KeyJoin: Privacy-Focused CoinJoin Protocol for Bitcoin

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Abstract

Bitcoin is based on the Blockchain, an open ledger containing information about each transaction in the Bitcoin network. Blockchain serves many purposes, but it allows anyone to track all transactions and activities of each Bitcoin address. The privacy of the network is being threatened by some organizations that track transactions. Tracking and subsequent filtering of coins lead to the loss of exchangeability of Bitcoin.

Despite Bitcoin's transparency, it is possible to increase user privacy using a variety of existing methods. One of these methods is called CoinJoin, was proposed by Bitcoin developer Greg Maxwell in 2013[1]. This technology involves combining several users transactions to create a single transaction with multiple inputs and outputs, which makes transaction analysis more complicated.

This work describes the KeyJoin, a privacy-focused CoinJoin protocol based on the keyed-verification anonymous credentials (KVAC).

1 Introduction

Bitcoin uses the funds of previous transactions (UTXO)[2] as inputs in subsequent transactions [Nak09]. Bitcoin's rules ensure the impossibility of coin inflation and double-spending but openly transmits all the information about the amounts, inputs and outputs as part of the transaction. Because of this, it becomes impossible to make a transaction privately.

The prevention of double spending and supply control is the main requirements for cryptocurrencies, which is achieved in Bitcoin by decentralized system. This approach had an advantage over earlier methods of ensuring security and anonymity in e-cash [DFT+97].

Privacy issues affect Bitcoin users, making them vulnerable because it is technically difficult to resist on-chain tracking and analysis. [Rog15]. Even using one-time Bitcoin addresses, which is widespread [GLL18], some information about transactions will still be publicly available. This makes it practical to cluster the output data according to heuristic methods [HF16], with public reusable addresses of certain companies or people. Exchanges that comply with regulatory requirements (KYC/AML) must additionally collect and store information that links Bitcoin transactions to a specific person.

The spending conditions of an output are specified in its `scriptPubKey`, typically requiring that the transaction using this output is signed by a particular key. The signatures confirming transaction authorization are usually responsible for the entire transaction, which makes it possible for parties to create transactions jointly without the risk of incorrect outputs: participants will sign the transaction only after ensuring that their outputs are included, and the transaction is valid only when all parties have signed it.

1.1 KeyJoin

KeyJoin is a CoinJoin protocol based on the KVAC scheme [CPZ19] (introduced in [CMZ14]). The KVAC scheme uses homomorphic value commitments, similar to Confidential Transactions [Max16], when the sum of the output values does not exceed the sum of input values, and when all the values are hidden from the coordinator. KeyJoin builds on a proven approach to ensuring anonymity [DM06].

KeyJoin can be used to construct various CoinJoin transaction models. The use of this technology increases the anonymity of the sender and recipient of the CoinJoin transaction and the values will be entangled with each other, making it ineffective to analyze such transactions. CoinJoin transactions can reduce overall blockspace utilization by reducing the number of single transactions.

[1] See: `https://bitcointalk.org/?topic=139581` and `https://bitcointalk.org/?topic=279249`

[2] UTXO - Unspent transaction output

2 Background

In this section, we provide an introduction to Bitcoin privacy issues and proposals to enhance transaction privacy. We describe the current Bitcoin privacy issues and motivate this work.

2.1 Privacy issues and CoinJoin

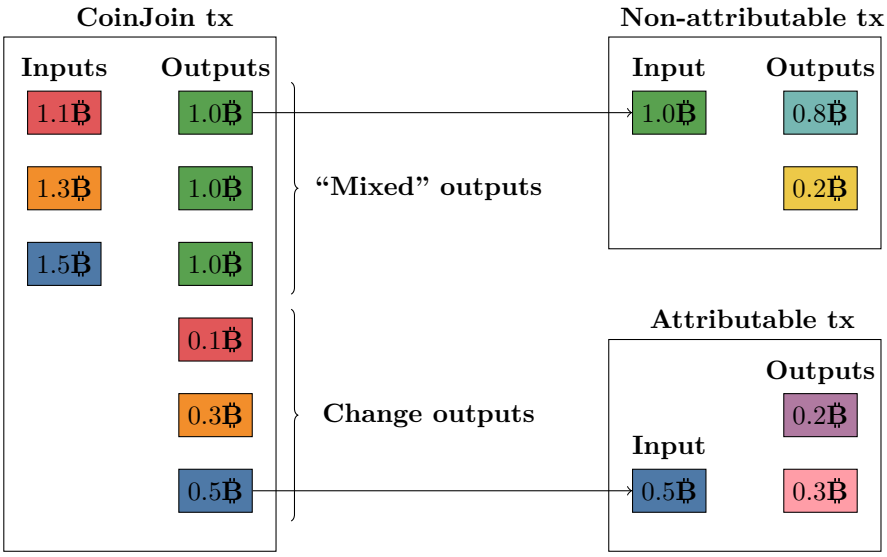


Figure 1: A simple CoinJoin transaction and two post-mix transactions. Privacy-enhanced outputs are colored green. Each of them improved their k-anonymity ($k = 3$). Change outputs have the color of their corresponding inputs. Arrows indicate which transaction output has been spent by the referencing transaction input. The payer of the first post-mix transaction is non-attributable. However, the payer of the second post-mix transaction is easily linkable to the third input of the CoinJoin transaction, since the post-mix transaction spends a change output of the CoinJoin transaction. Coins are only represented by their BTC (₿) value. For simplicity, transaction fees are omitted.

