Deanonymization and linkability of cryptocurrency transactions based on network analysis

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Tx clustering
Parallel connections
Weighting timestamp vectors
Correlation matrix
Measuring anonymity

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Bitcoin

- The first to solve double-spending with proof-of-work
- Senders broadcast transactions into a P2P network
- Miners construct blocks (thus confirming transactions)

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Privacy in Bitcoin

- Transactions not linked to "real-world" identity
- Users can generate as many key pairs as they wish
- False sense of privacy?

Taint analysis heuristics

- All transaction inputs *probably* belong to the sender
- One output *probably* also belongs to the sender

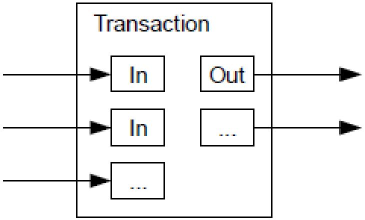

Figure: Bitcoin transaction structure

Privacy coins hinder blockchain analysis...

- Dash: mixing by masternodes
- Monero: ring signatures
- Zcash: zk-SNARKs

...but what about network analysis?

- How do messages propagate through the network?
- What does a well-connected adversary learn?
- Is it possible to link txs by the same user?

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Our contributions

- We introduce a **new transaction clustering method** based on weighted vectors of IP addresses
- We validate our method with **experiments on Bitcoin and three major privacy-focused cryptocurrencies**

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Message propagation in Bitcoin

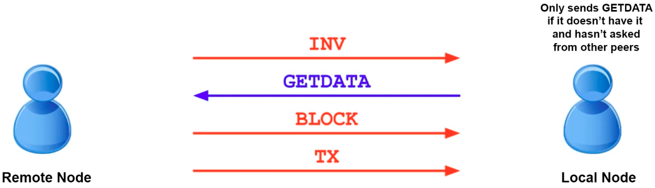

Figure: Bitcoin's 3-step message exchange

Broadcast randomization in Bitcoin and forks

- trickling: send to a random subset once every 100 ms
- diffusion: send to each neighbor after a random delay

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Intuition

Transactions issued from the same node have correlated broadcast patterns.

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Outline of our clustering method

- Establish parallel connections to many nodes
- Log timestamps of received tx announcements
- For each tx, consider IPs which announced it to us
- Cluster transactions with "similar" IP vectors
- Measure the decrease in anonymity

Parallel connections

- Default connections: 8 outgoing + up to 117 incoming
- We are unlikely to get a new tx quickly with only one connection per node
- `bcclient` establishes parallel connections to nodes
- Bitcoin and Zcash show similar distribution of free slots

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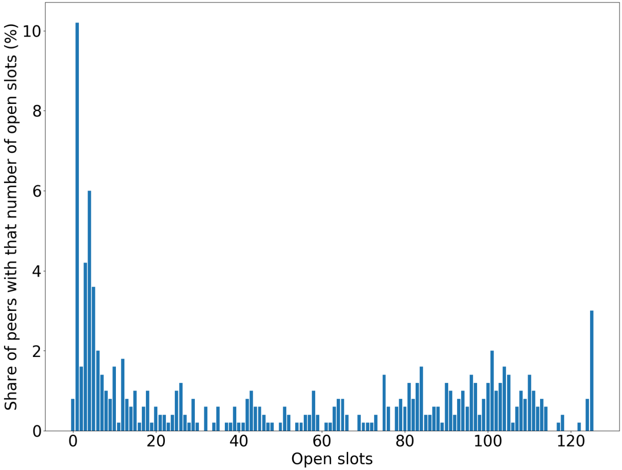
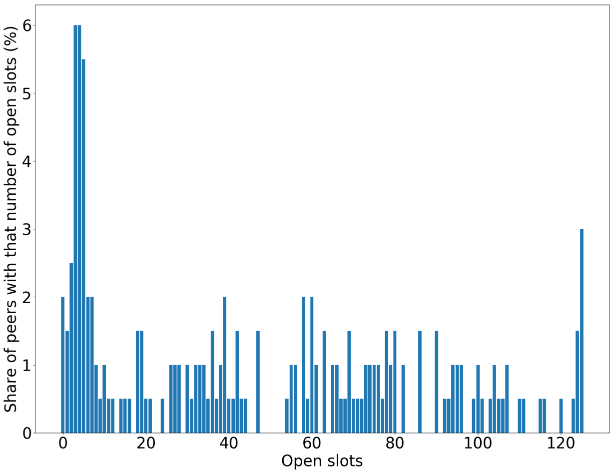
Bitcoin free slots



