SUMMARY  Blockchain is a distributed ledger technology used for trading digital assets, such as cryptocurrency, and trail records that need to be audited by third parties. The use cases of blockchain are expanding beyond cryptocurrency management. In particular, the token economy, in which tokenized assets are exchanged across different blockchain ledgers, is gaining popularity. Cross-chain technologies such as atomic swap have emerged as security technologies to realize this new use case of blockchain. However, existing approaches of cross-chain technology have unresolved issues, such as application limitations on different blockchain platforms owing to the incompatibility of the communication interface and crypto algorithm and inability to handle a complex business logic such as the escrow trade. In this study, the ConnectionChain is proposed, which enables the execution of an extended smart contract using abstracted operation on interworking ledgers. Moreover, field experimental results using the system prototype are presented and explained.

key words:  blockchain, token economy, interoperability, cross-chain, smart contract

1. Introduction

Blockchain is a distributed ledger technology used for trading digital assets, such as cryptocurrency, and trail records that need to be audited by third parties. Although several variations of blockchain exist, the following functionalities are commonly provided: “data chaining for ensuring tamper resistance,” “transparency,” and “decentralized management.” The legitimacy of the record on the blockchain ledger cannot be guaranteed because there is no authority verifying the records in the blockchain world. As a countermeasure for this uncertainty, blockchain uses a consensus algorithm in the verification process. Consensus algorithms are less prone to fraud in blockchain networks, where honest nodes dominate the network. Blockchain also uses another approach for verifying the transaction that requires a more complex computation, called “smart contract.” A smart contract is implemented as a small program that can run on any node in the blockchain network. Its computation result can be verified using a consensus algorithm, similar to normal transactions. When the field of blockchain application is expanded beyond cryptocurrency exchange, users may want to trade their owning assets with other assets representing different market values. This corresponds to a token economy, which is a new use case of blockchain. A real token economy requires multiple transfers of digital assets on different blockchains that must be executed immediately. However, this is quite difficult to achieve because any entity cannot be fully trusted in this trade. A smart contract can be a trustworthy party to intermediate the trade; however, the secure operation of the smart contract is limited within the same blockchain owing to the nature of blockchain. To solve this problem, cross-chain technologies such as atomic swap and Polkadot have emerged as security technologies; however, there are application limitations on different blockchain platforms owing to the incompatibility of the communication interface and crypto algorithm and inability to handle a complex business logic such as escrow trade.

Contribution: In this study, a blockchain interworking platform “ConnectionChain” is proposed, which enables the secure trade of digital assets managed on different blockchains. The ConnectionChain is designed to solve the following problems:

1. This variety of choices on blockchain implementations makes it difficult to manipulate these ledgers programmatically because their communication protocol and transaction data format are often incompatible.
2. It is impossible to use a smart contract as the Trusted Third Party for the trade involving transactions on different blockchains because the smart contract can only control assets on the same blockchain.

The remaining of the paper is organized as follows. In Sect. 2, the blockchain basics are summarized. In Sect. 3, the previous work related to the topic discussed in this paper is introduced. The proposed blockchain interworking platform “ConnectionChain” is introduced and detailed in Sect. 4. The feasibility of ConnectionChain is verified by conducting field experiments using a prototype implementation in Sect. 5. The findings of this study and future research directions are summarized in Sect. 6.

2. Background

2.1 Blockchain and Smart Contract

Blockchain is an example of distributed ledger technology, in which independent nodes record transactions and reach a consensus regarding a shared state without any centralized authority. The name blockchain refers to a particular type of
data structure, where each “block” represents a group of digital transactions and the “chain” refers to how each “block” is linked to ensure that the transactions are recorded in a specific, unalterable order. Blockchain has the following three characteristics to safely manage digital assets:

- Data chaining for ensuring tamper resistance
- Transparency
- Decentralized management

These characteristics will be explained for further discussion.

**Data chaining for ensuring tamper resistance**

The world relies on data to make decisions, for example, the number of votes to determine the result of an election, the bank on whether they should grant you a loan, and even in linking a nation state to a cyber attack. The traditional approach against the threats of tampering data is digitally signing on the data using cryptographic techniques. Because the electronic signature itself can be recreated by a manager, it is still difficult to handle data falsification or concealment owing to internal impropriety. Alternatively, it is extremely difficult to change or delete the record of transactions on the blockchain. Every modification in the blockchain is visible to all participants on the blockchain network. Thus, it is almost impossible to make changes without someone noticing them. Public–private keys or cryptographic signatures also ensure the integrity and authentication of transactions.

