A Compendium of Practices for Central Bank Digital Currencies for Multinational Financial Infrastructures

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ABSTRACT Over five thousand digital currencies have been issued by private sector actors since the release of the Bitcoin digital currency in 2009. Private sector issuance of distributed ledger technology (DLT)-based digital currencies such as Bitcoin, Ethereum and other altcoins threaten the stability of financial market infrastructures and preservation of monetary policy. Consequently, many central banks and monetary authorities have begun research and experimentation on central bank-issued digital currencies (CBDCs) to mitigate this threat. In this paper, we present a comprehensive survey of publicly available DLT-based CBDC experiments with completed proof-of-concept prototypes from across the world to enable an understanding of the motivations and best practice approaches for undertaking CBDC experiments. We provide a classification and generic framework for CBDCs and highlight existing DLT platform limitations and use cases in the financial services industry. Overall, our paper organizes in one place, all the relevant, publicly available DLT-based CBDC experiments with completed proof-of-concept prototypes to serve as a reference point for central banks, monetary authorities and researchers desiring to undertake research on DLT-based CBDCs. Ultimately, we present a survey on the technical feasibility and challenges of leveraging DLT to issue the selected CBDC experiments surveyed in this paper.

INDEX TERMS Central bank, CBDC, CBDC experiment, digital currency, DLT, financial market infrastructure, proof-of-concept, prototype.

I. INTRODUCTION

A central bank controls economic activity in a given economy through the use of monetary policy and other relevant economic management tools. Central banks implement monetary policy by controlling the money supply, managing interest rates and maintaining price stability or inflation for goods and services in a given nation-state [1]. Central banks, therefore, enjoy a legal monopoly on the issuance of currency in a given economy [2].

The invention of Bitcoin [4] in 2009, however, has given rise to the global issuance of alternative forms of currencies referred to as digital or crypto-currencies by private actors,

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a role reserved solely for central banks. In less than a decade since the introduction of Bitcoin, private sector actors have issued more than five thousand digital currencies [5] that lack intrinsic value and are not backed by any tangible resources. Besides Bitcoin [4], other notable private sector-issued digital currencies include Ethereum [6], Ripple [7], Tether [8], Stellar [9] and other altcoins.

Facing the threat of monetary policy and financial market instability by such private sector digital currency issuances, many central banks have delved into research and experimentation on central bank-issued digital currencies (CBDCs) to guarantee financial market stability and monetary policy preservation [10], [11].

In a recent survey [12] conducted by the Bank for International Settlements (BIS) to examine central banks efforts on

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CBDC research, more than 70% of the central bank respondents indicated that they were investigating the possibility of issuing a CBDC. Cumulatively, the BIS survey participants are located in jurisdictions covering more than 70% of the world population and over 90% of its gross domestic product [12]. 65% of the survey participants were from emerging market economies (EMEs) while 35% were from advanced economies. Overall, survey participants from EME cited financial inclusion and domestic payment efficiency as their motivation for investigating CBDCs and thus, indicated the strongest preparedness to issue a CBDC over the medium term (1-6 years). In total, about 30% of all survey respondents indicated a preparedness to issue a CBDC in the medium term.

In this paper, we present a survey of the relevant, publicly available CBDC experiments from across the world to enable an understanding of the motivations and best practice approaches for undertaking CBDC experiments.

Ultimately, we present a survey on the technical feasibility and challenges of leveraging distributed ledger technology (DLT) to issue the selected CBDC experiments surveyed in this paper. Issues regarding cost, economic, political, legal and social implications for DLT-based CBDC issuance are out of scope in this paper. Additionally, other non-technical implications unrelated to the *Principles for Financial Market Infrastructures* (PFMIs) [50] are also considered out of scope in this paper.

Broadly, we refer to all CBDC research initiatives as *CBDC research*, and specifically, all CBDC research initiatives with proof-of-concept (PoC) prototypes as *CBDC experiments*. Consequently, we use the terms CBDC research and CBDC experiments interchangeably where applicable.

A. OUR CONTRIBUTION

- With CBDC research publications loosely organized in literature, we organize all the relevant, publicly available CBDC research publications in one place to serve as a reference point for central banks and monetary authorities desiring to learn more about CBDCs.
- We present a generic framework for CBDCs of various types to enable a general understanding of CBDCs in practice and theory.
- Lastly, we present a comprehensive survey of selected DLT-based CBDC experiments to enable an understanding of the technical feasibility, challenges and best practice approaches for leveraging DLT to issue CBDCs.

B. PAPER ORGANIZATION

The rest of the paper is organized as follows. In Section II, we present a background on CBDC research initiatives by various central banks from across the world. In Section III, we discuss similarities and differences between central bank-issued money and CBDCs. Further, we present a classification of CBDCs and generic frameworks for CBDCs of various types. In Section IV, we provide an introductory thesis on DLT, highlighting some of the shortfalls of traditional DLT

platforms and potential use cases for DLT in the financial services industry. In Section V, we describe our preliminary and secondary screening criteria based on which we identify and select the relevant CBDC experiments for our survey. In Section VI, we undertake a comprehensive review of our selected CBDC experiments, with the goal of enabling an understanding of the best practice approaches relevant for a successful CBDC experiment. We give our conclusion and indicate our future research direction in Section VII.

II. BACKGROUND

Central banks' interest in CBDCs dates back to 2012 [3]; however, major attempts at developing PoCs for DLT-based CBDCs and quantitatively examining their implications on the broader economy began around 2015.

In this section, we present some of the relevant CBDC research initiatives from across the world from 2015 to 2019.

We organize the CBDC research discussed in this section under three broad categories, namely *Early Adopters, Followers*, and *New Entrants*. All relevant CBDC research publications from 2015-2016 are organized under the *Early Adopters* category. Relevant publications from 2017-2018 are organized under the *Followers* category while relevant publications in 2019 are organized under the *New Entrants* category.

Owing to our *year-based* categorization, multiple CBDC research outputs published in different years by the same central bank or a group of central banks may be organized under different categories.

A. EARLY ADOPTERS (2015-2016)

With its publication of the ''One Bank Research Agenda'' [13] in 2015 and the subsequent development of the *RSCoin* CBDC [14] framework on its behalf by researchers at the University College London in February 2016, the Bank of England established itself as a pioneer in CBDC research.

The People's Bank of China (PBoC), China's central bank began its CBDC experiment in January 2016 to enable the PBOC to have greater control of money supply in China and improve payments system efficiency [85], [86].

In March 2016 in Canada, the Bank of Canada together with Payments Canada and R3 initiated *Project Jasper* [15], [16] a wholesale CBDC (W-CBDC) experiment to examine how DLT could transform the future of payments in the country.

Elsewhere in Europe, the Deutsche Bundesbank, Germany's central bank initiated *Project BLOCKBASTER* [24] in March 2016 to explore the potential of blockchains for interbank securities settlement in Germany. Additionally in Europe, the Bank of France began *Project MADRE* [23] in June 2016 to address challenges in the issuance of single euro payments area (SEPA) Credit Identifiers (SCIs) of for banks in France.

Separately in September 2016, the Banco Central do Brasil began the *Project SALT* [20] experiment while the United

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States Federal Reserve (US Fed) published its first known CBDC report [31].

MAS, Singapore's central bank and financial regulator began its *Project Ubin* [17] CBDC experiment in November 2016.

Lastly in the Early Adopters category, the European Central Bank (ECB) and the Bank of Japan announced *Project Stella* [84], a bilateral CBDC experiment in December 2016.

B. FOLLOWERS (2017-2018)

The Hong Kong Monetary Authority (HKMA) announced its CBDC project, *Project LionRock* [89], [90] in March 2017 with the goal to explore the potential of DLT for domestic interbank settlement functions in Hong Kong.

In May 2017, the Bank of Finland published a CBDC research paper [37] analysing the similarities and differences between cash and general purpose CBDC (G-CBDC) while the Sveriges Riksbank, the central bank of Sweden began its *e-Krona* [27], [28] CBDC research in September 2017 as a means to proactively address the declining use of cash in Sweden.

Independently in November 2017, the Central Bank of Uruguay initiated the *e-Peso* [22] CBDC project as a means to address financial inclusion challenges in Uruguay; while the Bank of Israel constituted a research team to examine potential merits for the issuance of an *e-Shekel* [34] CBDC in Israel.

In its CBDC report [38] published in December 2017, the Danmarks Nationalbank conducted a high-level assessment of CBDC and its implications for Denmark's financial market infrastructures (FMIs).

Independently in January 2018, the South African Reserve Bank (SARB) initiated the *Project Khokha* [21] CBDC experiment to explore the use of DLT for wholesale interbank payments settlement in South Africa; while in Venezuela, the SUPCAVEN launched *Project Petro* [25], a general purpose value-based CBDC (GV-CBDC) to reduce Venezuela's dependency on the US Dollar as the world's largest reserve currency and also overcome US and European Union (EU) sanctions [88].

