Blockchain-based Solar Electricity Exchange: Conceptual Architecture and Laboratory Setup

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***Abstract*— Over the past decade, high penetration of rooftop solar photovoltaics (PV) has been observed in many countries. The availability of rooftop solar PV at customer premises has transformed a house into an energy prosumer that can both consume and export electricity. With proper regulations in place, homeowners can become a market participant who can buy and sell excess solar electricity in a peer-to-peer (P2P) trading environment. With the emerging blockchain technology, it will be possible to securely keep track of such solar electricity exchange without a third party oversight. The objective of this paper is to discuss the conceptual architecture of the blockchain-based platform for exchange of solar electricity in a neighborhood. Several open-source blockchain platforms are reviewed, including Hyperledger, Ethereum and Corda. Experiments developed on one of the well-known open-source blockchain platforms are discussed that describe how a P2P exchange of solar electricity can be set up in a laboratory environment.**

***Index Terms*—blockchain, solar electricity, Hyperledger framework, peer-to-peer trading.**

I. INTRODUCTION

For over a century, the structure of the electric utility business has been a supplier driven monolithic model with consumers in the receiving end paying for electricity they use without any participation in how the electricity is produced, transmitted or consumed. With the introduction of consumer-owned solar PV, consumers have more interest and opportunities to participate in this business. However, there are no widely available and effective tools which can facilitate consumer participation and keep track of such a solar electricity exchange until the blockchain technology has emerged.

Blockchain, also known as a distributed ledger technology, is one of the emerging and leading techologies in various businesses sectors, e.g., financial services, supply chains, healtcare, energy, etc. [1]. The most important features of this technology are decentralized and trustable ledger of records. It allows transactions to be anonymous and secured among participants. In a blockchain network, all transactions are automatically verified and recorded by network nodes using cryptographic algorithms without the need for a central market authority. Bitcoin [2], the best known of the new cryptocurrencies, is one of the first applications of the blockchain technology. Today, the blockchain technology goes far beyond Bitcoin cryptocurrency applications, and is used in supporting various business applications.

In the energy sector, there have been several blockchain pilots. Some of the most well-known projects are the Brooklyn Microgrid, SolarCoin, Electron, Conjoule, Grid+, Blockcharge, EcoCoin, EnergyBlockchain Labs and the Tennet/IBM/ Vandebron/Sonnet battery pilot projects. The Brooklyn Microgrid project [3] has developed Exergy that allows transacting energy among prosumers. SolarCoin [4] is another project where participants are given rewards for solar electricity generation using blockchain to record all transactions. Electron [5] provides a blockchain-based trading platform for electricity, gas and community energy projects. Conjoule [6] offers a local energy market place to allow homes with renewables to sell their surplus energy in a neighborhood. Grid+ [7] allows homeowners to take advantage of time varying electricity prices and use the blockchain-based payment technology. Blockcharge [8] is a blockchain-based electric vehicle charging system that relies on a special type of smart plug to authenticate the owner and start the charging process. EcoCoin [9] aims to reward positive sustainable actions with EcoCoin. EnergyBlockchain Labs [10] provide a blockchain-based platform for carbon asset management. The Tennet/IBM/ Vandebron/Sonnet projects involve two pilots. One is to demonstrate the use of the blockchain-based platform for dispatching car batteries to maintain a stable grid frequency; and the other uses the blockchain-based platform to support the decentralized battery storage dispatch for congestion management. All of these projects have made their high-level documentations available, which mainly focus on the business and financial aspects of their blockchain-based platforms.

It is the objective of this paper to discuss the conceptual architecture of a blockchain-based platform for exchange of excess solar electricity, and provide an insight into how such a platform can be set up in a laboratory environment. Several open-source blockchain frameworks are reviewed, and one of the most promising ones is selected for the development of the P2P solar electricity exchange in a laboratory environment.

This work is supported in part by the U.S. Department of Energy (DOE) under the Small Business Technology Transfer (STTR) project "A Blockchain-enabled Peer-to-Peer Energy Trading Platform for Managing Complex Exchange of Kilowatt-hours and Negawatts" (STTR DE-SC0018894).

978-1-5386-8232-6/19/$31.00 ©2019 IEEE

II. Overview of Blockchain and Review of Open-Source Blockchain Platforms

This section discusses the blockchain technology and reviews several open-source blockchain frameworks.

