 contained more than a single address.

As in Bitcoin, using just this one heuristic is already quite effective but does not capture the common usage of *change addresses*, in which a transaction sends coins to the actual recipient but then also sends any coins left over in the input back to the sender. Meiklejohn et al. [27] use in their analysis a heuristic based on this behavior, but warn that it is somewhat fragile. Indeed, their heuristic seems largely dependent on the specific behavior of several large Bitcoin services, so we chose not to implement it in its full form. Nevertheless, we did use a related Zcash-specific heuristic in our case study of the Shadow Brokers in Section 8.

Heuristic 2. 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.

To justify this heuristic, we observe that users may not want to deposit all of the coins in their address when putting coins into the pool, in which case they will have to make change. The only risk of a false positive is if users are instead sending money to two separate individuals, one using a z-address and one using a t-address. One notable exception to this rule is users of the zcash4win wallet. Here, the address of the wallet operator is an output t-address if the user decides to pay the developer fee, so would produce exactly this type of transaction for users putting money into the shielded pool. This address is identifiable, however, so these types of transactions can be omitted from our analysis. Nevertheless, due to concerns about the safety of this heuristic (i.e., its ability to avoid false positives), we chose not to incorporate it into our general analysis below.

5.2 Tagging addresses

Having now obtained a set of clusters, we next sought to assign names to them. To accomplish this, we performed a scaled-down version of the techniques used by Meiklejohn et al. [27]. In particular, given that Zcash is still relatively new, there are not many different types of services that accept Zcash. We thus restricted ourselves to interacting with exchanges.

We first identified the top ten Zcash exchanges according to volume traded [1]. We then created an account with each exchange and deposited a small quantity of

Service	Cluster	# deposits	# withdrawals
Binance	7	1	1
Bitfinex	3	4	1
Bithumb	14	2	1
Bittrex	1	1	1
Bit-z	30	2	1
Exmo	4	2	1
HitBTC	18	1	1
Huobi	26	2	1
Kraken	12	1	1
Poloniex	0	1	1
ShapeShift	2	1	1
zcash4win	139	1	2

Table 2: The services we interacted with, the identifier of the cluster they were associated with after running Heuristic 1, and the number of deposits and withdrawals we did with them. The first ten are exchanges, ShapeShift is an inter-cryptocurrency exchange, and zcash4win is a Windows-based Zcash client.

ZEC into it, tagging as we did the output t-addresses in the resulting transaction as belonging to the exchange. We then withdrew this amount to our own wallet, and again tagged the t-addresses (this time on the sender side) as belonging to the exchange. We occasionally did several deposit transactions if it seemed likely that doing so would tag more addresses. Finally, we also interacted with ShapeShift, which as mentioned in Section 3.2 allows users to move amongst cryptocurrencies without the need to create an account. Here we did a single "shift" into Zcash and a single shift out. A summary of our interactions with all the different exchanges is in Table 2.

Finally, we collected the publicized addresses of the founders [8], as well as addresses from known mining pools. For the latter we started by scraping the tags of these addresses from the Zchain explorer [10]. We then validated them against the blocks advertised on some of the websites of the mining pools themselves (which we also scraped) to ensure that they were the correct tags; i.e., if the recipient of the coingen transaction in a given block was tagged as belonging to a given mining pool, then we checked to see that the block had been advertised on the website of that mining pool. We then augmented these sets of addresses with the addresses tagged as belonging to founders and miners according to the heuristics developed in Section 6. We present these heuristics in significantly more detail there, but they resulted in us tagging 123 founder addresses and 110,918 miner addresses (belonging to a variety of different pools).

5.3 Results

As mentioned in Section 5.1, running Heuristic 1 resulted in 560,319 clusters, of which 97,539 contained more than a single address. We assigned each cluster a unique identifier, ordered by the number of addresses in the cluster, so that the biggest cluster had identifier 0.

5.3.1 Exchanges and wallets

As can be seen in Table 2, many of the exchanges are associated with some of the biggest clusters, with four out of the top five clusters belonging to popular exchanges. In general, we found that the top five clusters accounted for 11.21% of all transactions. Identifying exchanges is important, as it makes it possible to discover where individual users may have purchased their ZEC. Given existing and emerging regulations, they are also the one type of participant in the Zcash ecosystem that might know the real-world identity of users.

In many of the exchange clusters, we also identified large fractions of addresses that had been tagged as miners. This implies that individual miners use the addresses of their exchange accounts to receive their mining reward, which might be expected if their goal is to cash out directly. We found some, but far fewer, founder addresses at some of the exchanges as well.

Our clustering also reveals that ShapeShift (Cluster 2) is fairly heavily used: it had received over 1.1M ZEC in total and sent roughly the same. Unlike the exchanges, its cluster contained a relatively small number of miner addresses (54), which fits with its usage as a way to shift money, rather than hold it in a wallet.

5.3.2 Mining pools and founders

Although mining pools and founders account for a large proportion of the activity in Zcash (as we explore in Section 6), many re-use the same small set of addresses frequently, so do not belong to large clusters. For example, Flypool had three single-address clusters while Coinotron, coinmine.pl, Slushpool and Nanopool each had two single-address clusters. (A list of mining pools can be found in Table 4 in Section 6.2). Of the coins that we saw sent from clusters associated with mining pools, 99.8% of it went into the shielded pool, which further validates both our clustering and tagging techniques.

