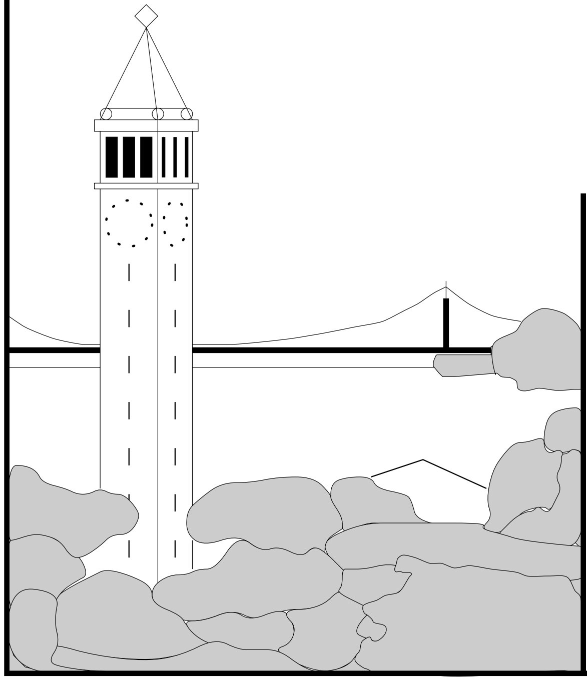
WhoPay: A Scalable and Anonymous Payment System for Peer-to-Peer Environments

Kai Wei[†], *Yih-Farn Chen*[‡], *Alan J. Smith*[†], *Binh Vo*[*]
[†]*Department of Electrical Engineering and Computer Sciences*
University of California, Berkeley, CA
[‡]*AT&T Labs Research, Florham Park, NJ*
[*]*Laboratory for Computer Science*
Massachusetts Institute of Technology, Cambridge, MA



Report No. UCB/CSD-5-1386

May 2005

Computer Science Division (EECS)
University of California
Berkeley, California 94720

WhoPay: A Scalable and Anonymous Payment System for Peer-to-Peer Environments [*]

Kai Wei[†], Yih-Farn Chen[‡], Alan J. Smith[†], Binh Vo[*]
[†]Department of Electrical Engineering and Computer Sciences
University of California, Berkeley, CA
[‡]AT&T Labs Research, Florham Park, NJ
[*]Laboratory for Computer Science
Massachusetts Institute of Technology, Cambridge, MA

Abstract

An electronic payment system ideally should provide security, anonymity, fairness, transferability and scalability. Existing payment schemes often lack either anonymity or scalability. In this paper we propose WhoPay, a peer-to-peer payment system that provides all the above properties. For anonymity, we represent coins with public keys; for scalability, we distribute coin transfer load across all peers, rather than rely on a central entity such as the broker. This basic version of WhoPay is as secure and scalable as existing peer-to-peer payment schemes such as PPay, while providing a much higher level of user anonymity. We also introduce the idea of real-time double spending detection by making use of distributed hash tables (DHT), which further improves the security level of WhoPay.

To evaluate how well WhoPay distributes load among peers, we have run simulations with several different configurations. The simulation results show that the majority of the system load is handled by the peers under typical peer availability, indicating that WhoPay should scale well.

1 Introduction

E-commerce is rapidly becoming the preferred way for many consumers to obtain goods and services. Payments for such transactions on the Web are frequently fulfilled using credit cards or an online payment system such as PayPal [17]. These electronic payment systems generally incur considerable per transaction cost. For example, most credit card processors charge merchants a minimum fee of between 15 and 35 cents per transaction [13]. As a consequence, these payment schemes are generally considered unsuitable for items that cost $5 or less. Micropayment systems, which try to aggregate many small micropayments into a few bigger payments, are designed to address this issue.

Another issue with traditional payment technologies like the credit card system and PayPal is the lack of privacy provided to the parties involved in the transactions. With credit cards or PayPal, the identities of the payer and payee of each transaction are exposed not only to each other, but also to the credit card companies or PayPal.com. These exposed identities, together with the transaction itself, can reveal precious or sensitive information about the parties involved. In response to this concern, numerous anonymous payment systems [29] have been proposed to hide user identities during transactions, mostly by using blind signatures [9] or public key cryptography.

Total anonymity has its negative side. Particularly, it makes it more difficult to punish fraud such as double spending and allows illegal activities such as blackmail and money laundering. What we really want is a payment system where users remain anonymous under normal circumstances but a trusted authority, called the judge, can be called in to reveal relevant identities for law enforcement purposes when fraud is detected. The notion of fairness was introduced by Camenisch [5] to describe this property. Vo and Hohenberger have proposed such a fair system [29].

A common characteristic shared by all the payment schemes mentioned above is that every transaction goes through a central authority, which we refer to in general as the broker. This means the broker needs to handle a huge amount of load and thus presents a scalability

[*]Principal support for this research has been provided by AT&T Laboratories and the State of California MICRO program, with some additional support from Toshiba Corporation.

and performance bottleneck. While credit card companies and PayPal have so far been able to sustain the ever growing transaction load by increasing investment in hardware, this certainly sets the threshold for entry to the payment business very high and makes it infeasible for use in many applications. For example, one can imagine a pay-per-download file sharing system, where a virtual payment system is used to encourage fair sharing of resources among peers and discourage free riders. There is probably no business model in such a system that can make someone willing to invest the amount of money needed to assume the role of the broker.

PPay [30] is a scalable payment system that is inspired by the success of P2P file sharing systems. Such systems as KaZaA [15] can scale to millions of peers because they pool together and harness the massive resources at the "edge" of the network, rather than relying on expensive centralized resources. As noted by its authors, PPay exploits two main characteristics of P2P applications:

- First, peers are generally both consumers and merchants. As a result, coins received from other peers can be used in many transactions before being deposited at the broker.

- Second, if we can shed the broker's load onto the peers, we can build a payment scheme with much better scalability and performance properties than existing ones.

PPay is secure, fair and scalable, but provides no anonymity. In contrast, the Vo-Hohenberger system is secure, anonymous and fair, but is not scalable. In this paper, we propose WhoPay, a P2P payment system that is secure, anonymous, fair, and scalable, thus combining the best of both worlds.

The rest of the paper is organized as follows. In the next section, we will formally define our design goals. Then in Section 3, we will describe some background information that should help us understand WhoPay's architecture. This is followed by the description of the basic version of WhoPay in Section 4. Several extensions to this basic design will be introduced in Section 5, including a real-time double spending detection mechanism and others that further improve the anonymity property of WhoPay. We present our simulation work in Section 6 and discuss related work in Section 7. We conclude in Section 8.

Notation: We will let B denote the broker, pk_X the public key of some entity X, sk_X the private key of X, and gk_X the group private key of X. A message M signed by some key K is denoted as $\{M\}_K$.

2 Design Goals

Vo and Hohenberger defined a set of desirable properties for digital payment systems, denoted SAFT, which stands for Security, Anonymity, Fairness, and Transferability [29]. These properties were defined with the assumption that every coin transfer goes through the broker. We will adopt their terminology, but slightly redefine each property to make it applicable to our peer-to-peer design.

