Generalized HTLC for Cross-Chain Swapping of Multiple Assets with Co-Ownerships

Krishnasuri Narayanan  
IBM Research, India  
knaraya3@in.ibm.com

Venkatraman Ramakrishna  
IBM Research, India  
vramakr2@in.ibm.com

Dhinakaran Vinayagamurthy  
IBM Research, India  
dvinaya1@in.ibm.com

Sandeep Nishad  
IBM Research, India  
sandeep.nishad1@ibm.com

Abstract—A core enabler for blockchain or DLT interoperability is the ability to atomically exchange assets held by mutually untrusting owners on different ledgers. This atomic swap problem has been well-studied for several years, with the Hash Time Locked Contract (HTLC) emerging as a canonical solution. HTLC ensures atomicity of exchange, albeit with caveats for node failure and timeliness of claims. But a bigger limitation of HTLC is that it only applies to a model consisting of two adversarial parties having sole ownership of an asset each. Realistic extensions of the model in which assets may be jointly owned by multiple parties, all of whose consents are required for exchanges, or where multiple assets must be exchanged for one, cannot be handled by HTLC because these scenarios present distinctly new threats of collusions among subsets of parties. In this paper, we generalize the model of asset exchanges across DLT networks, present the consequent threat model, and propose and analyze an augmented HTLC protocol for atomic multi-party-and-asset exchanges. We also show how our protocol can be implemented easily by augmenting existing HTLC capabilities in the Weaver interoperability framework to enable asset exchanges between networks built on Hyperledger Fabric or Corda.

Index Terms—blockchain, distributed ledger technology, asset exchange, HTLC, shared assets, co-ownership

I. INTRODUCTION

The presence of diverse blockchain and distributed ledger technologies (DLTs) and the continued existence of networks built on them have spurred research [1], [2], development [3], [4], and standardization [5], [6] efforts in interoperability. The popularity of permissioned networks (which restrict membership and ledger visibility to authorized parties) in industry, and the resulting fragmentation of the blockchain ecosystem, with siloed assets and disconnected business processes, have only increased the salience of these efforts. Interoperability poses challenges on different levels, from communication (protocol units and data formatting) to cross-ledger transactions to policy management. Most specific to DLT (as opposed to networking in general) are cross-ledger transactions, which can be broadly categorized into distinct interoperation modes [6]:

- **Asset Transfer:** transfer of asset from an owner in one ledger/network to an owner in another
- **Asset Exchange:** atomic exchange of assets in two different ledgers/networks (we will use these interchangeably) between a pair of owners
- **Data Transfer:** communicating state information from one ledger/network to another with proof [1], [7]

In this paper, we focus solely on the relatively prominent asset exchange (or atomic swap) problem [8]. The canonical example goes as follows. Alice and Bob possess accounts in both the Bitcoin and Ethereum Main networks. They come to an (offline) exchange agreement whereby Alice will give Bob 10 BTC in exchange for, say, 12 ETH. The final outcome of an exchange, or atomic swap, is that a transfer of 10 BTC from Alice to Bob is confirmed on the Bitcoin network while simultaneously a transfer of 12 ETH from Bob to Alice is confirmed on the Ethereum Mainnet. Both transfers occur or neither does, ideally without requiring a trusted mediator or complex synchronization (using a global clock) between the two networks. A similar example can be conceived between two permissioned networks too, built on Hyperledger Fabric and Corda for example, using tokens designed for those DLT platforms [9], [10]. Just for added motivation, here is another example that is quite salient in the Decentralized Finance (DeFi) world [11]. Consider a DLT network where different commercial banks possess retail accounts of Central Bank Digital Currency (CBDC) and another DLT network where banks allow investors to trade securities (e.g. bonds). The transfer of a bond on the latter must simultaneously accompany a CBDC payment on the former [12].

Fig. 1: Asset Exchange (Atomic Swap) Model

From these examples, we can extrapolate a general model of exchanging an asset M, owned by party X in network A, for asset N, owned by party Y in network B (Figure 1). The canonical solution to complete such atomic swaps is the **Hash Time Locked Contract (HTLC)** [13]. This describes both a contract that supports the locking and claiming of an asset within a fixed time duration and a protocol (see Figure 2), whose "happy path" is as follows:

- X hashes secret s to produce H = Hash(s)
- X locks M on Network A with H as guard for duration T using a blockchain or smart contract transaction
• Y similarly locks N on Network B with H (now publicly known) for duration $T/2$
• X claims N on B by revealing $s$ (which, when hashed, must match $H$) via a transaction within $T/2$
• Y similarly claims M on A by supplying $s$ (now publicly known) after X’s claim but within $T$

Fig. 2: Hash Time Locked Contract (HTLC) Protocol

Key elements that make this protocol work are (i) both X and Y have visibility into both ledgers, whether they be in public or permissioned networks, (ii) X’s secret is revealed to Y only after both assets are locked, (iii) the secret is revealed in public within a transaction block, thereby allowing Y to use it, and (iv) Y has sufficient time (at least $T/2$) to make a claim after X does so by revealing $s$. To support HTLC, a DLT platform must offer a capability to lock an asset (or, more generally, enforce any constraint) for a fixed time duration.