**Transparency**

The blockchain ledger is accessible to all participants or a predefined set of participants. While access to records can be restricted to certain participants in private or closed blockchains, everyone with an Internet connection to the network has the same rights to access and/or update the ledger in public or open blockchains based on the consensus mechanism in place. Thus, all transactions are transparent and visible, which may increase auditability and trust in the network. However, transparent data might be a problem when certain information needs to be altered later owing to errors, inaccuracies, or other problems in data entry. This is currently one of the most disputed issues, and it is still an unsolved tradeoff between transparency and privacy.

**Decentralized management**

A blockchain is run by a distributed network of participants who do not necessarily trust each other. The trust among the participants in the blockchain is based on a set of rules, i.e., everyone agrees to verify, validate, and add transactions to the blockchain. This is a consensus mechanism. The fact that there is no central entity controlling the system creates a strong resilience for blockchains. There is no central point of failure; additionally, the system is complicated to attack.

Newer blockchain implementation also provides a unique service called a smart contract. Smart contracts are computer programs that can perform the terms of agreements faithfully between parties by executing blockchain transactions without the need for human coordination or intervention. This independence from the user allows smart contract to behave as the Trusted Third Party with internal state management and “if-then” instructions. However, some argue that this is actually a misnomer such that smart contracts are neither “smart” nor “contracts.” Because smart contracts are currently only feasible or applicable under limited and strictly circumscribed conditions.

### 2.2 Token Economy and Blockchain Interoperability

Currently, the blockchain is in the deployment stage and some practical business models are being considered. When the field of blockchain applications is expanded beyond cryptocurrency exchange, users will want to trade their owning assets with other assets, which are expected to increase their market values. This is a new use case of blockchain, called the token economy. The token economy can bring many benefits such as great liquidity, faster and cheaper transactions, more transparency, and more accessibility. To ensure safe issuing and trading of tokens, legal regulators encourage financial institutions to conform to the requirements on the “security token.” Under such circumstances, the momentum for starting commercial services of the token economy is increasing. However, unlike the existing stock exchange market, where the trading market is open, it is necessary for participants to participate in a specific blockchain to buy tokens. The fact that the number of token buyers does not increase reduces the liquidity of tokens. Unfortunately, the difference among blockchain platforms is so large that it is difficult to build interconnected networks to merge the token market. Considering this situation, cross-chain technologies such as atomic swap and Polkadot, which are described in Sects. 3.1 and 3.2, respectively, are rapidly emerging as security technologies absorbing differences in blockchain infrastructures and enhancing interconnectivity between networks.

### 2.3 Consortium Blockchain “Hyperledger Fabric”

The “Hyperledger fabric” has been adopted by many organizations and projects as a consortium blockchain for enterprise use. The Hyperledger fabric is developed and maintained by Hyperledger, one of the biggest open source software communities hosted by the Linux Foundation. As of March 2021, Hyperledger hosts six blockchain platform frameworks, four libraries, five tools, and a group of experimental projects called “LABS,” which are designed to promote them to official projects. The Hyperledger fabric is designed using a modular architecture to adapt to various requirements of a general-purpose blockchain platform. The unique consensus algorithm specially designed for the consortium chain allows the Hyperledger fabric to process hundreds of transactions per second. Furthermore, it does not require mining to maintain the blockchain network. It also supports the key–value store database named “world state,” which can be manipulated only through the smart contract.
These unique characteristics can be useful in implementing complex business logics, such as stateful processing for smart contracts. The prototype implementation of the proposed ConnectionChain uses Hyperledger fabric v1 for the blockchain ledger, which maintains transaction records and enables the running of smart contracts. This is because the Hyperledger fabric provides good extension support that requires network communication in its smart contract feature called the “chaincode.” Additionally, the smart contract can easily program complex stateful business logics because the ledger data of Hyperledger fabric are stored in non-SQLDB.

3. Previous Work

In this section, atomic swap and Polkadot are described as well-known cross-chain technologies that enable interworking between different blockchain ledgers.