5.3.3 Philanthropists

Via manual inspection, we identified three large organizations that accept Zcash donations: the Internet Archive, `torservers.net`, and Wikileaks. Of these, `torservers.net` accepts payment only via a z-address, so we cannot identify their transactions (Wikileaks accepts payment via a z-address too, but also via a t-address). Of the 31 donations to the Internet Archive that we were able to identify, which totaled 17.3 ZEC, 9 of them were made anonymously (i.e., as z-to-t transactions). On the other hand, all of the 20 donations to Wik-

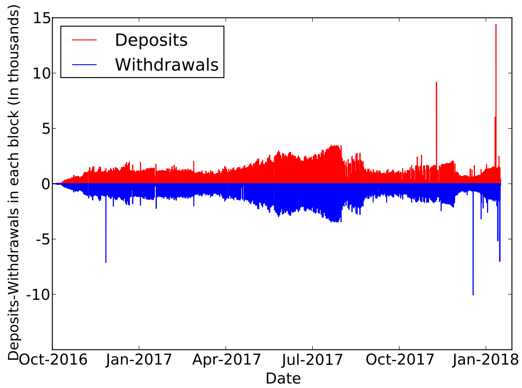


Figure 5: Over time, the amount of ZEC put into the shielded pool (in red) and the amount taken out of the pool (in blue).

ileak's t-address were made as t-to-t transactions. None of these belong to clusters, as they have never sent a transaction.

6 Interactions with the Shielded Pool

What makes Zcash unique is of course not its t-addresses (since these essentially replicate the functionality of Bitcoin), but its shielded pool. To that end, this section explores interactions with the pool at its endpoints, meaning the deposits into (t-to-z) and withdrawals out of the pool (z-to-t). We then explore interactions within the pool (z-to-z transactions) in Section 7.

To begin, we consider just the amounts put into and taken out of the pool. Over time, 3,901,124 ZEC have been deposited into the pool,[3] and 3,788,889 have been withdrawn. Figure 5 plots both deposits and withdrawals over time.

This figure shows a near-perfect reflection of deposits and withdrawals, demonstrating that most users not only withdraw the exact number of ZEC they deposit into the pool, but do so very quickly after the initial deposit. As we see in Sections 6.1 and 6.2, this phenomenon is accounted for almost fully by the founders and miners. Looking further at the figure, we can see that the symmetry is broken occasionally, and most notably in four "spikes": two large withdrawals, and two large deposits. Some manual investigation revealed the following:

"The early birds" The first withdrawal spike took place at block height 30,900, which was created in December 2016. The cause of the spike was a single transaction in which 7,135 ZEC was taken out of the pool; given the exchange rate at that time of 34 USD per ZEC, this was equivalent to 242,590 USD. The coins were distributed across 15 t-addresses, which initially we had not tagged as belonging to any named user. After running the heuristic described in Section 6.1, however, we tagged all of these addresses as belonging to founders. In fact, this was the very first withdrawal that we identified as being associated with founders.

"Secret Santa" The second withdrawal spike took place on December 25 2017, at block height 242,642. In it, 10,000 ZEC was distributed among 10 different t-addresses, each receiving 1,000 ZEC. None of these t-addresses had done a transaction before then, and none have been involved in one since (i.e., the coins received in this transaction have not yet been spent).

"One-man wolf packs" Both of the deposit spikes in the graph correspond to single large deposits from unknown t-addresses that, using our analysis from Section 5, we identified as residing in single-address clusters. For the first spike, however, many of the deposited amounts came directly from a founder address identified by our heuristics (Heuristic 3), so given our analysis in Section 6.1 we believe this may also be associated with the founders.

While this figure already provides some information about how the pool is used (namely that most of the money put into it is withdrawn almost immediately afterwards), it does not tell us who is actually using the pool. For this, we attempt to associate addresses with the types of participants identified in Section 3.2: founders, miners, and 'other' (encompassing both services and individual users).

When considering deposits into the shielded pool, it is easy to associate addresses with founders and miners, as the consensus rules dictate that they must put their block rewards into the shielded pool before spending them further. As described in Section 5.2, we tagged founders according to the Zcash parameters, and tagged as miners all recipients of coingen transactions that were not founders. We then used these tags to identify a founder deposit as any t-to-z transaction using one or more founder addresses as input, and a miner deposit as any t-to-z transaction using one or more miner addresses as input. The results are in Figure 6.

Looking at this figure, it is clear that miners are the main participants putting money into the pool. This is not particularly surprising, given that all the coins they receive must be deposited into the pool at least once, so if we divide that number of coins by the total number deposited we would expect at least 63.7% of the deposits to come from miners. (The actual number is 76.7%.) Founders, on the other hand, don't put as much money into the pool (since they don't have as much to begin with), but when they do they put in large amounts that cause visible step-like fluctuations to the overall line.

[3] This is greater than the total number of generated coins, as all coins must be deposited into the pool at least once, by the miners or founders, but may then go into and out of the pool multiple times.

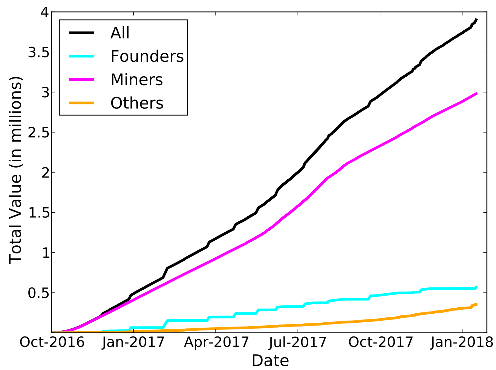


Figure 6: Over time, the amount of ZEC deposited into the shielded pool by miners, founders, and others.

