March 2024 Suspected Black Marble Flooding Against Monero: Privacy, User Experience, and Countermeasures

Draft v0.2

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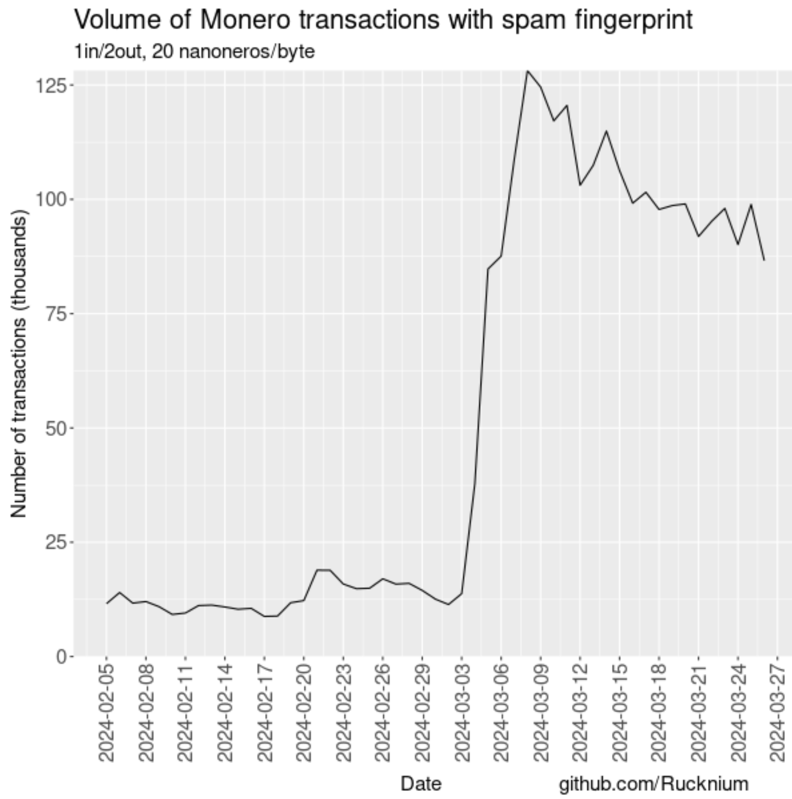
Abstract

On March 4, 2024, aggregate Monero transaction volume suddenly almost tripled. This note analyzes the effect of the large number of transactions, assuming that the transaction volume is an attempted black marble flooding attack by an adversary. According to my estimates, mean effective ring size has decreased from 16 to 5.5 if the black marble flooding hypothesis is correct. At current transaction volumes, the suspected spam transactions probably cannot be used for large-scale "chain reaction" analysis to eliminate all ring members except for the real spend. Effects of increasing Monero's ring size above 16 are analyzed.

1 March 4, 2024: Sudden transaction volume

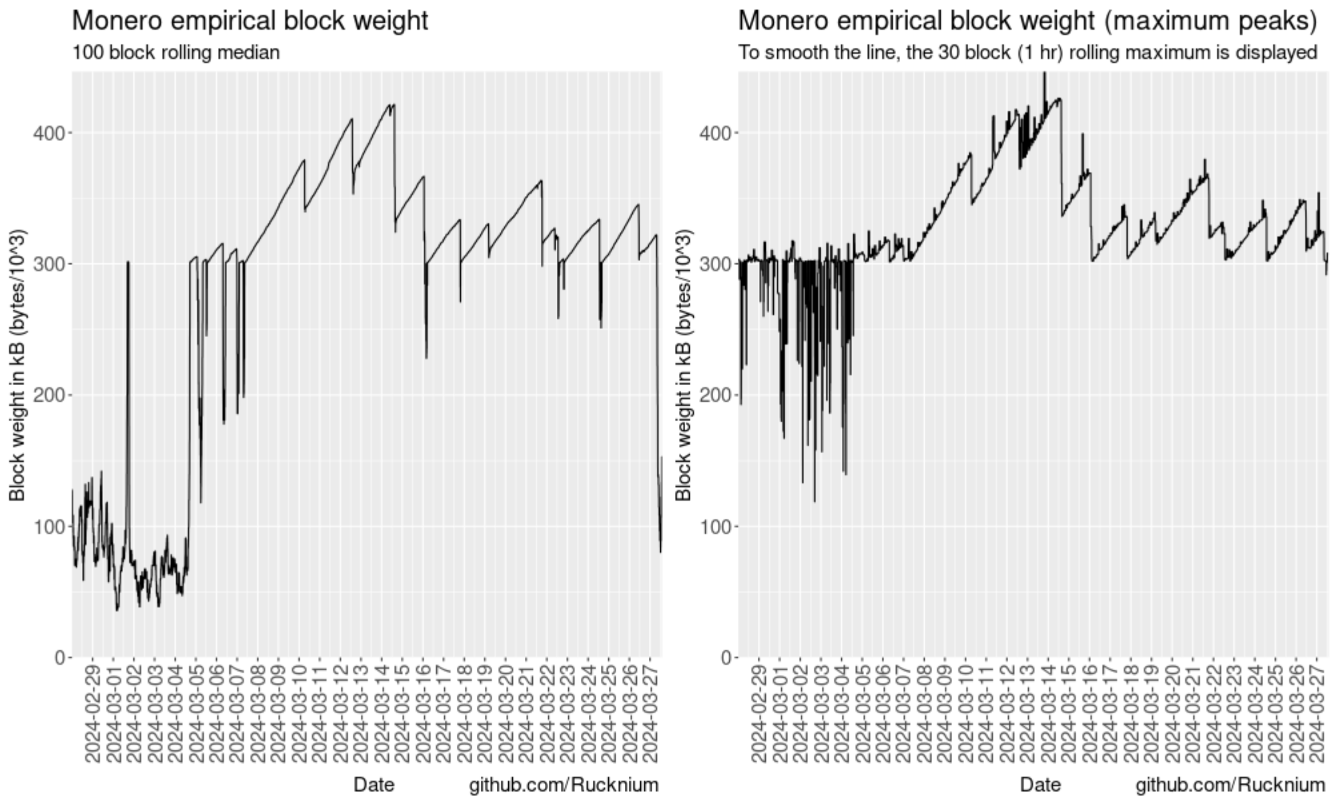
Figure 1: Volume of Monero transactions with spam fingerprint



On March 4, 2024 at approximately block height 3097764 (15:21:24 UTC), the number of 1input/2output minimum fee (20 nanoneros/byte) transactions sent to the Monero network rapidly increased. Figure 1 shows daily volume of this type of transaction increasing from about 15,000 to over 100,000.

The large volume of these transactions was enough to entirely fill the 300 kB Monero blocks mined about every two minutes. Monero's dynamic block size algorithm activated. The 100 block rolling median block size slowly increased to adjust for the larger number of transactions that miners could pack in blocks. Figure 2 shows the adjustment. The high transaction volume raised the 100 block median gradually for period of time. Then the transaction volume reduced just enough to allow the 100 block median to reset to a lower level. Then the process would restart. Block sizes have usually remained between 300 kB and 400 kB. Occasionally, high-fee transactions would allow miners to get more total revenue by giving up some of the 0.6 XMR/block tail emission and including more transactions in a block. The "maximum peaks" plot shows this phenomenon.

Figure 2: Monero empirical block weight



The sudden transaction volume rise may originate from a single entity. The motive may be spamming transactions to bloat the blockchain size, increase transaction confirmation times for real users, perform a network stress test, or execute a black marble flooding attack to reduce the privacy of Monero users. I will focus most of my analysis on the last possibility.

2 Literature review

The very first research bulletin released by the Monero Research Lab described black marble transaction flooding. [Noether et al., 2014] points out that the ring signature privacy model requires rings to contain transaction outputs that are could be plausible real spends. If a single entity owns a large share of outputs (spent or not), it can use its knowledge to rule out ring members in other users' transactions that cannot be the real spend. Since the entity knows that itself did not spend the output(s) in a particular ring, the effective ring size that protects other users' privacy can be reduced — even to an effective ring size of 1 when the entity knows the real spend with certainty. Rings with known real spends can be leveraged to determine the real spend in other rings in a "chain reaction" attack.