Can HTLC be generalized to support atomic exchanges of more than two assets and joint ownership (or co-ownership) of assets by multiple parties? As an example, let us add party W to our model so that X and W jointly own M in A (Figure 3), with the desired outcome of X and W co-owning N in B and Y owning M in A. In a different example, W owns a third asset R in A, and the desired outcome is that Y acquires M and R in A in exchange for transferring N in B jointly to X and W (Figure 4). Though these scenarios seem superficially similar to the base case, application of the basic HTLC protocol in either is susceptible to attack whereby X can cheat W by colluding with Y so that W loses ownership of its asset while both X and Y gain something, as we will see in Section II. Addressing this flaw and creating a generalized HTLC solution for a generalized asset exchanges is the goal of this paper.

In Section II we generalize the asset exchange (or atomic swap) problem, and model the scenarios and resulting threats. Our solution for the general model that handles these threats is covered in Section II and analyzed in Section IV. Implementation considerations are discussed, and guidelines presented, in Section V. After covering related work in Section VI, we conclude with suggestions for future work in Section VII.

II. PROBLEM AND THREAT MODELING

We extrapolate a generalized asset exchange model between groups of parties across two distinct ledgers from the examples illustrated earlier involving multiple assets and co-ownerships. Later in this section, we will show why the basic HTLC technique when applied to this model is prone to attack, thereby motivating the need for a new solution.

A. Asset Co-Ownership

Before describing the model, we will define precisely what we mean by co-ownership of an asset and state the properties expected from a blockchain or DLT to enforce such co-ownership.

To understand co-ownership, we must understand ownership first. Conventionally, ownership of an asset in any blockchain or smart contract system refers to the possession of sole authority over any property or ownership changes or locking ability (carried out through transactions) associated with that asset. The properties of an asset are subject to change according to rules defined in scripts (e.g., Bitcoin [14]) or contracts (e.g., Ethereum [15], Hyperledger Fabric [16]). An asset can also be transferred from one owner to another, or locked so that the asset state cannot be modified until certain constraints are fulfilled. Blockchain/DLT systems are expected to limit property and ownership changes and locking abilities to rightful owners through consensus mechanisms and well-written scripts/contracts.

Co-ownership refers to the ability of a blockchain or smart contract system to enforce similar integrity rules on assets but where the owner is a collective rather than a single entity. Any state update or transfer or lock must require the unanimous consent of every co-owner in the collective. A canonical way to enforce this is multisig, or multiple signatures, [17], [18], though other techniques can be used as well. Our minimal expectation from a blockchain or smart contract system is its ability to enforce unanimous consent on asset modifications. The system may do more, like manage shares or stakes for co-owners. We defer it to future work to study those settings.
B. Generalized Asset Exchange Model

In a nutshell, we are modeling the problem of atomically changing the co-ownership configurations of assets in two independent ledgers, where the co-owners across all assets are drawn from a common and closed group of parties.

Definition 1 (generalized asset exchange: $\mathcal{GAE}$). This is a tuple $\langle \mathcal{L}_1, \mathcal{L}_2, \mathcal{P}, \mathcal{A}_1, \mathcal{A}_2, \mathcal{IO}_1, \mathcal{IO}_2, \mathcal{AE}_1, \mathcal{AE}_2, \mathcal{FO}_1, \mathcal{FO}_2 \rangle$ where:

- $\mathcal{L}_1$ and $\mathcal{L}_2$ are two distinct ledgers
- $\mathcal{P}$ is a common set of parties possessing accounts in both $\mathcal{L}_1$ and $\mathcal{L}_2$
- $\mathcal{A}_1$ is a set of assets on $\mathcal{L}_1$
- $\mathcal{A}_2$ is a set of assets on $\mathcal{L}_2$
- $\mathcal{IO}_1$ is the initial asset ownership function in $\mathcal{L}_1$, defined as $\mathcal{IO}_1: \mathcal{A}_1 \rightarrow 2^{\mathcal{P}} - \{\emptyset\}$
- $\mathcal{IO}_2$ is the initial asset ownership function in $\mathcal{L}_2$, defined as $\mathcal{IO}_2: \mathcal{A}_2 \rightarrow 2^{\mathcal{P}} - \{\emptyset\}$
- $\mathcal{AE}_1$ is a set of assets in $\mathcal{L}_1$ to be exchanged, where $\mathcal{AE}_1 \subseteq \mathcal{A}_1$
- $\mathcal{AE}_2$ is a set of assets in $\mathcal{L}_2$ to be exchanged, where $\mathcal{AE}_2 \subseteq \mathcal{A}_2$
- $\mathcal{FO}_1$ is the final asset ownership function in $\mathcal{L}_1$ after the exchange, defined as $\mathcal{FO}_1: \mathcal{A}_1 \rightarrow 2^{\mathcal{P}} - \{\emptyset\}$, where:
  - $\forall a \in \mathcal{A}_1 - \mathcal{AE}_1, \mathcal{FO}_1(a) \mapsto \mathcal{IO}_1(a)$, and
  - $\forall a \in \mathcal{AE}_1, \mathcal{FO}_1(a) \subseteq \bigcup_{e \in \mathcal{AE}_1} \mathcal{IO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_2} \mathcal{IO}_2(e)$
- $\mathcal{FO}_2$ is the final asset ownership function in $\mathcal{L}_2$ after the exchange, defined as $\mathcal{FO}_2: \mathcal{A}_2 \rightarrow 2^{\mathcal{P}} - \{\emptyset\}$, where:
  - $\forall a \in \mathcal{A}_2 - \mathcal{AE}_2, \mathcal{FO}_2(a) \mapsto \mathcal{IO}_2(a)$, and
  - $\forall a \in \mathcal{AE}_2, \mathcal{FO}_2(a) \subseteq \bigcup_{e \in \mathcal{AE}_2} \mathcal{IO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_1} \mathcal{IO}_2(e)$

The initial owners are also part of the final owners list:

- $\forall a \in \mathcal{AE}_1, \mathcal{IO}_1(a) \subseteq \bigcup_{e \in \mathcal{AE}_1} \mathcal{FO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_2} \mathcal{FO}_2(e)$,
- $\forall a \in \mathcal{AE}_2, \mathcal{IO}_2(a) \subseteq \bigcup_{e \in \mathcal{AE}_2} \mathcal{FO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_1} \mathcal{FO}_2(e)$.