Bitcoin is a pseudonymous cryptocurrency [Nak09]: coins are associated with so called addresses, which encode the spending conditions of the coin (their `scriptPubKey`). Bitcoin transactions spend coins as inputs and create new coins output in place of the spent ones. The Bitcoin protocol mandates the rules of a valid transaction (no double-spending, valid signatures, etc.), which is verified by all nodes of the network. Since every transaction is recorded in a public ledger, the flow of money is traceable. Several idioms of use allow one to cluster addresses likely to be controlled by the same user. Many heuristics were devised in previous work [MPJ+13; AKR+13; RH13; RS13]. The most commonly used heuristic to cluster Bitcoin addresses is the *common input ownership heuristic*. It states that in any Bitcoin transaction, all the inputs are likely controlled by the same user. This heuristic already facilitates a fine-grained clustering of Bitcoin addresses, with high accuracy[Nic15].

CoinJoin transactions aim to contradict to the common ownership heuristic, because multiple users collaboratively create the transaction. There are several types of privacy-enhancing techniques in Bitcoin, e.g. PayJoin[3], CoinSwap [Bel20]. However, in this work, we solely focus on CoinJoin. In an equal-amount CoinJoin transaction (see fig. 1) each user contributes at least one input and receives at least one output with the same amount as the other users. Assuming the output types are uniform individual outputs differ only in the keys associated with them, which are indistinguishable from uniformly random data. Consequentially it is not possible to link inputs to specific mixed outputs. The privacy of such outputs can be modeled using k-anonymity [Swe02] with amounts and script types as quasi-identifiers, but this analysis becomes rather complicated in a broader context than that of a single transaction in isolation because the graph structure can reveal additional information.

3 Preliminaries

Hereby we give an informal and high-level description of applied cryptographic primitives. In the following, the security parameter is denoted as λ.

[3]See: `https://en.bitcoin.it/wiki/PayJoin`

3.1 Commitment schemes

A commitment scheme allows one to commit to a chosen message while preventing them from changing the message after publishing the commitment. Secure commitments hide the chosen message until they are opened. We assume Pedersen commitments throughout this work.

$\mathsf{Commit}(m, r) \mapsto \mathcal{C}$**:** generate a commitment $\mathcal{C}$ to message m using randomness r.

$\mathsf{OpenCom}(\mathcal{C}, m, r) \mapsto \{True, False\}$**:** verify the correctness of the opening of a commitment by checking $\mathcal{C} \stackrel{?}{=} \mathsf{Commit}(m, r)$. If equality holds the algorithm outputs *True*, otherwise *False*.

3.2 MAC

A message authentication code (MAC) ensures the integrity of a message and consists of the following three probabilistic polynomial-time algorithms:

$\mathsf{GenMACKey}(\lambda) \mapsto \mathsf{sk}$**:** generate a secret key sk for MAC generation and verification.

$\mathsf{MAC}_{\mathsf{sk}}(m) \mapsto t$**:** generate a tag t on a message m using secret key sk.

$\mathsf{VerifyMAC}_{\mathsf{sk}}(m, t) \mapsto \{True, False\}$**:** verify that tag t is valid for message m using secret key sk.

One might intuitively think of a MAC as the symmetric-key counterpart of digital signatures. They both have the same goals and similar security requirements, however a MAC requires a secret rather than public key to verify.

3.3 Zero-knowledge proofs of knowledge

A very high-level, and hence somewhat imprecise, description of zero-knowledge proofs is provided. This protocol involves a prover and a verifier. A prover wishes to prove that a relation $\mathcal{R}$ holds with respect to a secret input w, called witness, and public input x. Specifically, the prover wants to prove that $(x, w) \in \mathcal{R}$ without revealing anything about w.

$\mathsf{Prove}_{\mathcal{R}}(x, w) \mapsto \pi$**:** Given x and the private witness w the prover generates a proof π. For the specific outputs of Prove we use the notation of [CS97], with the witness and statement: $\pi = \mathrm{PK}\{(w) : (x, w) \in \mathcal{R}\}$.

$\mathsf{Verify}_{\mathcal{R}}(x, \pi) \mapsto \{True, False\}$**:** The verifier is given the proof π and x with which they determine whether the prover knows a secret w such that $(x, w) \in \mathcal{R}$ holds.

4 System model

In this section, we introduce our system model. We present the participants of our mixing protocol. Subsequently, we describe our communication and threat models along with our high-level goals.

4.1 Participants

There are four components of the KeyJoin system: the users, the coordinator, the anonymity network nodes and the Bitcoin peer-to-peer (P2P) network nodes.

User Numerous users wish to enhance their transaction privacy by collaboratively creating a CoinJoin transaction. Each of them registers at least one input and output in an unlinkable manner.

Coordinator To avoid quadratic communication-complexity in the number of users [RMK14], we apply a central, untrusted coordinator. The coordinator aids users in creating their CoinJoin transaction. The coordinator stores registered inputs and outputs. At last, it serves users with the final CoinJoin transaction for signing. Users sign the final transaction if and only if all of their registered input and outputs are contained in the transaction.