3.1 Atomic Swap

Atomic swap ([1], [2]) is a protocol for directly exchanging two types of cryptocurrencies among users. The cross-chain transaction is similar to the money exchange of a dollar into the yen, a legal currency. Still, it is not easy to perform this without intermediaries such as exchange merchants. In an atomic swap transaction, two remittance transactions are performed between each other. These remittance transactions must be atomic in such a way that only one transaction is successful. Any end user who wants to swap their owning digital assets can perform an atomic swap without any privilege. However, it is necessary for both blockchain network supports to run a special smart contract known as the hashed time-lock contract (HTLC).

To understand how this works, the processes will be described step-by-step, considering a case where an exchange transaction is made between Alice (owning litecoins, denoted as LTC) and Bob (owning bitcoins, denoted as BTC). First, Alice creates an HTLC that acts as a safety deposit box to hold LTC coins for swapping. When this HTLC is created, Alice gave the hash-value as a parameter, which HTLC will use for verifying the hash-secret which was used to calculate the hash-value, to authorize the claim() operation later. Note that Bob only knows the hash-value for the HTLC, and he does not know the hash-secret to claim deposited LTC yet. Next, Bob creates another HTLC for BTC using the hash-value that Alice shares to deposit his BTC here. After Alice confirmed Bob’s deposit, Alice executes the claim() operation at Bob’s created HTLC along with the hash-secret to receive the BTC deposited by Bob. Because Bob can observe the hash-secret on Alice’s claim() operation, Bob can execute the claim() operation on HTLC for LTC to receive the LTC deposited by Alice now.

The word atomic relates to the fact that transactions in these pairs are either successful or canceled. If one party fails to fulfill the expected role, the contract is canceled and the assets are automatically returned to the owner. Atomic swaps can be either on-chain or off-chain. On-chain atomic swaps occur in a network (in this case, bitcoin or light coin blockchain) of the currency being swapped. Alternatively, off-chain atomic swaps occur at the second layer. One example of a second layer implementation is a payment channel in a lightning network.

3.2 Polkadot

Polkadot ([3], [4]) is a network protocol that allows arbitrary data to be transferred across blockchains. Polkadot can build a multichain application environment that obtains data from a private blockchain and uses the data on a public blockchain. Polkadot unites a network of heterogeneous blockchains called parachains and parathreads. These chains connect to and are secured by Polkadot’s main network called the relay chain. They can also connect with external networks via bridges. Parachains are specialized blockchains connected with the Polkadot. The parachains can be customized for any number of uses and fed into the main chain so that parachain transactions benefit from the same security of the main chain. The interactions on parachains are processed in parallel, enabling the Polkadot network to be a highly scalable system. The transactions can be scattered across the chains, allowing more transactions to be processed in the same duration. Typical blockchains can only process dozens of transactions per second. However, Polkadot behaves like a huge virtual blockchain that can process thousands of transactions per second, operating a large number of interconnected parachains in parallel.

3.3 Existing Issues

While the realization of the token economy is expected to be a new use of blockchain, and the trade of token assets requires cross-chain technologies such as the atomic swap are emerging. However, existing cross-chain technologies could not solve some problems in the token economy use case.

For example, the atomic swap requires that compatible HTLC functionality be deployed on both the source and destination blockchain networks. Furthermore, the atomic swap requires some off-chain communications and observations of transactions by users. Thus, it is difficult to ma-
The following problems:

of the token economy. The ConnectionChain aims to solve

Herein, a new approach for interworking blockchains, called

is proposed, which provides a better in-

forcement for trading tokenized digital assets in the context

“ConnectionChain,” is proposed, which provides a better in-

with awareness of the trade context with neutral entities

involving multiple blockchains should control each transac-

same blockchain, but it is impossible for those on a di-

using a smart contract if all transactions are executed on the

cause a problem when the trade consisted of more than one

Let’s assume that the trade is expected that the

second transaction should be executed only when the first

transaction is successfully committed. When the trade was

executed, the second transaction failed because the account

balance was not sufficient. Since the user expects the trade

is handled as a single set of transactions, the first transaction

should be canceled if the second transaction failed. But im-

mutability of blockchain does not allow any entity to cancel

any finalized transaction. This scenario can be implemented

using a smart contract if all transactions are executed on the

same blockchain, but it is impossible for those on a different

blockchain. Thus, the system that can handle such trade

involving multiple blockchains should control each transac-

with awareness of the trade context with neutral entities

involved, such as escrow transactions.