- *Security*: The value of coins can not be tampered with. This means, only the broker can generate coins or increase the value of coins, and only the current holder of a coin can transfer, destroy, or decrease the value of the coin. This guarantees that no user can manipulate the system for profit or to harm another. In particular, fraud such as double spending is either prevented, or detectable and punishable.

- *Anonymity*: Payer and payee do not need to reveal their identities to any third party. This means, without the help of the judge, nobody (other than the participants themselves) can identify the participants of a transaction with probability better than random guessing. Optionally, payer and payee can hide identities from each other.

- *Fairness*: The broker and the judge, working together, can reveal the identities of all parties involved in a particular transaction. If possible, this process should not reveal any information about other transactions.

- *Transferability*: The recipient of a coin can use the same coin to pay another user without identifying himself to the broker. All systems mentioned in this paper support transferability and thus this property will not be the focus of our discussion.

Besides, we want our scheme to reduce load on the broker:

- *Scalability*: The load of any particular entity does not grow to be unmanageable as the size of the system increases. In particular, the majority of the transaction load should be distributed among peers rather than handled by the broker.

3 Preliminaries

Before we present the WhoPay design, we first briefly describe some background information that will help us understand the architecture of WhoPay, namely PPay and group signatures.

3.1 PPay

PPay is a payment scheme designed for P2P systems. In PPay, user U *purchase*s coins from the broker, and hence becomes the *owner* and *holder* of the coins. To spend the coins he owns, U *issue*s the coins to another user, say V. After the issue, V becomes the current *holder* of the coins, but U remains their owner. If V wants to pay yet another user W with these coins, he can *transfer* these coins to W via U, the coins' owner. After the transfer, V relinquishes his holdership of the coins and W becomes the current holder of the coins; U remains the owner of the coins. W can further transfer these coins to others, and so on. Only the holder of a coin can spend the coin. Or, the holder can choose to deposit the coin at the broker for cash, by which time the coin comes out of circulation.

The main challenge in this scheme is to ensure that the security properties are not compromised, since we now want operations—in particular, transfers—normally done by the trusted broker to be performed by untrusted peers. As PPay is designed as a micropayment scheme, in that each payment is of a small amount, utmost security is not required; a security model where fraud is detectable (even after the fact) and punishable is probably good enough in most cases. PPay achieves such security as follows.

When user U purchases a coin from the broker, the coin is in the following form:

$$C = \{U, sn\}_{sk_B}$$

where sn is the serial number of a coin that uniquely identifies it. Once issued, the coin becomes:

$$Coin = \{C, H, seq\}_{sk_U}$$

where H is the current holder of the coin, and seq is a sequence number. The coin owner maintains a sequence number counter for the coin and increments the coin's sequence number each time it is issued or transferred. For example, to issue the coin C to user V, U sends V:

$$C_V = \{C, V, seq_1\}_{sk_U}$$

which also serves as a proof of issue. Now for V to transfer the coin to W, V sends the following transfer request to owner U:

$$\{W, C_V\}_{sk_V}$$

and U will keep a record of this transfer request in order to later prove that V has "relinquished" the holdership of the coin, in case of a dispute. Finally, U sends W:

$$C_W = \{C, W, seq_2\}_{sk_U}$$

which also serves as a proof of transfer. Note that seq_2 must be greater than seq_1.

In summary, a coin explicitly contains the identities of both owner and holder; users sign their messages with their private keys, and keep audit trails of these signatures. These features ensure the "good enough" security mentioned earlier.

Finally, in practice peers come and go, so how do we deal with coins whose owners are offline (we will call such coins "offline coins" from now on)? To address this issue, PPay includes a downtime protocol, in which the broker temporarily handles the transfer/renewal of offline coins and keeps relevant state. Peers must synchronize state with the broker after they rejoin the system.

It is easy to see that PPay provides very weak, if any, anonymity for the parties involved in a transaction. For example, during coin transfer, the payee knows who the payer is and vice versa, and the coin owner knows who the payee and the payer are and thus can construct a complete transaction history for each coin it owns. In Section 4, we will describe how to modify this scheme to provide anonymity while preserving security, fairness and scalability.

3.2 Group Signatures

In the group signature protocol proposed by Chaum et al [10], a group consists of n private keys $G_1, \ldots, G_n$, one master public key G_p, and one master private key G_s. Each of $G_1, \ldots, G_n$ can be used to sign a message. The master public key G_p can be used to verify that the message was signed by one of $G_1, \ldots, G_n$, but cannot tell by which one. The master private key G_s can be used to pinpoint which key was used. G_s is also used to generate new private keys.

WhoPay uses group signatures to achieve fairness. Every user is required to register with a trusted authority, called the *judge*. The judge assigns each user U a (distinct) private key, denoted as gk_U, from a group[1] and records the user's identity with the private key. The judge also keeps the master private key to herself. (In practice, this master private key can be divided among N judges using Shamir's secret sharing protocol [26] and at least K judges are needed in order to recover the key; but we will make this assumption implicit in the rest of our discussions.) Whenever a user wants to remain anonymous, it signs its messages with its group private

[1] All users belong to the same group in WhoPay.

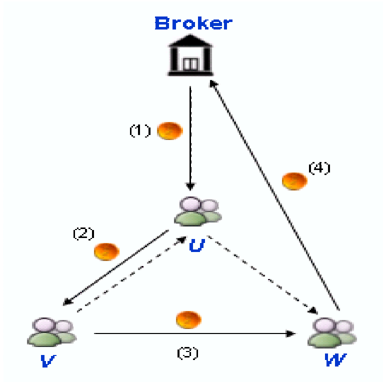


Figure 1: The WhoPay Model: (1) U ***purchases*** coin from broker; (2) U ***issues*** coin to V; (3) V ***transfers*** coin to W through U; (4) W ***deposits*** coin at broker.

key rather than its regular private key. These signatures allow everyone to verify (using the master public key) that the signer is a legitimate user in the system but do not expose its true identity under normal circumstances. However, once a fraud is detected, the judge can be called in to reveal the identities of the bad guys. This way, anonymity is preserved and justice is served.

4 WhoPay

4.1 Overview

WhoPay inherits its basic architecture from PPay. Coins have the same lifecycle as in PPay. Users purchase coins from the broker and spend them by issuing them to other users, who can either spend them by transferring them or deposit them at the broker for cash. Coins must be renewed periodically to retain their value. Coins get transferred/renewed via the coins' owners if they are online, or via the broker otherwise (Figure 1).