In plain language, $\mathcal{GAE}$ represents the atomic swap of a set of assets in one ledger with a different set of assets in another. The standard atomic swap assumption of common parties across ledgers is represented by $\mathcal{P}$. Co-ownership of assets are represented by the definitions of $\mathcal{IO}_1$ and $\mathcal{IO}_2$ where each asset maps to a subset of $\mathcal{P}$. The definitions of $\mathcal{FO}_1$ and $\mathcal{FO}_2$ indicate that the final co-owners of each asset being swapped are drawn from the set of parties that co-owned at least one of the assets being swapped in either ledger; the function mappings remain unchanged for assets outside the swap lists $\mathcal{AE}_1$ and $\mathcal{AE}_2$. We also have each initial co-owner co-owning an asset finally. Hence, from the last two conditions, we have that $\bigcup_{e \in \mathcal{AE}_1} \mathcal{IO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_2} \mathcal{IO}_2(e) = \bigcup_{e \in \mathcal{AE}_1} \mathcal{FO}_1(e) \cup \bigcup_{e \in \mathcal{AE}_2} \mathcal{FO}_2(e)$. Figure 5 illustrates this model with an instance.

Note that we exclude trivial instances of a party simply transferring or giving co-ownership of an asset to another party without receiving anything in return (i.e., a local transfer) from the $\mathcal{GAE}$ model as this does not require anything other than a smart contract transaction on a single ledger.

![Generalized 2-Ledger Asset Exchange](image)

Fig. 5: Generalized 2-Ledger Asset Exchange (in the example, X and U obtain co-ownership of Security and Deed in $\mathcal{L}_1$ in exchange for Z, T, and W obtaining co-ownership of House in $\mathcal{L}_2$)

To understand this model better, let us examine some simple but distinct instances of it (we refer to them as base cases):

- **Basic Atomic Swap (BAS)**: This is the scenario illustrated in Figure 1 where $\mathcal{L}_1 = A$, $\mathcal{L}_2 = B$, $\mathcal{P} = \{X, Y\}$, $\mathcal{A}_1 = \{M\}$, $\mathcal{A}_2 = \{N\}$, $\mathcal{IO}_1(M) \mapsto \{X\}$, $\mathcal{IO}_2(N) \mapsto \{Y\}$, $\mathcal{AE}_1 = \{M\}$, $\mathcal{AE}_2 = \{N\}$, $\mathcal{FO}_1(M) \mapsto \{Y\}$, and $\mathcal{FO}_2(N) \mapsto \{X\}$.

- **Co-ownership through Atomic Swap (CAS)**: This is a variation of Basic Atomic Swap in which Party Y ends up co-owning Asset M with Party $A'$ instead of being its sole owner. The only thing that will change in the above definition is $\mathcal{FO}_1(M) \mapsto \{X, Y\}$. This scenario can be extrapolated to arbitrary number of existing owners (instead of just $\{X\}$) and co-owner additions (instead of just $\{Y\}$) while preserving its essential feature.

- **Co-owned Asset Atomic Swap (CAAS)**: This is the scenario illustrated in Figure 3 where X and W are co-owners, initially of M and finally of N. Changes from Basic Atomic Swap are: $\mathcal{P} = \{X, Y, W\}$, $\mathcal{IO}_1(M) \mapsto \{X, W\}$, and $\mathcal{FO}_2(N) \mapsto \{X, W\}$. Hence, the $\mathcal{IO}$ and $\mathcal{FO}$ mappings are as follows: $\mathcal{IO}_1(M) \mapsto \{X, W\}$, $\mathcal{IO}_2(N) \mapsto \{Y\}$, $\mathcal{FO}_1(M) \mapsto \{Y\}$ and $\mathcal{FO}_2(N) \mapsto \{X, W\}$. This scenario can be extrapolated to arbitrary number of co-owners in either ledger (instead of just $\{X, W\}$) or $\{Y\}$ while preserving its essential feature.

- **Multi-Asset Atomic Swap (MAAS)**: This is the scenario illustrated in Figure 4 where Y gets two assets in
exchange for one. Additions to Basic Atomic Swap are: $\mathcal{IO}_1(R) \mapsto \{W\}$ and $\mathcal{FO}_1(R) \mapsto \{Y\}$. Changes to Basic Atomic Swap are: $\mathcal{P} = \{X,Y,W\}$, $A_1 = \{M,R\}$, $\mathcal{AE}_1 = \{M,R\}$, and $\mathcal{FO}_2(N) \mapsto \{X,W\}$. Hence, the $\mathcal{IO}$ and $\mathcal{FO}$ mappings are as follows: $\mathcal{IO}_1(M) \mapsto \{X\}$, $\mathcal{IO}_2(R) \mapsto \{W\}$, $\mathcal{IO}_2(N) \mapsto \{Y\}$, and $\mathcal{FO}_2(M) \mapsto \{Y\}$, $\mathcal{FO}_1(R) \mapsto \{Y\}$, and $\mathcal{FO}_2(N) \mapsto \{X,W\}$. This scenario can be extrapolated to arbitrary number of singly-owned assets (instead of just $\{M,R\}$) or counterparties (instead of just $\{Y\}$) while preserving its essential feature.