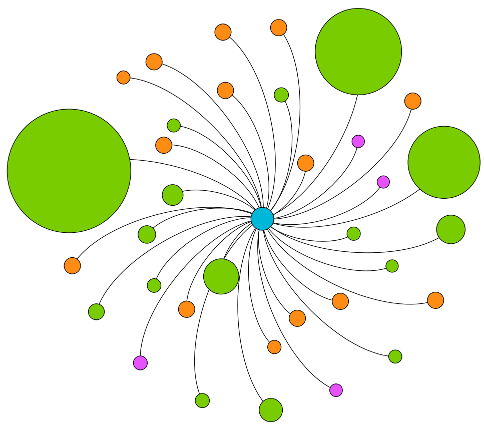


Figure 7: The addresses that have put more than 10,000 ZEC into the shielded pool over time, where the size of each node is proportional to the value it has put into the pool. The addresses of miners are green, of founders are orange, and of unknown 'other' participants are purple.

In terms of the heaviest users, we looked at the individual addresses that had put more than 10,000 ZEC into the pool. The results are in Figure 7.

In fact, this figure incorporates the heuristics we develop in Sections 6.1 and 6.2, although it looked very similar when we ran it before applying our heuristics (which makes sense, since our heuristics mainly act to link z-to-t transactions). Nevertheless, it demonstrates again that most of the heavy users of the pool are miners, with founders also depositing large amounts but spreading them over a wider variety of addresses. Of the four 'other' addresses, one of them belonged to ShapeShift, and the others belong to untagged clusters.

While it is interesting to look at t-to-z transactions on their own, the main intention of the shielded pool is to provide an anonymity set, so that when users withdraw their coins it is not clear whose coins they are. In that sense, it is much more interesting to link together t-to-z and z-to-t transactions, which acts to reduce the anonymity set. More concretely, if a t-to-z transaction can be linked to a z-to-t transaction, then those coins can be "ruled out" of the anonymity set of future users withdrawing coins from the pool. We thus devote our attention to this type of analysis for the rest of the section.

The most naïve way to link together these transactions would be to see if the same addresses are used across them; i.e., if a miner uses the same address to withdraw their coins as it did to deposit them. By running this simple form of linking, we see the results in Figure 8a. This figure shows that we are not able to identify any withdrawals as being associated with founders, and only a fairly small number as associated with miners: 49,280 transactions in total, which account for 13.3% of the total value in the pool.

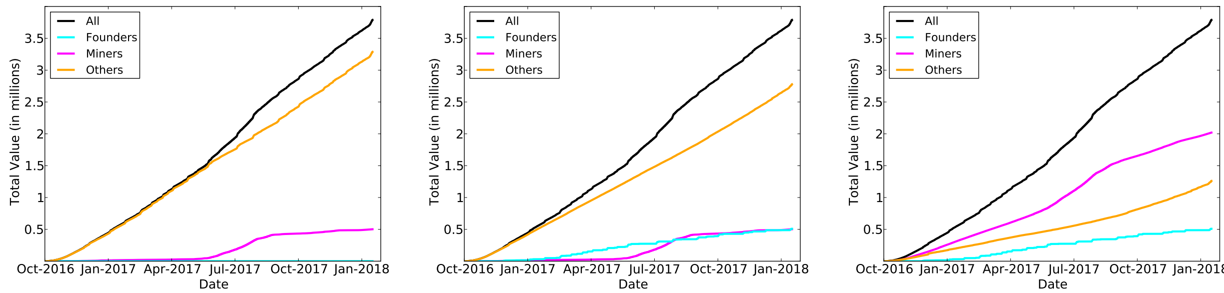
Nevertheless, using heuristics that we develop for identifying founders (as detailed in Section 6.1) and miners (Section 6.2), we are able to positively link most of the z-to-t activity with one of these two categories, as seen in Figures 8b and 8c. In the end, of the 177,009 z-to-t transactions, we were able to tag 120,629 (or 68%) of them as being associated with miners, capturing 52.1% of the value coming out of the pool, and 2,103 of them as being associated with founders (capturing 13.5% of the value). We then examine the remaining 30-35% of the activity surrounding the shielded pool in Section 6.3.

6.1 Founders

After comparing the list of founder addresses against the outputs of all coingen transactions, we found that 14 of them had been used. Using these addresses, we were able to identify founder deposits into the pool, as already shown in Figure 6. Table 3 provides a closer inspection of the usage of each of these addresses.

This table shows some quite obvious patterns in the behavior of the founders. At any given time, only one address is "active," meaning it receives rewards and deposits them into the pool. Once it reaches the limit of 44,272.5 ZEC, the next address takes its place and it is not used again. This pattern has held from the third address onwards. What's more, the amount deposited was often the same: exactly 249.9999 ZEC, which is roughly the reward for 100 blocks. This was true of 74.9% of all founder deposits, and 96.2% of all deposits from the third address onwards. There were only ever five other deposits into the pool carrying value between 249 and 251 ZEC (i.e., carrying a value close but not equal to 249.9999 ZEC).

Thus, while we were initially unable to identify any withdrawals associated with the founders (as seen in Figure 8a), these patterns indicated an automated use of the shielded pool that might also carry into the withdrawals. Upon examining the withdrawals from the pool, we did not find any with a value exactly equal to 249.9999 ZEC. We did, however, find 1,953 withdrawals



(a) No heuristics (b) Founder heuristic (c) Founder and miner heuristics

Figure 8: The z-to-t transactions we associated with miners, founders, and 'other', after running some combination of our heuristics.

