Pinpointing and Measuring Wasabi and Samourai CoinJoins in the Bitcoin Ecosystem

Johann Stockinger\textsuperscript{1}, Bernhard Haslhofer\textsuperscript{2}, Pedro Moreno-Sanchez\textsuperscript{3}, and Matteo Maffei\textsuperscript{1}

\textsuperscript{1} Technical University of Vienna
\textsuperscript{2} AIT Austrian Institute of Technology
\textsuperscript{3} IMDEA Software Institute

Abstract. We present a first measurement study on two popular wallets with built-in distributed CoinJoin functionality, Wasabi and Samourai, in the context of the broader Bitcoin ecosystem. By applying two novel heuristics, we can effectively pinpoint 25,070 Wasabi and 134,569 Samourai transactions within the first 689,255 (2021-07-01) blocks. Our study reveals a somewhat steady adoption of these services and found a growing trend with a total amount of 190,777.11 mixed BTC with a value of ca. 3.02 B USD. Within the recent six months, we measured an average monthly mixing throughput of 5410.98 BTC (ca. 240.14 M USD). Among all actors, which were directly or indirectly involved in CoinJoins, we also found a lower-bound of 32 distinct exchanges and traced a lower-bound of 6683.19 BTC (ca. 95.98 M USD) mixed coins received by exchanges. Our analysis further shows that linking heuristics over Wasabi and Samourai transactions allows us to narrow down the anonymity set provided by these wallets over time. Furthermore, we estimate the number of mixing outputs that are handled in Wasabi and Samourai correspondingly over time. Overall, this is the first paper to provide a comprehensive picture of the adoption of distributed CoinJoin and to discuss implications for end-users, cryptoasset exchanges, and regulatory bodies.

Keywords: Cryptoassets · Mixing · CoinJoin

1 Introduction

Wasabi and Samourai are two non-custodial, privacy-focused Bitcoin wallets with integrated distributed CoinJoin functionality. They combine coins from multiple users into a single transaction. They have become increasingly popular because they implement privacy behind the scenes via a simple, relatively intuitive interface. On the one hand, these wallets fulfill the increasing need for privacy, which is not given by default because it is possible to effectively de-anonymize end users \cite{10.1145/3457626.3467536} and trace funds. However, on the other hand, privacy-focused wallets like Wasabi or Samourai pose significant challenges to cryptoasset service providers that must enforce Know-Your-Customer (KYC) checks to fulfill increasingly tightening Anti-Money-Laundering (AML) rules. In
addition, current regulatory efforts (e.g., [2]) expand the traceability-of-funds requirement to cryptoassets and impose that obligation to cryptoasset service providers. However, that requirement opposes the design goal of Wasabi and Samourai, which both aim to make it difficult for third parties to trace where a particular coin came from and where it went.

The role of centralized services like JoinMarket [13], where a trusted third party matches CoinJoin participants, has been researched in the past. However, little empirical evidence is available on the adoption of decentralized mixing services facilitating CoinJoin transactions. Therefore, in this work, we study the role of two popular wallets with built-in CoinJoin functionality, Wasabi and Samourai, in the context of the broader Bitcoin ecosystem. We want to understand how these wallets’ adoption evolved, how they are related to cryptoasset services such as exchanges, and how their embedding into a network of actors affects the anonymity of the coins they hold.

Our contributions. First, we propose two novel heuristics to detect on-chain CoinJoin transactions generated by Wasabi and Samourai wallets. As discussed in Section 3, our Wasabi CoinJoin Detection Heuristic is highly effective (F-1-score 0.82) and outperforms previously known heuristics such as those proposed by Ficsőr [34]. Also, it can find 99% of all known Wasabi transactions in our ground-truth dataset in combination with simple filtering rules. Also, our Samourai CoinJoin Detection Heuristics reduces the number of false positives compared to Ficsőr’s heuristics. After applying our heuristics, we found 25,070 Wasabi and 134,569 Samourai transactions within the block range 1 - 689,255 (2021-07-01). Second, we analyzed how the number of transactions and the amount of mixed BTC evolved and found a somewhat steady adoption of Wasabi since November 2018 (release 1.0) and Samourai since January 2020. We found a total amount of 190,777.11 mixed BTC (ca. 3.02 B USD) and an average amount of 4563.11 mixed BTC for Wasabi (ca. 204.82 M USD) and 847.87 BTC (ca. 35.32 M USD) for Samourai in recent months (Jan 2021 - Jun 2021). We also analyzed the connections between Wasabi and Samourai CoinJoins and other actors, most importantly cryptoasset exchanges. Our results reveal a lower bound of 32 different exchanges that received 6683.19 BTC (ca. 95.98 M USD) mixed coins via one hop or two hops. We also see that accepting such transactions is a living practice and not a phenomenon of the unregulated past. Third, we investigated how Wasabi and Samourai embedded in a network of related actors affects their anonymity. We observe relations among addresses established by state-of-the-art clustering techniques that narrow the upper bound of the anonymity set offered by Wasabi and Samourai down significantly. Finally, we estimate the upper bound on the number of outputs being mixed at Wasabi and Samourai throughout their lifetime.