The examples in Table I illustrate different scenarios beyond the base cases that can be satisfied by our model, and examples in Figure 5 illustrates another.

**Claim 1.** Every instance of $\mathcal{CAAS}$ can be decomposed into a collection of base cases listed above.

We do not formally prove this but justify it using the given examples as a basis. Case I in Table I is simply an extrapolation of $\mathcal{CAAS}$ where both assets have 2 co-owners each. Case II is an extrapolation of $\mathcal{MAAS}$ where the asset in $\mathcal{L}_2$ has 2 co-owners. Case III is simply an instance of $\mathcal{CAAS}$ where $\mathcal{X}$ retains its co-ownership in $\mathcal{M}$ and plays no role in the exchange. Case IV is a simultaneous application of both $\mathcal{CAAS}$ ($\mathcal{Y}$ gets co-ownership of $\mathcal{M}$ in exchange for $\mathcal{W}$ and $\mathcal{Z}$ co-owning $\mathcal{N}$) and $\mathcal{MAAS}$ ($\mathcal{Y}$ gets co-ownership of $\mathcal{M}$ and $\mathcal{R}$ in exchange for $\mathcal{W}$, $\mathcal{Z}$, and $\mathcal{U}$ co-owning $\mathcal{N}$); $\mathcal{X}$ retains its co-ownership in $\mathcal{M}$ and plays no role in the exchange. Finally, the example in Figure 5 is similar to Case IV as $\mathcal{X}$ and $\mathcal{U}$ exchange $\mathcal{R}$ for $\mathcal{M}$ with $\mathcal{Z}$ and $\mathcal{T}$, and simultaneously get $\mathcal{N}$ too in exchange with $\mathcal{Z}$; $\mathcal{Y}$ and $\mathcal{W}$ retain their co-ownership and play no role in the exchange. If we construct scenarios with more assets and more co-owners, we can similarly decompose them into instances of our base cases.

In cases like III and IV where a party ($\mathcal{X}$) sees no change in its co-ownership of any asset, a blockchain or smart contract system may optionally require its consent to permit other co-owners to trade their shares. This can be done simply by requiring such parties to register their consent on the ledger, which is simply an attestation (using a public key) and is a basic operation supported by any blockchain or smart contract system. Whether or not such consent is part of the ownership model of a given system has no bearing on our problem model or solution and therefore, we will exclude it from subsequent discussion.

**Threat model:** All participants are rational. They can deviate from the specified protocol, collude with other participants and attempt to maximize the value that they gain through the protocol.

**C. Limitations of HTLC for co-ownerships**

Let us apply standard HTLC to our four base cases.

- **BAS:** this is the classic atomic swap and hence can be handled by standard HTLC.
  - **Threats/Attacks:** None

- **CAAS:** using standard HTLC, $\mathcal{X}$ first locks $\mathcal{M}$ using its secret and then $\mathcal{Y}$ locks $\mathcal{N}$ using the same hash. $\mathcal{X}$ and $\mathcal{Y}$ can then claim assets respectively in sequence. The only difference here is that $\mathcal{X}$’s lock permits only co-ownership for another party rather than a full transfer (as in standard HTLC); therefore, $\mathcal{Y}$ will be claiming a co-ownership instead of the full asset in the final step of the protocol.
  - **Threats/Attacks:** None

- **CAAS:** standard HTLC can be applied in two different ways: (i) $\mathcal{X}$ and $\mathcal{W}$ agree offline on a secret; either of them locks $\mathcal{M}$ with its hash and signatures (i.e., consents) of both $\mathcal{X}$ and $\mathcal{W}$, following which $\mathcal{Y}$ locks $\mathcal{N}$ with the same hash; either $\mathcal{X}$ or $\mathcal{W}$ claims $\mathcal{N}$ (on behalf of both parties), and then $\mathcal{Y}$ claims $\mathcal{M}$ (illustrated in Figure 6). (ii) $\mathcal{X}$ and $\mathcal{W}$ independently lock $\mathcal{M}$ using two different secrets, following which $\mathcal{Y}$ locks $\mathcal{N}$ with both the hashes; $\mathcal{X}$ and $\mathcal{W}$ submit claims to $\mathcal{N}$ (by revealing their respective secrets in any order), following which $\mathcal{Y}$ claims $\mathcal{M}$ using both the revealed secrets (illustrated in Figure 6).
  - **Threats/Attacks:** Both approaches are vulnerable to collusion between $\mathcal{Y}$ and one of $\mathcal{X}$ and $\mathcal{W}$ to cheat the other: (i) after $\mathcal{M}$ is locked, either of its co-owners (let’s say $\mathcal{W}$) may strike a deal with $\mathcal{Y}$ to give $\mathcal{M}$ away (using the same hash lock) and $\mathcal{Y}$ in turn will lock $\mathcal{N}$ only for that party (in this case, $\mathcal{W}$) rather than jointly to $\mathcal{X}$ and $\mathcal{W}$; $\mathcal{W}$ may also provide some other incentive to $\mathcal{Y}$ to encourage it to collude against $\mathcal{X}$; since $\mathcal{X}$ has already locked away its co-ownership of $\mathcal{M}$ using a secret that $\mathcal{W}$ also possesses, it is left at a disadvantage (ii) if $\mathcal{W}$ submits its claim in $\mathcal{L}_2$ first by revealing its secret, $\mathcal{X}$ may avoid revealing its secret and submitting a claim, following which $\mathcal{Y}$ may allow its earlier lock to lapse and instead lock $\mathcal{N}$ again only in favor of $\mathcal{X}$; having revealed its secret, $\mathcal{W}$ is now at a disadvantage as $\mathcal{Y}$ can claim its share of $\mathcal{M}$ but $\mathcal{X}$ now will get all of $\mathcal{N}$ instead of having to co-own it with $\mathcal{W}$. In this protocol, the party that acts first (i.e., submits a claim) stands at a disadvantage as its co-owner may collude with its counterparty(ies) to rob it of its rightful share of an asset.
### Initial Asset Ownership