The Bank of Lithuania in March 2018 announced its plans for the development of the *LBChain* [29], [30], [83] platform, a DLT-based regulatory sandbox to promote the development of the country's financial services industry.

The Swiss National Bank in April 2018 examined the suitability of DLT for Switzerland's financial services industry [39].

In May 2018 the Norges Bank of Norway published the findings of the first phase of its CBDC research [35]. The Norwegian CBDC research assessed the potential for CBDC to guarantee payments system efficiency and instill confidence in Norway's FMIs. Around the same period in May 2018, the Reserve Bank of New Zealand published a high-level report [36] assessing the role of DLT in improving payments system efficiency.

The Bank of Thailand announced *Project Inthanon* [26], a DLT-based CBDC experiment in August 2018 to assess the potential of DLTs on Thailand's FMIs.

At the multilateral level, the Bank of Canada, the Bank of England and MAS jointly published a CBDC report [45] that assessed alternative models for improving the efficiency of cross-border interbank payments using DLT in November 2018.

C. NEW ENTRANTS (2019)

Separately in February 2019, the Bank of Korea published a research paper assessing the impact of general purpose account-based CBDC (GA-CBDC) on financial market stability using two distinct monetary general equilibrium models [32]; while the Bank of Japan published its first official position paper [33] on CBDCs to assess the potential impact of CBDCs on payment efficiency on FMIs generally.

In May 2019, the Bank of Canada and MAS published the *Project Jasper-Ubin* [40] report, the world's first CBDC experiment that enabled the settlement of cross-border interbank payments on two distinct DLT platforms denominated in two different currencies. Project Jasper-Ubin was based on the alternative cross-border interbank payments settlement model proposed in [45].

Under the auspices of the ECB, the ECB Crypto-Asset Task Force published an analysis of crypto-assets [87] in May 2019. The paper, [87], provided a standardized definition for crypto-assets and examined their implications for the broader economy from the monetary policy perspective.

In Figure 1, we present the CBDC research discussed in this section under the corresponding categories.

III. CENTRAL BANK MONEY AND CBDC
A. CENTRAL BANK MONEY

At the basic level, central banks issue two types of money: *physical money or cash* (banknotes and coins) and *electronic central bank money* otherwise known as reserves or settlement accounts [64].

Cash, which we refer to as general purpose money is accessible by everyone in a given economy. General purpose money is non-interest bearing and can be used to make payments in a peer-to-peer anonymous manner without intermediation from third-parties [27], [65]. Cash transactions settle immediately and are irrevocable [37]. In cash transactions, counterparties are each responsible for independently keeping records of the given transaction, therefore record-keeping for cash transactions is distributed [37].

Reserves or settlement accounts which we refer to as wholesale e-money are accessible by only authorized payment service providers (PSPs) such as commercial banks (CMBs) and other high-value customers who maintain settlement accounts on the books of a central bank. Wholesale e-money is interest-bearing and does not have the anonymity property of cash. All participants in a wholesale interbank payments system must be pre-registered, validated and
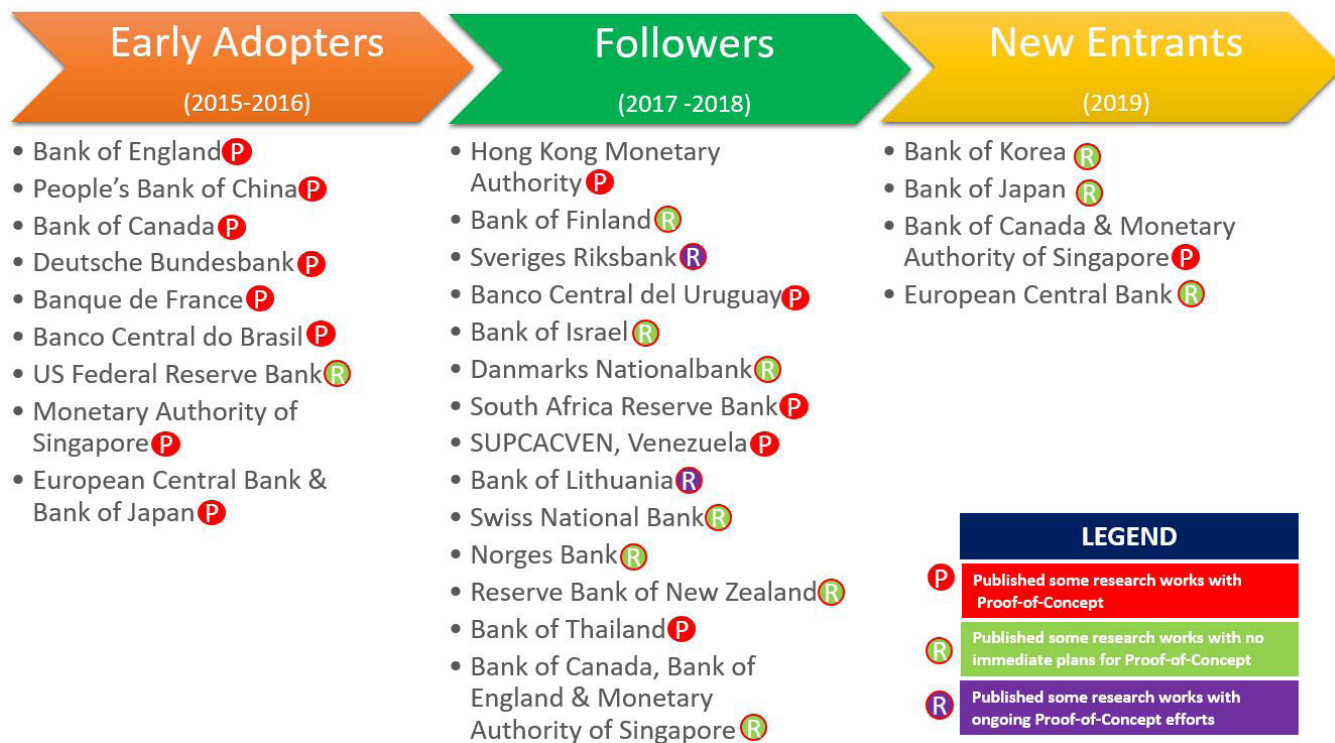
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FIGURE 1. CBDC research landscape.

authorized by the central bank in order to access and conduct transactions on the central bank's FMIs [28], [64]. Wholesale payment transactions are processed on a real-time gross settlement (RTGS) system which is owned and managed by either a central bank or a legally authorized PSP. An RTGS system is also referred to as a large-value transfer system (LVTS). All wholesale interbank transactions are therefore centrally recorded by the central bank.

B. CBDC
Similar to the central bank money, there are two types of CBDCs: *G-CBDC* and *W-CBDC*.

A CBDC may be defined as monetary value similar to central bank money that is stored electronically and represents a claim on asset on the central bank [64]. It may be distributed in a decentralized manner and used to make payments [65].

The Bank for International Settlements (BIS), widely regarded as the central bank of all central banks provides a classification of money and CBDCs based on four properties: *issuer* of money (central bank or not); *form* (digital or physical); *accessibility* (widely or restricted) and *technology* (account-based or token-based) [66]. The BIS further develops the *money flower* to depict its classification of money.

We present an annotated version of the BIS money flower in Figure 2. In Figure 2, the dark grey shaded area represents the types of digital currencies issuable by a central bank.

1) W-CBDC
A W-CBDC a is digital currency similar to a settlement account at a central bank. A W-CBDC is accessible by only

authorized PSPs or high-value customers who are participants in an RTGS system [10], [51], [64]. W-CBDCs are issued, distributed, stored and maintained solely by a central bank or an entity designated by the central bank to perform such functions.

A W-CBDC system has no anonymity requirements as each participant in the system must be pre-registered, authenticated and authorized by the central bank in order to access and conduct transactions on the LVTS FMI [28], [64]. Nevertheless, only parties involved in a specific W-CBDC transaction are able to access data related to the given transaction, thereby guaranteeing counterparty data privacy in conformance with the PFMIs [50].

We present a generic framework for a W-CBDC system in Figure 3.

2) G-CBDC
G-CBDCs are of two types: GA-CBDC and GV-CBDC [27].