Our work has several implications: First, it shows privacy-seeking end-users that third parties can pinpoint CoinJoin transactions generated by these wallets. For end-users, this implies that, depending on the jurisdiction, having CoinJoins in the payment chain could raise issues when cashing out at AML compliant exchanges. Second, it also shows that exchanges can implement CoinJoin checks
using relatively simple heuristics. Third, our work offers a picture of the current use of CoinJoins and an expandable framework for future, more comprehensive analyses. Fourth, our anonymity analysis sheds light on the anonymity losses suffered by participants of Wasabi and Samourai wallets due to the traceability of their pre-mixed and post-mixed addresses.

2 Background and Related Work

2.1 Coin Swapping, Mixing Services, and CoinJoin

Swapping coins of different users is a well-known method to disrupt existing de-anonymization methods, such as the multiple-input or co-spent heuristics [11], and to complicate traceability of funds. In the early days of Bitcoin, centralized mixing services such as “Bitcoin Fog” or “Bitmixer” offered coin swapping. CoinJoin is a specific mixing method for combining transactions from multiple senders into one transaction [9], as illustrated in Figure 1. Centralized mixing services or decentralized mixing protocols are possible implementation strategies for CoinJoins. Early examples of decentralized mixing protocols making use of the CoinJoin technique include CoinShuffle [18], CoinShuffle++ [19], and ValueShuffle [17]. In a distributed setting, the challenge lies in coordinating participants and the input and output addresses they want to include in a CoinJoin transaction. By splitting outputs into a fixed set of standard denominations, which obscure the relationship between individual inputs and outputs, it is possible to improve user privacy on the network. Recently, CoinJoin has become an integral privacy feature of Bitcoin wallets like Wasabi or Samourai, which are the focus of our investigation.

2.2 Empirical Analysis of Mixing Services

Back in 2013, Möser et al. [14] analyzed transactions of three centralized mixing services. They already concluded that enforcement of the KYC principle appears unlikely if mixing services are involved. Later, Möser and Böhme [13] conducted a longitudinal measurement study of JoinMarket, an online market designed to match Bitcoin users wishing to participate in CoinJoin transactions. They [12] also studied second-generation mixing techniques not requiring users to trust in a single entity that might steal their coins. More recently, Pakki et al. [15] explored the Bitcoin mixer ecosystem and analyzed qualitatively how existing mixing services adopt academia’s proposed security features. Finally, Wu et al. [21] proposed a generic model for mixing services and a method for identifying mixing transactions and estimating the profit.

Our work continues and complements this line of research. It contributes two novel heuristics for detecting transactions and drawing a timely picture on two CoinJoin implementations that managed to bring that second-generation mixing technique closer to the end-user: Wasabi Wallet [4] and Samourai Wallet [5].

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4 https://github.com/zkSNACKs/WalletWasabi
5 https://github.com/Samourai-Wallet
Fig. 1: The basic idea of a CoinJoin transaction based on [9]. A regular Bitcoin transaction (left) represents a relationship between two users (A and B; C and D). A CoinJoin transaction (right) combines inputs signed by several users (A and C). It assigns values to outputs controlled by multiple distinct users (B and D). For a third party, it becomes increasingly complex to link the various outputs to individual users as the number of participants in a CoinJoin transaction increases.

Both are available as open-source software and backed by an active developer community.

2.3 Wasabi and Samourai Wallet

CoinJoins form the basis for the ZeroLink framework [9], which in turn serves as the foundation for both Wasabi and Samourai wallets. ZeroLink defines three conceptual wallets: a pre-mix wallet for unmixed coins, a post-mix wallet for mixed coins, and a mixing technique that moves coins from the pre-mix into the post-mix wallet. While ZeroLink is compatible with various on-chain mixing protocols, it also defines Chaumian CoinJoin [9] used by both Wasabi and Samourai. It allows participants to construct collaborative transactions via a central coordinator without revealing the links between the in- and outputs.