[Noether et al., 2014] gave the name "black marble" to the outputs owned by an anti-privacy adversary since they modeled the problem using a marble draw problem with a hypergeometric distribution. When a specific number of marbles are drawn *without* replacement from an urn containing a specific number of white and black marbles, the hypergeometric distribution describes the probability of drawing a specific number of black marbles. In my modeling I use the binomial distribution, which is the same as the hypergeometric except marbles are drawn *with* replacement. The binomial distribution makes more sense now ten years after [Noether et al., 2014] was written. The total number of RingCT outputs on the blockchain that can be included in a ring is over 90 million. The hypergeometric distribution converges to the binomial distribution as the total number of marbles increases to infinity. Moreover, Monero's current decoy selection algorithm does not select all outputs with equal probability. More recent outputs are selected with much higher probability. The hypergeometric distribution cannot be used when individual marbles have unequal probability of being selected.

[Chervinski et al., 2021] simulates a realistic black marble flood attack. They consider two scenarios. The adversary could create 2input/16output transactions to maximize the number of black marble outputs per block or the adversary could create 2input/2output transactions to make the attack less obvious. The paper uses Monero transaction data from 2020 to set the estimated number of real outputs and kB per block at 41 outputs and 51 kB respectively. The nominal ring size at this time was 11. The researchers simulated filling the remaining 249 kB of the 300 kB block with black marble transactions. A "chain reaction" algorithm was used to boost the effectiveness of the attack. In the 2in/2out scenario, the real spend could be deduced (effective ring size 1) in 11% of rings after one month of spamming black marbles. Later I will compare the results of this simulation with the current suspected spam incident.

[Krawiec-Thayer et al., 2021] analyze a suspected spam incident in July-August 2021. Transactions' inputs, outputs, fees, and ring member ages were plotted to evaluate evidence that a single entity created the spam. The analysis concluded, "All signs point towards a single entity. While transaction homogeneity is a strong clue, a the [sic] input consumption patterns are more conclusive. In the case of organic growth due to independent entities, we would expect the typically semi-correlated trends across different input counts, and no correlation between independent users' wallets. During the anomaly, we instead observed an extremely atypical spike in 1–2 input txns with no appreciable increase in 4+ input transactions."

TODO: A few papers like [Ronge et al., 2021, Egger et al., 2022] discuss black marble attacks too.

3 Black marble theory

The binomial distribution describes the probability of drawing x number of "successful" items when drawing a total of n items when the probability of a successful draw is p. It can be used to model the number of transaction outputs selected by the decoy selection algorithm that are not controlled by a suspected adversary.

The probability mass function of the binomial distribution with $n \in \{0, 1, 2, \ldots\}$ number of draws and $p \in [0, 1]$ probability of success is

$$f(x,n,p) = \binom{n}{x} p^x (1-p)^{n-x}, \text{ where } \binom{n}{x} = \frac{n!}{x!(n-x)!} \quad (1)$$

The expected value (the theoretical mean) of a random variable with a binomial distribution is np.

Monero's standard decoy selection algorithm programmed in `wallet2` does not select outputs with equal probability. The probability of selecting each output depends on the age of the output. Specifics are in [Rucknium, 2023]. The probability of a single draw selecting an output that is not owned by the adversary, p_r, is equal to the share of the probability mass function occupied by those outputs: $p_r = \sum_{i \in R} g(i)$, where R is the set of outputs owned by real users and $g(x)$ is the probability mass function of the decoy selection algorithm.

3.1 Spam assumptions

There is some set of criteria that identifies suspected spam. The early March 2024 suspected spam transactions: 1) have one input; 2) have two outputs; 3) pay the minimum 20 nanoneros per byte transaction fee. The normal volume of these transactions produced by real users must be estimated. The volume in excess of the normal volume is assumed to be spam. I followed this procedure:

1. Compute the mean number of daily transactions that fit the suspected spam criteria for the four weeks that preceded the suspected spam incident. A separate mean was calculated for each day of the week (Monday, Tuesday,...) because Monero transaction volumes have weekly cycles. These volume means are denoted $v_{r,m}, v_{r,t}, v_{r,w}, \ldots$ for the days of the week.

2. For each day of the suspected spam interval, sum the number of transactions that fit the suspected spam criteria. Subtract the amounts found in step (1) from this sum, matching on the day of the week. This provides the estimated number of spam transactions for each day: $v_{s,1}, v_{s,2}, v_{s,3}, \ldots$

3. For each day of the suspected spam interval, randomly select $v_{s,t}$ transactions from the set of transactions that fit the suspected spam criteria, without replacement. This randomly selected set is assumed to be the true spam transactions.

4. During the period of time of the spam incident, compute the expected probability p_r that one output drawn from the `wallet2` decoy distribution will select an output owned by a real user (instead of the adversary) when the wallet constructs a ring at the point in time when the blockchain tip is at height h. The closed-form formula of the `wallet2` decoy distribution is in [Rucknium, 2023].

5. The expected effective ring size of each ring constructed at block height h is $1 + 15 \cdot p_r$. The coefficient on p_r is the number of decoys.

Figure 3 shows the results of this methodology. The mean effective ring size settled at about 5.5 by the fifth day of the large transaction volume. On March 12 and 13 there was a large increase in the number of 1input/2output transactions that paid 320 nanoneros/byte (the third fee tier). This could have been the spammer switching fee level temporarily or a service that uses Monero increasing fees to avoid delays. I used the same method to estimate the spam volume of these 320 nanoneros/byte suspected spam. The 1in/2out 320 nanoneros/byte transactions displaced some of the 1in/2out 20 nanoneros/byte transactions because miners preferred to put transactions with higher fees into blocks. Other graphs and analysis will consider only the 1in/2out 20 nanoneros/byte transactions as spam unless indicated otherwise.