A *GA-CBDC* is similar to a W-CBDC in that it is issued, distributed, stored and maintained by a central bank or an entity designated by the central bank to perform such functions on its behalf [27]. Unlike a W-CBDC which is accessible by only PSPs, a GA-CBDC is accessible by the general-public [28]. GA-CBDC users therefore, must be pre-registered and approved by a central bank before they can hold GA-CBDC accounts at the bank. A GA-CBDC, therefore represents a claim on the assets of the central bank. A GA-CBDC user can access their CBDC using an electronic application (wallet) or other access mechanisms provided by the central bank [28].
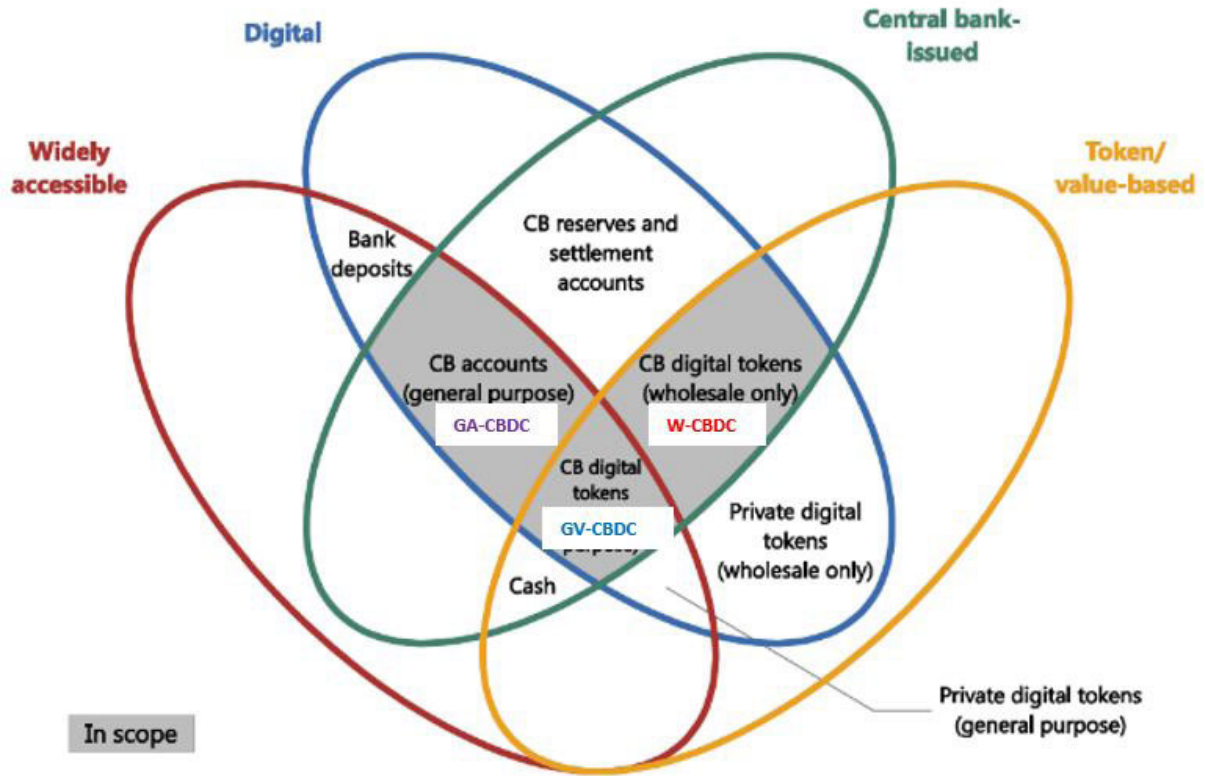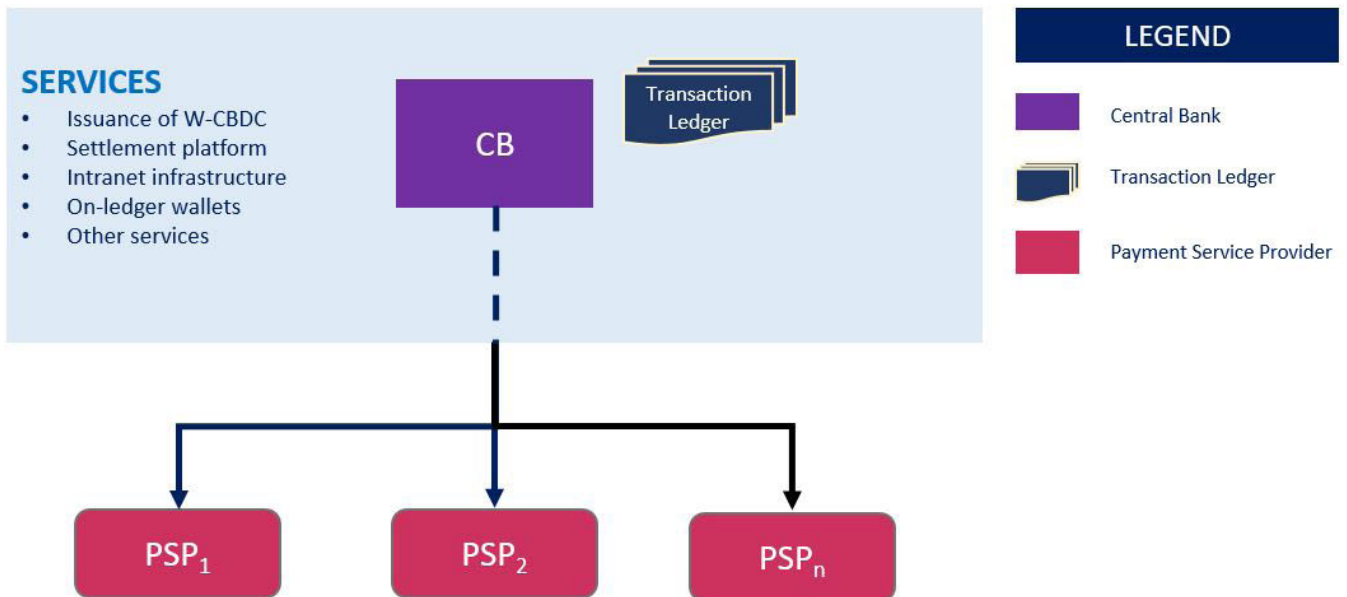
FIGURE 2. Annotated money flower [66].

FIGURE 3. W-CBDC system generic framework.

In Figure 4, we present a generic framework for a GA-CBDC system.

A *GV-CBDC* is similar to cash [64]. It is accessible by the general-public and may be embedded with anonymity properties similar to that of cash [27], [28].

In [129], the authors describe a CBDC framework similar to our GV-CBDC framework; however the authors refer to their framework as an account-based model. This has the tendency to create confusion about the differences between a GA-CBDC and a GV-CBDC. We present that, a key

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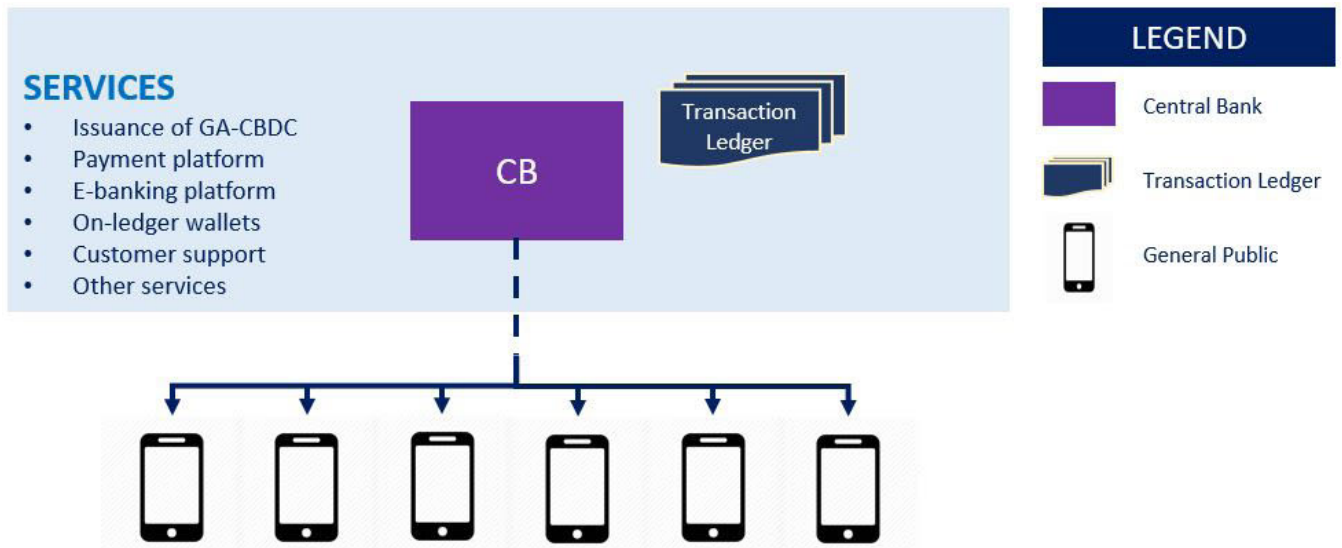
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FIGURE 4. GA-CBDC system generic framework.

difference between a GV-CBDC and a GA-CBDC lies in how both CBDCs are distributed, stored and/or transferred to the general public [12]. Unlike a GA-CBDC whose issuance grants the general public direct access to accounts held at the central bank; a GV-CBDC once issued by a central bank is distributed to PSPs into special PSP accounts held at the central bank for onward transmission to the general-public [64]. The general-public will then store the GV-CBDC in special customer accounts provided by the PSP [28]. To access the GV-CBDC held at the PSP, the general public may use e-wallets, payment cards or other access mechanisms provided by the PSP [64]. Depending on the mode of implementation, a GV-CBDC may represent a claim on the assets of the central bank or the PSP.