|   | \(L_1\) | \(L_2\) |
|---|---|---|
| I | \(X\) and \(Y\) own \(M\) | \(Z\) and \(W\) own \(N\) |
| II | \(X\) owns \(M\) and \(Y\) own \(K\) | \(Z\) and \(W\) own \(N\) |
| III | \(X\), \(W\), and \(Z\) own \(M\) | \(Y\) owns \(N\) |
| IV | \(X\), \(W\), and \(Z\) own \(M\) and \(U\) owns \(K\) | \(Y\) owns \(N\) |

### Final Asset Ownership

|   | \(L_1\) | \(L_2\) |
|---|---|---|
| I | \(X\) and \(Y\) own \(M\) | \(Z\) and \(W\) own \(N\) |
| II | \(X\) own \(M\) and \(Y\) own \(K\) | \(Z\) and \(W\) own \(N\) and \(M\) |
| III | \(X\), \(Y\), and \(Z\) own \(M\) | \(Y\) and \(Z\) own \(N\) |
| IV | \(X\), \(Y\), and \(Z\) own \(M\) and \(U\) owns \(K\) | \(Y\) and \(Z\) own \(N\) |

**Table I: Examples of generalized asset exchanges**

![Fig. 7: HTLC Protocol with Multiple Secrets](image)

- **MAAS**: the same techniques used for CAAS can be applied, except that two assets are being locked in \(L_1\) instead of one.
- **Threats/Attacks**: The threat model is identical to that specified for CAAS above.

Standard HTLC is therefore vulnerable to attack when we add co-ownership and multiple assets to a 2-ledger exchange scenario. In the next section, we will describe our solution for \(GA\) that thwarts the attacks identified above.

## III. Solution: Multi-Party Hash Time Locked Contract: MPHTLC

We state that the ledgers are capable of implementing our proposed MPHTLC protocol for the generalized asset exchange \(GA\) model, if the ledgers are capable of implementing the standard HTLC protocol [13] for the classic atomic swap BAS model. In other words, we do not expect any additional capability from the ledgers except that they are able to protect a locked asset from being spent by a party as required by the standard HTLC protocol. This is also known as the ability of the ledgers to enforce hash locks and time locks.

### A. MPHTLC protocol

We make use of the secret sharing scheme in order to achieve the MPHTLC protocol. Let us define \(O_1\) as the set of initial owners of assets in \(AE_1\) (i.e., \(O_1 = \bigcup_{e_1 \in AE_1} IO_1(e_1)\)).

Below are the protocol steps:

1) Let \(x_1, x_2, \ldots, x_n\) be the secrets chosen by the \(n\) parties of \(O_1\) respectively in \(L_1\), where \(|O_1| = n\). They compute a hash \(H = F_1(x_1, x_2, \ldots, x_n)\) where \(F_1\) is an MPC protocol (described in Section III-B) between the \(n\) parties.

2) Each asset \(a \in AE_1\) is locked by one of its initial owners \(IO_1(a)\) using hash \(H\) in \(L_1\) till time \(T\) for the parties in \(FO_1(a)\) (all other initial co-owners of the asset \(a\) are required to sign the transaction if \(|IO_1(a)| > 1\).

3) Each asset \(a \in AE_2\) is locked by one of its initial owners \(IO_2(a)\) using hash \(H\) in \(L_2\) till time \(T/2\) for the parties in \(FO_2(a)\) (all other initial co-owners of the asset \(a\) are required to sign the transaction if \(|IO_2(a)| > 1\). Note that hash \(H\) can be obtained from the ledger \(L_1\).

4) The \(n\) parties of \(O_1\) compute \(x = F_2(x_1, x_2, \ldots, x_n)\) such that \(Hash(x) = H\), using their respective secrets chosen in Step 1 as inputs. Here, \(F_2\) is an MPC protocol (described in Section III-B) between the \(n\) parties.

5) Each asset \(a \in AE_2\) is claimed by one of its final owners \(FO_2(a)\) by revealing the secret \(x\) before time \(T/2\) elapses. Thus, all the parties \(FO_2(a)\) co-own the asset \(a\) in \(L_2\).

6) Each asset \(a \in AE_1\) is claimed by one of its final owners \(FO_1(a)\) by using the secret \(x\) before time \(T\) elapses. Thus, all the parties \(FO_1(a)\) co-own the asset \(a\) in \(L_1\). Note that \(x\) can be obtained from the ledger \(L_2\).