	# Deposits	Total value	# Deposits (249)
1	548	19,600.4	0
2	252	43,944.6	153
3	178	44,272.5	177
4	192	44,272.5	176
5	178	44,272.5	177
6	178	44,272.5	177
7	178	44,272.5	177
8	178	44,272.5	177
9	190	44,272.5	176
10	188	44,272.5	176
11	190	44,272.5	176
12	178	44,272.5	177
13	191	44,272.5	175
14	70	17,500	70
Total	2889	568,042.5	2164

Table 3: The behavior of each of the 14 active founder addresses, in terms of the number of deposits into the pool, the total value deposited (in ZEC), and the number of deposits carrying exactly 249.9999 ZEC in value.

of exactly 250.0001 ZEC (and 1,969 carrying a value between 249 and 251 ZEC, although we excluded the extra ones from our analysis).

The value alone of these withdrawals thus provides some correlation with the deposits, but to further explore it we also looked at the timing of the transactions. When we examined the intervals between consecutive deposits of 249.9999 ZEC, we found that 85% happened within 6-10 blocks of the previous one. Similarly, when examining the intervals between consecutive withdrawals of 250.0001 ZEC, we found that 1,943 of the 1,953 withdrawals also had a proximity of 6-10 blocks. Indeed, both the deposits and the withdrawals proceeded in step-like patterns, in which many transactions were made within a very small number of blocks (resulting in the step up), at which point there would be a pause while more block rewards were accumulated (the step across). This pattern is visible in Figure 9, which shows the deposit and withdrawal transactions associated with the founders. Deposits are typically made in few large steps, whereas withdrawals take many smaller ones.

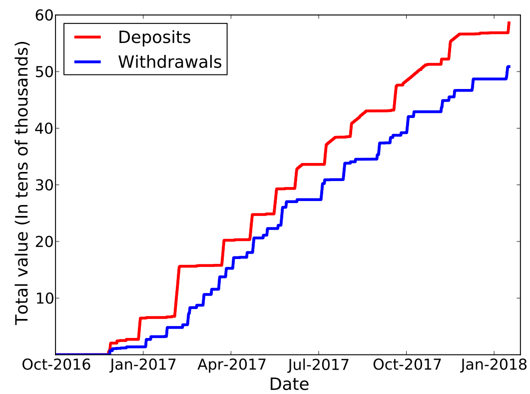


Figure 9: Over time, the founder deposits into the pool (in red) and withdrawals from the pool (in blue), after running Heuristic 3.

Heuristic 3. Any z-to-t transaction carrying 250.0001 ZEC in value is done by the founders.

In terms of false positives, we cannot truly know how risky this heuristic is, short of asking the founders. This is in contrast to the t-address clustering heuristics presented in Section 5, in which we were not attempting to assign addresses to a specific owner, so could validate the heuristics in other ways. Nevertheless, the high correlation between both the value and timing of the transactions led us to believe in the reliability of this heuristic.

As a result of running this heuristic, we added 75 more addresses to our initial list of 48 founder addresses (of which, again, only 14 had been used). Aside from the correlation showed in Figure 9, the difference in terms of our ability to tag founder withdrawals is seen in Figure 8b.

6.2 Miners

The Zcash protocol specifies that all newly generated coins are required to be put into the shielded pool before they can be spent further. As a result, we expect that a large quantity of the ZEC being deposited into the pool are from addresses associated with miners.

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

Table 4: A summary of our identified mining pool activity, in terms of the number of associated addresses used in coingen transactions, and the numbers of each type of transaction interacting with the pool.

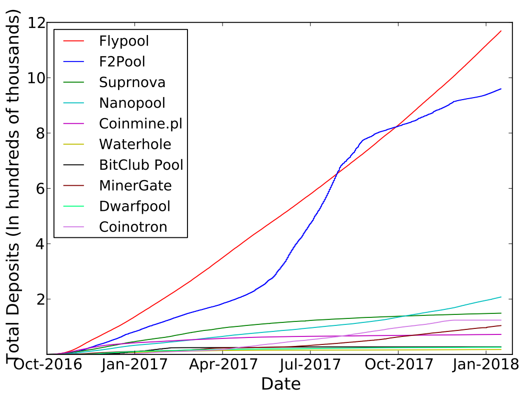


Figure 10: Over time, the value of deposits made by known mining pools into the shielded pool.

6.2.1 Deposits

As discussed earlier and seen in Figure 6, it is easy to identify miner deposits into the pool due to the fact that they immediately follow a coin generation. Before going further, we split the category of miners into individual miners, who operate on their own, and mining pools, which represent collectives of potentially many individuals. In total, we gathered 19 t-addresses associated with Zcash mining pools, using the scraping methods described in Section 5.2. Table 4 lists these mining pools, as well as the number of addresses they control and the number of t-to-z transactions we associated with them. Figure 10 plots the value of their deposits into the shielded pool over time.

In this figure, we can clearly see that the two dominant mining pools are Flypool and F2Pool. Flypool consistently deposits the same (or similar) amounts, which we can see in their linear representation. F2Pool, on the other hand, has bursts of large deposits mixed with periods during which it is not very active, which we can also see reflected in the graph. Despite their different behaviors, the amount deposited between the two pools is similar.

6.2.2 Withdrawals

While the withdrawals from the pool do not solely re-use the small number of mining addresses identified using deposits (as we saw in our naïve attempt to link miner z-to-t transactions in Figure 8a), they do typically re-use some of them, so can frequently be identified anyway.