Zcash free slots



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Weighting timing vectors

IP addresses p_i announce a new tx to us at times t_i.
We assign exponentially decreasing weights to p_i:

$$w(p_i) = e^{-(t_i/k)^2}$$

where the median IP gets weight 0.5:

$$k = \frac{t_{median}}{\sqrt{-\ln(0.5)}}$$

Weighting timing vectors: example

High values indicate higher probability of an IP to be the sender or one of its entry nodes.

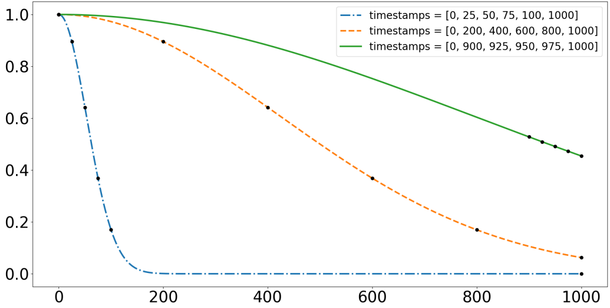

Figure: Weight functions for 3 timestamp vectors

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Clustering the correlation matrix

- For each pairwise correlations of weight vectors of txs
- Hypothesis: correlation matrix has a *block-diagonal* structure
- With a right permutation of rows and columns, related transactions will form clusters along the main diagonal

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Heatmap visualization

- Display correlations between weight vectors as matrix
- Darker color means higher correlation
- Matrix is symmetric by definition: $corr(i, j) = corr(j, i)$
- The main diagonal is black: correlation with oneself

Measuring anonymity

We use anonymity degree proposed by Díaz et al.[1]:

$$d = \frac{-\sum_{i=1}^{N} p_i log_2(p_i)}{log_2(N)}$$

where p_i is the probability of the i-th tx to originate from the given source.

- $d = 1$: users are equally likely to be the senders of a given message
- $d = 0$: the attacker knows the senders of all messages

[1] Díaz, Seys, Claessens, Preneel. Towards measuring anonymity. 2002

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Putting the pieces together

- Connect to many nodes from servers on 3 continents
- Log transaction announcements
- Assign weights to vectors of timestamps
- Calculate pairwise correlations between weight vectors
- Apply the spectral co-clustering algorithm [2]
- Calculate anonymity degree for our txs as ground truth
- Ethical considerations: mostly testnet, our own txs

[2] I.S.Dhillon. Co-clustering documents and words using bipartite spectral graph partitioning. 2001

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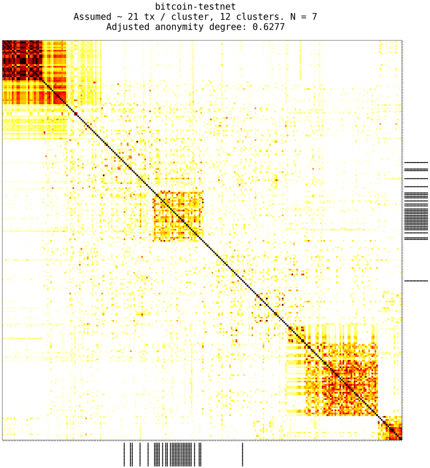
Bitcoin testnet: anonymity degree = 0.63