We present a generic framework for a GV-CBDC system in Figure 5.

IV. DLT

DLT refers to a combination of technologies and capabilities that provide strong auditability and traceability guarantees to enable multiple system participants to share in a trustless environment, access to the same data over multiple logical and geographic locations.

Blockchain, a type of DLT introduced by Satoshi Nakamoto [46], [47] in 2008 popularized the term DLT following the release of the Bitcoin core [4] in 2009.

All blockchains are a type of DLT; however, not all DLTs are blockchains as various approaches other than *blocks* may be used to chronologically and immutably record transactions on a ledger. Nonetheless, in this paper, we use the term blockchain and DLT interchangeably.

Key characteristics of DLT include distributedness, security, privacy, immutability, data integrity, and redundancy [48], [49], making DLT suitable for addressing the needs

of several industries and applications that require these characteristics.

A. CLASSIFICATION OF DLT

Two main types of DLT platforms are identified in literature, namely permissionless and permissioned DLT platforms [74].

1) PERMISSIONLESS DLT PLATFORMS

Permissionless DLT platforms also known as public DLT platforms refer to DLT systems that are open for adoption and/or usage by the general public without the need for authorization by a trusted party. Anyone can join such DLT systems and begin to publish or mine blocks. Additionally, anyone can fork (download and modify) versions of such DLT systems to create new applications and services without requiring authorization from a trusted party.

Due to the absence of a trusted party who ensures that participants in a permissionless DLT system behave in an acceptable and non-malicious manner, resource-intensive consensus mechanisms such as PoW [4] and PoS [72], [73] are used to guarantee trust and integrity of the system.

Examples of permissionless DLT platforms include the Bitcoin and Ethereum DLT platforms.

2) PERMISSIONED DLT PLATFORMS

Permissioned DLT platforms also known as private DLT platforms refer to DLT systems that require authorization from a trusted party before participants can join the system.

All participants or members of a permissioned DLT system must be authorized and authenticated by the trusted party before they are able to carry out transactions in the system.

Various consensus approaches including but not limited to Practical Byzantine Fault Tolerance (PBFT), Istanbul Byzantine Fault Tolerance (IBFT), Kafka and Raft-based
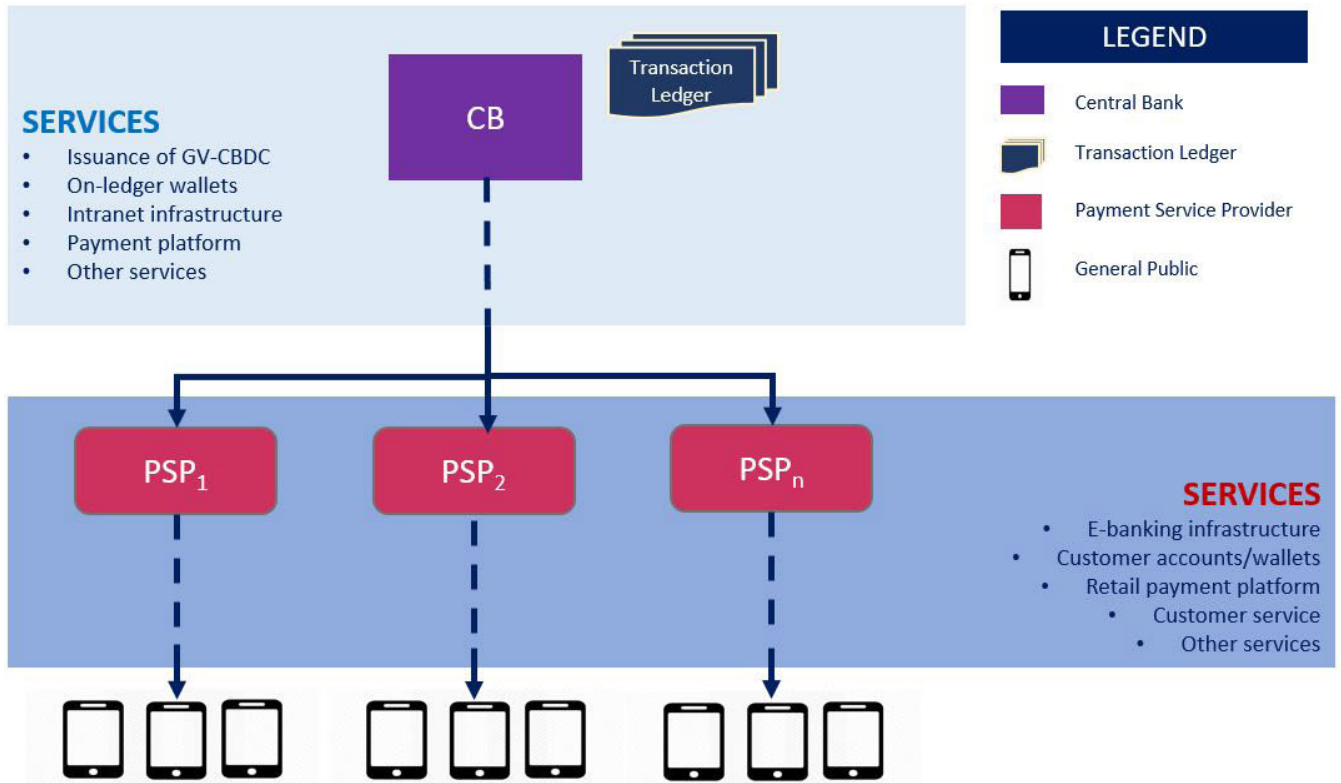
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FIGURE 5. GV-CBDC system generic framework.

consensus mechanisms have been proposed for permissioned DLT systems.

Examples of popular permissioned DLT platforms include Quorum, Hyperledger Fabric and Corda.

B. DLT PLATFORM LIMITATIONS

Permissionless DLT platforms such as Bitcoin and Ethereum are also known as first generation DLT platforms as they were the first DLT platforms of any kind to be developed. While these DLT platforms possess several desirable attributes for the financial services industry, a number of shortfalls in their original design and implementation undermines their suitability for FMIs.

Firstly, a majority of the first generation DLT platforms are public, allowing anyone to join and conduct transactions on the platforms without a need for approval from anyone [6], [47]. Ensuring compliance with the PFMIs requires that counterparties in an FMI must meet strict access and participation requirements (*PFMI Principle 18 - Access and Participation Requirements*) in order to guarantee the safety and security of the underlying FMI [50].

Secondly, the public nature of the first generation DLT platforms means that all transactions are publicly visible, representing a lack of compliance with *PFMIs Principle 17 - Operational Risk*, whose goal is to ensure transaction and data privacy for FMI transaction participants.

Thirdly, the dominant consensus protocol leveraged by a majority of the first generation DLT platforms is the Proof-of-Work (PoW) consensus protocol [128]. PoW is designed to mitigate against double spending attacks through the use of miners who must deploy energy-intensive computing systems [128]. The energy consumption of PoW-based DLT systems may be likened to that of a large power plant [14]. Central banks and PSPs do not require such excessive amounts of energy for their daily operations. As a result, PoW-based DLT systems are unsuitable for implementing financial industry functions and use cases that could benefit from the potential of DLT. Additionally, the PoW consensus mechanism is probabilistic rather than deterministic [62], therefore, there is a small chance that transactions in blocks farthest from the *genesis block* of a first generation DLT network may be reversed, invalidating the settlement irrevocability requirement of the PFMIs (*Principle 8 - Settlement Finality*).

In FMIs, payment transactions usually require a fraction of a second to achieve settlement finality. Bitcoin only adds transactions to blocks and propagates such blocks to the blockchain ledger every 10 minutes [47]. This design feature of blockchains violates the immediate and final settlement requirement (*Principle 8 - Settlement Finality*) of the PFMIs.

Other limitations of the first generation DLT platforms include but are not limited to scalability challenges [76] (*PFMIs Principle 17 - Operational Risk*) as well as susceptibility to the 51% attack [74].

To address the limitations of the first generation DLT platforms, leading CMBs are collaborating with financial

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technology companies to develop permissioned DLT platforms that meet the needs of the financial services industry [51]. Notable DLT platforms in this category include JP Morgan Chase's Quorum, R3's Corda, and Linux Foundation's Hyperledger Fabric.

Other less known but notable permissioned DLT systems with desirable features for the financial services industry include Digital Asset's Digital Asset [99] platform, Blockstream's Elements [77], Anquan Capital's Anquan Permissioned Blockchain [78], and Chain Inc.'s Chain Core [79] DLT platforms.

We describe the Quorum, Corda, and Hyperledger Fabric DLT platforms in the subsequent subsection.

C. FINANCE INDUSTRY-ORIENTED DLT PLATFORMS
1) QUORUM
Built in 2016 by JP Morgan Chase, Quorum is an open source Ethereum-based permissioned DLT platform with support for smart contracts, transaction and contract privacy, and multiple voting-based consensus mechanisms [52].

Quorum is a fork of go-Ethereum with support for IBFT and Raft-based consensus mechanisms, ensuring faster block propagation times and guaranteeing transaction finality and irrevocability [53], [54].