Wasabi Wallet provides an implementation of the Chaumian CoinJoin that supports a mix of multiple denominations in the same CoinJoin transaction, with 0.01 BTC being the lowest possible denomination. A coordinator fee of 0.003 * \(a\), where \(a\) is the target anonymity set, is charged for each transaction. Samourai’s implementation of the Chaumian CoinJoin, Samourai Whirlpool, does not support multi-denomination transactions but instead features four distinct pools with denominations of 0.001, 0.01 BTC, 0.05 BTC, and 0.5 BTC. Each Samourai Whirlpool transaction features exactly five inputs and five out-
puts. In summary, although both implementations are rooted in the same ZeroLink framework, they include different design alternatives and thus have been studied separately.

2.4 Existing Wasabi and Samourai Measurement Studies

Our approach builds on the initial work of Ficsőr, the creator of Wasabi, who analyzed transactions of both wallets to compute various metrics such as transaction volume. He published two GitHub repositories [3,4] intending to compare various statistics for both Wasabi and Samourai, such as the volume of CoinJoin transactions, the number of fresh CoinJoin inputs, the average count of remix inputs, fees paid by users, and estimation of coordinator income.

Wasabi wallet transactions initially used two static coordinator addresses to collect all fees, which made their detection relatively simple: a transaction is a Wasabi wallet CoinJoin if one of the static coordinator addresses is in the list of output addresses, and if there are at least three indistinguishable outputs with the same value. However, since January 2020, Wasabi wallet has generated new coordinator addresses for every CoinJoin, rendering the original heuristic obsolete. Ficsőr, therefore, published a new heuristic which categorizes transactions as Wasabi wallet CoinJoins if they feature at least ten outputs of equal value, the most common output value is equal to $0.02 \pm 0.02$ BTC, and if it features more inputs than outputs of the most frequent equal value.

Ficsőr also proposed a heuristic for detecting Samourai Whirlpool transactions: if the number of inputs and outputs is equal to 5 and all outputs have the same value, which must equal one of the Samourai Whirlpool pool sizes (0.01, 0.05, or 0.5 BTC) $\pm 0.0011$ BTC for [3] and $\pm 0.01$ BTC for [4], then a transaction can be categorized as Samourai wallet transaction. However, we found that this heuristic relies on simplified assumptions and identifies false positives, concretely 34 and 39 Samourai transactions in blocks mined before the introduction of Samourai.

Recently, Wu et al. [21] already included Wasabi CoinJoin transactions in their study. However, in contrast to analyzing historical transactions on the public ledger, they continuously queried the Wasabi coordinator API to retrieve ongoing CoinJoins. Gathered CoinJoins were then used as a seed to detect related transactions that generate anonymity sets using indistinguishable outputs of equal denomination. However, the proposed algorithm only considers outputs of the supplied seed and fails to consider historical transactions.

Furthermore, there has been little research on the embedding of CoinJoin transactions in the larger Bitcoin ecosystem. Therefore, in this work, we try to identify which entities conduct CoinJoin transactions either directly or are in the near vicinity of participants. For instance, if entity A sends coins to entity B which then participates in a CoinJoin. Where possible, we also try to label these entities as, e.g., exchanges or services. Furthermore, we look at the anonymity offered by the ZeroLink framework as well as usage patterns from users of Wasabi and Samourai wallets and investigate whether there are any fundamental weaknesses.
3 CoinJoin Detection Heuristics

We now propose novel heuristics to detect Wasabi and Samourai transactions and compare their accuracy to already known heuristics.

3.1 Wasabi

We first established a ground truth for evaluating our heuristics by extracting all Bitcoin transactions in the block range 1 to 609,999 (2019-12-27) that have one of the known static coordinator addresses identified by Ficsor (see Section 2.4) as output. While inspecting these transactions, we found that 73 transactions feature CoinJoin output values outside the allowed range for Wasabi Wallet, e.g., 0.05 BTC. We believe that these values were tests conducted by the developers of Wasabi to, for instance, determine how changing the minimum denomination of CoinJoins impacts the fees paid for by users. Furthermore, these transactions occurred between August and October 2018 (with a single occurrence in November 2018), supporting our hypothesis that these were test transactions. We have therefore decided to exclude transactions featuring these values from the ground truth data. In total, we keep 7333 Wasabi CoinJoin transactions, which we hereby use as ground-truth to evaluate the effectiveness of CoinJoin detection heuristics.