Anonymity network nodes Users need to communicate with the coordinator in an unlinkable fashion. To that end, we apply onion-routing [RSG98]. Users send messages to the coordinator using a path consisting of multiple intermediary anonymity network nodes. Each anonymity network node only knows her preceding and succeeding destination along the path. Therefore, the coordinator cannot link users to a specific request or output registration.

Bitcoin P2P network nodes Typically users do not run Bitcoin full nodes. Therefore, they rely on other full nodes to serve them necessary data from the Bitcoin blockchain. For instance, users invoke full nodes whenever they verify the inclusion of a CoinJoin transaction in the blockchain or query their own balance. Note, that for the sake of privacy, these queries needs to be made unlinkable as well.

4.2 Communication model

We assume all messages (onion-routed messages, broadcast transactions, queries about the blockchain) are delivered with a maximum delay under the bounded synchronous communication setting [AW04]. Furthermore, we assume all actors can access and read the current head of the blockchain to verify if transactions are appended to the blockchain. We remark that these are standard assumptions in the blockchain literature [BMT+17].

4.3 Threat model

We assume that the cryptographic primitives (see § 3) are secure. Specifically, we assume that the discrete logarithm is hard in the underlying group, as well as the validity of the random oracle model for hash functions. We further assume that adversaries are computationally bounded and can only corrupt at most $\frac{1}{3}$ of the consensus participants of the blockchain. We assume that users can always read the blockchain state and write to the blockchain. Also, we assume that the adversary can always read all transactions issued, while the transactions are propagating on the P2P network, and afterwards when they are written to the blockchain. We assume that the coordinator remains available throughout the entire mixing protocol. Last but not least, we presume that in case of onion-routed messages for network privacy, at least one intermediary on the source-routed path is not controlled by the adversary, i.e. users can achieve network-level privacy.

4.4 High-level goals

We state informally our desired security and privacy goals.

Availability An ideal CoinJoin protocol should remain secure and should eventually complete successfully even if certain mixing participants are malicious or off-line.

Unlinkability KeyJoin users aim to create outputs in a CoinJoin transaction, that have enhanced transaction privacy than their corresponding inputs.

Theft prevention Mixing participants should not be able to obtain more funds from the CoinJoin transaction than they are rightfully entitled to.

Performance We aim to create a high performance mixing protocol that supports computationally or bandwidth constrained users.

We remark that we consider network-level privacy as given. It can be achieved by using, for example, onion-routing [RSG98] or mix-networks [PHE+17].

5 Protocol overview

In this section, we provide a high-level overview of the KeyJoin protocol.

5.1 Phases

A CoinJoin round consists of an Input Registration, an Output Registration and a Transaction Signing phase. To defend against Denial of Service attacks it is important to ensure the inputs of users who do not comply with the protocol are identified so these inputs can be excluded from the following rounds in order to ensure completion of the protocol.

1. While identifying non-compliant inputs during Input Registration phase is trivial, there is no reason to issue penalties at this point.
2. Identifying non-compliant inputs during Output Registration phase is not possible, thus this phase always completes and progresses to the Signing phase.
3. During Signing phase, inputs which are not signed are non-compliant inputs, and they shall be issued penalties.

The protocol ensures that if the coordinator is honest the transaction would be valid once signed and honest participants would always agree to sign the final CoinJoin transaction as it would not misallocate their funds. Anonymous credentials allow the coordinator to verify that amounts of each user's output registrations are funded by input registrations without learning specific relationships between inputs and outputs.

5.2 Credentials

The coordinator issues anonymous credentials [Bra94; Bra00; BL13] which authenticate attributes in response to registration requests. We use KVAC, specifically the scheme from [CPZ19] which supports *group attributes* (attributes whose value is an element of the underlying group $\mathbb{G}$). A user can then prove possession of a credential in zero-knowledge in a subsequent registration request, without the coordinator being able to link it to the registration from which it originates.

In order to facilitate construction of a CoinJoin transaction while protecting the privacy of participants, we instantiate the scheme with a single group attribute M_a which encodes a confidential Bitcoin amount as a Pedersen commitment. These commitments are never opened. Instead, properties of the values they commit to are proven in zero-knowledge, allowing the coordinator to validate requests made by honest participants. In ideal circumstances, the coordinator would not learn anything beyond what can be learned from the resulting CoinJoin transaction but despite the unlinkability of the credentials timing of requests or connectivity issues may still reveal information about links.

5.3 Registration

To aid intuition we first describe a pair of protocols, where credentials are issued during input registration, and then presented at output registration. k denotes the number of credentials used in registration requests, and $a_{max} = 2^{51} - 1$ constrains the range of amount values[4]. For better privacy and efficiency, these are then generalized into a unified protocol used for both input and output registration, where every registration involves both presentation and issuance of credentials. This protocol is described in detail in § 6.

In order to maintain privacy clients must isolate registration requests using unique network identities. A single network identity must not expose more than one input or output, or more than one set of requested or presented credentials.

For fault tolerance, request handling should be idempotent, allowing a client to retry a failed request without modification using a fresh network identity, or one which was previously used to attempt that request (the same network identity should not be associated with more than one input or output).

5.3.1 Input Registration

The user submits an input of amount a_{in} along with k group attributes, (M_{a_i}). She proves in zero-knowledge that the sum of the requested sub-amounts is equal to a_{in} and that the individual amounts are fall within in the allowed range.

The coordinator verifies the proofs, and issues k MACs on the requested attributes, along with a proof of correct generation of the MAC, as in *Credential Issuance* protocol of [CPZ19].