In particular, mining pool payouts in Zcash are similar to how many of them are in Bitcoin [27, 18]. The block reward is often paid into a single address, controlled by the operator of the pool, and the pool operator then deposits some set of aggregated block rewards into the shielded pool. They then pay the individual reward to each of the individual miners as a way of "sharing the pie," which results in z-to-t transactions with many outputs. (In Bitcoin, some pools opt for this approach while some form a "peeling chain" in which they pay each individual miner in a separate transaction, sending the change back to themselves each time.) In the payouts for some of the mining pools, the list of output t-addresses sometimes includes one of the t-addresses known to be associated with the mining pool already. We thus tag these types of payouts as belonging to the mining pool, according to the following heuristic:

Heuristic 4. 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.

As with Heuristic 3, short of asking the mining pool operators directly it is impossible to validate this heuristic. Nevertheless, given the known operating structure of Bitcoin mining pools and the way this closely mirrors that structure, we again believe it to be relatively safe.

As a result of running this heuristic, we tagged 110,918 addresses as belonging to miners, and linked a much more significant portion of the z-to-t transactions, as seen in Figure 8c. As the last column in Table 4 shows, however, this heuristic captured the activity of only a small number of the mining pools, and the large jump in linked activity is mostly due to the high coverage with F2Pool (one of the two richest pools). This implies that further heuristics developed specifically for other pools, such as Flypool, would increase the linkability even more. Furthermore, a more active strategy in which we mined with the pools to receive payouts would reveal their structure, at which point (according to the

1.1M deposited by Flypool shown in Figure 10 and the remaining value of 1.2M attributed to the 'other' category shown in Figure 8c) we would shrink the anonymity set even further.[4]

6.3 Other Entities

Once the miners and founders have been identified, we can assume the remaining transactions belong to more general entities. In this section we look into different means of categorizing these entities in order to identify how the shielded pool is being used.

In particular, we ran the heuristic due to Quesnelle [37], which said that if a unique value (i.e., a value never seen in the blockchain before or since) is deposited into the pool and then, after some short period of time, the exact same value is withdrawn from the pool, the deposit and the withdrawal are linked in what he calls a *round-trip transaction*.

Heuristic 5. [37] 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.

In terms of false positives, the fact that the value is unique in the blockchain means that the only possibility of a false positive is if some of the z-to-z transactions split or aggregated coins in such a way that another deposit (or several other deposits) of a different amount were altered within the pool to yield an amount identical to the initial deposit. While this is possible in theory, we observe that of the 12,841 unique values we identified, 9,487 of them had eight decimal places (the maximum number in Zcash), and 98.9% of them had more than three decimal places. We thus view it as highly unlikely that these exact values were achieved via manipulations in z-to-z transactions.

By running this heuristic, we identified 12,841 unique values, which means we linked 12,841 transactions. The values total 1,094,513.23684 ZEC and represent 28.5% of all coins ever deposited in the pool. Interestingly, most (87%) of the linked coins were in transactions attributed to the founders and miners, so had already been linked by our previous heuristics. We believe this lends further credence to their soundness. In terms of the block interval, we ran Heuristic 5 for every interval between 1 and 100 blocks; the results are in Figure 11.

As this figure shows, even if we assume a conservative block interval of 10 (meaning the withdrawal took place

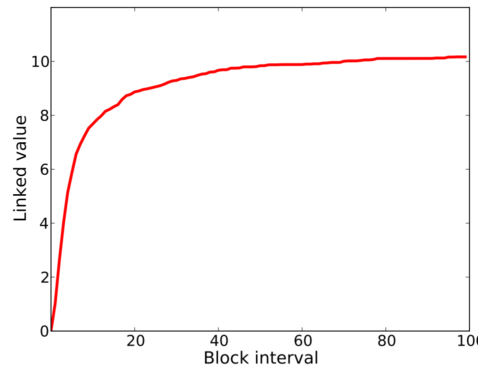


Figure 11: The value linked by Heuristic 5, as a function of the block interval required between the deposit and withdrawal transactions.

25 minutes after the deposit), we still capture 70% of the total value, or over 700K ZEC. If we require the withdrawal to have taken place within an hour of the deposit, we get 83%.

7 Interactions within the Shielded Pool

In this section we consider private transactions; i.e., z-to-z transactions that interact solely with the shielded pool. As seen in Section 4.1, these transactions form a small percentage of the overall transactions. However, z-to-z transactions form a crucial part of the anonymity core of Zcash. In particular, they make it difficult to identify the round-trip transactions from Heuristic 5.

Our analysis identified 6,934 z-to-z transactions, with 8,444 vJoinSplits. As discussed in Section 3.1, the only information revealed by z-to-z transactions is the miner's fee, the time of the transaction, and the number of vJoinSplits used as input. Of these, we looked at the time of transactions and the number of vJoinSplits in order to gain some insight as to the use of these operations.

We found that 93% of z-to-z transactions took just one vJoinSplit as input. Since each vJoinSplit can have at most two shielded outputs as its input, the majority of z-to-z transactions thus take no more than two shielded outputs as their input. This increases the difficulty of categorizing z-to-z transactions, because we cannot know if a small number of users are making many transactions, or many users are making one transaction.

In looking at the timing of z-to-z transactions, however, we conclude that it is likely that a small number of users were making many transactions. Figure 12 plots the cumulative number of vJoinSplits over time. The occurrences of vJoinSplits are somewhat irregular, with 17% of all vJoinSplits occurring in January 2017. There are four other occasions when a sufficient number of vJoinSplits occur within a sufficiently short period of time as to be visibly noticeable. It seems likely that these

[4] It is possible that we have already captured some of the Flypool activity, as many of the miners receive payouts from multiple pools. We thus are not claiming that all remaining activity could be attributed to Flypool, but potentially some substantial portion.