Figure 3: Estimated mean effective ring size

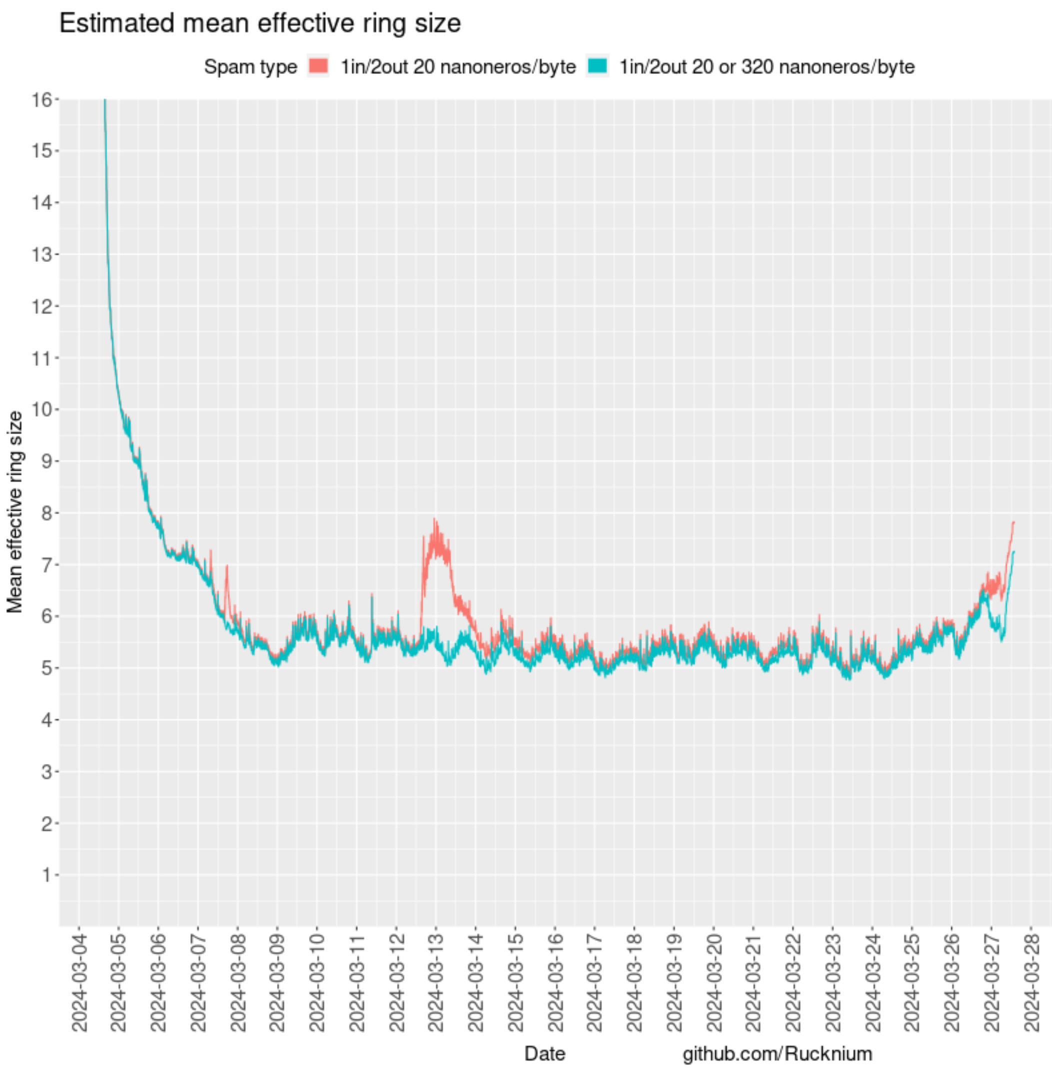
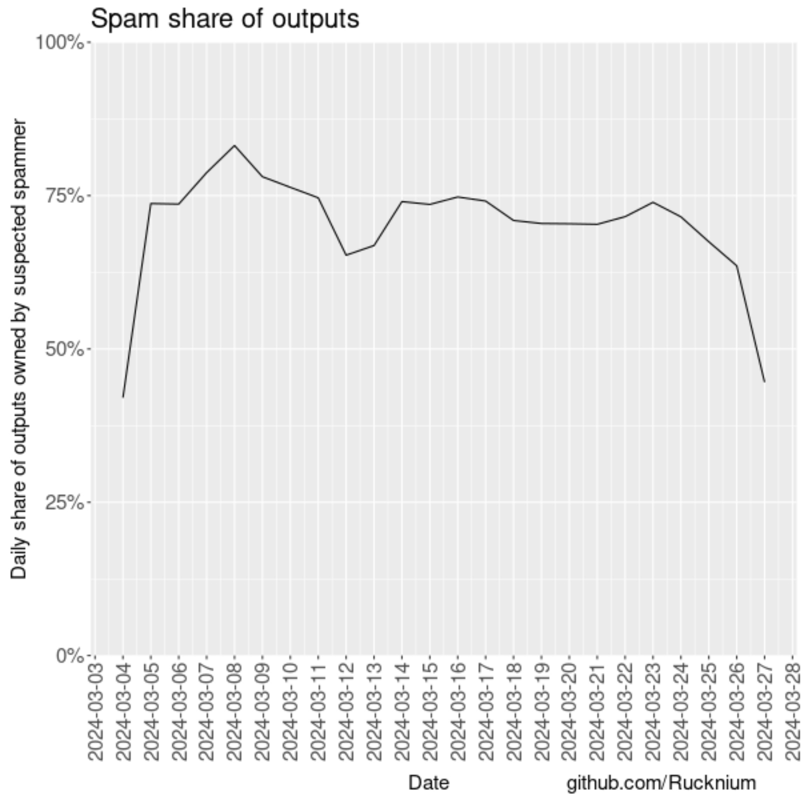


Figure 4 shows the daily share of outputs on the blockchain that are owned by the suspected spammer. The mean share of outputs since the suspected spam started is about 75 percent.

Figure 4: Spam share of outputs



3.2 Long term projection scenarios at different ring sizes

Fix the number of outputs owned by real users at r. The analysis will let the number s of outputs owned by the adversary vary. The share of outputs owned by real users is

$$p_r = \frac{r}{r+s} \tag{2}$$

The 2 expression can be written $p_r = \frac{1}{r} \cdot \dfrac{r}{1+\frac{1}{r}s}$, which is the formula for hyperbolic decay with the additional $\frac{1}{r}$ coefficient at the beginning of the expression [Aguado et al., 2010].

Let n be the nominal ring size (16 in Monero version 0.18). The number of decoys chosen by the decoy selection algorithm is $n-1$. The mean effective ring size for a real user's ring is one (the real spend) plus the ring's expected number of decoys owned by other real users.

$$\mathrm{E}\left[n_e\right] = 1 + (n-1) \cdot \frac{r}{r+s} \tag{3}$$

The empirical analysis of Section 3.1 considered the fact that the `wallet2` decoy selection algorithm draws a small number of decoys from the pre-spam era. Now we will assume that the spam incident has continued for a very long time and all but a negligible number of decoys are selected from the spam era. We will hold constant the non-spam transactions and vary the number of spam transactions and the ring size. Figures 5, 6, and 7 show the results of the simulations.

Figure 5: Long-term projected mean effective ring size

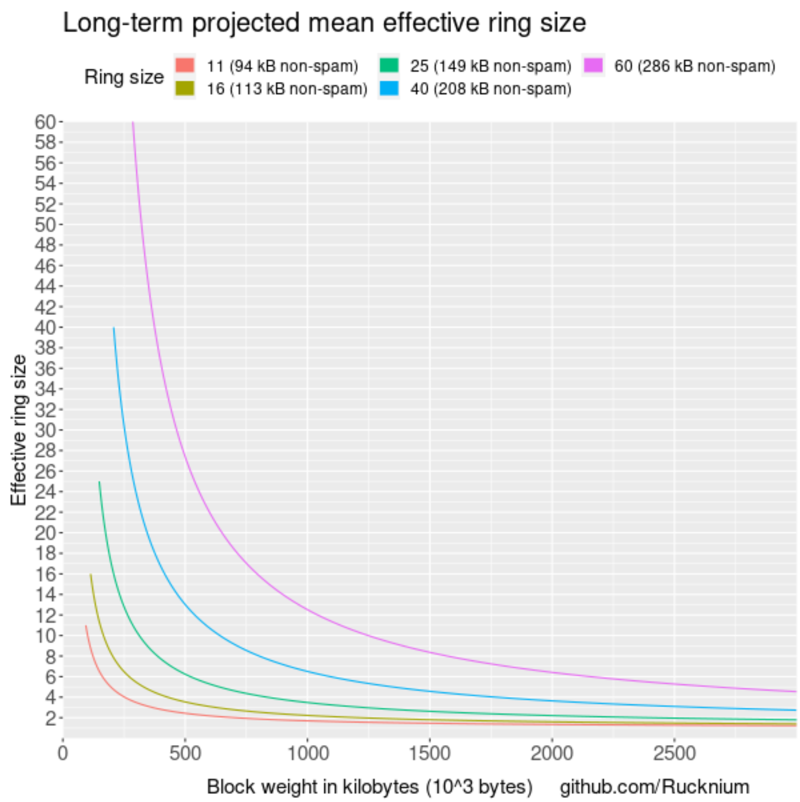


Figure 6: Long-term projected mean effective ring size (log-log scale)