Quorum provides for a single shared blockchain underpinned by cryptographic mechanisms that ensures that only parties to a transaction can see data related to the transaction.

The architecture of Quorum is presented in Figure 6. It is made up of the transaction manger, crypto enclave, consensus, and network manager.
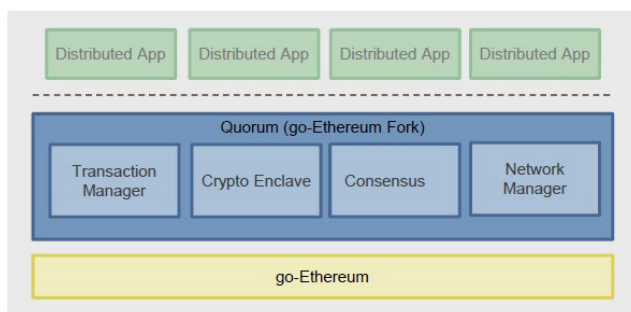
FIGURE 6. Quorum DLT platform architecture [54].

The *Transaction Manager* manages access to encrypted transaction data in Quorum as well as managing the platform's interactions with other transaction managers and the local data store of a Quorum node.

The *Crypto Enclave* is responsible for key management and data encryption and decryption in Quorum.

The *Consensus* component provides for the use of various consensus mechanisms in Quorum. Consensus mechanisms currently supported on Quorum are the Raft-based consensus mechanisms and the IBFT consensus mechanism.

Raft-based consensus mechanisms are suitable for a closed membership-based consortium/organization where

transaction settlement finality is a requirement. In such a system, there exists a leader/follower relationship such as in a wholesale interbank payments settlement setting where the central bank is the defacto leader for authenticating and validating transactions while CMB participants are considered followers.

An IBFT is a three-phase consensus mechanism suitable for DLT implementations where fault tolerance is a key requirement. IBFT also provides for settlement finality.

The *Network Manager* controls access to a Quorum network, thereby enabling a permissioned network of nodes to be created for a Quorum implementation.

2) CORDA
Corda is an open-source permissioned enterprise DLT platform developed from the ground up with a focus on the financial services industry by the R3 consortium in 2016. R3 is a distributed ledger technology consortium established in 2014 [55]. The consortium is made of more than 300 members and partners across multiple industries from the private and public sector [56].

Inspired by developments in the blockchain industry, Corda introduces a new consensus algorithm that is based on the concept of notary nodes. A notary's primary responsibility is preventing double spending in Corda. For a given transaction in Corda, a notary ensures that it has not signed another transaction consuming any of the same input states, thereby preventing double spending [57]. Input states are represented by unspent transaction outputs (UTXO) in Corda.

A Corda state is an immutable object representing a fact known by one or more Corda nodes at a specific point in time. Every Corda state has an appointed notary. Each Corda node has its own database, known as a vault where it stores any relevant states to itself. A Corda node's internal architecture is presented in Figure 7.
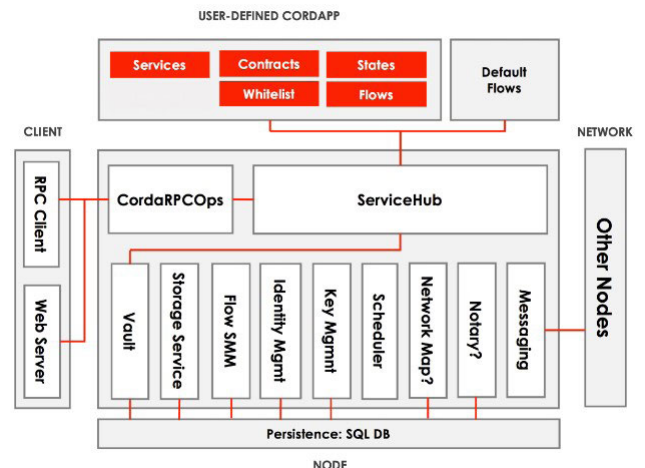
FIGURE 7. Corda node internal architecture [58].

The Corda DLT architecture is made up of five key layers which are the persistence layer, network interface layer,

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remote procedural calls (RPC) client layer, service hub layer, and user-defined CorDapp interface layer [58].

The *Persistence* layer is responsible for data storage in Corda.

The *Network* interface layer is responsible for interaction between a Corda node and other nodes in a Corda network.

The *RPC Client* allows a Corda node owner to interact with the node under its ownership through RPC calls.

The *ServiceHub* provides capabilities that allow a given Corda node to call its other services.

The *CorDapp* layer allows a given Corda node to be extended through the installation of CorDapps.

CorDapps are distributed applications that run on a Corda platform.

3) HYPERLEDGER FABRIC

Hyperledger Fabric [59] is an open source plug-and-play permissioned DLT platform started in 2016 by IBM and Digital Asset and currently hosted and managed by the Linux Foundation [60].

Fabric has a modular and configurable architecture with support for smart contracts (known as chaincode in Fabric) written in general-purpose programming languages such as Java, Go and Node.js, rather than restrictive domain-specific languages, therefore allowing for easy Fabric deployments by enterprises with no additional training required [59], [61].

Fabric provides flexibility with its support for pluggable consensus protocols such as Kafka and Raft-based consensus protocol that do not require the use of cryptocurrencies, thus, allowing different consensus mechanisms to be implemented for various use case scenarios [61].

Unlike most DLT platforms including Quorum and Ethereum's PoW implementation that employ an order-execute architecture whereby the blockchain network orders transactions first using a consensus protocol, and then executes them in the same order on all peers sequentially [61], Fabric employs an execute-order-validate architecture allowing Fabric deployments to achieve better performance (throughput), resiliency, scalability and confidentiality for transactions. The Fabric approach makes it a deterministic DLT platform and provides for concurrent transaction execution [62].

The key components of a Fabric DLT platform are ordering service, membership service provider, peer-to-peer gossip service, chaincode service, transaction ledger, and the endorsement and validation policy enforcement protocol [63]. We present Fabric's reference architecture in Figure 8.

The *ordering service* is responsible for establishing consensus on the order of transactions and broadcasting of blocks to peers through a shared communication channel. A channel in Fabric is a ''subnet'' provisioned by the ordering service for private and confidential communication between two or more peers in a given Fabric network.
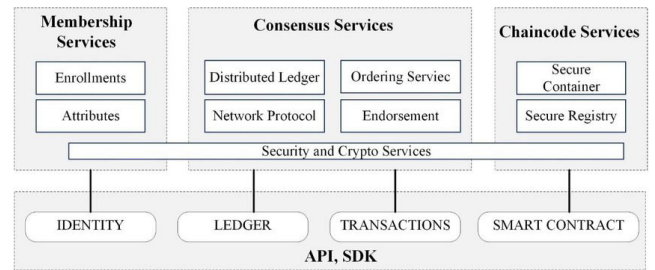

FIGURE 8. Hyperledger fabric reference architecture [75].

The *membership service provider* performs identity management functions in Fabric by associating entities in the Fabric network with cryptographic identities.

The *peer-to-peer gossip service*, which is optional, is responsible for disseminating the ordering service's outputs to other peers.

The *chaincode service* provides for the execution of chaincodes in a container environment to guarantee transaction isolation.

The *transaction ledger* is responsible for recording all transactions on Fabric.

Lastly, the *endorsement policy* is used by a chaincode to specify the Fabric nodes that participate in transactions and for validating transactions before they are committed to the transaction ledger.

D. FINANCE INDUSTRY DLT USE CASES

DLT has applicability across several domains of the financial services industry. It is envisaged that DLT will drive operational and regulatory efficiency, improve transaction processing times, and minimize fraud and risks associated with transactions in the financial services industry.

In Table 1, we highlight some of the use cases for DLT in the financial services industry identified in literature [76], [80].

All identified use cases are giving standard codes *UC + number* for ease of referencing throughout this paper.

We note that the use cases in Table 1 are non-exhaustive.

V. CBDC EXPERIMENT SELECTION
A. RESEARCH IDENTIFICATION

To identify the relevant CBDC experiment for our survey, we crawled the data stores of a number of reputable institutions and academic journals.

We crawled the database of the World Economic Forum (WEF), a renowned global organization that is an active participant in world economic affairs and CBDC related initiatives at *https://www.weforum.org*.

Secondly, we searched the data stores of the BIS at *https://www.bis.org*.

Further, we crawled the database of IEEE, an entity renowned for publishing high quality engineering, computing and multidisciplinary research outputs at *https://ieeexplore.ieee.org*.

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TABLE 1. Finance industry DLT use uses.