A. Overview of the Blockchain Technology

In general, main blockchain components are: Peers, Ordering Service (OS), Certificate Authority (CA), Ledgers and Smart Contracts. These are explained below:

- *Peer:* is a network entity of a blockchain network owned and maintained by each group of participants. It executes transactions, maintains a ledger and runs validation checks against blocks of transactions before appending to the ledger.
- *Ordering Service (OS):* provides a broadcast service to participants [11]. Additional services that are provided by OS are, such as, delivery guarantees, authentication of clients and maintenance of a system chain, and filtering and validation for configuration transactions.
- *Certificate Authority (CA):* provides certificate services to participants of the blockchain network [12], such as, identity registrations and enrollment certificate issuances.
- *Ledger:* is a distributed database stored and updated independently by each peer of the blockchain network. It can be replicated and synchronized among peers. A ledger records transactions, e.g., the exchange of assets or data, and is updated after agreeing on ledger content through a consensus protocol.
- *Smart Contract:* is a business logic agreed upon by blockchain participants. A smart contract facilitates an exchange of solar electricity (for the case discussed in this paper).

B. Review of Open-Source Blockchain Platforms

After the first cryptocurrency, i.e., Bitcoin, was introduced, several open-source blockchain frameworks have emerged, such as Hyperledger Fabric [13], Ethereum [14], Corda [15], Omni [16], Ripple [17], MultiChain [18], OpenChain [19] and Chain Core [20]. The motivation of these frameworks is to provide more adaptable and flexible platforms for various blockchain-based business applications in addition to cryptocurrency applications. In this paper, leading open-source blockchain platforms are reviewed, including Hyperledger Fabric, Ethereum and Corda.

1) Hyperledger Fabric

The Hyperledger Fabric is an open-source blockchain platform (by Linux Foundation). It supports the private/ permissioned mode of operation [21], i.e., only selected participants can access the blockchain network. Two most commonly used consensus mechanisms are Fault-tolerant and Byzantine-Fault-tolerant [22]. It supports supports Golang, Javascript and Java programming languages [21]. Hyperledger has been used to support several blockchain-based projects, such as the battery pilots by Tennet/IBM/ Vandebron/Sonnet, EcoCoin and EnergyBlockchain Labs [23].

2) Ethereum

Ethereum is another well-known blockchain platform that has its own cryptocurrency, called ether [24]. Ethereum supports permissionless blockchain, i.e., anybody is allowed to participate in a business network. Ethereum uses the proof-of-work (PoW) scheme for mining [21]. However, PoW requires an expensive computer calculation, and negatively affects the blockchain performance in processing transactions. Ethereum supports Python, Go and C++ programming languages [21]. Ethereum has been used to support several blockchain-based projects, such as Brooklyn Microgrid, Electron, Conjoule, Grid+ and Blockcharge [25].

3) Corda

With a particular focus on financial services, Corda manages financial agreements among business entities using blockchain. It supports several consensus mechanism, such as Notary and Raft [26]. Corda supports Java and other Java virtual machine (JVM) languages [27].

Among these three well-known open-source blockchain frameworks, Hyperledger Fabric is selected in this study for development of a blockchain-based platform supporting P2P trading of solar electricity in a simulated environment. This is because Hyperledger Fabric is perceived to be faster and more scalable than other platforms [28]. In addition, Hyperledger Fabric offers online development environment, i.e., Hyperledger Composer Playground [29], which allows a business network to be easily tested and deployed.

III. Conceptual Architecture of the Blockchain-based Platform for Exchange of Solar Electricity

The conceptual architecture of the proposed blockchain-based P2P energy trading for exchange of solar PV electricity is depicted in Fig. 1.

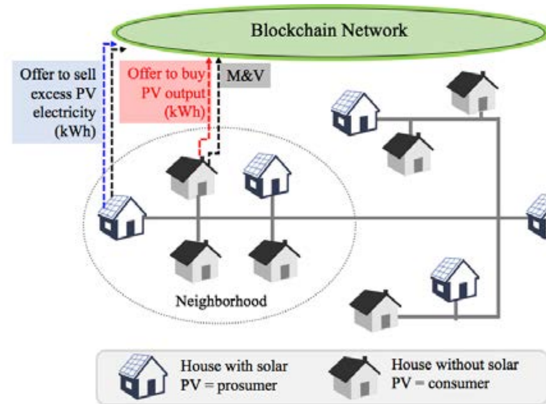

Fig. 1. The conceptual architecture of the proposed P2P trading for exchange of solar electricity (Note: M&V = measurement and verification).