Note that, even if one of the parties in \(O_1\) decides not to reveal its secret in Step 4, then all the assets will be owned by their respective initial owners (\(IO_1\) and \(IO_2\)) in both the ledgers (\(L_1\) and \(L_2\)) at the end of the period \(T\). This is analogous to the sore loser attack [19] in BAS model.

### B. Selection of the MPC functions \(F_1\) and \(F_2\)

The \(n\) parties compute a hash \(H\) by participating in an MPC protocol \(F_1\) with \((x_1, x_2, \ldots, x_n)\) as their respective inputs to output \(Hash\) \((g(x_1, x_2, \ldots, x_n))\), where \(g\) can be any function with the following properties:

1) The output of \(g\) contains sufficient entropy for input from each party, such that inputs of any \(n-1\) parties cannot be used to guess the output with non-negligible probability.

2) The output of function \(g\) need not hide information about the inputs \(x_1, x_2, \ldots, x_n\). This is what differentiates \(g\) from, say, a secret sharing protocol.

3) The onewayness of \(H\) ought to be retained when hashing \(g(x_1, x_2, \ldots, x_n)\) instead of \(x_1, x_2, \ldots, x_n\). Note that the security of HTLC assumes the onewayness of \(H\) on randomly chosen inputs.

In our instantiation, \(g\) can just be an identity function, which outputs \(x_1, x_2, \ldots, x_n\). But if our MPHTLC protocol is used as a module in another protocol and additional constraints are to be enforced, any \(g\) satisfying these properties can be supported. Any maliciously secure MPC protocol with fairness can be used for \(F_1\), where the fairness property guarantees that either all the parties get the output or none of them do.
The MPC protocol $F_2$ between $n$ parties of $O_1$ in $L_1$ involves computing $x = g(x_1, x_2, \ldots, x_n)$ using their respective inputs $x_1, x_2, \ldots, x_n$ chosen in Step 1. Note that $Hash(x) = H$. The MPC protocol is fair and hence either all the parties in $O$ obtain $x$ or none of them do.

a) Fair MPC protocols: a discussion: Fairness in MPC is extensively studied in the cryptography literature, and there are different possibilities of instantiating a fair MPC based on the requirements of $MPHTLC$. It is possible to achieve fairness with just point-to-point secure communication between each pair of individual parties if less than one-third of the parties are malicious [20], [21], and with the use of a broadcast network to protect up to $⌈n/2⌉-1$ parties being malicious [20], [22].

If the goal is to protect against a majority of the parties being malicious, it is proven that the standard definition of fairness is impossible to achieve this without additional assumptions [23], and this impossibility holds even in the presence of a trusted hardware without trusted clocks [24]. There are different relaxed definitions of fairness proposed in the literature that protect against a dishonest majority of parties [25]–[28]. But if a use of $MPHTLC$ demands the standard definition of fairness against a dishonest majority of parties, there are protocols that use public blockchains, financial penalties and sometimes additionally trusted hardware like Intel SGX (to make the protocol more efficient) to enable this [24], [29]–[31].

C. CAAS with $MPHTLC$

We illustrate the working of the $MPHTLC$ protocol in Figure 8 using the CAAS (Co-owned Asset Atomic Swap) model in Figure 3. Below are the actions by the different parties as per the protocol.

1) Let $s_1$ and $s_2$ be the secrets chosen by $\mathcal{X}$ and $\mathcal{W}$ respectively. They compute a hash $H = H_1(s_1, s_2)$ where $F_1$ is a MPC protocol instance agreed by both of them.
2) Party $\mathcal{X}$ locks the asset $\mathcal{M}$ using $H$ in $L_1$ till time $T$ with the signature of the party $\mathcal{W}$ for party $\mathcal{Y}$, or vice versa.
3) Party $\mathcal{Y}$ locks the asset $\mathcal{N}$ using $H$ in $L_2$ till time $T/2$ for both the parties $\mathcal{X}$ and $\mathcal{W}$.

4) Parties $\mathcal{X}$ and $\mathcal{W}$ in $L_1$ compute $s = F_2(s_1, s_2)$ using their respective secrets chosen in Step 1 above where $F_2$ is another MPC protocol instance chosen by them such that $Hash(s) = H$.
5) Party $\mathcal{X}$ (or $\mathcal{W}$) submits a claim on asset $\mathcal{N}$ in $L_2$ by revealing the secret $s$ before time $T/2$ elapses.
6) Party $\mathcal{Y}$ submits a claim on asset $\mathcal{M}$ in $L_1$ by using the secret $s$ (obtained from ledger $L_2$) before time $T$ elapses.

If either of the party $\mathcal{X}$ or $\mathcal{W}$ do not reveal its secret in Step 4, then $\mathcal{X}$ and $\mathcal{W}$ will co-own $\mathcal{M}$ in ledger $A$ and $\mathcal{Y}$ will own $\mathcal{N}$ in ledger $B$ at the end of the period $T$.

D. MAAS with $MPHTLC$

We illustrate the working of the $MPHTLC$ protocol in Figure 9 using the MAAS (Multi-Asset Atomic Swap) model in Figure 4. Below are the actions by the different parties as per the protocol.