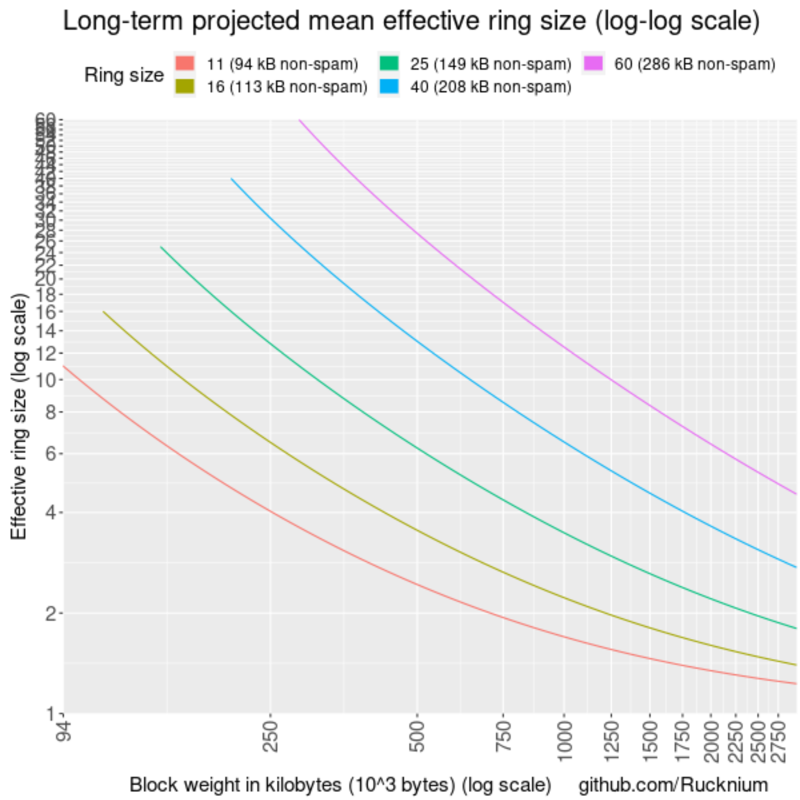
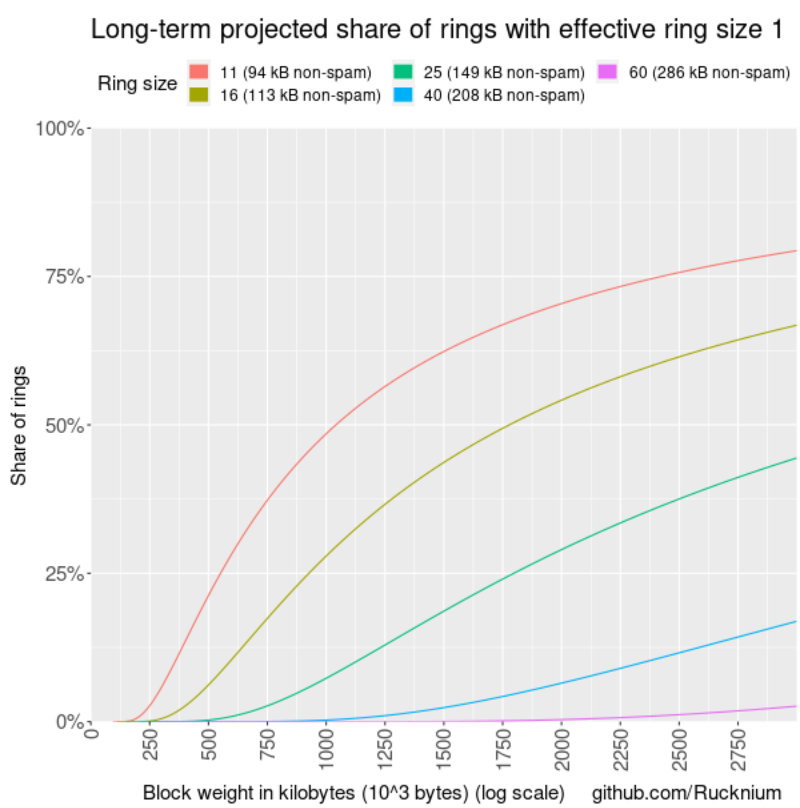


Figure 7: Long-term projected share of rings with effective ring size 1



3.3 Guessing the real spend using a black marble flooder's simple classifier

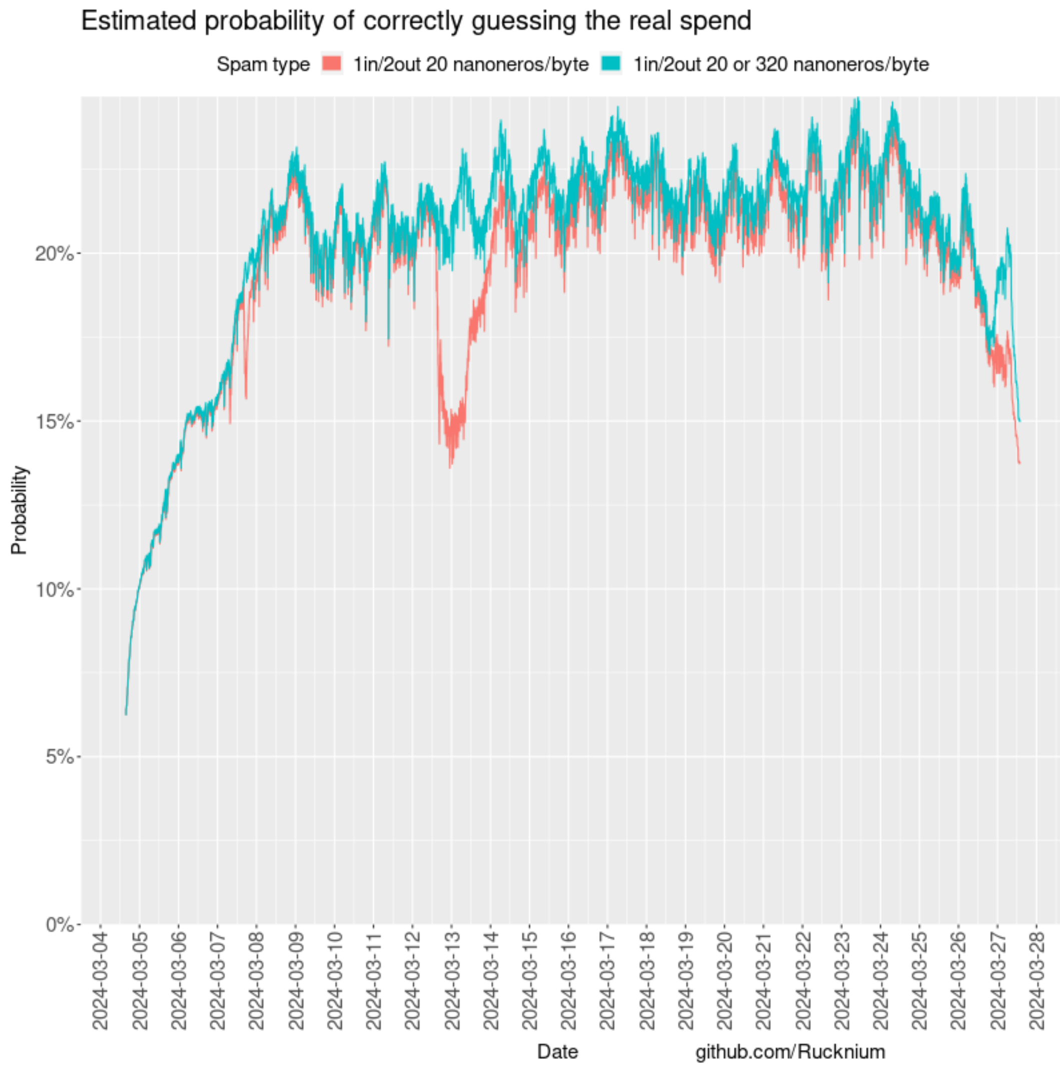
The adversary carrying out a black marble flooding attack could use a simple classifier to try to guess the real spend: Let n be nominal ring size and n_s be the number of outputs in a given ring that are owned by the attacker. n_s is a random variable because decoy selection is a random process. The adversary can eliminate n_s of the n ring members as possible real spends. The attacker guesses randomly with uniform probability that the ith ring member of the $n - n_s$ remaining ring members is the real spend. The probability of correctly guessing the real spend is $\frac{1}{n-n_s}$. If the adversary owns all ring members except for one ring member, which must be the real spend, the probability of correctly guessing the real spend is 100%. If the adversary owns all except two ring members, the probability of correctly guessing is 50%. And so forth.