This architecture provides a local energy market solution, which allows prosumers (i.e., sellers or homeowners with solar PV) to sell renewable generation produced locally directly to consumers (i.e., buyers or homeowners without PV). A few keywords need to be explained, including participants, assets, transactions and transaction flows.

A. Participants and Assets

In this simplified blockchain network, only one peer is involved. The 'peer' has many *participants*, which are homeowners. Each homeowner can interact with the blockchain network in several ways. That is, a prosumer can submit an offer to sell their excess PV electricity; and a consumer can submit a bid to buy PV electricity during a particular duration, e.g., one-hour intervals.

Assets of the proposed blockchain network are PV units and PV electricity for sales. Registration of a PV unit is required before a prosumer can start offer his/her PV electricity for sales. In addition, digital assets of this blockchain network are tokens. Tokens are used to compensate for the exchange of solar electricity. Such digital assets can be used like other assets in exchange for goods and services.

B. Transactions and Transaction Flows

This study defines four types of transactions necessary to support the P2P exchange of solar electricity. First, the blockchain network has to emit the 'AcceptOfferBroadcast' to inform all participants that the network is now open to accept offers. Prosumers who want to sell their excess PV output can then place offers to sell their PV electricity or 'PVOffer'. Consumers who want to purchase PV electricity can also place bids to purchase 'BUYOffer'. The blockchain network can close the bid by issuing the 'CloseBidding' transaction.

A smart contract embedded in the blockchain network is required to process the 'PVOffer' and 'BUYOffer' received from participants. In this particular case, a smart contract needs to match the sell offers to the buy offers, and clear the market. After the market is cleared, measurement and verification (M&V) is performed to verify the actual excess PV generation and the actual consumption of all participants. The blockchain network then credits/debits the corresponding tokens from seller/buyer balances.

C. Other Blockchain Components

Using Hyperledger Fabric, the 'Ledger' in the peer, as well as the OS and CA are already handled in the development environment. This simplified the development process.

IV. A Blockchain Network Setup using Hyperledger Composer Playground

This section discusses how the blockchain network for P2P exchange of solar electricity –whose conceptual architecture is discussed in the previous section– has been developed using the development environment of the Hyperledger Fabric, called Hyperledger Composer.

A. Creating a Business Network with Hyperledger Composer

In this study, the Hyperledger Composer has been used to create and deploy the 'pvtrading' business network, with the network admin card 'admin@pvtrading'. Three files have been created to complete the business network definition:

- The model file '*model.cto*', which defines participants, assets, transactions and events in the business network. The model file uses the Hyperledger Composer's modeling language (**.cto*).
- The transaction processor script file '*logic.js*', which defines the transaction logic of the business network. JavaScript functions (**.js*) are used to express the logic of a business network, which are automatically executed when the selected transaction is called for.
- The access control list (ACL) '*permission.acl*' file, which defines the rules related to permissions to perform a defined transaction and system-level operations.

B. Defining the Model File, 'model.cto'

In the context of P2P exchange of solar electricity, participants, assets, transactions and events of this 'pvtrading' business network have been defined in the '*model.cto*' file. See Fig. 2.