Use Case	Use Case Description
UC1	**G-CBDC** – DLT may be used to issue G-CBDCs for retail and other general-purpose transactions.
UC2	**W-CBDC** – DLT may be used to issue W-CBDCs for inter bank payments settlement.
UC3	**RTGS System** – DLT may be used to improve payment system resiliency by implementing various RTGS system or LVTS functions in a decentralized manner to eliminate the single-point-of-failure problem in traditionally centralized RTGS system implementations.
UC4	**KYC and AML** – KYC/AML are essential regulatory requirements in the financial services industry. DLT may be used to implement immutable user identities (KYC) that may be shared across multiple stakeholders in the financial services industry and other vertical industries to minimize money laundering (AML) and other fraudulent transactions. KYC/AML may then be connected to CBDCs to achieve AML regulatory and transaction anonymity requirements for different CBDC implementations.
UC5	**Trade Finance** – DLT may be used to improve the efficiency of trade finance activities which are pre dominantly manual, time-consuming and inefficient. DLT-based KYC/AML processes may then be connected to DLT-based trade finance implement ations to enhance the overall trade finance sub-sector of the financial services industry.
UC6	**Securities Settlement** – Processing times for securities settlement functions may be improved with DLT. DLT-based implementation of securities settlement functions may enable the simultaneous and efficient exchange of multiple asset types such as the exchange of bond assets for cash tokens.
UC7	**Bond Issuance** – DLT may be used to implement bond issuance and lifecycle management functions to improve the efficiency and cost of bond issuance activities both domestically and internationally.
UC8	**Information Exchange and Data Sharing** – DLT implementation of KYC is a first step to achieving a coherent and consistent global database of immutable user identities that may be shared across multiple horizontal and vertical industries or with governments in a decentralized manner to improve global transaction efficiency while mitigating against fraudulent transactions.
UC9	**Cross-Border Payments** – DLT may be used to improve the efficiency of interbank cross-border payments.
UC10	**Cash Supply Chain** – In scenarios where CBDCs are implemented as complement to cash and not replace ment of cash, DLTs may be used to improve the lifecycle of the production, transfer and management of cash from the central bank to CMBs and to end users.

Due to DLTs strong cryptographic underpinnings, we also combed through the IACR database at *https://www.iacr.org* to identify the relevant CBDC research articles for our survey.

Finally, we searched the WhitepaperDatabase.Com (WDC), a renowned data source in the cryptocurrency world where whitepapers for leading cryptocurrency projects such as Ethereum, Ripple, Tether, Stellar and other altcoins were all published at *https://whitepaperdatabase.com*.

We searched for the following keywords on all our identified data stores: *CBDC, CBDC research, CBDC experiment, CBDC project, central bank digital currency, central bank digital currency research, central bank digital currency experiment, central bank digital currency project,*

national digital currency, national digital currency research, national digital currency experiment, national digital currency project, national cryptocurrency, national cryptocurrency research, national cryptocurrency experiment, and national cryptocurrency project.

We present our keywords search results in Table 2. Further, we evaluate the articles identified in Table 2 based on a set of preliminary and secondary screening criteria to determine their suitability for our study.

TABLE 2. Keyword search results.

Keywords	Data Source/No. of Articles				
	WEF	BIS	IEEE	IACR	WDC
CBDC	94	87	9	1	0
CBDC research	76	38	5	1	0
CBDC experiment	9	7	1	0	0
CBDC project	32	28	0	1	0
Central bank digital currency	1,920	1,027	9	192	2
Central bank digital currency research	1,420	482	2	227	0
Central bank digital currency experiment	363	51	2	197	0
Central bank digital currency project	1,280	344	1	174	0
National digital currency	1,890	737	32	203	3
National digital currency research	1,500	364	13	263	0
National digital currency experiment	384	44	2	226	0
National digital currency project	1,440	289	4	165	0
National crypto-currency	197	45	168	251	1
National crypto-currency research	287	27	89	356	0
National crypto-currency experiment	112	8	20	185	0
National crypto-currency project	275	20	26	305	0
TOTAL	**11,279**	**3,598**	**383**	**2,747**	**6**

B. PRELIMINARY SCREENING CRITERIA

We establish a preliminary screening criteria to remove duplicates and other publications that do not meet our research objectives.

For an article to be considered for inclusion in our survey, it must meet the following preliminary screening criteria.

The article must be:

- Written in English.
- Published on or before November 30, 2019.
- Published under the authorization of a central bank or related government entity in the country in which the CBDC experiment is to be implemented.
- A full length research publication on CBDC and not a speech, news item or magazine publication.

We undertook a quick review of the *title, abstract and/or introduction* of all the publications in Table 2 to determine their relevance for our survey inline with our preliminary screening criteria.

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We present our article identification, screening and selection process in Figure 9.
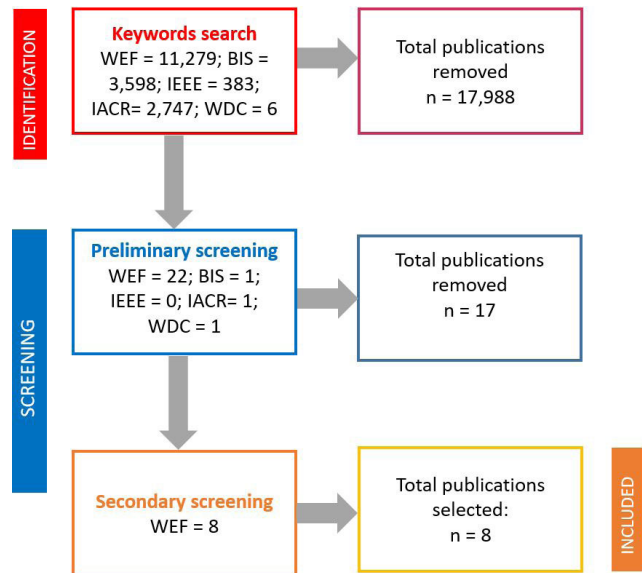
FIGURE 9. CBDC research identification and screening process.

TABLE 3. Preliminary screening results.

Jurisdiction	Responsible Institution	Research Name
England	Bank of England	RSCoin
Canada	Bank of Canada	Project Jasper
Singapore	MAS	Project Ubin
Brazil	Banco Central do Brasil	Project SALT
Hong Kong	HKMA	Project LionRock
South Africa	SARB	Project Khokha
Uruguay	Banco Central del Uruguay	e-Peso
Germany	Deutsche Bundesbank	BLOCKBASTER
Venezuela	SUPCAVEN	Petro
Thailand	Bank of Thailand	Project Inthanon
Sweden	Sveriges Riksbank	e-Krona
Lithuania	Bank of Lithuania	LBChain
USA	US Federal Reserve Bank	Fedcoin
Korea	Bank of Korea	N/A
Japan	Bank of Japan	N/A
Israel	Bank of Israel	e-Shekel
Norway	Norges Bank	N/A
New Zealand	Reserve Bank of New Zealand	N/A
Finland	Bank of Finland	N/A
Denmark	Danmarks Nationalbank	N/A
Switzerland	Swiss National Bank	N/A
EU	ECB	N/A
Canada, England & Singapore	Bank of Canada, Bank of England & MAS	N/A
Canada & Singapore	Bank of Canada & MAS	Jasper–Ubin
EU & Japan	ECB & Bank of Japan	Project Stella

1) PRELIMINARY SCREENING RESULTS

We reviewed all the articles and publications identified on the WEF data store and found twenty-two articles curated at [11] that met our preliminary screening criteria.

We found one article on BIS [22], no articles on IEEE, one article on IACR [14] and one article on WDC [25] respectively that met our preliminary screening criteria.

Using our preliminary screening criteria, a total of twenty-five CBDC research articles were identified. The twenty-five identified articles are presented in Table 3.

Next, we submitted the twenty-five articles to further evaluation using our secondary screening criteria described in the next subsection.

C. SECONDARY SCREENING CRITERIA

Our research objective is *to identify DLT-based CBDC experiments with completed PoC prototypes that enable us to comprehensively assess the motivations and practices for the given experiment*.

In line with our research objective, we establish the following secondary screening criteria in order of importance.

All the items in our secondary screening criteria are mandatory. A CBDC experiment is excluded even if only one of the criteria items is not met by the given experiment.

Criteria 1: Goal of Research - Does the final goal of the CBDC research publication include the development of a PoC? If yes, move to **Criteria 2**. Otherwise, discard the experiment.

Criteria 2: PoC Development - Has a PoC prototype been developed for the CBDC research under consideration? If yes, move to **Criteria 3**. Otherwise, discard the experiment.

Criteria 3: PoC Documentation - if a PoC has been developed, is a detailed documentation on the experiment publicly available? If yes, move to **Criteria 4**. Otherwise, discard the experiment.

Criteria 4: DLT Platform – Does the experiment use at least one of Quorum, Fabric, Corda or Ethereum for its implementation? If yes, move to **Criteria 5**. Otherwise, discard the experiment.

Criteria 5: Type of CBDC - Does the research publication clearly state the type of CBDC implemented? If yes, does the type of CBDC prototype implemented fit into our CBDC classification in **Section III-B**? If yes, indicate the type of CBDC and select the experiment. If not explicitly stated, can the type of CBDC implemented be inferred from the available CBDC research publication taking into consideration our classification of CBDCs in **Section III-B**? If yes, indicate the type of CBDC and select the experiment. Discard the experiment if the type of CBDC implemented is neither explicitly stated nor can it be inferred from the available CBDC research publication.