4. Proposal

Herein, a new approach for interworking blockchains, called

“ConnectionChain,” is proposed, which provides a better in-

frastructure for trading tokenized digital assets in the context

of the token economy. The ConnectionChain aims to solve

the following problems:

1. This variety of choices on blockchain implementations

makes it difficult to manipulate these ledgers programmatic-

ally because their communication protocol and

transaction data format are often incompatible.

2. It is impossible to use a smart contract as the Trusted

Third Party for the trade involving transactions on differ-

ent blockchains because the smart contract can only

control assets on the same blockchain.

4.1 Basic Design

The proposed method for trading digital assets across in-

dependent blockchain ledgers adopts the concept of a smart

contract, named the “extended smart contract.” Figure 2 out-

lines the behavior of an enhanced smart contract.

A unique factor of the proposed method is that a

blockchain, the “ConnectionChain ledger,” is dedicated for

interworking independently working blockchains. A smart

contract that controls the business logic to perform multiple

transactions, which may depend on each other, runs on the

special blockchain. The smart contract has features for sub-

mitting a transaction to operate the interworking blockchain

ledger and monitor the block data generated as an event.

Another feature of the proposed extended smart con-

tract is the ability to customize business logic. The busi-

ness logic must be less susceptible to external influences

to ensure processing neutrality and transparency. More-

over, parameters must be customized to support various

processing, such as trading rates and account addresses,

for use. ConnectionChain supports system parameters pre-

set by administrators or service providers and startup pa-

rameters specified when the user invokes them. Admin-

istrators can change the system parameters; however, oth-

ers monitor all operations because all administrative oper-

ations are performed using the smart contract. The oper-

ation result is publicly shared on the ledger. An ordinary

smart contract merely handles the events occurring within

the ledger. Alternatively, an extended smart contract is de-

signed for enabling communication with external ledgers

through the blockchain abstraction layer. You may notice all

blockchain platforms have common functionalities such as

verifying the digital signature on submitted transactions, fi-

nalizing transaction by using consensus algorithm, and gen-

erating blocks which provide immutability of the transac-

tion records. ConnectionChain’s business logic can accom-

modate various types of the data format of block data and

prepare transaction data by filling out the transaction tem-

plate, which contains variables replaced with given startup

parameters. Note that the startup parameter can include

the OAuth2 access tokens to request the Web Wallet Server for

signing the prepared transaction as part of business logic.

The user obtains the access token before starting a business

logic on the ConnectionChain, and they are attached with

the request. Those access tokens are stored in the Trade

Manager for later use. The service provider will also store

the access code for signing service transactions when the

extended smart contract is deployed. These access tokens

allow ConnectionChain to get a temporary delegation of the

privileges for issuing a signed transaction on behalf of the

user or service provider.

Additionally, the REST-API enables users to issue

asynchronous requests to invoke or monitor an extended
smart contract with multiple internal states.

4.2 Implementation of ConnectionChain

Figure 3 shows the system configuration of the prototype system that realizes the ConnectionChain architecture.

In Sect. 4.1, it was explained that the ConnectionChain has a REST-API to interact with the user. However, the prototype system also introduces a front-end server named “web wallet service,” which improves the usability of the system. The web wallet service collects necessary information to prepare a REST-API request such as account addresses, choice of business logic, and runtime parameters. The web wallet service restricts access to address information on its database with authentication for users. The blockchain abstraction layer consists of an adaptor and a connector. The adaptor establishes a bidirectional communication channel with the connector, which interfaces to the blockchain network behind it (Fig. 4). In the prototype implementation, the open source software socket.io is used for creating the bidirectional communication channel so that the adapter can receive notifications from the connector even when restricted to accept incoming messages from the Internet. Alternatively, the connector will behave like a pier of the ConnectionChain. It will forward the transactions using the platform-specific communication protocol as the participating node on the interworking blockchain network. The connector monitors the block data generation, which contains only verified transactions, and forwards it to the adaptor. We assumed the connector would play both the communication pier and the node for the interworking blockchain. Still, the additional feature is merely handling socket.io communication, which does not increase much on computation processing power and management costs.