The first major difference of WhoPay from PPay is that coins are identified by public keys, rather than serial numbers. To purchase a coin, user U generates a random public/private key pair pk_{C_U}/sk_{C_U}, keeps the private key sk_{C_U} secret and asks the broker to sign the public key pk_{C_U}.[2] The broker sends the coin back in the following form:

$$C = \{U, pk_{C_U}\}_{sk_B}$$

where pk_{C_U} should (with very high probability) uniquely identify the coin. Once issued, the coin becomes:

$$Coin = \{C, pk_{C_H}, seq, exp\_date\}_{sk_U}$$

where H is the current holder of the coin, exp_date is the expiration date of the coin, and seq is the sequence number of the coin and serves the same function as in PPay. For example, to issue the coin C, the payee V generates a random public/private key pair pk_{C_V}/sk_{C_V}, keeps the private key sk_{C_V} secret and asks the coin owner U to sign the binding (pk_{C_U}, pk_{C_V}). The binding (pk_{C_U}, pk_{C_V}) means "coin pk_{C_U} is now represented by pk_{C_V}", and is a way of conveying the information of who the current holder of a coin is, in that whoever knows the private key sk_{C_V} is the current holder of the coin pk_{C_U}. At any point of time, each user remembers one such binding for each coin it owns. To complete the issue procedure, U sends V:

$$C_V = \{C, pk_{C_V}, seq_1, exp\_date_1\}_{sk_U}$$

which also serves as a proof of issue. Similarly, for V to transfer the coin, the intended payee, say W, also generates a random public/private key pair pk_{C_W}/sk_{C_W}, keeps the private key sk_{C_W} secret and sends the public key pk_{C_W} to V. V then sends the following transfer request to owner U:

$$\{\{pk_{C_W}, C_V\}_{sk_{C_V}}\}_{gk_V}$$

and U will keep a record of this transfer request in order to later prove that V has "relinquished" the holdership of the coin, in case of a dispute. Finally, U sends W:

$$C_W = \{C, pk_{C_W}, seq_2, exp\_date_2\}_{sk_U}$$

which also serves as a proof of transfer. Note that seq_2 must be greater than seq_1.

4.2 Protocol Details

The details of the WhoPay protocols are given below.

Purchase: To purchase a coin from the broker, user U generates a random public/private key pair pk_{C_U} and sk_{C_U}. He keeps sk_{C_U} to himself and sends pk_{C_U} along with his identity (e.g., in the form of a public key certificate) signed by his private key sk_U to the broker. After verifying the signature, the broker adds pk_{C_U} to the list of valid coins, signs the coin with its private key and sends it back to U. The transaction completes after U verifies the broker's signature. It should be straightforward to modify this procedure to purchase coins in batch.

Issue: For U to issue V a coin pk_{C_U}, V generates a random public/private key pair pk_{C_V} and sk_{C_V}, keeps

[2]As different users generate these public/private key pairs independently, there is a probability of key collision. The length of the renewal period of coins can be used to keep this probability small. In this paper, we assume this probability is small enough so that, say, the broker is willing to absorb this risk.

sk_{C_V} to himself, and sends pk_{C_V} to U. U sends V the broker-signed coin pk_{C_U}, and answers a challenge by V to prove he is the owner of the coin. U then updates its coin binding list to bind pk_{C_U} to pk_{C_V}, a randomly chosen sequence number and an appropriate expiration date. U signs the binding with sk_{C_U}, and sends V the signed binding, which serves as a proof of issue of the coin to V. The transaction completes after V verifies the signature.

Transfer: For V to transfer W a coin pk_{C_U}, W generates a random public/private key pair pk_{C_W} and sk_{C_W}, keeps sk_{C_W} to himself, and sends pk_{C_W} to V. V sends the coin owner U a transfer request identifying pk_{C_U} and pk_{C_W}. The transfer request is signed with both sk_{C_V} and V's group private key gk_V, with the first to prove V's holdership of the coin and the second to help ensure the fairness of the system. After receiving this transfer request and verifying it is a valid request, U sends W the broker-signed coin pk_{C_U}, and answers a challenge by W to prove he is the owner of the coin. U then updates its coin binding list to bind pk_{C_U} to pk_{C_W}, an incremented sequence number and an appropriate new expiration date. U signs this binding with sk_{C_U} and sends W the signed binding, which serves as a proof of transfer of the coin to W. The transaction completes after W verifies the signature.

Deposit: For W to deposit a coin pk_{C_U}, it sends a deposit request to the broker identifying the coin to be deposited. The deposit request is signed with both sk_{C_W} and W's group private key gk_W, with the first to prove W's holdership of the coin and the second to help ensure the fairness of the system. After receiving this deposit request and verifying it is a valid request, the broker sends payment to W.

Renewal: For W to renew a coin pk_{C_U}, it sends a renewal request to the coin owner U identifying the coin to be renewed. The renewal request is signed with both sk_{C_W} and W's group private key gk_W, with the first to prove W's holdership of the coin and the second to help ensure the fairness of the system. After receiving this renewal request and verifying its validity, U updates its binding for pk_{C_U} with an incremented sequence number and an appropriate new expiration date. U signs this updated binding with sk_{C_U} and sends W the signed binding, which serves as a proof of renewal. The transaction completes after W verifies the signature.

Downtime transfer: For V to transfer W a coin pk_{C_U} via the broker, W generates a random public/private key pair pk_{C_W} and sk_{C_W}, keeps sk_{C_W} to himself, and sends pk_{C_W} to V. V sends the broker a transfer request identifying pk_{C_U} and pk_{C_W}. The transfer request is signed with both sk_{C_V} and V's group private key gk_V, with the first to prove V's holdership of the coin and the second to help ensure the fairness of the system. After receiving this transfer request and verifying it is a valid request, the broker records the binding of pk_{C_U} to pk_{C_W}, an incremented sequence number and an appropriate new expiration date. The broker signs this binding with sk_B and sends W the signed binding, which serves as a proof of transfer of the coin to W. The transaction completes after W verifies the signature.

In the details, there are two flavors of the downtime transfer protocol, depending on whether the coin was last issued/transferred/renewed through its owner, or was it transferred/renewed through the broker. In the first case, most likely the broker has not established any state about the coin and thus needs to verify the coin owner's signature. In the second case, most likely the broker has the up-to-date binding information for the coin and only needs to perform a bit-by-bit comparison of the signed binding received to the locally stored signature.

Downtime renewal: For V to renew a coin pk_{C_U} via the broker, V sends the broker a renewal request identifying the coin to be renewed. The renewal request is signed with both sk_{C_V} and V's group private key gk_V, with the first to prove V's holdership of the coin and the second to help ensure the fairness of the system. After receiving this renewal request and verifying it is a valid request, the broker records the binding of pk_{C_U} to pk_{C_V}, an incremented sequence number and an appropriate new expiration date. The broker signs this binding with sk_B and sends V the signed binding, which serves as a proof of renewal of the coin. The transaction completes after V verifies the signature. Similar to the downtime transfer case, there are two flavors of the downtime renewal protocol, depending on whether the coin was last issued/transferred/renewed through its owner, or was it transferred/renewed through the broker.

Sync: For U to synchronize state with the broker after it rejoins the system, it identifies itself to the broker and proves its claimed identity through a challenge-response procedure. The broker then looks up the bindings for the coins whose owner is U, which it has been maintaining for U during U's downtime, signs them with its private key sk_B, and sends it to U. After verifying the signed bindings, U updates its coin binding list accordingly.

In summary, coin ownership is still exposed as in PPay, but coin holdership is hidden[3]. Peers only use their private keys to sign messages when they play the role of coin owners, e.g., when they issue coins or handle coin transfers/renewals. When peers act as coin holders, e.g., when they transfer or deposit coins, they use two keys

[3]In section 5, we will show how to anonymize coin ownership as well.

to sign their messages. The first is the coin private key that proves the peer's holdership of the coin and the other is the peer's group private key. Neither signature reveals the peer's identitiy during normal operations and the group signature allows the identity to be recovered by the judge in exception cases, e.g., in order to identify culprits when fraud is detected.

4.3 System Properties

In this section, we analyze the properties of WhoPay to evaluate how well our design goals outlined in Section 2 have been met.