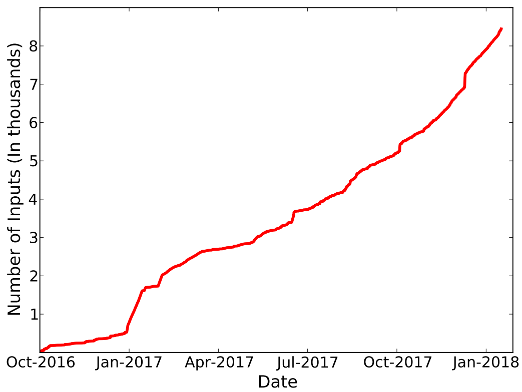


Figure 12: The number of z-to-z vJoinSplits over time.

occurrences belong to the same group of users, or at least by users interacting with the same service.

Finally, looking back at the number of t-to-z and z-to-t transactions identified with mining pools in Table 4, it is possible that BitClub Pool is responsible for up to 1,300 of the z-to-z transactions, as it had 196 deposits into the pool and 1,516 withdrawals. This can happen only because either (1) the pool made extra z-to-z transactions, or (2) it sent change from its z-to-t transactions back into the shielded pool. As most of BitClub Pool's z-to-t transactions had over 200 output t-addresses, however, we conclude that the former explanation is more likely.

8 Case Study: The Shadow Brokers

The Shadow Brokers (TSB) are a hacker collective that has been active since the summer of 2016, and that leaks tools supposedly created by the NSA. Some of these leaks are released as free samples, but many are sold via auctions and as monthly bundles. Initially, TSB accepted payment only using Bitcoin. Later, however, they began to accept Zcash for their monthly dump service. In this section we discuss how we identified t-to-z transactions that could represent payments to TSB. We identified twenty-four clusters (created using our analysis in Section 5) matching our criteria for potential TSB customers, one of which could be a regular customer.

8.1 Techniques

In order to identify the transactions that are most likely to be associated with TSB, we started by looking at their blog [5]. In May 2017, TSB announced that they would be accepting Zcash for their monthly dump service. Throughout the summer (June through August) they accepted both Zcash and Monero, but in September they announced that they would accept only Zcash. Table 5 summarizes the amount they were requesting in

May/June	July	August	September	October
100	200 400	500	100 200 500	500

Table 5: Amounts charged for TSB monthly dumps, in ZEC. In July and September TSB offered different prices depending on which exploits were being purchased.

each of these months. The last blog post was made in October 2017, when they stated that all subsequent dumps would cost 500 ZEC.

To identify potential TSB transactions, we thus looked at all t-to-z transactions not associated with miners or founders that deposited either 100, 200, 400, or 500 ZEC $\pm$ 5 ZEC. Our assumption was that users paying TSB were not likely to be regular Zcash users, but rather were using it with the main purpose of making the payment. On this basis, addresses making t-to-z transactions of the above values were flagged as a potential TSB customer if the following conditions held:

1. They did not get their funds from the pool; i.e., there were no z-to-t transactions with this address as an output. Again, if this were a user mainly engaging with Zcash as a way to pay TSB, they would need to to buy their funds from an exchange, which engage only with t-addresses.

2. They were not a frequent user, in the sense that they had not made or received more than 250 transactions (ever).

3. In the larger cluster in which this address belonged, the total amount deposited by the entire cluster into the pool within one month was within 1 ZEC of the amounts requested by TSB. Here, because the resulting clusters were small enough to treat manually, we applied not only Heuristic 1 but also Heuristic 2 (clustering by change), making sure to weed out false positives. Again, the idea was that suspected TSB customers would not be frequent users of the pool.

As with our previous heuristics, there is no way to quantify the false-positive risks associated with this set of criteria, although we see below that many of the transactions matching it did occur in the time period associated with TSB acceptance of Zcash. Regardless, given this limitation we are not claiming that our results are definitive, but do believe this to be a realistic set of criteria that might be applied in the context of a law enforcement investigation attempting to narrow down potential suspects.

Month	100	200	400	500
October (2016)	0	0	0	0
November	0	0	0	0
December	0	0	0	0
January (2017)	1	0	0	0
February	0	0	0	0
March	0	0	0	0
April	0	0	0	0
May (before)	0	0	0	0
May (after)	3	1	0	0
June	2	1	1	0
July	1	2	0	0
August	1	0	0	1
September	0	0	0	0
October	2	0	0	0
November	1	0	0	0
December	2	3	0	1
January (2018)	0	1	0	0

Table 6: Number of clusters that put the required amounts (± 1 ZEC) into the shielded pool.

8.2 Results

Our results, in terms of the number of transactions matching our requirements above up until 17 January 2018, are summarized in Table 6. Before the first TSB blog post in May, we found only a single matching transaction. This is very likely a false positive, but demonstrates that the types of transactions we were seeking were not common before TSB went live with Zcash. After the blog post, we flagged five clusters in May and June for the requested amount of 100 ZEC. There were only two clusters that was flagged for 500 ZEC, one of which was from August. No transactions of any of the required quantities were flagged in September, despite the fact that TSB switched to accepting only Zcash in September. This is possible for a number of reasons: our criteria may have caused us to miss transactions, or maybe there were no takers. From October onwards we flagged between 1-6 transactions per month. It is hard to know if these represent users paying for old data dumps or are simply false positives.

Four out of the 24 transactions in Table 6 are highly likely to be false positives. First, there is the deposit of 100 ZEC into the pool in January, before TSB announced their first blog post. This cluster put an additional 252 ZEC into the pool in March, so is likely just some user of the pool. Second and third, there are two deposits of 200 ZEC into the pool in June, before TSB announced that one of the July dump prices would cost 200 ZEC. Finally, there is a deposit of 400 ZEC into the pool in June before TSB announced that one of the July dump prices would cost 400 ZEC.