1) SECONDARY SCREENING RESULTS

The *Bank of England* through researchers at the University College London implemented the RSCoin [14] CBDC framework in 2016. In [14], the authors propose a cryptocurrency model that gives control for the issuance and distribution of digital currencies to a central bank, while control for the maintenance of the transaction ledger is transferred to mintettes. Mintettes refers to CMBs or any financial institutions authorized and verified by a central bank to provide financial services in a given country [81]. RSCoin is only

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TABLE 4. Selected CBDC experiment list.

Jurisdiction	Responsible Institution	Experiment Name	Type of CBDC
Canada	Bank of Canada	Project Jasper	W-CBDC
Germany	Deutsche Bundesbank	BLOCKBASTER	W-CBDC
Brazil	Banco Central do Brasil	Project SALT	W-CBDC
Singapore	MAS	Project Ubin	W-CBDC
EU & Japan	ECB & Bank of Japan	Project Stella	W-CBDC
South Africa	SARB	Project Khokha	W-CBDC
Thailand	Bank of Thailand	Project Inthanon	W-CBDC
Canada & Singapore	Bank of Canada & MAS	Jasper–Ubin	W-CBDC

a CBDC framework and not an actual CBDC experiment. We are therefore unable to definitively determine the type of CBDC implemented in the RSCoin publication. The RSCoin CBDC experiment is therefore excluded from our final list of selected experiments based on **Criteria 5**.

Hong Kong's HKMA implemented a DLT-based PoC for its LionRock CBDC experiment [82] on multiple DLT platforms; however, a detailed PoC documentation for the experiment is not publicly available. Consequently, we exclude the Project LionRock from our final list of selected CBDC experiments based on **Criteria 3**.

The *Uruguayan e-Peso* CBDC experiment did not use DLT for its implementation according to [12]; therefore, the e-Peso experiment is discarded and omitted from our survey based on **Criteria 4**.

The *Sveriges Riksbank* provides a detailed description of its planned CBDC experiment in the e-Krona project reports [27], [28]. The Bank plans to implement a G-CBDC PoC prototype; however, the PoC prototype is yet to be developed. Additionally, the Riksbank indicated in [28] that it may not use DLT for its e-Krona implementation as the technology is less mature. The e-Krona CBDC experiment is therefore excluded from our final list of selected CBDC experiments based on **Criteria 2** and **Criteria 4**.

The *Venezuelan Petro* CBDC is a G-CBDC implemented on the Ethereum DLT platform with the goal to reduce Venezuela's dependency on the US Dollar as the world's largest reserve currency [25] and overcome US and EU sanctions [88]. However, there is limited documentation on the Petro CBDC in English. As a result, the Venezuelan Petro project is excluded from our final list of selected CBDC experiments based on **Criteria 3**.

Lithuania's LBChain CBDC experiment seeks to promote the development of the country's financial services industry through innovative blockchain applications. The Bank of Lithuania is undergoing multiple procurement processes to select preferred service providers for the development of the LBChain platform [29], [30]. As the Bank of Lithuania is yet to conclude its procurement processes, a completed PoC of the LBChain platform is currently unavailable. We therefore exclude the LBChain CBDC experiment from our final list of selected CBDC experiments based on **Criteria 2**.

The concept of Fedcoin was proposed by various researchers [67]–[69] and not by the *US Federal Reserve*. The US Fed has not indicated plans to develop a Fedcoin PoC in the medium to long term, therefore, Fedcoin is eliminated from the final list of CBDC experiments surveyed in this paper based on **Criteria 1**.

The *Bank of Korea* [32], the *Bank of Japan* [33], the *Bank of Israel* [34], the *Norges Bank* [35], the *Reserve Bank of New Zealand* [36], the *Bank of Finland* [37], the *Danmarks Nationalbank* [38], the *Swiss National Bank* [39] and the *European Central Bank* [70], [71] have each published CBDC research outputs with no intentions to implement DLT-based CBDC PoCs in the medium to long term. The CBDC research publications from these central banks are therefore omitted from our final list of selected CBDC experiments based on **Criteria 1**.

The joint research publication by the *Bank of Canada*, the *Bank of England* and the *MAS* [44], [45] seeks to explore new models to improve the efficiency of cross-border payments. Aspects of the research publication focuses on improving cross-border interbank transaction efficiency using DLT; however, an implementation of a PoC arising out of the joint research effort is not a stated goal of the publication. In this regard, the multilateral effort by the Bank of Canada, the Bank of England and the MAS is excluded from our final list of selected CBDC experiments based on **Criteria 1**.

The final list of CBDC experiments that meets our secondary screening criteria and therefore are selected and surveyed in this paper are the experiments undertaken by the *Bank of Canada*, *Deutsche Bundesbank*, *Banco Central do Brasil*, *MAS*, *SARB* and the *Bank of Thailand*.

Additionally, the joint experiment by the *ECB* and the *Bank of Japan* as well as the bilateral experiment by the *Bank of Canada* and the *MAS* are selected and surveyed in this paper.

The final list of CBDC experiments selected and surveyed in this paper is presented in Table 4.

VI. CBDC EXPERIMENT PRACTICES

In this Section, we examine best practice approaches adopted by central banks for their CBDC research initiatives.
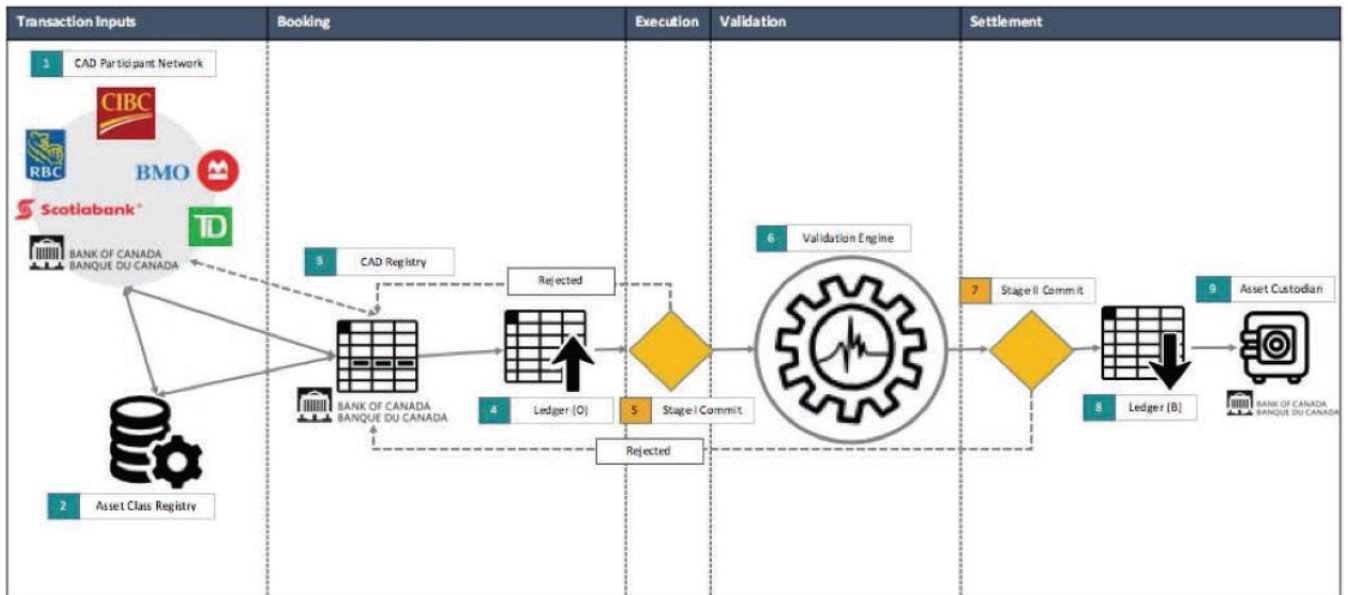
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FIGURE 10. Project Jasper Phase I transaction lifecycle [15].

We present the specific motivations, use cases, choice of technology and notable outputs for our selected CBDC experiments presented in Table 4.

A. PROJECT JASPER

Project Jasper [15], a W-CBDC experiment was launched in Canada in March 2016 through the partnership of Payments Canada, the Bank of Canada, a selected number of Canadian CMBs and R3 [55], a blockchain-based company.

The motivation for Project Jasper was to build and evaluate the applicability of DLT for domestic wholesale interbank payments settlement in Canada [16].

Canada's wholesale interbank payments settlement system is called the *LVTS* [16].

The LVTS processes approximately 32,000 large-value interbank transactions per day or ten transactions per second at peak hours [15].

The LVTS is made up of seventeen participating financial institutions including the Bank of Canada [127]. It is owned and operated by Payments Canada [102], with the Bank of Canada providing oversight for its operation in accordance with international PFMIs [15]. All the CMB participants in Project Jasper were participants in Canada's LVTS.

Implemented over three phases, Project Jasper sought to understand how DLT could transform the future of payments in Canada [16].