1. The user sends k credential requests with accompanying range and sum proofs to the coordinator: $((M_{a_i}, \pi_i^{range})_{i=1}^k, \pi^{sum}, a_{in})$.
2. The coordinator verifies the received proofs. If they are not verified it aborts the protocol, otherwise it issues k MACs on the requested attributes $(\mathsf{MAC}_{\mathsf{sk}}(M_{a_i}), \pi_i^{\text{iparams}})_{i=1}^k$.

Figure 2: Input Registration protocol

5.3.2 Output Registration

To register her output the user randomizes the attributes and generates a proof of knowledge of k valid credentials issued by the coordinator.

Additionally, she proves the serial number is valid. These serial numbers are required for double-spending protection and must correspond but unlinkable to a specific M_a.

[4] $\log_2(2099999997690000) \approx 50.9$

Finally, she proves that the sum of her randomized amount attributes C_a matches the requested output amount a_{out}, analogously to input registration.[5]

She submits these proofs, the randomized attributes, and the serial numbers. The coordinator verifies the proofs, and if accepted the output will be included in the transaction constructed by the coordinator.

1. The user sends k randomized commitments, a proof of a valid MAC for the corresponding non-randomized commitments, serial numbers with a proof of their validity, and finally a proof of the sum of the amounts: $((C_{a_i}, \pi_i^{MAC}, S_i, \pi_i^{serial})_{i=1}^k, \pi^{sum}, a_{out})$.
2. The coordinator verifies proofs and registers requested output iff. all proofs are valid and the serial numbers have not been used before.

Figure 3: Output Registration protocol

5.3.3 Unified Registration

In order to increase flexibility in a dynamic setting where a user may not yet know her desired output allocations during input registration, and to allow setting a small[6] value of k as a protocol level constant (ensuring that requests are uniform) we can generalize input and output registration into a single unified protocol for use in both phases, which also supports reissuance. For complete definitions see § 6.

1. During both input and output registration phases the user submits:
   - k credential requests with accompanying range and sum proofs to the coordinator: $(M_{a_i}, \pi_i^{range})_{i=1}^k$
   - k randomized commitments, proofs of valid credentials issued for the corresponding non-randomized commitments, serial numbers, and proofs of their validity: $(C_{a_i}, \pi_i^{MAC}, S_i, \pi_i^{serial})_{i=1}^k$
   - A balance Δ_a and a proof of its correctness π^{sum}
   - If $\Delta_a \neq 0$, an input or output with value $|\Delta_a|$.
2. The coordinator verifies the received proofs, and that the serial numbers have not been used before, and depending on the current phase, $\Delta_a \geq 0$ (input) or $\Delta_a \leq 0$ (output). If it accepts, it issues k MACs on the requested attributes $(\mathsf{MAC}_{\mathsf{sk}}(M_{a_i}), \pi_i^{\text{iparams}})_{i=1}^k$, and if $\Delta_a \neq 0$, registers the input or output with value $|\Delta_a|$.

Figure 4: Unified Registration protocol

The user submits k valid credentials and k credential requests, where the sums of the underlying amount commitments must be balanced (fig. 4).

1. During input registration phase the user submits k credential requests: $(M_{a_i}, \pi_i^{null})_{i=1}^k$
2. The coordinator verifies the received proofs. If it accepts, it issues k MACs on the requested attributes $(\mathsf{MAC}_{\mathsf{sk}}(M_{a_i}), \pi_i^{\text{iparams}})_{i=1}^k$.

Figure 5: Credential bootstrapping protocol

To prevent the coordinator from being able to distinguish between initial vs. subsequent input registration requests (which may merge amounts) credential presentation should be mandatory. Initial credentials can be obtained with an auxiliary bootstrapping operation (fig. 5). A more sophisticated approach would be to prove either knowledge of a valid MAC or that the amount attribute has a value of zero, but because the

[5] Note that there is no need for range proofs since amounts have been previously validated.

[6] Specifically, $2 \leq k \leq 10 \approx \log_2\left(\frac{\texttt{MAX\_STANDARD\_TX\_WEIGHT}-58}{274+124}\right)$ the maximum number of participants, because although $k = 1$ suffices for flexibility it limits parallelism, leaking privacy by temporal fingerprinting. The limit on participant count is because 274 and 124 are the minimum weight units required for a participant with only a single input and output, and 58 is the shared per transaction overhead.

input registration phase starts synchronously when enough users have indicated their intent to participate this would not actually save a round trip in practice.

5.4 Signing phase

The user fetches the finalized but unsigned transaction from the coordinator. If it contains her registered outputs she will sign her inputs and submit each signature separately using the network identity used for the corresponding input's registration.

5.5 Examples

To illustrate the above protocols, figs. 6a and 6b show how a user might register inputs and outputs with the simplified protocols, where credentials are only requested at input registration and presented at output registration. Figures 6c and 6d show the unified protocol, when credentials are both presented and requested in every request.

Input and output registrations are depicted as vertices labelled by $|\Delta_a|$, with a double stroke denoting output registrations. A credential is an edge from the registration in which it was requested to the registration where it was presented, also labelled with the amount. The vertex's label must be equal to the balance of the labels of its incoming edges and its outgoing edges. Note that edges and their labels are only known to the owners of the credentials. For simplicity, we omit credentials with zero value.