Next, the detailed behavior of the extended smart contract of ConnectionChain is described. The module named “scenario manager” will register the scenario definitions in the “state management contract,” which is the smart contract deployed on the ConnectionChain ledger (Step 0 in Fig. 6). A scenario definition is a set of state information comprising the “stateId,” “operation,” and “(judge) scripts” (Fig. 5). Each scenario is identified by a scenarioId, and runtimeParams is provided when the extended smart contract is invoked by users. The ConnectionChain starts to monitor the ledger to detect the result of transactions verified by the participating nodes on the blockchain network. The actual monitoring is performed by the adaptor, as shown in Fig. 4. The adaptor will generate the event notification called “ledger event” for the “trade manager,” who determines the executing business logic and routes it to “state manager” (Step 1 in Fig. 6). When the waiting event is notified to the state manager contract, it will replace the current state information with the next one, which is determined by the event evaluation script (Steps 2–4 in Fig. 6). The state information is updated by the invocation of the smart contract on the ConnectionChain ledger. It will be verified using a consensus algorithm among the participating nodes in the blockchain network. When an observed update on the state in-
5. Field Experiments

To evaluate the feasibility of the proposed method, field experiments are performed by implementing the ConnectionChain prototype.

5.1 Cashless Payment Using Local Currency Exchange

The use case in this field experiment is a cashless payment model, which enables the acceptance of various cryptocurrencies for purchasing items at a store. In addition to ordinal cash payment or credit card payment, electronic money payment using smartphone terminals is rapidly increasing because they are mostly accepted at small stores. However, users may experience inconvenience if their preferred payment network is occasionally unacceptable because the store must have a contract for each payment network with an additional fee. Moreover, a traveler from a foreign country will experience additional difficulty because they cannot use the residents’ electronic money. Herein, a new approach for cashless payment using local currency exchange is proposed to solve the aforementioned problem. Local currency tokens are transferable among users and may replace the role of electronic money. The value of local currency tokens can also be pegged to real money. Let us assume that a traveler, Alice, is visiting Tokyo for sightseeing from the USA and she wants to purchase a souvenir item at a store. She wants to pay in the local currency “D-coin” pegged with USD. However, the store owner, Bob, wants to receive the payment in the local currency “Y-coin” pegged with JPY. The ConnectionChain will help this use case by involving Charlie, who provides the payment collecting service (Fig. 8).

As a mechanism, Alice uses the service in which Charlie makes payment to Bob using Y coins on behalf of Alice. Only when the payment is successfully completed, the equivalent valued plus commission fee will be collected using D-coins by Charlie. The important thing is that Alice does not have to register herself as a member of the service to make the payment. Bob will refer Charlie’s service to Alice to pay using D-coins.

In this experiment, local currencies with different currency units were constructed as two independent private chains. The block generation interval was adjusted to a few seconds to complete the entire transaction within one minute. On the other hand, if the blockchain network for the interworking local currency has a very long block generation interval, it is expected that the time required for the transaction will be longer. However, since ConnectionChain allows any number of blockchains to be linked within a transaction, it is possible to improve the apparent response speed by introducing a technique to confirm the transaction’s approval with a private chain that confirms the transaction quickly. This field experiment is performed by implementing the ConnectionChain prototype, with customization for the cashless payment using local currency exchange, and is reported in the press release published by FUJITSU [5].

5.2 Security Token Exchange

The use case in this field experiment is the security token exchange model settlement, which reduces time and commis-
sion fees in a security token trade. The process flow of this use case is similar to that of the cashless payment use case described in Sect. 5.1. This use case is mainly adopted to develop a connector and an adaptor to adapt to the newly introduced ledger platform, named ibet. It was also tested the feasibility of implementing escrow transactions since buyers of the security token may not pool a sufficient balance of settlement tokens in their account. Thus, the reusability of the ConnectionChain in the different use cases can be proven. This field experiment is performed by implementing the ConnectionChain prototype, with customization for the security token exchange, and is reported in the press release published by FUJITSU [6].

6. Conclusion and Future Work

A new approach for blockchain interworking that expands the ordinary smart contract’s scope and feature was proposed. The results of field experiments proved the benefits and feasibility of the proposed method. After performing the field experiments, we realized the importance of interworking with various blockchain platforms even more. We then decided to publish the codes of ConnectionChain as an open source software at GitHub.com and asked the Internet’s developers for their help in building such an infrastructure. The source codes of the ConnectionChain prototype are published as an open source software at GitHub in 2019 for evaluation. Our idea was merged with a newly established project, Hyperledger CACTUS [7], which aims to abstract developers from protocol-specific implementations of blockchains and enable interoperability between them. We will contribute to the development of Hyperledger CACTUS using the knowledge collected during the development of ConnectionChain to build a more open infrastructure for the token economy.

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