Next, we evaluated Ficsor’s second heuristic, which yields 2367 transactions that were not in our ground-truth dataset (false positives) as well as 7.325 ground-truth transactions that we correctly detected (true positives) and 8 not found transactions (false negatives). This outcome gives a relatively low precision of 0.756, a high recall of 0.999, and an F-1 score of 0.86. We want to improve the precision and reduce the number of false-positive transactions incorrectly flagged as Wasabi CoinJoins. We conducted an error analysis of false positives and made the following observations: first, we found that Ficsor’s heuristic does not consider that the fee collected by the coordinator is very likely to be distinct from any other output produced by the same transaction. Second, it does not reflect that every Wasabi CoinJoin transaction is likely to contain at least one CoinJoin output, one coordinator fee output, and one change output. These observations inform our Wasabi CoinJoin Detection heuristic, which is defined as follows:

\textit{Wasabi CoinJoin Detection Heuristic (WCDH)} If a transaction \( t \) has at least ten equal value outputs, with 0.1 ± 0.02 BTC being the most frequent one, and if it has at least three distinct output values with at least one being unique, and if it features at least as many inputs as occurrences of the most frequent output, then \( t \) is a Wasabi Wallet CoinJoin transaction.

Evaluation and Results We evaluated the effectiveness of our heuristics against the same benchmark found a precision of 0.824, a recall of 0.999, and an F-1 score of 0.899. Thus, an improvement in precision by 0.068 and reduced false positives from 2367 to 1567.
Wasabi and Samourai CoinJoins in the Bitcoin

|                          | Precision | Recall | F-1 Score |
|--------------------------|-----------|--------|-----------|
| Ficsor [4]               | 0.76      | 1.00   | 0.86      |
| WCDH                     | 0.82      | 1.00   | 0.90      |
| WCDH + Filtering Rules  | 0.98      | 1.00   | 0.99      |

Table 1: Effectiveness of Wasabi CoinJoin Detection Heuristics. Our Wasabi CoinJoin Detection Heuristics (WCDH) shows an improvement of 0.06 in precision, and 0.04 in F-1 score over Ficsor’s heuristic. By applying simple filtering rules, the effectiveness can be improved even further.

An error analysis of the remaining 1567 false positives has shown that we could further improve our results by applying some simple filtering rules:

1. Exclude transactions whose CoinJoin output addresses are used by known gambling services starting with 1Lucky or 1dice.
2. Exclude transactions that reuse input addresses as outputs. Reuse of addresses is strongly discouraged by the ZeroLink protocol and, therefore, should not occur in normal Wasabi Wallet transactions.
3. Output values which are exactly 0.08, 0.09, 0.1, 0.11, or 0.12 BTC. The exact values for CoinJoin outputs always feature a slight discrepancy, such precise values are therefore unlikely. We did not observe any such cases in our ground truth data set.
4. Output values which are between 0.08 - 0.085 and 0.115 - 0.12 BTC. While there is a slight discrepancy, such edge cases should again be unlikely, and we again did not observe any such cases in our ground truth data.

We applied these filters and found 153 false positives, 8 false negatives, and 7325 true positives. Table 1 shows the precision, recall, and F1-score values for our heuristic and how it compares to the heuristic proposed by Ficsör. This new heuristic resulted in a total of 25,070 Wasabi Wallet CoinJoin transactions from block 1 to block 689,255.

Our results show that applying a simple heuristic, which can automatically examine the inputs and outputs of atomic Bitcoin transactions, can effectively detect Wasabi CoinJoins with a precision of 0.82. Applying additional filter rules, which are hard to generalize and require manual investigations, can further increase precision. Also, the high recall shows that our Wasabi CoinJoin detection method hardly misses any relevant CoinJoin transactions.

3.2 Samourai

We cannot generate a ground truth data set in the same manner as we could for Wasabi because we lack a comprehensive set of known true positive transactions. However, we can safely assume that all transactions which occurred before block 570,000, which was the first block to feature Samourai Whirlpool transactions [4], are not related to Samourai and, therefore, false positives.
We evaluated both heuristics proposed by Ficsór \cite{3,4} against transactions in this block range and found 34 and 39 false positives, respectively. Analyzing these errors revealed that existing heuristics make inaccurate assumptions. While they correctly demand CoinJoins to feature exactly five inputs and five outputs, with the output values being uniform, they presume the output values to be within \( p \pm f \), where \( p \) refers to a pool-size, and \( f \) refers to a fee of 0.0011 BTC or 0.01 BTC. This assumption is incorrect, as Samourai output values are exactly equal to some specific pool size, while the inputs comprise 1 - 2 remix inputs, which are outputs of previous Whirlpool transactions and are therefore exactly equal to the respective pool size, and 3 - 4 premix inputs. Furthermore, these inputs are slightly higher than the pool size to pay for miner fees \cite{20}. Based on observation, we conclude that a Samourai Whirlpool transaction may contain up to 3 remix inputs. We build upon Ficsór’s heuristics and utilize 0.0011 BTC as a maximum added value for premix inputs to consider miner fees. These observations inform our Samourai CoinJoin Detection heuristic, which is defined as follows:

**Samourai CoinJoin Detection Heuristic (SCDH)** If a transaction \( t \) has exactly five uniform outputs that equal \( p \) BTC and if it has precisely five inputs, with at least one and at most three equal \( p \) BTC, while the remaining two to four inputs are between \( p \) and \( p + 0.0011 \) BTC, then \( t \) is a Samourai Whirlpool CoinJoin transaction.

**Evaluation and Results** Table \( 2 \) shows the results of our heuristic and how it compares to those proposed in \cite{3} and \cite{4}. It did not detect any false positives before block 570,000.

|                  | Block \# < 570,000 | Block \# \geq 570000 |
|------------------|-------------------|----------------------|
| Ficsor \cite{3}  | 34                | 134,626              |
| Ficsor \cite{4}  | 39                | 134,631              |
| SCDH             | 0                 | 134,569              |

Table 2: Number of false positives detected by our CoinJoin Detection Heuristics (SCDH) and previously proposed heuristics.

Our heuristics detected almost the same number of true positive Samourai CoinJoins as the heuristics proposed by Ficsór. However, it reduces the number of known false positives, allowing a more reliable detection.

**4 Empirical Analysis**

Building on the heuristics presented in the previous section, we now explore the role of both Wasabi and Samourai in the Bitcoin ecosystem. We first investigate how these services evolved over time (Section 4.1) and then analyze their interactions with other services (Section 4.2).
4.1 Longitudinal Analysis

**Number of transactions** Using our heuristics, we have identified 25,070 Wasabi and 134,569 Samourai CoinJoin transactions. For Wasabi, the average number of inputs per transaction is 79 with the average number of outputs being 128. For Samourai, every transaction has exactly 5 inputs and outputs. If we aggregate the number of transactions on a monthly basis, as shown in Figure 2a, we can see that two major Wasabi releases (v1.0 on 31.10.2018 and v1.1.10 on 14.12.2019) clearly affected adoption. Version v1.0 was the first stable release, so an increase in usage is to be expected, while version v1.1.10 featured a large number of changes, particularly regarding the UI and client side. Other major updates such as v.1.1.11, which added, among other features, multi-wallet support and the ability to set custom change addresses, seem to have no major adoption effect. For Samourai we see that transactions have also risen sharply around March 2020 and that the introduction of the 0.001 pool in March 2021, which should make CoinJoin more affordable, briefly led to a decline in the other pools. In general, we can observe higher use of smaller denomination (0.01, 0.001) pools, which is understandable because Samourai wallet users need more small than high denominations for assembling some target value. Interestingly, while the 0.5 BTC Samourai pool only makes up for 5.43% of Samourai transactions, it is responsible for 57.1% of the total Samourai output. Overall, we can observe a somewhat steady adoption of Wasabi since Nov 2018 and Samourai since Jan 2020. We can also see that Wasabi mixes more coins with fewer transactions than Samourai because it allows more input and output addresses in a single CoinJoin transaction.

**Mix outputs** Next, we are interested in the value of mixed Wasabi and Samourai coins in the Bitcoin ecosystem; i.e., coins which have been mixed and are not
used as remix inputs in subsequent CoinJoins. Figure 2b shows the amount of mixed BTC leaving the Wasabi and Samourai ecosystems and we can see that, for Wasabi, the amount of mixed BTC is rising steadily with a large spike in August and September 2019. This spike coincides with a spike in fresh inputs (see Figure 6 in Appendix A.1) and indicates that a large mix, which we cannot explain further, has taken place within that period. For Samourai, on the other hand, there is a spike within the 0.5 BTC pool in April and May 2020, followed by a drop and another increase in August 2020. The amount of BTC leaving the 0.01 and 0.05 BTC pools also increases steadily. In total, we found that the total value of mixed coins is $190,777.11$ BTC (ca. 3.02 B USD). Wasabi was used to mix $177,291.66$ BTC (ca. 2.71 B USD) and Samourai for $13,485.45$ BTC (ca. 311 M USD). Within recent months (Jan 2021 - Jun 2021), Wasabi users mixed on average $4563.11$ BTC (ca. 204.82 M USD), Samourai users $847.87$ BTC (ca. 35.32 M USD) per month.