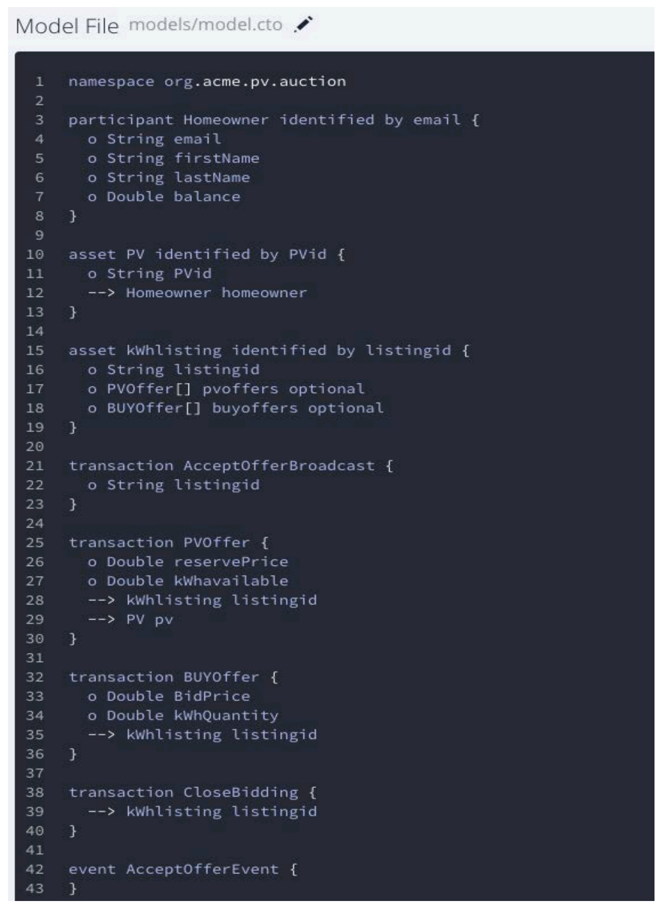

Fig. 2. The model file of the 'pvtrading' business network showing how participants, assets, transactions and events are defined.

The model file includes definitions of:

Participants: These are "Homeowners" who participate in the P2P trading market. A "Homeowner" is identified by an email address, first name, last name and the token balance.

Assets: "PV" and "kWhlisting" are defined as the physical assets in this 'pvtrading' business network. The "PV" asset is identified by a unique PVid and homeowner's unique ID (i.e., an email address). The "kWhlisting" asset, identified by the listing ID, gathers offers to sell PV electricity from prosumers and bids to buy PV electricity.

Transactions: This business network involves:

- "AcceptOfferBroadcast" is the broadcast event to notify all participating homeowners of the opportunity to place offers/bids for a specific listing ID of "kWhlisting". Homeowners can respond to this broadcast message by submitting the "PVOffer" or the "BUYOffer".
- "PVOffer" is for prosumers to offer PV electricity for sales by specifying the reserve price and kWhavailable. The "PVOffer" must be associated with a unique PVid.
- "BUYOffer" allows consumers to place their bids to purchase PV electricity by specifying the bid price and quantity. "BUYOffer" is associated with the listingid.
- "CloseBidding" initiates the smart contract embedded in the business logic in matching the offers to sell PV electricity with the offers to buy PV electricity.
- *Event:* One event has been defined in this 'pvtrading' business network called "AcceptOfferEvent". By creating this event, the Hyperledger Composer can broadcast a message that is subscribed by external applications representing homeowners. The event emitting has been defined in the '*logic.js*' file.

C. Defining the Script File, 'logic.js'

The script file defines the business logics implemented when each transaction is called. In this case, four Javascript functions have been defined to append the desired functions to the four transactions, as follows:

1) Defining the "PVOffer" and "BUYOffer" Transactions

Fig. 3 shows a part of the script file that defines the "PVOffer" transaction. Basically, the code for "PVOffer" transaction initializes and submits a PVOffer to the 'pvtrading' business network. The "BUYOffer" transaction have been defined in a similar manner.

2) Defining the "AcceptOfferBroadcast" Transaction

Using transaction Javascript, the code in Fig. 4 is used to emit the "AcceptOfferEvent" event previously defined in the model file of the business network definition in Fig. 2 (line 42). Once homeowners receive this broadcast message, they can place offers/bids to sell/buy PV electricity.

3) Defining the "CloseBidding" Transaction

The "CloseBidding" transaction is responsible for matching the sellers' and buyers' offers and clearing the market. This transaction has been embedded with a smart contract that defines the underlying business logic of the P2P exchange of solar electricity. There are several ways to implement this transaction, depending upon the agreements among different participants.

Several rules shall be defined, for example:

Rule 1–the order in which PV electricity is sold: Since not all PV electricity can be sold, depending on the demand for PV electricity, it is important to agree upon a method to rank and identify which offers are to be sold first. For example, PVOffer can be ranked based on: (a) the time the offer is placed; (b) the reserve price from low to high; or (c) the amount of kWh available from high to low.

Rule 2–the order in which a buyer purchases PV electricity: Similar to the above example, not all bids to purchase PV electricity can be met, depending on the availability of PV electricity, it is important to agree upon a method to rank and identify which bids are met first. For example, BUYOffer can be ranked based on: (a) the time the bid is placed; (b) the bid price from high to low; (c) the amount of kWh to purchase from high to low; or (d) the bid price multiplied by the amount of kWh to purchase from high to low.