Of the remaining clusters, there is one whose activity is worth discussing. From this cluster, there was one deposit into the pool in June for 100 ZEC, one in July for 200 ZEC, and one in August for 500 ZEC, matching TSB prices exactly. The cluster belonged to a new user, and most of the money in this user's cluster came directly from Bitfinex (Cluster 3).

9 Conclusions

This paper has provided the first in-depth exploration of Zcash, with a particular focus on its anonymity guarantees. To achieve this, we applied both well-known clustering heuristics that have been developed for Bitcoin and attribution heuristics we developed ourselves that take into account Zcash's shielded pool and its unique cast of characters. As with previous empirical analyses of other cryptocurrencies, our study has shown that most users are not taking advantage of the main privacy feature of Zcash at all. Furthermore, the participants who do engage with the shielded pool do so in a way that is identifiable, which has the effect of significantly eroding the anonymity of other users by shrinking the overall anonymity set.

Future work

Our study was an initial exploration, and thus left many avenues open for further exploration. For example, it may be possible to classify more z-to-z transactions by analyzing the time intervals between the transactions in more detail, or by examining other metadata such as the miner's fee or even the size (in bytes) of the transaction. Additionally, the behavior of mining pools could be further identified by a study that actively interacts with them.

Suggestions for improvement

Our heuristics would have been significantly less effective if the founders interacting with the pool behaved in a less regular fashion. In particular, by always withdrawing the same amount in the same time intervals, it became possible to distinguish founders withdrawing funds from other users. Given that the founders are both highly invested in the currency and knowledgeable about how to use it in a secure fashion, they are in the best place to ensure the anonymity set is large.

Ultimately, the only way for Zcash to truly ensure the size of its anonymity set is to require all transactions to take place within the shielded pool, or otherwise significantly expand the usage of it. This may soon be computationally feasible given emerging advances in the underlying cryptographic techniques [6], or even if more mainstream wallet providers like Jaxx roll out support for z-addresses. More broadly, we view it as an interesting regulatory question whether or not mainstream exchanges would continue to transact with Zcash if it switched to supporting only z-addresses.

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References

[1] Cryptocurrency market capitalizations. https://coinmarketcap.com/.

[2] Dash. https://www.dash.org.

[3] Monero. https://getmonero.org.

[4] Shapeshift. https://shapeshift.io.

[5] The Shadow Brokers. https://steemit.com/@theshadowbrokers.

[6] What is Jubjub? https://z.cash/technology/jubjub.html.

[7] Zcash. https://z.cash.

[8] Zcash chain parameters. https://github.com/zcash/zcash/blob/v1.0.0/src/chainparams.cpp#L135-L192.

[9] Zcash faqs. https://z.cash/support/faq.html.

[10] Zchain explorer. http://explorer.zcha.in/.

[11] Alphabay will accept Zcash starting July 1st, 2017. DarkNetMarkets Reddit post, 2017. https://www.reddit.com/r/DarkNetMarkets/comments/6d7q81/alphabay_will_accept_zcash_starting_july_1st_2017/.

[12] E. Androulaki, G. Karame, M. Roeschlin, T. Scherer, and S. Capkun. Evaluating user privacy in Bitcoin. In A.-R. Sadeghi, editor, *FC 2013*, volume 7859 of *LNCS*, pages 34–51, Okinawa, Japan, Apr. 1–5, 2013. Springer, Heidelberg, Germany.

[13] E. Ben-Sasson, A. Chiesa, C. Garman, M. Green, I. Miers, E. Tromer, and M. Virza. Zerocash: Decentralized anonymous payments from Bitcoin. In *2014 IEEE Symposium on Security and Privacy*, pages 459–474, Berkeley, CA, USA, May 18–21, 2014. IEEE Computer Society Press.

[14] G. Bissias, A. P. Ozisik, B. N. Levine, and M. Liberatore. Sybil-resistant mixing for Bitcoin. In *Proceedings of the 13th Workshop on Privacy in the Electronic Society (WEIS)*, pages 149–158, 2014.

[15] J. Bonneau, A. Narayanan, A. Miller, J. Clark, J. A. Kroll, and E. W. Felten. Mixcoin: Anonymity for Bitcoin with accountable mixes. In N. Christin and R. Safavi-Naini, editors, *FC 2014*, volume 8437 of *LNCS*, pages 486–504, Christ Church, Barbados, Mar. 3–7, 2014. Springer, Heidelberg, Germany.

[16] J. Buntinx. The Shadow Brokers only accept ZCash payments for their monthly dump service, May 2017. https://themerkle.com/the-shadow-brokers-only-accept-zcash-payments-for-their-monthly-dump-service/.

[17] J. Dunietz. The Imperfect Crime: How the WannaCry Hackers Could Get Nabbed, Aug. 2017. https://www.scientificamerican.com/article/the-imperfect-crime-how-the-wannacry-hackers-could-get-nabbed/.

[18] I. Eyal. The miner's dilemma. In *2015 IEEE Symposium on Security and Privacy*, pages 89–103, San Jose, CA, USA, May 17–21, 2015. IEEE Computer Society Press.

[19] Y. J. Fanusie and T. Robinson. Bitcoin laundering: An analysis of illicit flows into digital currency services, Jan. 2018. A memorandum by the Center on Sanctions and Illicit Finance and Elliptic.