Security. WhoPay supports as good security as PPay. Assuming digital (group or otherwise) signatures are not forgeable, nobody other than the broker can create coins and nobody is able to pose as somebody else, for example, to spend coins he does not hold or handle transfer of coins he does not own. While certain kinds of fraud are still possible, the audit trails of peers and the broker ensure they will be detected and the culprits identified and punished. Most of these fraud requires the collusion of the coin owner, and exposed coin ownership in WhoPay means these fraud is easily punishable. Even for fraud committed by coin holders, the hidden coin holdership in WhoPay does not pose a serious problem as the group signatures allow holder identities to be revealed in these cases.

Anonymity. WhoPay provides much stronger anonymity than PPay. During coin transfer, the coin does not contain holder identity and both the payer and the payee use their group private keys to sign messages, so the payee does not know who the payer is and vice versa. For the same reason, the coin owner does not know who the payee and the payer are. Thus coin transfer is completely anonymous. Similarly, during coin renewal, the coin owner does not know who is requesting the renewal and during coin deposit, the broker does not know who is requesting the deposit.

During coin issue, the payee knows who the payer is since the coin contains owner identity and the owner signs its messages with its private key. The payer, however, does not know who the payee is as the payee signs its messages with its group private key. Thus, coin issue is semi-anonymous and we will discuss mechanisms to improve issue anonymity in Section 5.

Finally for each coin, the broker knows who made the initial purchase, but not who made the final deposit. Therefore, although it can still link purchases to deposits by matching the public keys that represent the coins, there is little information it can infer from this link.

Note that so far we have been talking about anonymity in terms of application level identities such as those encoded in public key certificates. In many situations network level identities (e.g., IP addresses) can convey a lot of information and are hence worth hiding as well. There have been many studies in this area, most of which, such as Onion Routing [22] and Tarzan [12], involve hiding end points IP addresses by using third party proxies. In this paper, we will assume such mechanisms will be adopted whenever network level anonymity is desired.

Fairness. Recall that fairness means the broker and the judge, working together, can reveal the identities of all parties involved in a particular transaction without learning any information about other transactions. Transactions signed with (non-group) private keys expose signer identities and are automatically fair. For those signed with group private keys, the broker sends the transactions of interest to the judge, who recovers the identities of the signers of these transactions and sends them back. Note that no information about other transactions is learned in this process. Thus WhoPay is fair.

Transferability. Recall that transferability means the recipient of a coin can use the same coin to pay another user without identifying himself to the broker. In WhoPay, when the coin owner is online, broker is not involved in coin transfers and hence does not learn the identity of the payer. In fact, even the coin owner does not learn the identity of the payer, due to the anonymity property mentioned above. When transferring an offline coin via the broker, the payer also remains anonymous throughout the transaction. Thus WhoPay supports transferability.

Scalability. During the lifetime of a WhoPay coin, there is one purchase, one issue and one deposit, but there could be an arbitrary number of transfers and renewals. Thus we expect transfers and renewals to dominate the system load. Transfer and renewal load is distributed across peers. In general, the more coins a peer issues, the more transfers and renewals he needs to handle. This is desirable, as we expect more active peers to do more work. The broker is only involved in coin purchases, deposits, synchronizations and downtime transfers/renewals. The load generated by the last three items depends on the availability of peers, but we expect the majority of transaction load is handled by the peers rather than by the broker and the broker load increases sublinearly as the number of peers (or the total system load) increases. We will run simulations to study scalability in detail in Section 6.

5 Extensions

5.1 Real-time Double Spending Detection

By making sure all fraud will eventually be detected and punished, WhoPay as described so far already provides a level of security as good as PPay. One might be concerned that detecting fraud until coin deposit time may be too late and much damage could have been done by that time. To address this issue, WhoPay also provides **real-time double spending detection**. The idea is to make every peer's coin binding list globally readable. To make sure every coin owner publishes its list faithfully, a peer does not accept payment until verifying that the relevant public binding has been properly updated. Each peer constantly monitors the public bindings for the coins it currently holds, and any unexpected update can trigger appropriate actions.

The major challenge is how to implement this public coin binding list. Publishing and serving all the bindings in a central trusted server would not be a good idea, as that would create a single point of failure and performance bottleneck. We cannot give any peer too much control over where the bindings are published, as doing so would undoubtedly breed fraud. We propose to publish the coin bindings in a trusted, access-controlled distributed hash table (DHT) infrastructure. Like hash tables, distributed hash tables provide a put/get interface for storing/retrieving values under given keys. Unlike hash tables that are stored in local memory, DHTs are distributed across a network. The intelligence of a DHT design lies in its routing algorithm that ensures that a query under a given key is always routed toward the same host in the network. CAN [20], Chord [28], Pastry [25] and Tapestry [14] are early examples of DHT.

Naturally, only the owner of a coin should be allowed to write to the coin's binding, while anyone can read the binding. To enforce such access control policy, recall that the coin bindings are keyed by public keys, such as pk_{C_U}. The DHT should be designed in such a way that only users who know sk_{C_U} (which, supposedly, is only the owner of the coin) can write to the id pk_{C_U} (by providing the right signature, which can be published along with the binding to back it up), but anyone can read the id pk_{C_U}. This way, any user can verify the binding but only the owner of the coin can modify this binding. To allow the broker to take over during downtime, the broker should also be allowed to write to any id. By allowing the broker to update the bindings in the public list, real-time double spending detection will continue working during the owner's downtime. To monitor this DHT-based public binding list, peers can either poll the bindings of interest periodically or use a register/notify mechanism such as Bayeux [31], Scribe [7, 8], or CAN-mc [21].

We understand that there is a huge amount of trust placed in this DHT infrastructure for its access control and register/notify service. To address this issue, we can either assume this infrastructure is provided as a service by a trusted entity (e.g., AT&T), or in the case that this infrastructure consists of arbitrary members and lacks administrative control, introduce mechanisms to detect and remove misbehaving nodes. Either way, further study is needed.

5.2 Issuer Anonymity

As pointed out in Section 4, the identity of the payer is exposed during coin issues. We identify three approaches to this issue. The first approach is just to live with it. We expect peers to be fully aware that there is no payer anonymity when you issue a coin. Peers can issue coins to pay for less sensitive items or services. When anonymity matters, peers should choose to transfer instead of issue coins. As long as peers have enough coins to transfer, this should not be a major concern.

In the second approach, we introduce *coin shops* into the system. Coin shops purchase coins from the broker, and peers purchase coins, using the issue procedure, from the coin shops. The only transactions a coin shop performs is to purchase coins from the broker, to issue coins to peers, and to manage (i.e., handle the transfers and renewals of) the coins it has issued. Coin shops do not care about anonymity; they are in this business for profit, e.g., by charging a small fee for each coin issued. Peers do not own, and hence never issue coins. Peers spend coins only using the transfer procedure, which is anonymous.