Rule 3–the market clearing price: The market clearing price (MCP) is the price that buyers pay for purchasing PV electricity from sellers. Several options are possible, for example, the MCP can be set equal to: (a) the highest bid/offer price of all executed bids/offers; and (b) the average bid/offer price of all executed bids/offers. Each method has different implications and some may imply market power of sellers over buyers and vise versa.

Rule 4–the market clearing intervals: The market clearing intervals are the time intervals the market is cleared. This parameter is also to be agreed upon among participants. The market can be cleared every one hour, one day or any period.

```
/**
 * @param {org.acme.pv.auction.PVOffer} pvoffer
 * @transaction
*/
function makeOffer1(pvoffer) {
    var listing = pvoffer.listingid;
    if (listing.pvoffers == null) {
        listing.pvoffers = [];
    }
    listing.pvoffers.push(pvoffer);
    return getAssetRegistry('org.acme.pv.auction.kWhlisting')
        .then(function(kWhlistingRegistry) {
            return kWhlistingRegistry.update(listing);
        });
}
```

Fig. 3. A part of the script file of the 'pvtrading' business network defining the "PVOffer" transaction.

```
/**
 * @param {org.acme.pv.auction.AcceptOfferBroadcast} acceptOfferBroadcast
 * @transaction
 */
function acceptOfferBroadcast(acceptOfferBroadcast) {
    var factory = getFactory();
    var acceptOfferEvent = factory.newEvent('org.acme.pv.auction',
'AcceptOfferEvent');
    emit(acceptOfferEvent);
}
```

Fig. 4. A part of the script file of the 'pvtrading' business network defining the "AcceptOfferBroadcast" transaction.

D. Defining the ACL file, 'permission.acl'

At this experimental step, the default access control rules have been used, which gives the participants full access to the business network and system-level operations.

E. Transaction History

By defining the model file, the script file and the permission file, the business network 'pvtrading' has been completely set up and the Hyperledger Fabric handles all underlying blockchain components. Any transactions submitted to the blockchain network, e.g., "AcceptOffer Broadcast", "PVOffer", "BUYOffer" and "CloseBidding", are now recorded with timestamp, entry type and participant who initiates the transaction. An example of the recorded transactions is illustrated in Fig. 5, showing from the beginning (when the identity was issued, the business network was started, the identity was activated) to the participant/asset registration and initiating the four transactions.

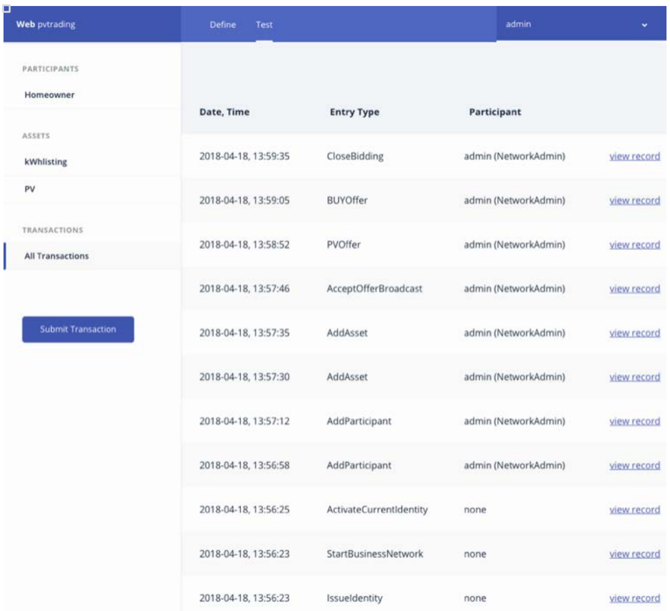

Fig. 5. Recorded transactions with timestamps.

V. Blockchain-based P2P Transactions in a Laboratory Environment

After the ‘pvtrading’ business network has been set up. The Hyperledger Composer REST server has been launched to generate REST API to interact with the business network. Homeowners can now interact with the business network via REST API. For this implementation, a piece of Python code has been written to allow each homeowner to receive the ‘AcceptOfferBroadcast’ message from the ‘pvtrading’ business network, and place an offer to sell their excess PV output or place a buy offer. Solar PV generation data have been gathered from the 6.4kW rooftop solar PV available at the Advanced Research Institute of Virginia Tech. The blockchain server that hosts the ‘pvtrading’ business network has been set up to broadcast ‘AcceptOfferBroadcast’ message hourly at the beginning of each hour, and clear the market hourly at the end of each hour. Historical transaction data with timestamps are now recorded in blockchain.