[20] C. Farivar and J. Mullin. Stealing bitcoins with badges: How Silk Road's dirty cops got caught, Aug. 2016. https://arstechnica.com/tech-policy/2016/08/stealing-bitcoins-with-badges-how-silk-roads-dirty-cops-got-caught/.

[21] E. Heilman, L. Alshenibr, F. Baldimtsi, A. Scafuro, and S. Goldberg. TumbleBit: an untrusted Bitcoin-compatible anonymous payment hub. In *Proceedings of NDSS 2017*, 2017.

[22] A. E. Kosba, A. Miller, E. Shi, Z. Wen, and C. Papamanthou. Hawk: The blockchain model of cryptography and privacy-preserving smart contracts. In *2016 IEEE Symposium on Security and Privacy*, pages 839–858, San Jose, CA, USA, May 22–26, 2016. IEEE Computer Society Press.

[23] A. Kumar, C. Fischer, S. Tople, and P. Saxena. A traceability analysis of Monero's blockchain. In *Proceedings of ESORICS 2017*, pages 153–173, 2017.

[24] G. Maxwell. CoinJoin: Bitcoin privacy for the real world. bitcointalk.org/index.php?topic=279249, Aug. 2013.

[25] S. Meiklejohn and R. Mercer. Möbius: Trustless tumbling for transaction privacy. *Proceedings on Privacy Enhancing Technologies*, 2018.

[26] S. Meiklejohn and C. Orlandi. Privacy-enhancing overlays in Bitcoin. In M. Brenner, N. Christin, B. Johnson, and K. Rohloff, editors, *FC 2015 Workshops*, volume 8976 of *LNCS*, pages 127–141, San Juan, Puerto Rico, Jan. 30, 2015. Springer, Heidelberg, Germany.

[27] S. Meiklejohn, M. Pomarole, G. Jordan, K. Levchenko, D. McCoy, G. M. Voelker, and S. Savage. A fistful of bitcoins: characterizing payments among men with no names. In *Proceedings of the 2013 Internet Measurement Conference (IMC)*, pages 127–140, 2013.

[28] I. Miers, C. Garman, M. Green, and A. D. Rubin. Zerocoin: Anonymous distributed E-cash from Bitcoin. In *2013 IEEE Symposium on Security and Privacy*, pages 397–411, Berkeley, CA, USA, May 19–22, 2013. IEEE Computer Society Press.

[29] A. Miller, M. Möser, K. Lee, and A. Narayanan. An empirical analysis of linkability in the Monero blockchain. arXiv:1704.04299, 2017. https://arxiv.org/pdf/1704.04299.pdf.

[30] P. Moreno-Sanchez, M. B. Zafar, and A. Kate. Listening to whispers of Ripple: Linking wallets and deanonymizing transactions in the Ripple network. *Proceedings on Privacy Enhancing Technologies*, 2016(4):436–453, 2016.

[31] M. Möser and R. Böhme. Join me on a market for anonymity. In *Proceedings of the 15th Workshop on the Economics of Information Security (WEIS)*, 2016.

[32] M. Möser and R. Böhme. Anonymous alone? measuring Bitcoin's second-generation anonymization techniques. In *Proceedings of IEEE Security & Privacy on the Blockchain*, 2017.

[33] M. Möser, R. Böhme, and D. Breuker. An inquiry into money laundering tools in the Bitcoin ecosystem. In *Proceedings of the APWG E-Crime Researchers Summit*, 2013.

[34] S. Nakamoto. Bitcoin: A Peer-to-Peer Electronic Cash System, 2008. bitcoin.org/bitcoin.pdf.

[35] S. Noether, A. Mackenzie, and the Monero Research Lab. Ring confidential transactions. *Ledger*, 1:1–18, 2016.

[36] R. R. O'Leary. Edward Snowden: Zcash Is 'Most Interesting Bitcoin Alternative', Sept. 2017. https://www.coindesk.com/edward-snowden-zcash-is-most-interesting-bitcoin-alternative/.

[37] J. Quesnelle. On the linkability of Zcash transactions. arXiv:1712.01210, 2017. https://arxiv.org/pdf/1712.01210.pdf.

[38] F. Reid and M. Harrigan. An analysis of anonymity in the Bitcoin system. In *Security and privacy in social networks*, pages 197–223. Springer, 2013.

[39] D. Ron and A. Shamir. Quantitative analysis of the full Bitcoin transaction graph. In A.-R. Sadeghi, editor, *FC 2013*, volume 7859 of *LNCS*, pages 6–24, Okinawa, Japan, Apr. 1–5, 2013. Springer, Heidelberg, Germany.

[40] T. Ruffing, P. Moreno-Sanchez, and A. Kate. CoinShuffle: Practical decentralized coin mixing for Bitcoin. In M. Kutylowski and J. Vaidya, editors, *ESORICS 2014, Part II*, volume 8713 of *LNCS*, pages 345–364, Wroclaw, Poland, Sept. 7–11, 2014. Springer, Heidelberg, Germany.

[41] M. Spagnuolo, F. Maggi, and S. Zanero. BitIodine: Extracting intelligence from the Bitcoin network. In N. Christin and R. Safavi-Naini, editors, *FC 2014*, volume 8437 of *LNCS*, pages 457–468, Christ Church, Barbados, Mar. 3–7, 2014. Springer, Heidelberg, Germany.

[42] L. Valenta and B. Rowan. Blindcoin: Blinded, accountable mixes for Bitcoin. In M. Brenner, N. Christin, B. Johnson, and K. Rohloff, editors, *FC 2015 Workshops*, volume 8976 of *LNCS*, pages 112–126, San Juan, Puerto Rico, Jan. 30, 2015. Springer, Heidelberg, Germany.