In fig. 6a Alice first registers an input of amount 10 and requests 2 credentials with amount 7 and 3 in a single input registration request. At the output registration phase, Alice, with a different network level identity registers one output with each.

The flexibility of the credential scheme allows to achieve the same outputs originating from multiple different inputs. For instance, in fig. 6b Alice registers 2 inputs (with different network identities) of value 6 and 4. The input of value 4 is broken up to 2 credentials of value 1 and 3. At output registration Alice then combines her credentials of value 6 and 1 to be able to register an output (with yet another network identity) of value 7. Note that individual credential amounts are not known to the coordinator, which only learns their sum.

In the unified protocol at every step users must request as well as present credentials. Alice begins by obtaining bootstrap credentials (credentials with a 0 amount) in order to be able to make her first input registration. The example in fig. 6c achieves the same results as fig. 6b, but utilizes the credentials differently. At input registration Alice first obtains a credential with value 6, and then presents it in her next input registration for the input valued 4.

The most interesting application of the credential system is presented in fig. 6d. Here Alice begins by registering her inputs as in fig. 6c. Another user, Bob, also obtains bootstrap credentials, but does not register an input of his own at this point. Alice and Bob can then communicate out of band, with Alice giving Bob the credential valued 7, which he then presents when registering his own input worth 4, effectively receiving a privacy enhanced payment of 7 from Alice. Note that in this last example Alice must ask Bob before signing during the final phase to ensure her funds were allocated as intended, and Bob must trust Alice to provide him with a valid credential, and cannot verify its validity without presenting it to the coordinator[7].

6 KeyJoin Credentials

In this section we provide the details of the unified protocol (§ 5.3.3) and its use of the KVAC scheme introduced in [CPZ19]. Following that work, our protocol is defined over an Abelian group $\mathbb{G}$ of prime order q, written in multiplicative notation. $\mathsf{HashTo}\mathbb{G} : \{0,1\}^* \mapsto \mathbb{G}$ is a function from strings to group elements, based on a cryptographic hash function [FT12].

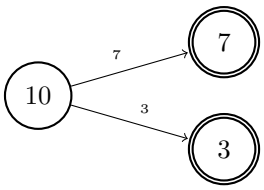
We require the following fixed set of group elements for use as generators with different purposes:

$$\underbrace{G_w, G_{w'}, G_{x_0}, G_{x_1}, G_V}_{\text{MAC and Show}} \qquad \underbrace{G_a}_{\text{attributes}} \qquad \underbrace{G_g, G_h}_{\text{commitments}} \qquad \underbrace{G_s}_{\text{serial numbers}}$$

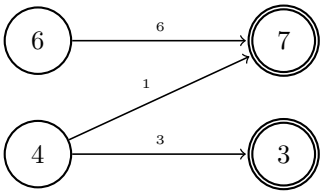
chosen so that nobody knows the discrete logarithms between any pair of them, e.g. $G_h = \mathsf{HashTo}\mathbb{G}(\text{“}\mathtt{h}\text{”})$.

Our notation deviates slightly from [CPZ19], in that we subscript the attribute generators G_{y_i} as G_a instead of using numerical indices, and we require two additional generators G_g and G_h for constructing the attribute M_a as a Pedersen commitment. As with the generator names, we modify the names of the attribute related components of the secret key $\mathrm{sk} = (w, w', x_0, x_1, y_a) \in_R \mathbb{Z}_q^5$.

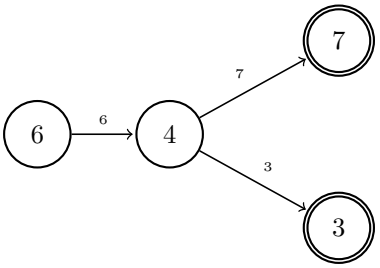
[7] For publicly verifiable credentials the scheme in [BL13] can be substituted for [CPZ19] with relatively minor changes to the proofs.



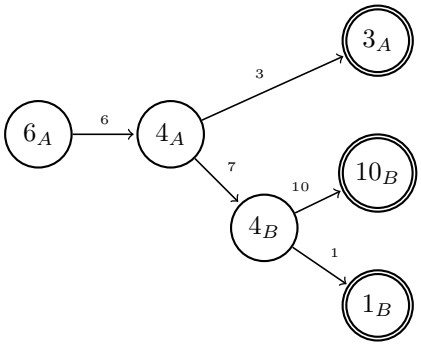
(a) Alice wants to spend an input of amount 10 and create two outputs with amounts 7 and 3 (e.g. a payment and change)



(b) Alice wants to combine her inputs of amounts 6 and 4 and register two outputs as in fig. 6a.



(c) Alice wants to spend two inputs and register two outputs using the unified protocol, which allows her to present the credential from her first input registration when registering her second input to combine the amounts.



(d) Alice wants to pay Bob, who is also participating in the protocol. Alice combines her amounts at input registration and reveals a credential corresponding to the payment amount to Bob. Bob presents this credential in his own input registration. Alice registers a change output, and Bob registers two outputs. Only Alice knows the details of the request in which the credential labeled 7 was issued and only Bob knows where it was presented, but both know the amount.