The mean effective ring size is $\mathrm{E}[n_e]$ from 3. Does this mean that the mean probability of correctly guessing the real spend is $\frac{1}{\mathrm{E}[n_e]}$? No. The $h(x) = \frac{1}{x}$ function is strictly convex. By Jensen's inequality, $\mathrm{E}\left[\frac{1}{n_e}\right] > \frac{1}{\mathrm{E}[n_e]}$. The mean probability of correctly guessing the real spend is

$$\mathrm{E}\left[\frac{1}{n_e}\right] = \sum_{i=1}^{n} \frac{1}{i} \cdot f(i-1, n-1, \frac{\mathrm{E}[n_e]-1}{n-1}) \tag{4}$$

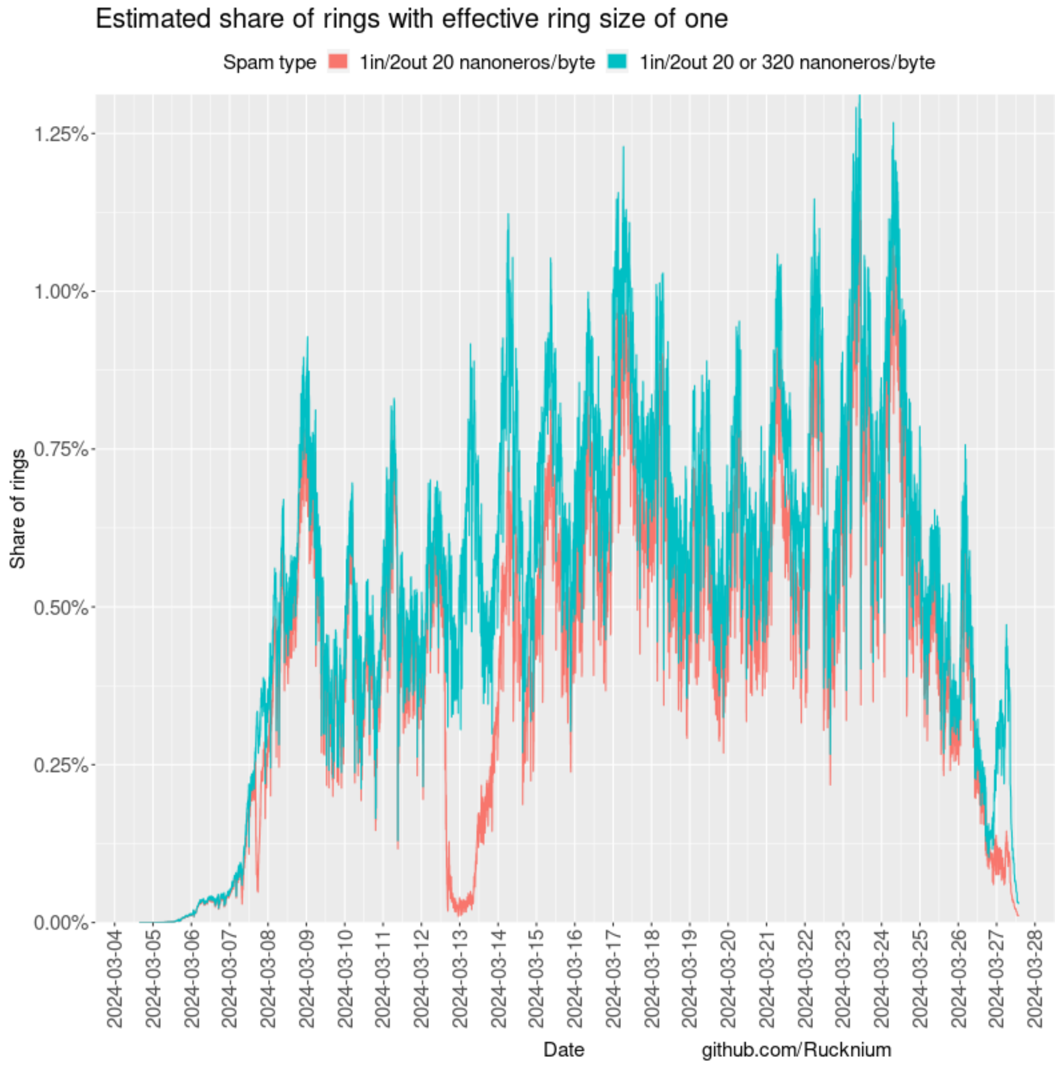
$\frac{1}{i}$ is the probability of correctly guessing the real spend when the effective ring size is i. f is the probability mass function of the binomial distribution. It calculates the probability of the decoy selection algorithm selecting $i-1$ decoys that are owned by real users. The total number of decoys to select is $n-1$ (that is the argument in the second position of f). The probability of selecting a decoy owned by a real user is $\frac{\mathrm{E}[n_e]-1}{n-1} = \frac{r}{r+s}$.

Figure 8: Estimated probability of correctly guessing the real spend



The probability of a given ring having all adversary-owned ring members except for the real spend is $f\left(0, n-1, \frac{\mathrm{E}[n_e]-1}{n-1}\right)$. Figure 9 plots the estimated share of rings with effective ring size one.

Figure 9: Estimated share of rings with effective ring size of one



4 Chain reaction graph attacks

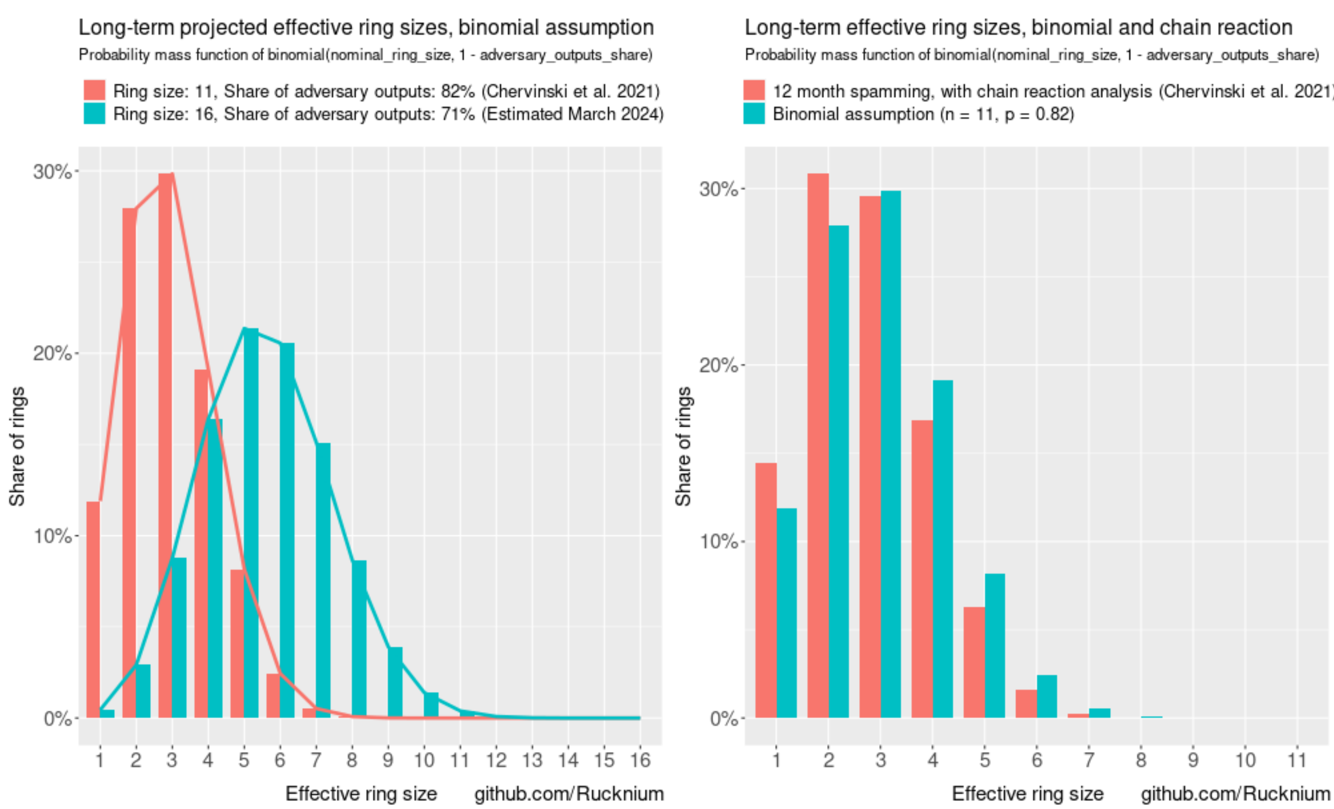
The effective ring size can be reduced further by applying a process of elimination to related rings. This technique is called a "chain reaction" or a "graph analysis attack". Say that the effective ring size in transaction A is reduced to two because of a black marble attack. One of the remaining two ring members is an output in transaction B. If the output in transaction B is known to be spent in transaction C because the effective ring size of transaction C was one, then that output can be ruled out as a plausible real spend in transaction A. Therefore, the adversary can reduce the effective ring size of transaction A to one.