The third approach is more complicated. Since the root cause for lack of issuer anonymity is the encoding of coin owner identity in coins, why not just remove this information from the coins? That is, given a coin, one should not be able to tell who the coin's owner is. Because we represent coins as public keys, we really do not need to hardcode coin owner information in coins; a peer can always prove its ownership of a coin by showing its knowledge of the right private key. Thus, a coin now has the initial form of

$$C = \{pk_{C_U}\}_{sk_B}$$

instead of $C = \{U, pk_{C_U}\}_{sk_B}$, for example. Once issued, the coin becomes:

$$Coin = \{C, pk_{C_H}, seq, exp\_date\}_{sk_U}$$

where only C has a different format now, but everything else stays the same as before.

The explicit coin owner information encoded in coins, however, was needed in three places in the original WhoPay design. First, when peers transfer coins, the payer needs to contact the coin owner to request the transfer. Second, when peers perform synchronization with the broker, the broker needs to map coins to owners in order to determine which coins' state to send to peers. Third, when certain fraud (e.g., double issuing) is detected, coin owners should be held responsible. By removing coin owner information from coins, we break these three things. Now we will present solutions to these problems such that WhoPay can still operate properly.

Our solution to the first problem is to use an anonymous indirection mechanism like the Internet Indirection Infrastructure, or *i*3 [27]. *i*3 is an overlay network consisting of *i*3 servers that store triggers and forward messages. Each coin now includes a handle and peers send messages to this handle when they want to contact the coin's owner. That is, coins now have the initial form of $C = \{h_{C_U}, pk_{C_U}\}_{sk_B}$, where h_{C_U} is the handle of the coin. The coin owner registers a trigger on this handle so that all messages sent to this handle will be forwarded to itself. These handles act as pseudonyms for the coin owner and obscure the identity of the coin owner. Note with the use of this indirection mechanism, the issue protocol and the transfer protocol look exactly the same from the payee's point of view, and thus the payee cannot tell whether the payer is the coin owner or some random peer.

A simple, but inefficient solution to the second problem would be to let the peer tell the broker which coins it owns, which could be a long list. Moreover, to ensure the secure and correct functioning of the system, the broker must ask the peer to prove its ownership of each of these coins. As a result, this process would incur huge communication and processing overhead. A better alternative, inspired by the observation that synchronization is needed if and only if the public binding for a coin and the local binding of the coin owner are different, is to use **lazy synchronization**. Instead of synchronizing everything immediately after rejoining the system (which we call *proactive synchronization*), the peer waits until it is absolutely necessary, i.e., when a transfer or renewal request is received. Upon receiving such a request, the coin owner checks the relevant binding in the public coin binding list and updates its local binding if it is outdated (we will refer to this operation as simply a *check*). This way, the involvement of the broker during synchronization becomes totally optional, which is certainly a desirable property.

The last problem is actually about fairness. Realizing this, the solution becomes obvious—using group signatures. Peers sign their messages with their group private keys when issuing coins. These signatures allow the issuers to remain anonymous under normal circumstances, while making sure that they will get caught and punished if they cheat.

6 Simulation

6.1 Simulation Setup

We have run simulations to study the load distribution among the peers and the broker under different scenarios. In particular, we want to show that a system based on our algorithm would scale well with increasing load.

We evaluated three policies in our simulation, which we denote as policy I, II, and III, respectively. While policy I and III represent two extreme scenarios, policy II covers the middle ground. As the results for policy II were less interesting, we will describe those for policy I and III only.

In policy I, each peer selects payment methods according to the following order of preferences:

1. Transfer an online coin (via the owner).
2. Transfer an offline coin (via the broker).
3. Issue an existing coin.
4. Purchase and issue a new coin.

In policy III, each peer selects payment methods according to the following order of preferences:

1. Transfer an online coin (via the owner).
2. Issue an existing coin.
3. Purchase and issue a new coin.
4. Deposit an offline coin, then purchase and issue a new coin.

In policy I, each peer tries to get rid of coins received from other peers as quickly as possible. The motivation behind this might be fear of fraud. Policy III simulates the best case in terms of broker load: each peer tries to avoid dealing with the broker as much as possible, and the way it deals with offline coins is the same as the second policy. These two policies are also different in the way they deal with offline coins. Policy I chooses to transfer offline coins through the broker, and the motivation for doing so might be that each peer wants to minimize the number of coins it needs to manage. In

Table 1: Simulation Setup

Setup	Policy	Sync	μ	ν	Number of peers
A	I, II.a, II.b, III	proactive, lazy	15 mins - 32 hrs	1 hr, 2 hrs, 4 hrs	1000
B	I, II.a, II.b, III	proactive, lazy	2 hrs	2 hrs	100 - 1000

policy III, peers deposit offline coins, and purchase new coins to issue. We suspect that doing this effectively moves the ownership of the coins from an offline peer to an online peer, and may reduce the load on the broker in the long run. For these reasons, we call policy I the user-centric policy, policy III the broker-centric policy.

We use simulations to study load distribution with different peer availability, load distribution under different spending policies, the impact of lazy synchronization vs. proactive synchronization, and finally, load distribution with different number of peers. To study the first three, we use the following setup, which we refer to as Setup A. There are a total of 1000 peers. Peers join and leave the system: online session lengths follow exponential distribution with mean μ, and offline session lengths follow exponential distribution with mean ν. In this setup, the availability of peers can be roughly indicated by the value $\alpha = \mu/(\mu + \nu)$. To model different peer availability, we run three sets of simulations, with ν set to 1 hour, 2 hours, and 4 hours, respectively. We call these three sets of simulations *short downtime simulation*, *median downtime simulation*, and *long downtime simulation*, respectively. In each of these simulations, we further vary μ from 15 minutes to 32 hours. For each peer, candidate payment events arrive as an independent Poisson process with rate 1 payment per 5 minutes, with the payee selected randomly. A candidate payment event will result in an actual payment event if and only if the randomly selected payee is online at the time, therefore the actual payment events (for each peer) form an independent Poisson process with rate α payments per 5 minutes. We use a renewal period of 3 days, and each run lasts for 10 days (in the simulated world).

To gain insights into how the system scales with increasing number of peers, we run another set of simulations, which we refer to as Setup B. In these simulations, we vary the size of the system from 100 peers up to 1000 peers. We fix the mean online and offline session lengths to 2hrs, i.e. $\mu = \nu = 2$ hrs, simulating a 50% peer availability. The rest of the configuration stays the same. The setups are summarized in table 1.

Next we present the simulation results. As it turned out the results for the short downtime simulation, median downtime simulation, and long downtime simulation are pretty similar to each other, we will only show the results for the median downtime simulation.

6.2 Simulation Results

Load distribution. The WhoPay system is built from the following coarse-grained operations: coin purchases, issues, transfers, deposits, renewals, downtime transfers, downtime renewals, synchronizations, checks, and lazy synchronizations. Here we first analyze load distribution in terms of these operations; later in this section we will give our estimates of the (CPU and communication) costs of these operations and analyze the aggregate load distribution.

Under policy I with proactive synchronization, the broker needs to handle purchases, downtime transfers, downtime renewals, and synchronizations. Figure 2 shows the broker load in terms of these operations. As peer availability increases, peers are online more often and hence generate more payment events. On the other hand, as peer availability increases, fewer transactions involve offline peers and need to go through the broker. The trend of broker load thus reflects the combined effect of these two competing forces. For purchases, the first force dominates since the number of purchases increases as peer availability increases. For downtime transfers and downtime renewals, the first force dominates when peer availability is low while the second force dominates when peer availability is high, shown by the fact that the numbers of these two operations first increase and then decrease as peer availability increases. One exception to this rule is the number of synchronizations, which decreases all the way as peer availability increases; this is because exactly one synchronization is performed for each peer join event.