Figure 6: Credential usage examples

The coordinator parameters $iparams = (C_W, I)$ are computed as:

$$C_W = {G_w}^w {G_{w'}}^{w'} \quad I = \frac{G_V}{{G_{x_0}}^{x_0} {G_{x_1}}^{x_1} {G_a}^{y_a}}$$

and published as part of the round metadata and are used by the coordinator to prove correctness of issued MACs, and by the users to prove knowledge of a valid MAC.

6.1 Credential Requests

For each $i \in [1, k]$ the user chooses an amount $a_i \mid 0 \leq a_i < a_{max}$ subject to the constraints of the balance proof (§ 6.5). She commits to the amount with randomness $r_i \in_R \mathbb{Z}_q$, and these commitments are the attributes of the requested credentials:

$$M_{a_i} = {G_h}^{r_i} {G_g}^{a_i}$$

For each amount a_i she also computes a proof that the amounts are in the allowed range, which ensures that finite field arithmetic will not overflow and the values will behave like positive integers when added or subtracted:

$$\pi_i^{range} = \mathrm{PK}\left\{(a_i, r_i) : M_{a_i} = {G_h}^{r_i} {G_g}^{a_i} \wedge 0 \leq a_i < a_{max}\right\}$$

In credential bootstrap requests the range proofs can be replaced with simpler proofs of $a_i = 0$:

$$\pi_i^{null} = \mathrm{PK}\left\{(r_i) : M_{a_i} = {G_h}^{r_i}\right\}$$

6.2 Credential Issuance

If the coordinator accepts the requests (see §§ 6.3 to 6.5), it registers the input or output if one is provided, and for each $i \in [1, k]$ it issues a credential by responding with $(t_i, V_i) \in \mathbb{Z}_q \times \mathbb{G}$, which is the output of

$\mathsf{MAC}_{\mathsf{sk}}(M_{a_i})$, where:

$$t_i \in_R \mathbb{Z}_q \qquad U_i = \mathsf{HashTo}\mathbb{G}(t_i) \qquad V_i = {G_w}^w {U_i}^{x_0+x_1 t_i} {M_{a_i}}^{y_a}$$

To rule out tagging of individual users the coordinator must prove knowledge of the secret key, and that (t_i, U_i, V_i) are correct relative to $iparams = (C_W, I)$:

$$\begin{aligned}\pi_i^{iparams} = \mathrm{PK}\{(w, w', x_0, x_1, y_a) : \\ C_W = {G_w}^w {G_{w'}}^{w'} \wedge \\ I = \frac{G_V}{{G_{x_0}}^{x_0} {G_{x_1}}^{x_1} {G_a}^{y_a}} \wedge \\ V_i = {G_w}^w {U_i}^{x_0+x_1 t_i} {M_{a_i}}^{y_a}\}\end{aligned}$$

6.3 Credential Presentation

The user chooses k unused credentials issued in prior registration requests, i.e. valid MACs $(t_i, V_i)_{i=1}^k$ on attributes $(M_{a_i})_{i=1}^k$.

For each credential $i \in [1, k]$ she executes the Show protocol described in [CPZ19]:

1. She chooses $z_i \in_R \mathbb{Z}_q$, and computes $z_{0_i} = -t_i z_i (\mathrm{mod} q)$ and the randomized commitments:

$$\begin{aligned}C_{a_i} &= {G_a}^{z_i} M_{a_i} \\ C_{x_{0_i}} &= {G_{x_0}}^{z_i} U_i \\ C_{x_{1_i}} &= {G_{x_1}}^{z_i} {U_i}^{t_i} \\ C_{V_i} &= {G_V}^{z_i} V_i\end{aligned}$$

2. To prove to the coordinator that a credential is valid she computes a proof:

$$\begin{aligned}\pi_i^{MAC} = \mathrm{PK}\{(z_i, z_{0_i}, t_i) : \\ Z_i = I^{z_i} \wedge \\ C_{x_{1_i}} = {C_{x_{0_i}}}^{t_i} {G_{x_0}}^{z_{0_i}} {G_{x_1}}^{z_i}\}\end{aligned}$$

   which implies the following without allowing the coordinator to link π_i^{MAC} to the underlying attributes (M_{a_i}):

$$\mathsf{Verify}((C_{x_{0_i}}, C_{x_{1_i}}, C_{V_i}, C_{a_i}, Z_i), \pi_i^{MAC}) \iff \mathsf{VerifyMAC}_{\mathsf{sk}}(M_{a_i})$$

3. She sends $(C_{x_{0_i}}, C_{x_{1_i}}, C_{V_i}, C_{a_i}, \pi_i^{MAC})$ and the coordinator computes:

$$Z_i = \frac{C_{V_i}}{{G_w}^w {C_{x_{0_i}}}^{x_0} {C_{x_{1_i}}}^{x_1} {C_{a_i}}^{y_a}}$$

   using its secret key (independently of the user's derivation), and verifies π_i^{MAC}.

6.4 Double-spending prevention using serial numbers

The user proves that the group element $S_i = {G_s}^{r_i}$, which is used as a serial number, was generated correctly with respect to C_{a_i}:

$$\pi_i^{serial} = \mathrm{PK}\{(z_i, a_i, r_i) : S_i = {G_s}^{r_i} \wedge C_{a_i} = {G_a}^{z_i} {G_h}^{r_i} {G_g}^{a_i}\}$$

The coordinator verifies π_i^{serial} and checks that the S_i has not been used before (but allowing for idempotent registrations).