Theorem 1 of [Yu et al., 2019] says that a "closed set" attack is as effective as exhaustively checking all subsets of outputs. The brute force attack is infeasible since its complexity is $O\left(2^m\right)$, where m is the total number of RingCT outputs on the blockchain. [Yu et al., 2019] implements a heuristic algorithm to execute the closed set attack that is almost as effective as the brute force method. [Vijayakumaran, 2023] proves that the Dulmage-Mendelsohn (DM) decomposition gives the same results as the brute force closed set attack, but the algorithm renders a result in polynomial time. The open source implementation of the DM decomposition in [Vijayakumaran, 2023] processes 37 million RingCT rings in about four hours.

In practice, how much further can chain reaction attacks reduce the effective ring size when combined with a black marble attack? [Egger et al., 2022] suggest some closed-form formulas to compute the vulnerability of different ring sizes to chain reaction attacks. However, [Egger et al., 2022] assume that decoys are selected by a partitioning process instead of Monero's actual mimicking decoy selection algorithm. It is not clear how relevant the findings of [Egger et al., 2022] are for Monero's mainnet. Monte Carlo simulations would be a better way to evaluate the risk of chain reactions.

[Chervinski et al., 2021] carries out a simulation using the old ring size of 11. In the 2input/2output spam scenario, 82% of outputs are black marbles. Assuming only the binomial distribution, i.e. no chain reaction analysis, Figure 10 compares the theoretical long-term distribution of effective ring sizes in the [Chervinski et al., 2021] scenario and the March 2024 suspected spam on Monero's mainnet. The share of rings with effective ring size 1 in the [Chervinski et al., 2021] scenario is 11.9 percent, but the share is only 0.8 percent with the suspected March 2024 spam. The mean effective ring sizes of the [Chervinski et al., 2021] scenario without chain reaction and the March 2024 spam estimate are 2.9 and 5.2, respectively.

Figure 10: Probability mass function of long-term effective ring sizes



[Chervinski et al., 2021] executes chain reaction analysis to increase the effectiveness of the attack. The second plot in Figure 10 compares the long term effective ring size achieved by [Chervinski et al., 2021] when leveraging chain reaction analysis and the effective ring size when only the binomial distribution is assumed. [Chervinski et al., 2021] increases the share of ring with effective ring size one from 11.9 to 14.5 percent. Mean effective ring size decreases from 2.94 to 2.76. This is a modest gain of attack effectiveness, but [Chervinski et al., 2021] appears to be using a suboptimal chain reaction algorithm instead of the closed set attack.

The actual risk from chain reaction analysis in the suspected March 2024 flooding is a gap in our knowledge. [Vijayakumaran, 2023] provides an open source implementation of the DM decomposition in Rust and excellent documentation.[1] A Monte Carlo simulation applying the DM decomposition to the March 2024 black marble estimates should be written.

5 Countermeasures

See `https://github.com/monero-project/research-lab/issues/119`

TODO

6 Estimated cost to suspected spammer

When the 1in/2out 20 nanoneros/byte spam definition is used, the total fees paid by the spam transactions over the 23 days of spam was 61.5 XMR. The sum total of the transaction sizes of the spam transactions was 3.08 GB.

When the 1in/2out 20 or 320 nanoneros/byte spam definition is used, the total fees paid by the spam transactions over the 23 days of spam was 81.3 XMR. The sub total of the transaction sizes of the spam transactions was 3.12 GB.

7 Transaction confirmation delay

Monero's transaction propagation rules are different from BTC's rules for good reasons, but two of the rules can make transactions seem like they are "stuck" when the txpool (mempool) is congested. First, Monero does not have replace-by-fee (RBF). When a Monero node sees that a transaction attempts to spend an output that is already spent by another transaction in the txpool, the node does not send the transaction to other nodes because it is an attempt to double spend the output. (Monero nodes do not know the real spend in the ring, but double spends can be detected by comparing the key images of ring signatures in different transactions.) Monero users cannot increase the fee of a transaction that they

[1] `https://github.com/avras/cryptonote-analysis`
`https://www.respectedsir.com/cna`

already sent to a node because the transaction with the higher fee would be considered a double spend. BTC has RBF that allows a transaction to replace a transaction in the mempool that spends the same output if the replacement transaction pays a higher fee. One of RBF's downsides is that merchants cannot safely accept zero-confirmation transactions because a malicious customer can replace the transaction in the mempool with a higher-fee transaction that spends the output back to themselves. Without RBF, Monero users must wait for their low-fee transaction to confirm on the blockchain. They cannot choose to raise their "bid" for block space even if they were willing to pay more. They have to get it right the first time. Fee prediction is especially important for Monero users when the txpool is congested because of the lack of RBF, but very little Monero-specific fee prediction research has been done.

Unlike BTC, Monero also does not have child-pays-for-parent (CPFP), which allows users to chain multiple transactions together while they are still in the mempool. With CPFP, users can spend the output of the unconfirmed parent transaction and attach a higher fee to the child transaction. Miners have an incentive to include the parent transaction in the block because the child transaction is only valid if the parent transaction is also mined in a block. Monero transaction outputs cannot be spent in the same block that they are confirmed in. Actually, Monero users need to wait at least ten blocks to spend new transaction outputs because benign or malicious blockchain reorganizations can invalidate ring signatures.[2]

Monero's transaction propagation rules can create long delays for users who pay the same minimum fee that the suspected spammer pays. When users pay the same fee as the spam, their transactions are put in a "queue" with other transactions at the same fee per byte level. Their transactions are confirmed in first-in/first-out order because the `get_block_template` RPC call to `monerod` arranges transactions that way.[3] Most miners use `get_block_template` to construct blocks, but P2Pool orders transactions randomly after they have been sorted by fee per byte.[4]

The first plot in Figure 11 shows the mean delay of transaction confirmation in each hour. The plot shows the mean time that elapsed between when the transaction entered the txpool and when it was confirmed in a block. Each hour's value in the line plot is computed from transactions that were confirmed in blocks in that hour. This data is based on txpool archive data actively collected from a few nodes.[5] The mean includes transactions with and without the spam fingerprint. Usually mean confirmation time was less than 30 minutes, but sometimes confirmations of the average transaction were delayed by over two hours.