4.2 Relations in the Bitcoin ecosystem

To understand the role of Wasabi and Samourai CoinJoins in the greater Bitcoin ecosystem, we analyzed their connections to other actors, such as cryptocurrency exchanges, via direct or indirect transaction relationships, as shown in Figure 3. First, we used GraphSense [8], which computes entities using the co-sent heuristic [10], to map all input and output addresses (Level 0) of CoinJoin transactions to entities. Since the heuristics joins addresses based on common input-ownership, it merges all input addresses of a CoinJoin transaction into a single entity, which does not represent a single actor but the participants of a CoinJoin. We denote entities that directly forwarded or received values from Wasabi or Samourai CoinJoins as Level 1 entities and all entities that are sending or receiving coins via two hops as Level 2 entities. Under the assumption that CoinJoins are filtered out, these entities typically represent clusters of addresses (wallets) controlled by some real-world actor (e.g., an exchange service).

Since large address clusters typically represent services [7] and service-to-service relations are not relevant for our analysis, we introduced the rule-of-thumb assumption that human users typically do not interact manually with more than 100 entities. Technically that means, that we stop traversal at entities with in- or out-degrees of more than 100 other entities. For attributing addresses and categorizing entities, we rely on openly available attribution tags retrieved from walletexplorer.com. Since these attribution tags cover fewer services than proprietary datasets (e.g., Chainalysis), we consider the following findings as lower-boundaries and point out that our analysis method is reproducible and easy to repeat with a more comprehensive attribution dataset. Table 3 summarizes the number of entities and types of services we identified at one and two hops away from the CoinJoin transactions that we identified previously.

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6 We converted BTC to USD using historic daily closing exchange rates retrieved from https://api.coindesk.com/v1/bpi/historical/close.json
Related entities and known services On the output side of CoinJoin transactions, we identified 376,535 distinct entities that forward coins via one hop and 557,834 entities that forwarded coins via two hops. Interestingly, we found 13 cryptoasset exchange services that accepted Wasabi transactions directly and 30 that accepted them via two hops. For Samourai, we found 8 direct relations and 16 services that accepted CoinJoin transactions via two hops. On the input side, we found that users of six cryptocurrency exchanges forwarded their funds from exchange-controlled hot wallets directly to Wasabi CoinJoin wallets or indirectly via two hops (16 for Wasabi / 8 for Samourai). In summary, we could identify a lower bound of 32 cryptoasset exchanges that accepted CoinJoin transactions from either Wasabi or Samourai wallets either directly or indirectly via two hops.

CoinJoin transactions received by exchanges To understand whether the direct and indirect relations between CoinJoin transactions and cryptoasset exchanges reflect the past or the present, we analyzed their evolution in terms of numbers and amounts of mixed BTC. For each CoinJoin output, we checked the shortest path between the output entity (level 0) to an entity categorized as exchange via one or two hops and summed up the values. As shown in Figure 4, we can clearly...
see almost linear growth in Wasabi and Samourai transactions that are directly accepted by exchanges and an even steeper rate on level 2, for both wallets. In total, we could pinpoint 7928 Wasabi and 1004 Samourai transactions that were directly accepted by exchanges and 36,439 and 1004 transactions that were accepted indirectly via two hops. In terms of mixed coins, this sums up to 1112.25 directly received BTC (ca. 15.23 M USD) and 5563 indirectly received BTC (ca. 80.59 M USD).

5 Anonymity Analysis

In this section, we analyze the anonymity loss suffered by users of Wasabi and Samourai wallets. Unlike in an ideal world where pre- and post-mixed addresses are fresh and unlinkable to any other, the traceability of addresses during the pre-mixing and post-mixing allows us to narrow down the anonymity set participating in the mixing. We also observe usage patterns during the mixing itself that harms anonymity. Finally, we present an upper bound on the number of outputs being mixed by each of the wallets throughout their lifetime.