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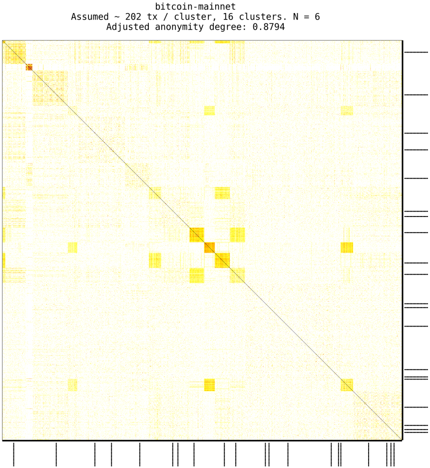
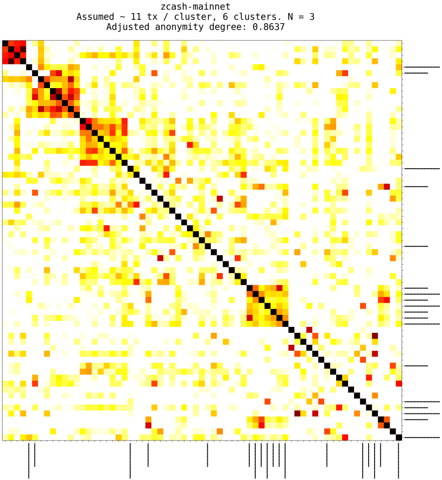
Bitcoin mainnet: anonymity degree = 0.88



Only connected to 1/10 of nodes, didn't occupy all slots.

Zcash: anonymity degree = 0.86



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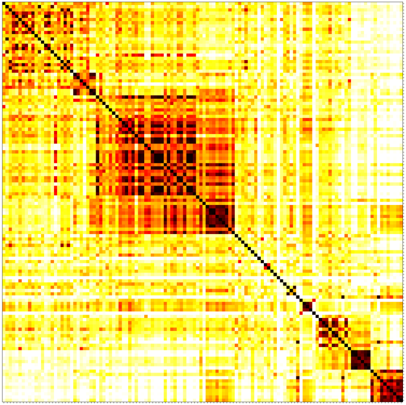
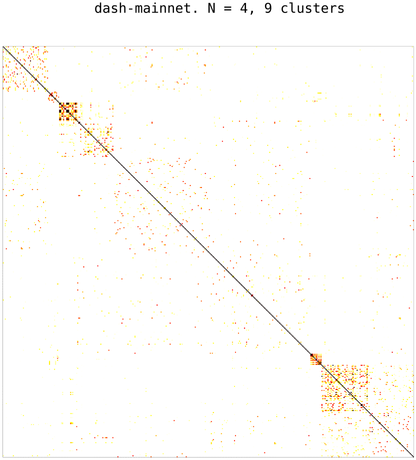
Monero



Experiment without our own transactions.

Dash



Experiment without our own transactions.

Estimating the source IP from ADDR messages

- A new node advertises its IP in ADDR messages
- We intersect the announced IPs from ADDRs with the highest-weighted IPs in tx clusters (Bitcoin testnet)
- In most experiments, the source IP appeared among top-5 highest weighted IPs in our transaction cluster

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Cost of attack

- Feasible for a moderately resourceful attacker
- Main cost components are bandwidth and storage
- We estimate the cost of a full-scale attack on Bitcoin mainnet at hundreds of US dollars
- Our experiments cost $35 on AWS

Countermeasures

- Don't issue many txs in the same session
- Run nodes with increased number of connections
- Periodically drop and re-establish random connections
- Implement stronger broadcast randomization

Countermeasures (contd): new relay protocols

- Dandelion++: two-stage propagation for better anonymity. Only outgoing connections for first phase. Hard to force a remote node to connect to us
- Erlay (proposed 2019-05-28): "[A]nnouncements are only sent directly over a small number of connections (only 8 outgoing ones). [...] We [...] better withstand timing attacks"

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- Announcement timings reveal related transactions
- Randomization techniques are not very efficient
- Clustering works better on small networks

Future work: mobile wallets

- In our experiments, txs were issues from a full node
- How are mobile wallets different in terms of networking?
- Can we cluster transactions issued from mobile wallets?

Questions?

- cryptolux.org (we are hiring postdocs)
- s-tikhomirov.github.io

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Image credits

- Transaction structure: Andreas Antonopoulos. https://bit.ly/2MPDpba
- Data exchange: Samuel Omidiora. https://bit.ly/2MO8Mmo