1) Let $s_1$ and $s_2$ be the secrets chosen by $\mathcal{X}$ and $\mathcal{W}$ respectively. They compute a hash $H = H_1(s_1, s_2)$ where $F_1$ is a MPC protocol instance agreed by both of them.
2) Party $\mathcal{X}$ locks the asset $\mathcal{M}$ using $H$ in $L_1$ till time $T$ for party $\mathcal{Y}$. Similarly, party $\mathcal{W}$ locks the asset $\mathcal{R}$ using $H$ in $L_1$ till time $T$ for party $\mathcal{Y}$.
3) Party $\mathcal{Y}$ locks the asset $\mathcal{N}$ using $H$ in $L_2$ till time $T/2$ for both the parties $\mathcal{X}$ and $\mathcal{W}$.
4) Parties $\mathcal{X}$ and $\mathcal{W}$ in $L_1$ compute $s = F_2(s_1, s_2)$ using their respective secrets chosen in Step 1 above where $F_2$ is another MPC protocol instance chosen by them such that $Hash(s) = H$.
5) Party $\mathcal{X}$ (or $\mathcal{W}$) submits a claim on asset $\mathcal{N}$ in $L_2$ by revealing the secret $s$ before time $T/2$ elapses.
6) Party $\mathcal{Y}$ submits a claim on asset $\mathcal{M}$ in $L_1$ by using the secret $s$ (obtained from ledger $L_2$) before time $T$ elapses.

If either of the party $\mathcal{X}$ or $\mathcal{W}$ do not reveal its secret in Step 4, then $\mathcal{X}$ will own $\mathcal{M}$ and $\mathcal{W}$ will own $\mathcal{R}$ in ledger $A$ and $\mathcal{Y}$ will own $\mathcal{N}$ in ledger $B$ at the end of the period $T$.

IV. ANALYSIS

We claim below that following the $MPHTLC$ protocol as proposed leads to optimal outcomes for the parties of the asset
swap. Hence our protocol is guaranteed to result in the asset swaps as expected if the parties reveal their respective secrets and compute the hash preimage $x$ in Step 4 of the protocol.

**Claim 2.** Assuming the participants of the generalized asset exchange $GAE$ model are rational, following the proposed $MPHTLC$ protocol is the Nash equilibrium for all the parties involved in the asset swap game $[33]$. Providing a formal proof of our claim above is not in the scope of the current work. However, we provide a high-level game-theoretic argument that supports our claim.

In particular, we argue that if the co-owners of an asset (if $a$ is the asset then $IO_1(a) > 1$ are the co-owners) don’t claim the asset in Step 5 of the $MPHTLC$ protocol after completing the Step 4, then it’s guaranteed that at least one or more co-owners of that asset always get cheated by the parties who would co-own after the asset swap (i.e., by the parties in $FIO_1(a)$).

We illustrate the justification to our argument considering the CAAS with $MPHTLC$ scenario in III-C. If neither of the parties $X$ and $W$ fails to claim the asset $N$ in $L_2$ before time $T/2$ elapses, then party $Y$ strikes a deal with one of them (let’s say $W$) to co-own the asset $N$ and provide incentives in turn. As per this deal, the party $Y$ locks the asset $N$ again only in favor of the party it colluded with (in this case, $W$). Then that party (in this case, $W$) submits a claim on asset $N$ in $L_2$ by revealing the secret $s$ before time $T$ elapses. Immediately, the party $Y$ claims the asset $M$ in $L_1$ by using the secret $s$. Note that both the claims now happen during the period $[T/2, T]$. Assuming all the parties are rational, it benefits the party (in this case, $W$) with whomever the party $Y$ colludes, thus resulting in cheating its initial co-owner (in this case, $X$). Hence, the rational parties $X$ and $W$ would claim the asset $N$ in Step 5 leaving the rational party $Y$ claiming the asset $M$ in Step 6.

This justifies our claim that there is no incentive for the participants of the $GAE$ model to deviate from the proposed $MPHTLC$ protocol and get a better outcome.

There are a variety of blockchain interoperability frameworks like Polkadot [34], Cosmos [35], Cactus [3] and Weaver [4]. Any framework that is capable of exercising the basic HTLC protocol can also exercise our $MPHTLC$ protocol it only needs time locks and hash locks to be supported by the interoperating blockchains.

### A. GAЕ model with more than two ledgers

The discussion till now has focused on parties present in two ledgers. The $GAE$ model naturally extends to the multi-ledger scenario where more than two ledgers are involved. Consider the asset exchange scenario in Figure 10. This is similar to the scenario introduced in Figure 4 (MAAS of $GAE$ model in Section II-B). The only difference here is that the assets $W$ and $R$ reside in different ledgers.

Our $MPHTLC$ protocol can be directly extended to support this multi-ledger scenario. The change from the $MPHTLC$ protocol in Section III-D is to have the locks and claims on the assets applied in the respective ledgers. We defer to future work to formally write down the multi-ledger $GAE$ model, thoroughly investigate the base scenarios and prove that the base cases and the solution to them are complete for a multi-ledger $GAE$.

### V. IMPLEMENTATION GUIDELINES AND CONSIDERATIONS

Any blockchain or DLT that can support HTLC can also support $MPHTLC$ through simple changes in the core logic of the locking and claiming modules. For a DLT to support $MPHTLC$ (or plain HTLC), it needs to be able to support the locking (or freezing) of state for a finite time period (a *time lock*). If that is given, HTLC or $MPHTLC$ capabilities can be built using native scripting or smart contract capabilities without requiring platform modification and chain forks.