Note that since the logical conjunction of π_i^{serial} and π_i^{MAC} is required for each credential, and because these proofs share both public and private inputs it is appropriate to use a single proof for both statements.

6.5 Over-spending prevention by balance proof

The user needs to convince the coordinator that the total amounts redeemed and the requested differ by the public input Δ_a, which she can prove by including the following proof of knowledge:

$$\pi^{sum} = \mathrm{PK}(\{(z, \Delta_r) : B = {G_a}^z {G_h}^{\Delta_r}\})$$

where

$$B = {G_g}^{\Delta_a} \prod_{i=1}^{k} \frac{C_{a_i}}{M'_{a_i}} \qquad z = \sum_{i=1}^{k} z_i \qquad \Delta_r = \sum_{i=1}^{k} r_i - r'_i$$

with r'_i denoting the randomness terms in the $(M'_{a_i})_{i=1}^k$ attributes of the credentials being requested and z_i, r_i denoting the ones in the randomized attributes $(C_{a_i})_{i=1}^k$ of the credentials being presented.

During the input registration phase Δ_a may be positive, in which case an input of amount $a_{in} = \Delta_a$ must be registered with proof of ownership. During the output registration phase Δ_a may be negative, in which case an output of amount $a_{out} = -\Delta_a$ is registered. If $\Delta_a = 0$ credentials are simply reissued, with no input or output registration occurring.

6.6 Unconditional Hiding

Note that S_i is not perfectly hiding because there is exactly one $r_i \in \mathbb{Z}_q$ such that $S_i = {G_s}^{r_i}$. Similarly, randomization by z_i only protects unlinkability of issuance and presentation against a computationally bounded adversary. Null credentials have the same issue, since the amount exponent is known to be zero.

To unconditionally preserve user privacy in the event that the hardness assumption of the discrete logarithm problem in $\mathbb{G}$ is broken it is possible to add an additional randomness term r'_i used with an additional generator G'_h to the amount commitments M_{a_i}, and similarly another randomness term z'_i and generators $G'_a, G'_{x_0}, G'_{x_1}, G'_V$. Assuming the coordinator is not able to attack network level privacy and proofs of knowledge are unconditionally hiding this would ensure unconditional unlinkability.

7 Security and Privacy

In this section, we discuss the security and privacy guarantees of the KeyJoin credential scheme for construction of CoinJoin transactions. Theft concerns are addressed through Bitcoin's security model, making KeyJoin trustless in that regard. Since CoinJoin is an overt technique privacy strongly depends on the structure of the transactions themselves. KeyJoin is designed as a general-purpose mechanism, so those details are outside of the scope of this work, and further research into its safe application is ongoing.

The goal of the protocol is to allow a coordinator to provide the service to honest participants, without learning anything about the mapping between registered input and outputs, apart from what is already deducible given the public amounts visible on the Bitcoin blockchain. KeyJoin leverages the unlinkability of anonymous credentials and the hiding property of the amount commitments to minimize privacy leaks when a set of participants utilizes a centralized coordinator to reach agreement about such a transaction.

7.1 Availability

7.1.1 Malicious Coordinator

Being a central point of failure, the coordinator is a trusted party with regards to availability. If competing coordinators charge fees for their services then this is a minimal assumption in practice given the financial incentive.

A malicious coordinator can fully disrupt the protocol by censoring certain inputs either at input registration or during the signing phase. The coordinator can also drop messages causing any user to appear to be non-compliant, and therefore disrupt the protocol arbitrarily.

7.1.2 Malicious Users

Signatures can only be made after a transaction has been negotiated, and all inputs must provide a valid signature. Consequentially users can always disrupt the protocol during the final phase. Failure to sign is attributable to specific inputs and therefore can be mitigated by the coordinator, allowing the remaining honest participants to restart the protocol and ensuring that a valid transaction can be output after a finite number of attempts. Denial of service is not costless because unspent transaction outputs are a limited resource.

7.2 Unlinkability

A mixing scheme should ensure that any links between registered inputs and outputs are only known to their owners. The unlinkability property in [CPZ19] ensures that the presentation of credentials cannot be linked back to their issuance. Since every registration request is only associated with a single input or output, the only information that would need to be broadcast publicly on the blockchain if the protocol succeeds is revealed directly.

However, because the protocol may be repeated several times before resulting in a valid transaction, and because the transaction data is still overt the unlinkability of credentials is not enough to guarantee privacy, and there are other means participants or the coordinator could attack it.

7.2.1 Passive attacks

We can model registration requests as vertices of a directed acyclic graph labeled by Δ_a and credentials as edges labelled by the amount in the attribute, connecting the registration request where a credential was issued to where it was presented, much like the graph depicted in § 5.5. Apart from the bootstrap requests which have indegree 0 (no credentials are presented) and final output requests which have outdegree 0 (credentials must be requested but not used since there are no subsequent registrations), this graph is k-regular. The serial number and balance proofs enforce a global invariant where the sums of the inwards and outwards edges of every vertex differ by its label, and so long as honest participants are able to make their registrations it will be balanced (both vertex and edge labels will sum to 0).

The unlinkability of credentials and hiding property of the amount commitments obscure the edges and their labels from the coordinator and other participants. However, the coordinator observes registration requests according to a partial order which is an extension of the partial order defined by the transitive completion of the graph. In other words, the coordinator knows that parallel requests do not share an edge and that dependent requests must be made sequentially. Information about the order and timing of requests as well as the inherently overt transaction data relayed in the registration requests can therefore constrain the graph topology allowing the coordinator to draw inferences about the edges despite not being able to observe the edge set directly.