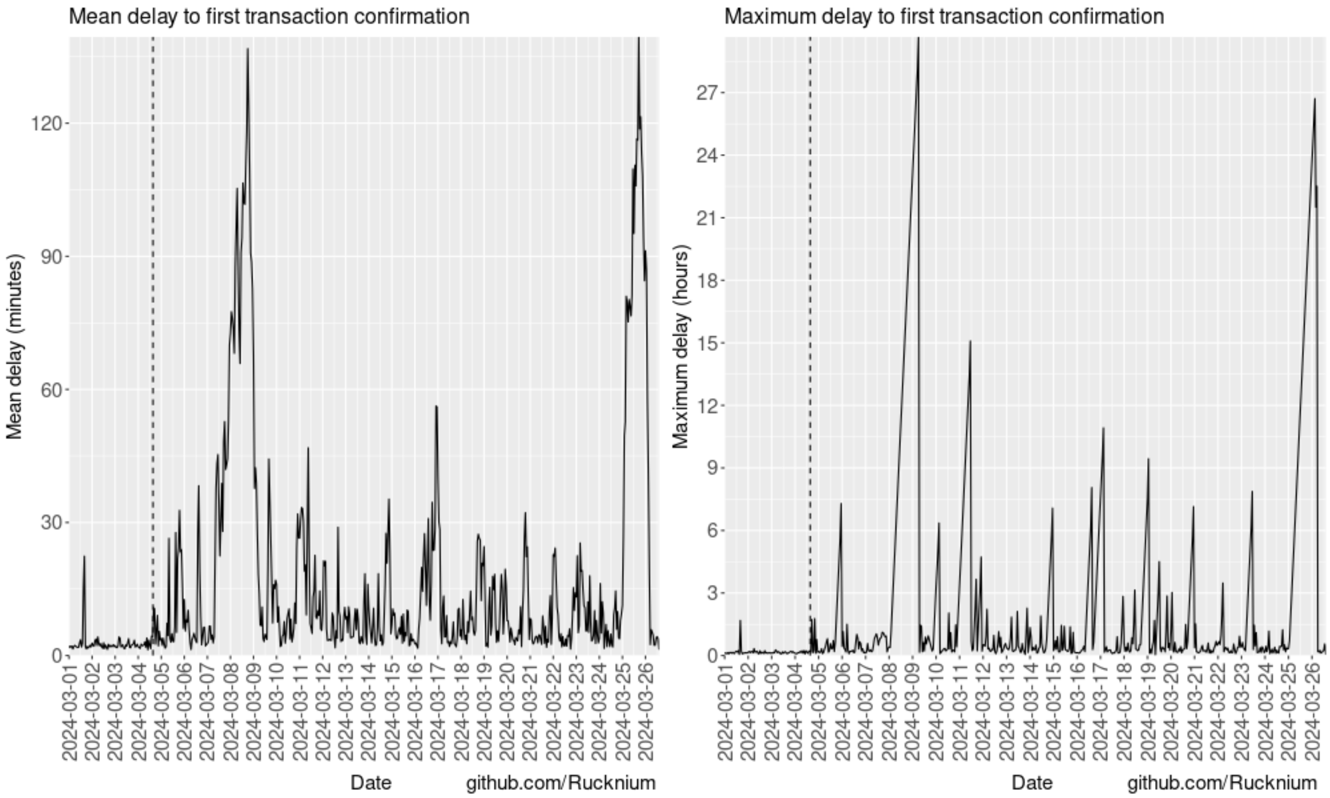
[2] "Eliminating the 10-block-lock" https://github.com/monero-project/research-lab/issues/95

[3] https://github.com/monero-project/monero/blob/9bf06ea75de4a71e3ad634e66a5e09d0ce021b67/src/cryptonote_core/tx_pool.cpp#L1596

[4] https://github.com/SChernykh/p2pool/blob/dd17372ec0f64545311af40b976e6274f625ddd8/src/block_template.cpp#L194

[5] https://github.com/Rucknium/misc-research/tree/main/Monero-Mempool-Archive

Figure 11: Delay to first transaction confirmation



The second plot in Figure 11 shows the *maximum* waiting time for a transaction to be confirmed. The value of the line at each hour is the longest time that a transaction waited to be confirmed in one of the block mined in the hour or the amount of time that a transaction was still waiting to be confirmed at the end of the hour (whichever is greater). There were a handful of transactions that paid fees below the 20 nanoneros/byte tier that the spam was paying. These transactions did not move forward in the queue when the spam transactions were confirmed. Instead, they had to wait until the txpool completely emptied. Exactly 100 transactions waited longer than three hours. They paid between 19465 and 19998 piconeros per byte. Most of the transactions appeared to have set fees slightly lower than 20 nanonerpos per byte because they had an unusual number of inputs. 92 of them had four or more inputs. The remaining eight of them had just one input. Those eight may have been constructed by a nonstandard wallet.

8 Real user fee behavior

During the suspected spam, users must pay more than the minimum fee to put their transactions at the front of the confirmation queue. If users pay more than the minimum fee, usually their transactions would be confirmed in the next mined block. Monero's standard fee levels are 20, 80, 320, and 4000 nanoneros per byte. Users are not required to pay one of these fee levels, but all wallets that are based on `wallet2` do not allow users to choose custom fees outside of the four standard levels because of the privacy risk of unusual transactions.[6]

The "auto" fee level of the Monero GUI and CLI wallets is supposed to automatically change the fee of a transaction from the lowest tier (20 nanoneros/byte) to the second tier (80 nanoneros/byte) when the txpool is congested. Unfortunately, a bug prevented the automatic adjustment. On March 9, 2024 the Monero Core Team released the 0.18.3.2 version of Monero and the GUI/CLI wallet that fixed the bug.[7] Users are not required to upgrade to the latest wallet version, so probably many users still use the version that is not automatically adjusting fees.

The first plot of Figure 12 shows the share of trasnactions paying each of the four fee tiers. Any transactions that do not pay in the standard ranges $\{[18,22],[72,82],[315,325],[3000,4100]\}$ were not included in the plot. The 320 nanoneros/byte tier is interesting. About 10 percent of transactions paid 320 nanonero/byte until Februray 17, 2024. The date could have something to do with Monero being delisted from Binance on February 20, 2024.[8] Then on March 12-13, 2024 there was a burst of 320 nanonero/byte transactions. The 0.18.3.2 GUI/CLI wallet release could not explain the burst since the auto fee adjustment would only increase fees from 20 to 80 nanoneros/byte. The burst of 320 nanonero/byte transactions must have been either from a central service producing fees or from the suspected spammer.

The second plot of Figure 12 shows the same data with the suspected spam transactions eliminated both the 80 and 320 nanoneros/byte transactions with the spam fingerprint were removed. There is a modest increase in 80 nanonero/byte transactions after the spam started.

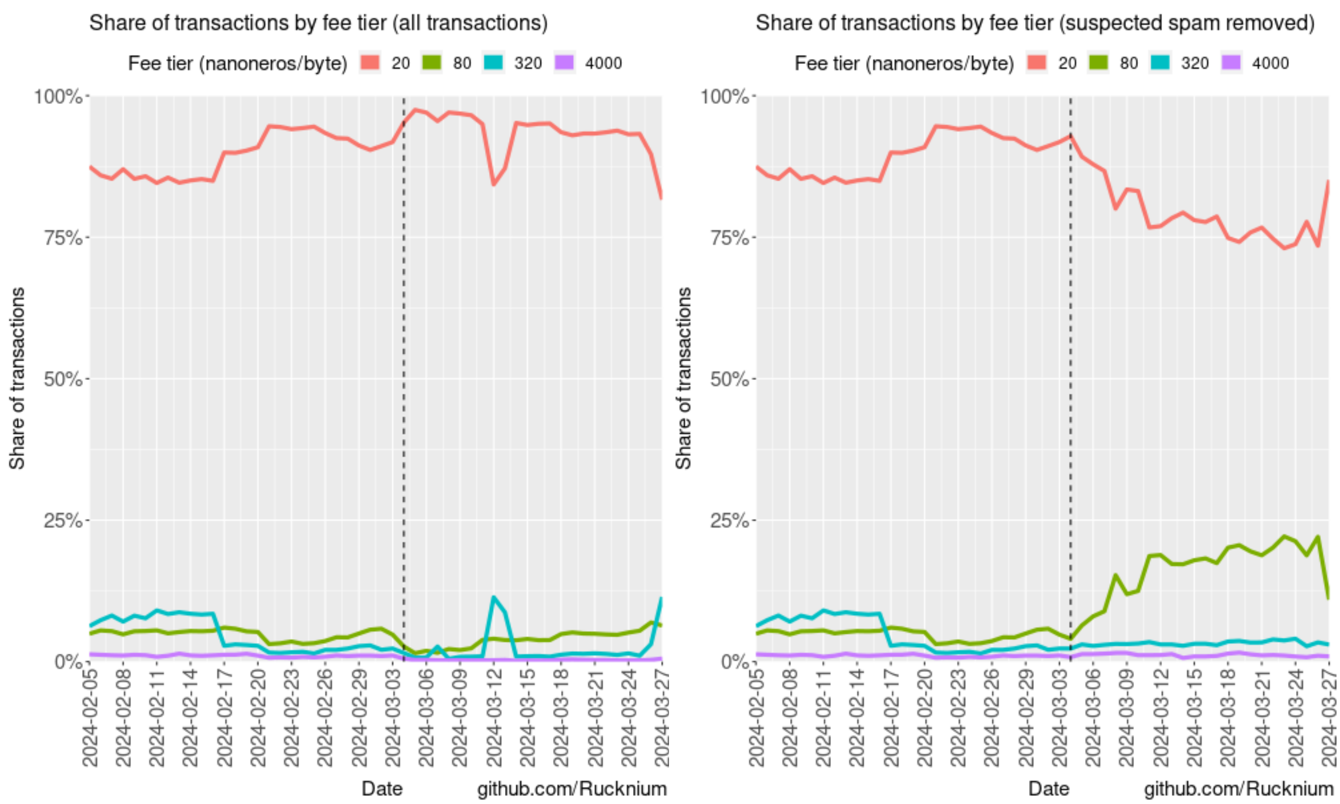
[6] https://github.com/Rucknium/misc-research/tree/main/Monero-Nonstandard-Fees