Under policy I with lazy synchronization, the broker needs to handle purchases, downtime transfers, and downtime renewals, but no synchronizations. The trend of broker load follows the same pattern as in the proactive synchronization case, as shown in Figure 3. The results for policy III are similar.

The story about peer load is pretty much the flip side of that about broker load: average peer load rises as peer availability increases (see Figures 4 and 5), for the same reason that broker load drops. One striking point though, is that under all configurations, transfers dominate peer load.

Now to compare the total load on the broker/peers under each configuration, we need to know the relative

Table 2: Measured Operation Cost

Operation	Average CPU time
DSA 1024-bit key generation	7.8 ms
DSA 1024-bit signature generation	13.9 ms
DSA 1024-bit signature verification	12.3 ms

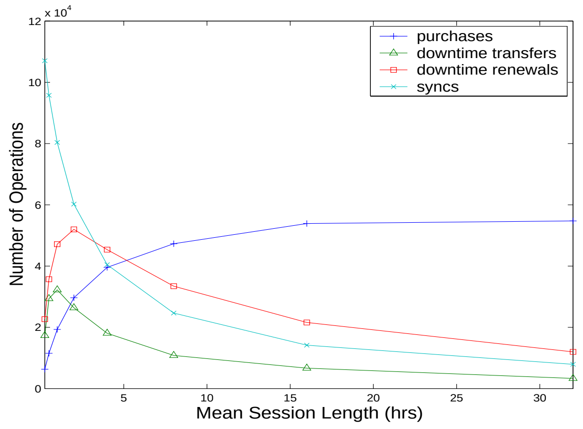


Figure 2: Broker Load: Policy I + Pro Sync

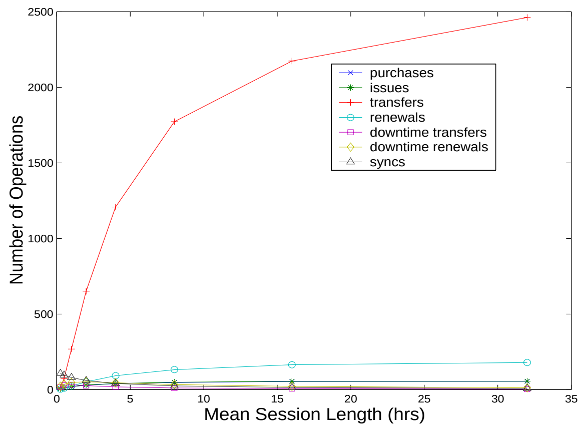


Figure 4: Average Peer Load: Policy I + Pro Sync

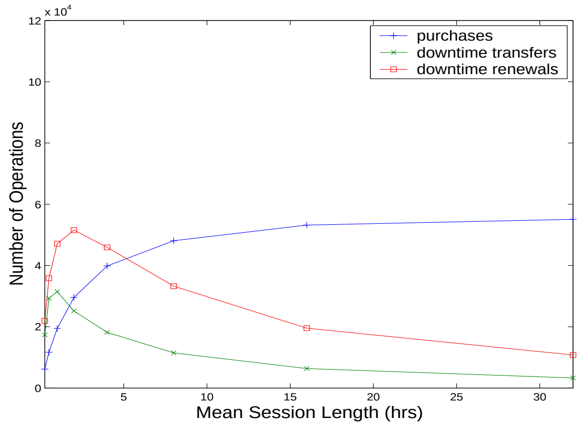


Figure 3: Broker Load: Policy I + Lazy Sync

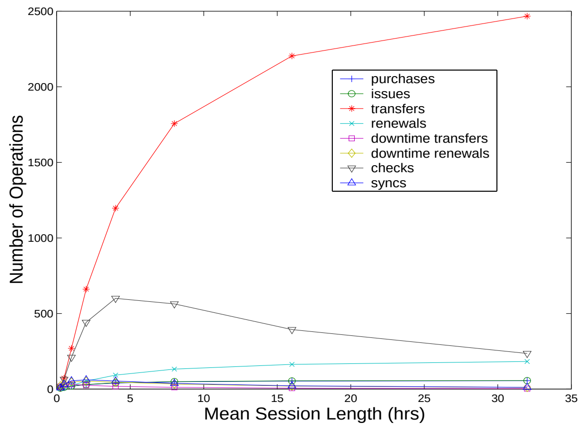


Figure 5: Average Peer Load: Policy I + Lazy Sync

costs of such operations as purchases and transfers. We look at two aspects of the cost: CPU cost and communication cost. Communication cost is the easy one to deal with, as we can pretty much determine (approximately) the number of messages and bits transmitted for each operation from the protocol specification alone. Since most of these messages can be sent in one packet, we will let the communication cost of each operation be proportional to the number of messages sent/received rather than the number of bits.

As for CPU cost, we observe that the costs of these operations are dominated by micro-operations including key pair generation, regular or group signature generation, and regular or group signature verification. For example, for peers, each transfer involves 1 key pair generation, 4 signature generations, 4 signature verifications, 1 group signature generation, and 1 group signature verification. Using the Bouncy Castle Crypto Package [2], we measured the CPU time it takes to perform 10,000 DSA 1024-bit key generations, 10,000 DSA 1024-bit signature generations, and 10,000 DSA 1024-bit signature verifications on a RedHat Enterprise Linux ES release 3 machine with a 3.06GHz Intel(R) Xeon(TM) CPU. The results are shown in Table 2.

We did not find detailed results about the complexity of group signature schemes in the literature, other

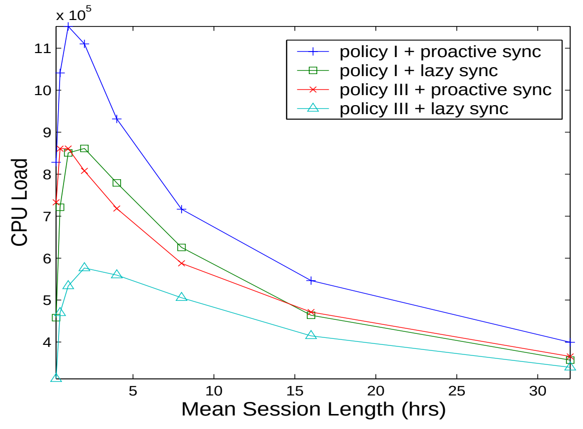


Figure 6: Broker CPU Load

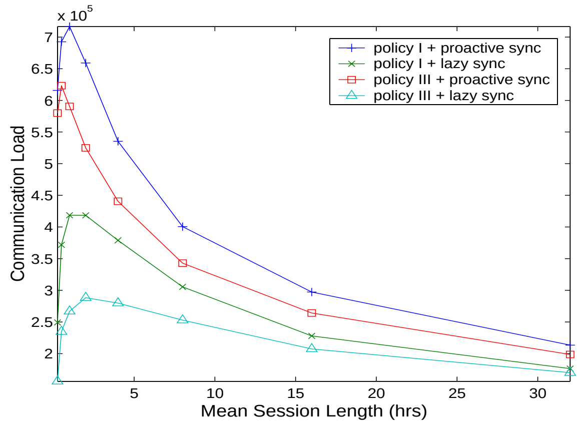


Figure 7: Broker Communication Load

than that they have been traditionally much more expensive than regular signature schemes but more efficient group signature schemes have been proposed in recent years [4, 6, 16]. In our analysis we are forced to make a wild guess that efficient group signature schemes exist such that signature generation and verification are twice as expensive as regular signature generation and verification. Therefore, using the cost of key pair generation as the base unit, we assume the relative costs of these micro-operations as shown in Table 3.