Clients can mitigate these leaks by minimizing dependencies between requests and scheduling requests randomly during the registration phases. Additional reissuance requests can be made by clients, including clients which do not actively participate in the transaction (cover traffic can be created using only the bootstrap credentials).

7.2.2 Active attacks

Sybil attacks [Dou02] are an inherent threat to privacy in mixing schemes because a transaction between n apparent participants $n-1$ of which are controlled by an attacker will fully link the victim's coins on both sides of the CoinJoin while giving the impression that the victim's privacy has been improved. There is a liquidity requirement for such an attack since participants must provide valid inputs[8], as well as a cost imposed by mining fees.

An attacker attempting to Sybil attack all CoinJoins would need to control some multiple of the combined Bitcoin volume contributed by honest participants, and to successfully partition honest participants to a sufficient degree. In the centrally coordinated setting, fees paid by users can arbitrarily increase the cost of Sybil attacks by other users. However, this does not protect against a malicious coordinator which is only bound by liquidity and mining fees. Furthermore, service fees paid by honest participants may reduce the cost of such an attack or even make it profitable.

A malicious coordinator may tag users by providing them with different issuer parameters. When registering inputs a proof of ownership must be provided. If signatures are used, by covering the issuer parameters and a unique round identifier these proofs allow other participants to verify that everyone was given the same parameters.

A malicious coordinator could also delay the processing of requests in order to learn more through timing and ordering leaks. In the worst case, the coordinator can attempt to linearize all requests by delaying individual to recover the full set of labelled edges. This is possible when $k = 1$ and users have minimal dependencies between their requests and tolerate arbitrary timeouts but issue requests in a timely manner.

Similarly the coordinator may delay information such as the set of ownership proofs or the final unsigned transaction. In the case of the latter, this can be used to learn about links between inputs. This is because a signature can only be made after the details of the transaction are known. If the unsigned was only known to one user but multiple inputs have provided signatures, it follows that those inputs are owned by the same user.

[8] See also JoinMarket fidelity bonds: `https://gist.github.com/chris-belcher/18ea0e6acdb885a2bfbdee43dcd6b5af`

Since the coordinator must be trusted with regards to denial of service a more practical variant of this attack would involve more subtle delays followed by sabotaging multiple successive rounds during the signing phase in order to learn of correlations between registrations while maintaining deniability.

More generally denial of service can amplify attacks on unlinkability, as it can be used to perform intersection attacks. The coordinator always learns the requested inputs and outputs, even if a round fails, and is able to partition users. A malicious participant will also learn all the input and output registrations if they wait until the signing phase to defect[9].

7.3 Theft prevention

Since the output of the protocol is a single Bitcoin transaction theft is prevented by only signing the transaction if the outputs are as expected, so the protocol inherits theft resistance directly from Bitcoin's security model.

A malicious user could claim more funds than she registered if and only if she is able to forge the coordinator's MAC on some credential. This is certainly not possible unless credentials can be forged under chosen message attacks, but even if that were the case this would only result in denial of service, as the honest users would refuse to sign such a transaction.

7.4 Security Proofs

The above outlined security and privacy guarantees directly follow from the underlying KVAC scheme of [CPZ19]. The unlinkability of KeyJoin credentials follows from unlinkability and the denial of service resistance of the KeyJoin protocol follows from unforgeability. We refer the to [CPZ19] for formal security arguments.

8 Performance

In this section we discuss the efficiency of our protocol. Because the protocol can only complete successfully when all participants are both honest and available, and due to the underlying anonymous overlay network it is desirable to operate with as little communication complexity as possible. Reducing communication costs can also make the protocol more robust against traffic analysis by a global passive adversary or targeted censorship by an active one. Computational complexity is mainly a consideration for the coordinator it must process the requests of all users, which follow a bursty pattern.

The following table estimates communication overheads for the protocol assuming simple Σ-protocol for linear relations [BS20, 19.5.3 pp. 747-8, 20.4.1 pp. 792]. These proofs are amenable to compression [BBB+18; AC20] and could be reduced to a size that is logarithmic in the bit width and the number of credentials per request.

	Request						Response	
	M_a	π^{range}	C_a	S	$(\pi^{serial} \wedge \pi^{MAC})$	π^{sum}	MAC	$\pi^{iparams}$
$\#\mathbb{G}$	k	$k(2n+1)$	k	k	$4k$	1	k	$3k$
$\#\mathbb{Z}_q$	–	$k(3n+1)$	–	–	$5k$	2	k	$5k$

Table 1: Communication overhead of the KeyJoin protocol. Each round trip corresponds to a single registered input and k denotes the number of requested credentials. The bit-width of the range proofs is denoted as n, and for bootstrap requests its value is zero.

9 Conclusion

In this work, we described KeyJoin, a privacy-focused protocol for Bitcoin based on the keyed-verification anonymous credentials scheme to centrally coordinating CoinJoin transactions. Our goal is to ensure the privacy of users in the world of cryptocurrencies and digital money. We are convinced that the described technology can make a significant contribution to the crypto industry and beyond.

[9] If `SIGHASH_ANYONECANPAY` is set in the signature flags the full set of inputs could be kept known only to the coordinator until all signatures have been provided.

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