Pre-mixed anonymity Using the entities provided by GraphSense (Section 4.2), we compute the number of Level-1 entities that transfer bitcoins into Samourai or Wasabi CoinJoins and we omit Level-0 entities since they do not represent distinct mixing participants (see Section 4.2). The results are shown in Figure 5a. For both of the wallets we observe that the number of distinct addresses is significantly narrowed down when clustering them into entities. This implies that the ideally large anonymity set of addresses is significantly reduced if they are not freshly used as input to Wasabi and Samourai. For instance, the possible anonymity set of almost 1M addresses in Jun’21 for Wasabi is largely reduced to less than 100K entities. We observe a similar reduction for Samourai.
Fig. 5: Comparison between number of addresses for Wasabi (\textcolor{red}{\textsquare}) and Samourai \textcolor{blue}{\textcircled{0}}, as well as their corresponding Level 0 (Wasabi \textcolor{red}{\textsquare}, Samourai \textcolor{blue}{\textcircled{0}}) and Level 1 (Wasabi \textcolor{red}{\textsquare}, Samourai \textcolor{blue}{\textcircled{0}}) entities.

Post-mixing anonymity

Similar to pre-mixing, the anonymity of the post-mixed addresses can be reduced depending on how they are used after they are mixed. For instance, if multiple post-mixed addresses can be linked to a single entity, the anonymity set gained during the mixing process is totally lost. The effect is even more severe because all participants of the mixing suffer since their anonymity set is also reduced by the number of mixed outputs linked to this entity.

Figure 5b shows the relation between post-mixed addresses in Wasabi and Samourai and the number of Level-0 and Level-1 entities computed as explained in Section 4. As with the pre-mixing case, we observe that the anonymity set of post-mixed addresses is significantly narrowed down to a smaller number of entities. For instance, the almost $1M$ addresses anonymized with Wasabi wallets by Jun’21 can be linked to about $100K$ entities when considering Level 0 and Level 1 entities.

Anonymity loss during mixing

The anonymity set of an output increases by having it being an input of other CoinJoin transactions (i.e., a remix input). Conversely, if a CoinJoin exclusively features fresh inputs, i.e. no remix inputs, its anonymity set is only as big as the number of its inputs. The importance of remix inputs is such that the design of Samourai CoinJoins mandates that every CoinJoin features at least one remix input (other than initial Genesis mixes).

However, Wasabi wallet does not require remix inputs. In fact, we detect 97/25,070 transactions do not feature any remix inputs. This adds to the misperception of anonymity given by Wasabi wallets because these transactions only provide the anonymity of a single mix (instead of the anonymity of several intertwined mixers). This should prompt users that find their addresses in such transactions, to remix them as soon as possible.
**Estimating number of mixing outputs** So far we have focused on addresses in our study of anonymity. However, since each input address might have an arbitrary number of bitcoins, in this section we narrow our study to the number of outputs of the same denomination that are being used for mixing in Wasabi and Samourai. For that, we first compute the number of bitcoins that are being actively mixed at each point of time (i.e., bitcoins added to the wallet until time $t$ minus the number of bitcoins withdrawn until time $t$). We denote this quantity by $\alpha_t$. Figure 7b in Appendix A.2 shows the concrete results for both wallets.

Second, since Samourai features a single denomination $\beta$ per pool, the number of coins being mixed at such pool is simply $\alpha_t/\beta$. The result is shown in Figure 7a in Appendix A.2. Given that in Wasabi there exist several denominations within the same pool, we consider the two extreme cases, where all participants use either (i) the maximum denomination $\beta_{\text{max}}$; or (ii) the minimum denomination. Following, the same reasoning as with Samourai, we establish the number of distinct outputs as $\alpha_t/\beta_{\text{max}}$ and $\alpha_t/\beta_{\text{min}}$, establishing thereby two upper bounds in the number of participants in Wasabi.

6 Concluding Remarks

Wasabi and Samourai offer privacy-behind-the-scenes via decentralized CoinJoin to users and are, as our results show, an integral part of the Bitcoin ecosystem since Nov 2018. We have shown that it is possible to pinpoint CoinJoin transactions using relatively simple heuristics effectively and analyze coin flows from and to services involved in CoinJoin transactions either directly or indirectly. Our analysis also reveals 190,777.11 mixed coins with a total value of ca. 3.02 B USD in the past and a mixing throughput of around 5410.98 BTC or ca. 240.14 M USD within recent months. Furthermore, by attributing services on the input and output side of CoinJoin transactions, we found a lower bound 32 exchanges that received coins from these wallets via one or two hops. Surprisingly, the amount of accepted CoinJoin transactions and mixed BTC are growing steadily despite increasingly tightening Anti-Money-Laundering (AML) regulations. These regulatory efforts demand traceability of funds, which opposes the design goal of decentralized mixing services like Wasabi or Samourai.

CoinJoin transactions and software facilitating them are a double-edged sword, and the implications of our work very much depend on the perspective.