With these cost metrics, we can now obtain the total CPU and communication loads on the broker under different configurations, as shown in Figures 6 and 7. The plots reveal two things. First, lazy synchronization cuts down broker load significantly. Second, the results apparently agree with our conjecture that the broker-centric policy yields less load on the broker than the user-centric policy.

Figures 8 and 9 plot the broker-peer load ratio. Note only the data corresponding to low peer availability is shown. With extremely low peer availability, broker load is two orders higher than average peer load. With higher peer availability (i.e., 4hr-32hr mean online session lengths), broker load is one order higher than average peer load. In either case, considering that we use 1000 peers in our simulations, the majority of the load is supported by the peers, rather than by the broker.

Table 3: Relative Operation Cost

Operation	Relative CPU cost
key pair generation	1
regular signature generation	2
regular signature verification	2
group signature generation	4
group signature verification	4

Load Scaling. In the second set of simulations, we fix peer availability at 50% and vary the size of the system from 100 peers up to 1000 peers, expecting that broker load will grow sublinearly with total system load. The reasoning behind such an expectation is that payment (transfer in particular) is the dominant transaction type, and with a larger peer pool, peers will have better chances of finding an online coin at the time of payments and thus avoid contacting the broker. Unfortunately, as shown in Figures 10 and 11, our simulation results contradict this hypothesis: the broker load grows about linearly with the total system load, rather than sublinearly.

We attribute this unexpected result to our oversimplified simulation model. In our simulation, peers are uniform: they act independently and select payees totally at random. Since we use a globally uniform peer availability, each payment event has the equal probability of requiring the involvement of the broker. As a result, broker load grows linearly with total system load. In reality, we are more likely to see power-law peers, where a small number of active peers are responsible for a large portion of total system activities. We can expect these peers to have good reputation and be highly reliable. Peers are more willing to do business with such super peers. As system grows, this pool of super peers will also grow, and peers will have better chances of finding a coin owned by a super peer (who is most likely online) at the time of payments. As a result, broker load will probably grow sublinearly with total system load. Certainly we need to do more simulation work to verify the validity of this conjecture.

On the other hand, even with linearly scaling broker load, our system is able to relieve the broker of around 95% of the system load and we feel it is a major improvement over previous centralized systems.

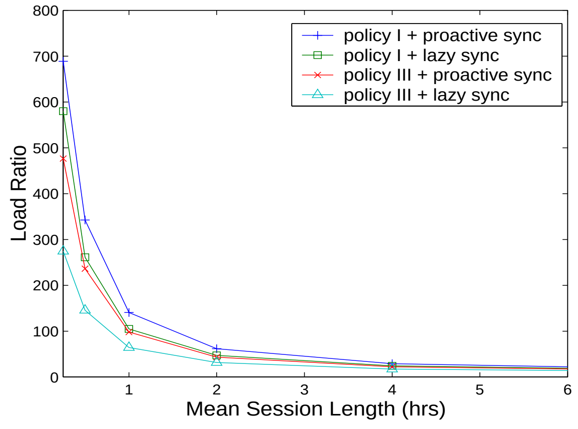


Figure 8: Broker-Peer CPU Load Ratio

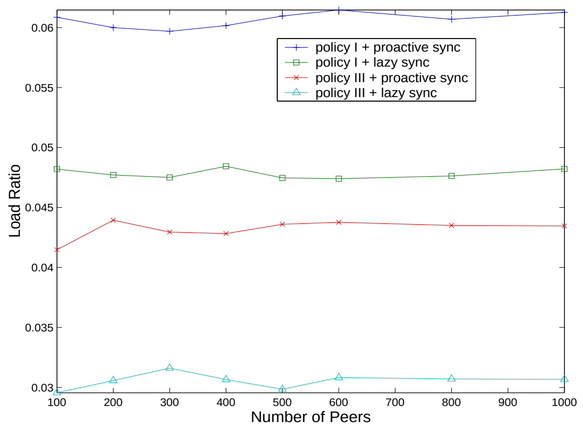


Figure 10: Broker CPU Load Scaling

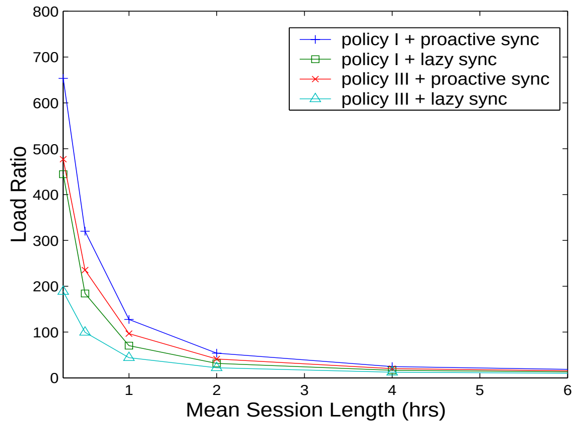


Figure 9: Broker-Peer Communication Load Ratio

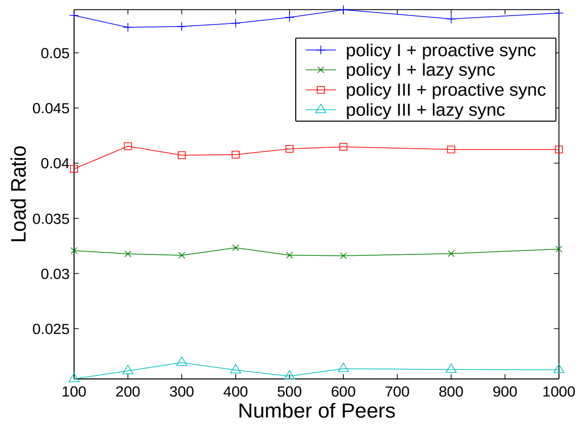


Figure 11: Broker Communication Load Scaling

In summary, as peer availability increases, broker load decreases and peer load increases. Both the broker-centric policy and lazy synchronization cut down broker load significantly. Transfer dominates peer load and transfer-via-owner is the dominant payment type. Most of the system load is handled by peers, rather than by the broker.

7 Related Work

We got the idea of using public keys to represent coins from the Burk-Pfitzmann anonymous transfer system [3]. The Vo-Hohenberger scheme [29] adds fairness to Burk-Pfitzmann with the use of group signatures. Both are online transfer systems, as is WhoPay; but while Who-Pay distributes transfer load across peers, each transfer in Burk-Pfitzmann and Vo-Hohenberger needs to go through a central entity.