A canonical DLT application model has 2 layers: Layer 1 has business logic in contracts which run on peers and update state through consensus, whereas Layer 2 refers to client applications which invoke transactions on contracts. Any asset exchange protocol (HTLC or $MPHTLC$) requires implementation in both layers to protect asset integrity modulo Byzantine failures; just a Layer 2 implementation without decentralized trust (consensus) guarantees cannot protect asset integrity. Core $MPHTLC$ capabilities of locking, claiming, and signature verifications can be built as smart contract capabilities (Layer 1) while client layer apps (Layer 2) can submit lock and claim transaction requests to these contracts.

We will show how an existing atomic swap capability built on HTLC can be augmented to support $MPHTLC$ between permissioned DLTs like Hyperledger Fabric and Corda in the Hyperledger Labs Weaver interoperability project [4]. Note that our protocol can easily be implemented on a permissionless network as well as long as the network supports the basic HTLC.

For Fabric, Weaver supports HTLC through: (i) a special *chaincode* (contract) called the Interop Chaincode that contains hash and time locking, and asset claiming, capabilities, and (ii) client library functions and API to trigger lock and claim transactions from Layer 2. Time locks are enforced in contract logic by comparing the timestamp presented in a claim transaction to a peer’s local time; the assumption is...
that peers’ local times are approximately in sync and therefore a consensus on expiration can be reached. Any asset management application’s chaincode needs to be modified only to trigger locks and claims by invoking the Interop Chaincode. The client portion of that application should also be modified, but only to submit asset lock and claim instructions to its chaincode using the Weaver API and libraries, and expose hashes and secrets after revelation via API functions.

To support MPHTLC, the additional capabilities (over plain HTLC) described in our solution can be implemented directly in the Weaver Interop Chaincode and client SDK. Application developers will need to change very little (just additional API calls in both layers) other than enforce the properties of asset co-ownerships.

In Corda, CorDapps deployed on network nodes scope business logic in contracts (Layer 1) and flows (Layer 2) (see Figure 12). To support HTLC, Weaver offers a special Interop CorDapp that contains features similar to those described earlier for Fabric (locks, claims, and time lock enforcement). Any CorDapp that manages assets must, as in the Fabric case, be augmented to exercise the Interop CorDapp (contract features and client libraries). To support MPHTLC in Weaver, we will just need to make suitable changes in the core HTLC protocol units, with very little work required on the part of an application CorDapp developer.

**VI. RELATED WORK**

Carrying out cross-chain atomic asset exchanges between mutually distrusting parties is studied extensively in [13], [36]–[38]. Reducing the vulnerability due to sore loser attacks (where one party decides to halt participation partway through leaving other party’s assets locked up for long duration) to an arbitrarily low level in n-party swaps is addressed in [19]. A game-theoretic analysis of cross-chain atomic swaps with HTLCs is carried out in [33], [39]. It is proved in [33] that following the swap protocol is a subgame perfect Nash equilibrium in dominant strategies. A concurrent work in [40] proposed a universal atomic swap protocol that does not make any assumptions on the features of the blockchain platform or the scripting functionality of the currencies and only assumes the ability to verify signatures on transactions. But an atomic swap with assets co-owned by a group of mutually distrusting parties (or assets with shared ownership) is not investigated in the literature. In contrast, this work prevents the asset co-owners to carry out swapping an asset with another asset without the consent of all the co-owners of that asset.

**VII. CONCLUSION AND FUTURE WORK**

Cross-chain atomic swaps and the HTLC protocol have been studied in recent years. In this paper, we have presented a general asset exchange model (GAE) whereby assets can be co-owned and multiple assets can be simultaneously exchanged. We have shown that HTLC cannot be applied directly to complete exchanges in GAE because of potential for collusion and fraud. We have presented a solution, MPHTLC (Multi-Party Hash Time Locked Contract), for GAE, and showed using game theory that parties in a GAE exchange achieve a Nash equilibrium. We have demonstrated how the protocol can be easily implemented in the Weaver interoperability framework. We have also observed that MPHTLC can address the multi-ledger GAE problem (i.e., assets exchanged among more than two ledgers) and we defer formalizing a multi-ledger GAE model and an associated MPHTLC protocol to future work.

**REFERENCES**

[1] E. Abebe, D. Behl, C. Govindarajan, Y. Hu, D. Karunamoorthy, P. Novotný, V. Pandit, V. Ramakrishna, and C. Vecchiola, “Enabling enterprise blockchain interoperability with trusted data transfer (industry track),” in Proceedings of the 20th International Middleware Conference Industrial Track. ACM, 2019, pp. 29–35.

[2] R. Belchior, A. Vasconcelos, S. Guerreiro, and M. Correia, “A survey on blockchain interoperability: Past, present, and future trends,” ACM Comput. Surv., vol. 54, no. 8, pp. 168:1–168:41, 2022. [Online]. Available: https://doi.org/10.1145/34771140.

[3] H. Montgomery, H. Borne-Pons, J. Hamilton, M. Bowman, P. Somogyvari, S. Fujimoto, T. Takeuchi, T. Kuhrt, and R. Belchior, “Hyperledger cactus whitepaper,” 2020, Accessed on 15-Dec-2021. [Online]. Available: https://github.com/hyperledger/cactus/blob/master/docs/whitepaper/whitepaper.md.

[4] “Weaver: Interoperability across dlt networks.” Accessed on 15-Dec-2021. [Online]. Available: https://github.com/hyperledger-labs/weaver-dlt-interoperability/blob/main/OVERVIEW.md.