For privacy-seeking end users, wallets like Wasabi and Samourai are a practical, low-entry barrier solution to Bitcoin’s anonymity problem. While it is, to the best of our knowledge, hardly possible to de-mix CoinJoins produced by these wallets, users should be aware that the use of such services is visible on-chain and that cryptoasset tracing and tracking solutions can detect them. Also pre-mixed and post-mixed addresses can be tracked, effectively reducing the anonymity guarantees provided by these mixing wallets. On the other hand, stricter regulations could require users to clearly explain the origin of their coins if they want to cash out coins at an AML-compliant exchange. Of course, this is more difficult to explain when CoinJoins are involved.
For cryptoasset exchanges our findings show that automatically detecting CoinJoin transactions created by two popular wallets is easily possible with relatively simple heuristics. Our results show that the number of transactions and mixed coins accepted is still growing from which we can infer that acceptance of CoinJoins currently does not yet raise compliance issues, at least for the exchanges in our dataset, three of them ranking in the top 15 by 24h trading volume.7 However, that may change when the AML compliance rules, which apply to traditional financial service providers, are also enforced in the cryptocurrency area.

For regulatory bodies our results provide insight into the current use of two popular mixing services preventing traceability of funds. One could even imagine to apply similar procedures to monitor adoption of AML compliance in cryptoassets ecosystems without invading users’ privacy. We also point out that imposing the traceability-of-funds requirement on cryptoasset exchanges essentially demands CoinJoins not to be part of a coin’s lineage. In the long run, this might discourage users from using tools that protect their fundamental right to privacy in a completely transparent financial ecosystem.

The empirical results reported herein should be considered in the light of some limitations. First, while we could evaluate our Wasabi CoinJoin detection heuristics against a strong ground-truth, we still miss a curated collection of known Samourai transactions for block ranges beyond 570,000. Thus, even though our results align with Ficsór, we cannot yet rule out false positives. Manually executing Samourai transactions to build up a more comprehensive ground truth and tracing the lineage of Samourai transactions to their genesis mix are possible strategies to improve that heuristic further. Furthermore, Ficsór et al. have recently published a generalization of the Chaumian CoinJoin named WabiSabi. WabiSabi serves as the basis for Wasabi Wallet 2.0, which is currently under development and is expected to be released in 2021. It offers, among other features, support for arbitrarily variable CoinJoin amounts. This is expected to severely limit the effectiveness of our proposed WCDH heuristic. Second, we point out that our attribution dataset is incomplete and that the numbers reported in our ecosystem analysis are lower-bounds. However, our analysis is easily reproducible with a more comprehensive attribution tag dataset, and it is even possible to name the involved exchanges, which we refrain from for ethical reasons. Therefore, another possible future direction is to run our analysis with a more comprehensive attribution tag dataset to obtain a complete picture of mixing activities in the Bitcoin ecosystem, make informed decisions, and assess compliance with AML regulation.

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7 https://coinmarketcap.com/rankings/exchanges/
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A Appendix

A.1 Fresh inputs

As with mix outputs, we can also compare the fresh inputs for both services
by analyzing CoinJoin inputs that are not the outputs of previous CoinJoins in
order to find fresh inputs entering either Wasabi or Samourai. Figure 6 shows
the development of fresh inputs for Wasabi and all Samourai pools. For Wasabi,
there are three separate spikes in fresh inputs: November 2018 - January 2019,
August & September 2019, and March/April 2020. Adjusting for a fluctuating
BTC price, however, flattens out the first and third spike, while the increase in
August/September 2019 remains. This is in line with the spike in mixed outputs
leaving Wasabi. For Samourai, the amount of fresh BTC co-evolves very closely
to the amount of mixed outputs with a steady increase in the 0.01 and 0.05 BTC
pools, and similar spikes in the 0.5 BTC pool.
Fig. 6: Amount of fresh BTC entering Wasabi and Samourai, as well as the 0.001, 0.01, 0.05, and 0.5 BTC pools, per month from July 2018 to July 2021.

A.2 Mixing outputs

Figure 7 represents the study of the estimated number of outputs in regards to coin anonymity, as well as the number of bitcoins present in the mixing process for both Wasabi and Samourai over time. As Wasabi uses multi-denomination CoinJoins we have estimated an upper and lower bound by dividing the number of coins by the lowest and highest available denomination for every CoinJoin transaction.
Fig. 7: Study of the amount of outputs as well as bitcoins used in Wasabi (lowest & highest denomination) and Samourai mixing, including the 0.0001, 0.001, 0.005, and 0.5 BTC pools, over time.