An alternative to these online transfer systems, quite naturally, is offline transfer systems. For example, peers can transfer coins by using layers: each time a coin is transferred, the current holder of the coin simply adds another layer of signature to the coin, which serves as a proof of relinquishment. Group signatures can be used to provide fairness without compromising anonymity. No third party is involved in the transfer and thus the scheme is extremely scalable. This scheme suffers two major problems though. First, coins grow in size after each transfer. Second, double spending is easier to commit and harder to defend than in online transfer systems. It has no real-time double spending detection. Anyone can double spend in this scheme, while in Who-Pay only coin owners can double spend. Nonetheless, layered coins can be a lightweight alternative to transfer-via-broker when coin owners are offline. To alleviate the size and security problems mentioned above, a maximum number of layers can be imposed.

Micropayment schemes are designed to handle payments of small amount, e.g., less than \$5. These schemes must be lightweight, otherwise the cost will outweigh the value of the payment. Their basic approach is to aggregate many small micropayments into a few bigger payments. Early examples include PayWord [24] and Electronic Lottery Tickets [23], both of which use secure hash chains, albeit in different ways. These algorithms, however, only allow aggregation by an individual merchant and thus are limited by the frequency of a given consumer's purchases with that merchant. More recently, schemes have been designed to allow aggregation across multiple consumers and multiple merchants. These schemes generally involve a third party payment service provider that sits between consumers and merchants and performs the aggregation for the merchants. Some of these schemes, including BitPass [1], Firstgate [11] and Paystone [18], require pre-enrollment or pre-deposit of funds with the payment service provider, while others, including PepperCoin [19], don't.

While WhoPay is not specifically designed as a micropayment scheme, it can certainly be extended to support micropayment. For example, we can use a scheme such as PayWord to first aggregate small micropayments into bigger payments and carry out the bigger payments using WhoPay. That is, each pair of users maintains a soft credit window between themselves and only makes payments when this window reaches a threshold value.

8 Conclusions

An electronic payment system ideally should provide security, anonymity, fairness, transferability and scalability. Existing payment schemes often lack either anonymity or scalability. In this paper we proposed WhoPay, a peer-to-peer payment system that provides all the above properties. For anonymity, we represent coins with public keys; for scalability, we distribute coin transfer load across all peers, rather than rely on a central entity such as the broker. This basic version of WhoPay is as secure and scalable as existing peer-to-peer payment schemes such as PPay, while providing a much higher level of user anonymity. We also introduced the idea of real-time double spending detection by making use of distributed hash tables (DHT), which further improves the security level of WhoPay. Through simulations, we have shown that WhoPay should scale well under typical operating conditions.

A trusted DHT infrastructure that supports access control and a register/notification mechanism is essential to WhoPay's real-time double spending detection mechanism. More work in this area is needed.

9 Acknowledgments

We would like to thank Kiem-Phong Vo and Doug Tygar for their valuable comments that helped us improve the quality of this paper.

References

[1] Bitpass. http://www.bitpass.com.

[2] Bouncy castle crypto apis. http://www.openjce.org.

[3] H. Burk and A. Pfitzmann. Digital payment systems enabling security and unobservability. *Computers and Security*, 8:399–416, 1989.

[4] J. Camenisch and M. Michels. A group signature scheme with improved efficiency. *Lecture Notes in Computer Science*, 1514:160–174, 1998.

[5] J. Camenisch, J. Piveteau, and M. Stadler. An efficient fair payment system. In *Third ACM Conference on Computer and Communications Security*, pages 88–94, 1996.

[6] J. Camenisch and M. Stadler. Efficient group signature schemes for large groups. *Lecture Notes in Computer Science*, 1296:410–424, 1997.

[7] M. Castro, P. Druschel, A.-M. Kermarrec, and A. Rowstron. Scribe: A large-scale and decentralized application-level multicast infrastructure. *IEEE Journal on Selected Areas in Communications (JSAC) (Special issue on Network Support for Multicast Communications)*, 2002.

[8] M. Castro, P. Druschel, A.-M. Kermarrec, and A. Rowstron. Scalable application-level anycast for highly dynamic groups. In *Proceedings of NGC 2003*, September 2003.

[9] D. Chaum. Blind signature system. *Advances in Cryptology*, 1983.

[10] D. Chaum and E. V. Heyst. Group signatures. *Lecture Notes in Computer Science*, 547:257–265, 1991.

[11] Firstgate. http://www.firstgate.com.

[12] M. Freedman, E. Sit, J. Cates, and R. Morris. Tarzan: A peer-to-peer anonymizing network layer. In *Proceedings for the 1st International Workshop on Peer-to-Peer Systems*, 2002.

[13] D. Geer. E-micropayments sweat the small stuff. *Computer*, 37(8), August 2004.

[14] K. Hildrum, J. Kubiatowicz, S. Rao, and B. Zhao. Distributed object location in a dynamic network. In *Proceedings of the Fourteenth ACM Symposium on Parallel Algorithms and Architectures (SPAA'02)*, August 2002.

[15] Kazaa. http://www.kazaa.com.

[16] W. Lee and C. Chang. Efficient group signature scheme based on the discrete logarithm. In *IEE Proceedings Comput. Digit. Tech. 145*, number 1, pages 15–18, 1998.

[17] Paypal. http://www.paypal.com.

[18] Paystone. http://www.paystone.com.

[19] Peppercoin. http://www.peppercoin.com.

[20] S. Ratnasamy, P. Francis, M. Handley, R. Karp, and S. Shenker. A scalable content-addressable network. In *Proceedings of ACM SIGCOMM*, September 2001.

[21] S. Ratnasamy, M. Handley, R. Karp, and S. Shenker. Application-level multicast using content-addressable networks. In *Proceedings of NGC 2001.*

[22] M. Reed, P. Syverson, and D. Goldschlag. Anonymous connections and onion routing. *IEEE Journal on Selected Areas in Communication Special Issue on Copyright and Privacy Protection*, 1998.

[23] R. Rivest. Electronic lottery tickets as micropayments. In *Proceedings of Financial Cryptography Conference*, 1997.

[24] R. Rivest and A. Shamir. Payword and micromint: Two simple micropayment schemes. In *Proceedings of 1996 International Workshop on Security Protocols.*

[25] A. Rowstron and P. Druschel. Pastry: Scalable, distributed object location and routing for large-scale peer-to-peer systems. In *IFIP/ACM International Conference on Distributed Systems Platforms (Middleware)*, pages 329–350, November 2001.

[26] A. Shamir. How to share a secret. *Communications of the ACM*, 22:612–613, 1979.

[27] I. Stoica, D. Adkins, S. Zhuang, S. Shenker, and S. Surana. Internet indirection infrastructure. In *Proceedings of ACM SIGCOMM*, August 2002.

[28] I. Stoica, R. Morris, D. Karger, M. F. Kaashoek, and H. Balakrishnan. Chord: A scalable peer-to-peer lookup service for internet applications. In *Proceedings of ACM SIGCOMM*, September 2001.

[29] B. Vo and S. Hohenberger. A fair payment system with online anonymous transfer.

[30] B. Yang and H. Garcia-Molina. Ppay: Micropayments for peer-to-peer systems. In *Proceedings of the 10th ACM Conference on Computer and Communications Security (CCS)*, 2003.

[31] S. Zhuang, B. Zhao, A. Joseph, R. Katz, and J. Kubiatowicz. Bayeux: An architecture for scalable and fault-tolerant wide-area data dissemination. In *The 11th International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV)*, 2001.