VI. Summary and Future Work

This paper discusses the overview of blockchain technologies and reviews several open-source blockchain platforms. The conceptual architecture of a blockchain-based platform for exchange of solar electricity in a neighborhood is discussed. Using Hyperledger Fabric, this work lays the groundwork to set up a blockchain-based business network for P2P exchange of solar electricity in a laboratory environment. It can serve as a basis to allow interested researchers to develop and deploy a blockchain-based platform once proper regulations are in place that allow P2P trading of excess solar PV output. Future work may include defining rules/smart contracts for P2P trading of solar electricity and analyzing how each rule impacts market clearing prices or participants. In addition, one may further develop and deploy this in a production environment on a commercial cloud-based platform, like Amazon Web Services (AWS) or Microsoft Azure. Proper security measures will need to be added using HTTPS and TLS (Transport Layer Security).

References

[1] A. Rosic, "What is Blockchain Technology? A Step-by-Step Guide For Beginners," [Online]. Available: https://blockgeeks.com/guides/what-is-blockchain-technology.
[2] Bitcoin [Online]. Available: https://bitcoin.org/en.
[3] Brooklyn Microgrid [Online]. Available: https://lo3energy.com.
[4] Solar Coin [Online]. Available: https://solarcoin.org.
[5] Electron project [Online]. Available: http://www.electron.org.uk.
[6] Conjoule project [Online]. Available: http://conjoule.de/en/home/.
[7] Grid+ project [Online]. Available: https://gridplus.io/.
[8] Slock.it [Online]. Available: https://slock.it.
[9] EcoCoin [Online]. Available: https://www.ecocoin.com/.
[10] EnergyBlockchain Labs [Online]. Available: https://www.ibm.com/case-studies/energy-blockchain-labs-inc.
[11] IBM Could Docs/IBM Blockchain Platform: Hyperledger Fabric [Online]. Available: https://console.bluemix.net/docs/services/blockchain/reference/v10_fabric.html#ordering-service.
[12] IBM Hyperledger: Certificate Authority Set up [Online]. Available: https://openblockchain.readthedocs.io/en/latest/Setup/ca-setup.
[13] Hyperledger Fabric [Online]. Available: https://www.hyperledger.org/projects/fabric.
[14] Ethereum [Online]. Available: https://www.ethereum.org/.
[15] Corda [Online]. Available: https://www.corda.net/.
[16] Omni Layer [Online]. Available: https://www.omnilayer.org/.
[17] Ripple [Online]. Available: https://ripple.com/.
[18] MutiChain [Online]. Available: https://www.multichain.com.
[19] Openchain [Online]. Available: https://www.openchain.org.
[20] Chain [Online]. Available: https://chain.com/.
[21] C. Decker. (2017, Nov.). Ethereum vs Hyperledger. *Blockchain Training Alliance* [Online]. Available: https://blockchaintrainingalliance.com/blogs/news/ethereum-vs-hyperledger.
[22] T. Friebe. (2017, Nov.). Trust your competitor? How you can do that with a Hyperledger Fabric blockchain. *BlockchainSpace* [Online]. Available: https://medium.com/blockchainspace/trust-your-competitor-how-you-can-do-with-hyperledger-fabric-5939bacffe76.
[23] L. Montemayer, T. Boersma and T. Dorp, “Comprehensive guide to Companies involved in blockchain & energy”, Feb 2018 [Online]. Available: http://ipci.io/wp-content/uploads/2017/12/Energy-Blockchain-Report.compressed.pdf.
[24] Ether [Online]. Available: https://www.ethereum.org/ether.
[25] R. Jaipur, “Blockchain use cases: Sample use cases across business domains”, *Blockdigest*, 2017 [Online]. Available: http://blockdigest.com/usecases.
[26] Corda v3.1 [Online]. Available: https://docs.corda.net/key-concepts-notaries.html.
[27] Corda Github [Online]. Available: https://github.com/corda/corda.
[28] T. Dinh, J. Wang, G. Chen, R. Liu, B. Ooi, K.L. Tan, “BLOCKBENCH: A Framework for Analyzing Private Blockchains”, *In Proc. 2017 ACM Int’l Conf. on Mngt of Data*, pp. 1085-1100, Chicago, IL, May 2017.
[29] Hyperledger Composer Playground [Online]. Available: https://composer-playground.mybluemix.net/.