[7] "Monero 0.18.3.2 'Fluorine Fermi' released" https://www.getmonero.org/2024/03/09/monero-0.18.3.2-released.html

"wallet2: adjust fee during backlog, fix set priority" https://github.com/monero-project/monero/pull/9220

[8] https://decrypt.co/218194/binance-finalizes-monero-delisting

Figure 12: Share of transactions by fee tier



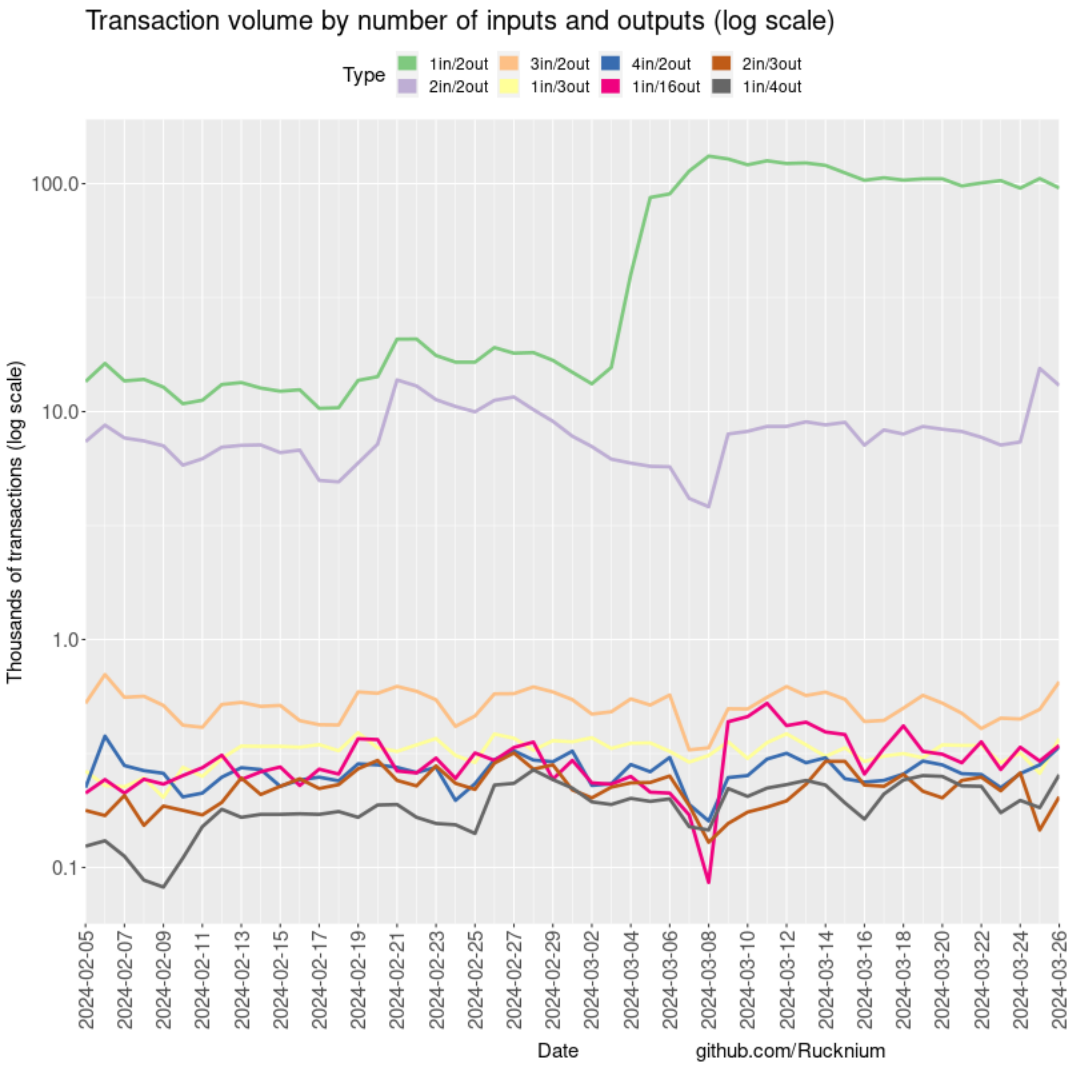
The mempool archive data suggest that merchants using zero-confirmation delivery were still safe during the spam incident. Once submitted to the network, transactions did not drop out of the mempool. They just took longer to confirm. There were only two transaction IDs in the mempool of one of the mempool archive nodes that did not confirm during the spam period. Both occurred on March 8 when the mempool was very congested. The the two "disappearing transactions" could happen if someone submits a transactions to an overloaded public RPC node, the transactions does not propagate well, and then the user reconstructs the transactions with another node. The first transaction will not confirm because it is a double spend. Seeing a transaction in the mempool that never confirms happens sometimes during normal transaction volumes, too. Single transactions like that appeared on February 14, 17, and 23 and March 1 in the mempool archive data.

9 Evidence for and against the spam hypothesis

Is the March 4, 2024 transaction volume a result of many real users starting to use Monero more, or is it spam created by a single entity? [Krawiec-Thayer et al., 2021] analyzed the July/August 2021 sudden rise in transaction volume. We concluded that it was likely spam. Our evidence was: 1) There was a sharp increase of 1in/2out and 2in/1out transactions, but the volume of other transaction types did not increase, 2) All the suspected spam paid minimum fees, 3) The distribution of ring members became much younger, suggesting that the spammer was rapidly re-spending outputs as quickly as possible.

Available time has not permitted a full run of the [Krawiec-Thayer et al., 2021] analysis on the March 2024 suspected spam data. It is easy to do a quick check of transaction volume by input/output type. Figure 13 plots the eight most common in/out transaction types on a log scale. Only the volume of 1in/2out transactions increased on March 4, supporting the spam hypothesis.

Figure 13: Transaction volume by number of inputs and outputs (log scale)



More can be done to generate evidence for or against the spam hypothesis. [Krawiec-Thayer et al., 2021] analyzed the age of all ring members. Using the OSPEAD techniques, the distribution of the age of the real spends can be estimated.[9] The Monero node network can be actively crawled to see if the spam transactions originate from one node. Dandelion++ can defeat attempts to discover the origin of most transaction because the signal of the real transaction is covered by the Dandelion++ noise. When the signal is huge like the spam, some statistical analysis could overcome the Dandelion++ protection. In-

[9] `https://github.com/Rucknium/OSPEAD`

vestigatory nodes could use `set_log net.p2p.msg:INFO` to view which neighboring nodes the suspected spam is coming from. Then the investigatory node could crawl the network in the direction of the highest incoming volume. The techniques of [Sharma et al., 2022] are useful at extremely high transaction volumes, like in the spam case, and could be used.

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