Phase I and II of Project Jasper realizes the implementation of a DLT-based RTGS FMI that enables the domestic interbank transfer of a W-CBDC asset in Canada on Ethereum and Corda respectively.

Phase III of Project Jasper implemented a DLT-based prototype for integrated securities and payments settlement in Canada using Corda.

1) JASPER PHASE I

Jasper Phase I was launched in March 2016 through the collaboration of Payments Canada, the Bank of Canada, five Canadian CMBs and R3.

The goal of Jasper Phase I was to build a DLT-based PoC prototype for domestic wholesale interbank payments settlement in Canada [15].

The transaction lifecycle of Jasper Phase I is presented in Figure 10.

In Jasper Phase I, distributed nodes were created for each participating entity on Ethereum.

The Bank of Canada was responsible for issuing DDRs; creating wallets for each CMB to hold DDRs; and approving or rejecting transactions through an autonomous *transaction agent* smart contract.

CMB nodes encompassed capabilities for creating accounts, initiating and executing transactions. All transactions on the Jasper Phase I platform were updated and synchronized onto each participating node regardless of whether a CMB is a counterparty to a transaction or not [15].

Payments Canada observed transactions on the Jasper platform in accordance with its mandate as the owner and operator of the LVTS.

The R3 node was responsible for accepting and recording all transactions onto a single shared ledger in Jasper Phase I.

In Jasper Phase I, a W-CBDC asset for interbank payments settlement was created to settle interbank transactions among participating CMBs of the project. The W-CBDC asset was called a digital depository receipt (DDR). Interbank payments on the Jasper platform were settled in DDR assets.

A DDR is a digital representation of the Canadian dollar. In Project Jasper, DDRs were issued by the Bank of Canada and backed one-for-one by cash pledged to the Bank of

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Canada by Jasper participating CMBs. DDRs therefore represented a claim on asset on the Bank of Canada [51].

As part of Phase I, a DLT-based LVTS was built on Ethereum to provide the mechanism and capabilities for the transfer of DDRs among participating CMBs [51].

To conduct transactions on the Jasper platform, capabilities for pledging, generating, exchanging, redeeming and archiving DDRs were built into the Ethereum-based LVTS platform.

The capabilties enabled the:
- CMB node to *pledge* Bank of Canada money to the Bank of Canada for DDRs.
- Bank of Canada node to *generate* DDRs and send them to a requesting CMB.
- Recipient CMB to *fund* its DDR wallet with DDRs received from the Bank of Canada.
- CMB node to *exchange* DDRs with a transaction counterparty.
- CMB to *redeem* DDRs for Bank of Canada money.
- Bank of Canada to *archive* redeemed DDRs.
- Bank of Canada *return* new net balance of DDRs on-ledger.

The pledge of Bank of Canada money for DDRs and the redemption of DDRs for Bank of Canada money by the participating CMBs meant that there was no increase in money circulating in the Canadian banking system [15].

The consensus mechanism used in Jasper Phase I was PoW built into Geth [15]. To validate a transaction between two transacting parties, all members of the R3 Consortium (forty-two nodes) were required to validate the transaction before it was accepted and recorded onto the transaction ledger although only participating Canadian CMBs (five nodes) could transact DDRs on the Jasper platform [15].

Following the development of the Jasper Phase I PoC, the prototype was tested in a non-production environment with the following evaluation results.

- *Throughput*: The Jasper Phase I prototype was able to process approximately fourteen transactions per second. This throughput was sufficient to handle current LVTS peak hour throughput requirements [15]. However, in the event of transaction volume spikes, the prototype may not be able to support the throughput requirements due to the fact that R3's forty-two distributed nodes would each be required to validate transactions before they are committed to the ledger. The platform may therefore not be able to deliver the LVTS' newly heightened volume requirements.
- *Data Privacy*: The Jasper Phase I prototype did not fully support participating entities requirements for *data privacy*. Ethereum is a permissionless DLT platform, therefore all transaction data on the Jasper Phase I prototype could be viewed by all system participants, thereby violating the data privacy requirement (*Principle 17 - Operational Risk*) of the PFMIs.
- *Settlement Finality*: The Ethereum prototype did not provide for settlement finality. The PoW consensus

algorithm is probabilistic, therefore there was always a small chance that a confirmed payment in Phase I could be reversed, invalidating the settlement irrevocability requirement (*Principle 8 - Settlement Finality*) of the PFMIs.

2) JASPER PHASE II

To address the limitations of Jasper Phase I, Jasper Phase II was launched in September 2016 to rebuild the Phase I prototype on a different DLT platform. Jasper Phase II was implemented on Corda.

Jasper Phase II attracted two more participating CMBs in addition to the original participants from Phase I.

In addition to the Phase I rebuild, Jasper Phase II implemented a Corda-based *atomic settlement* capability and a *liquidity-savings mechanism (LSM) settlement* option. The transaction capabilties supported in Phase I were thus extended to include support for atomic and deferred net settlement options in Phase II.

In Jasper Phase II, distributed nodes were created for each participating entity on Corda. Three types of nodes were created: *a supervisory node, a notary node and a participant node* [15].

The Bank of Canada was designated as both the notary node (Section IV-C2) and the supervisory node. The notary and supervisory nodes were combined into one system since both roles were performed by the same Bank of Canada entity. In its role as the supervisory node, the Bank of Canada had access to the entire transaction ledger with capabilities to query the ledger for monitoring and oversight purposes.

CMBs were each assigned a *participant node*. CMB nodes were updated and synchronized with only transaction records they were counterparty to.

Consensus on Jasper Phase II was achieved through the implementation of two Corda functions: a *validation function* and a *uniqueness function*.

Corda's validation function ensures that all details of a given transaction are verified and validated by the transacting parties and that the sender has the requisite amount of DDRs in their wallet to effect the transaction. In Jasper Phase II, the validation function was performed by CMB nodes that were counterparties to a transaction [15].

The uniqueness function was performed by the Bank of Canada in its role as the notary. Corda's uniqueness function ensured that DDRs proposed for exchange by CMBs had not been previously spent by the sender. The uniqueness function, thus prevents double spending by counterparties in Corda.

Following the development of the Jasper Phase II prototype, the platform was tested in a non-production environment with the following evaluation results:

- *Settlement Finality*: The introduction of a notary node ensured that settlement finality was achieved in Jasper Phase II.
- *Single Point of Failure*: The use of a trusted party to achieve settlement finality; however, introduced a

single-point-of-failure problem into Jasper Phase II prototype. In the event that the Bank of Canada node was unavailable, no transactions could be processed on the Jasper Phase II platform.

- *Scalability*: Consensus was achieved much faster on Jasper Phase II as only counterparties to a transaction and the Bank of Canada node were required to establish consensus on a given transaction. This ensured that the problem of transaction scalability at peak hours was eliminated.
- *Data Privacy*: The use of a notary node also ensured that counterparty data privacy requirements were met as transaction data were accessible by only the Bank of Canada and the CMBs involved in the given transaction.
- *Resiliency*: The resiliency of the Jasper Phase II prototype was diminished compared to Phase I. This is because participant nodes in Jasper Phase II recorded only transactions they were counterparty to. In the event that a participant node is unavailable or corrupted, the given node may incur extra costs to replicate its lost data from the Bank of Canada node. Participating CMBs may therefore have to invest in a high-availability system to mitigate against the impact of a corrupted node. Investment for high-availability node is also required for the Bank of Canada node to ensure that transactions can be processed on the Jasper Phase II platform at all times.

In conclusion, the participants of Project Jasper I and II emphasized that the true benefits and potential of DLT may only be realized if system reuse for the settlement of multiple asset classes is prioritized in CBDC experiment efforts.

3) JASPER PHASE III

The Bank of Canada initiated Jasper Phase III [93] in October 2017 with the objective to leverage DLT for the exchange of multiple asset types.

Participants of Jasper Phase III were the Payments Canada, the Bank of Canada, TMX Group, Accenture and R3.

The TMX Group is a Canadian financial services company that operates various securities exchanges [96]. It is the owner of the Canadian Depository for Securities (CDS) [96]. The CDS is the national clearing and settlement hub for securities depository in Canada [94], [95]. It administers the *CDSX*, Canada's securities settlement infrastructure. The Ontario Securities Commission, Quebec Securities Commission and the Bank of Canada have oversight responsibility over the CDS.

The goal of Jasper Phase III [93] was to implement a DLT-based PoC prototype for an integrated securities settlement infrastructure that allows for the exchange of multiple asset types on a shared ledger.

Jasper Phase III developed capabilities for the atomic settlement of tokenized financial assets on an integrated LVTS-CDSX platform. The prototype was implemented on Corda v2.0 and hosted on Microsoft Azure.

Six types of nodes were established for the Jasper Phase III platform as follows:

- *Bank of Canada node*: Responsible for the tokenization of cash.
- *Notary node*: Responsible for the performance of the uniqueness function in order to achieve transaction consensus and eliminate double spending.
- *Payments Canada node*: Observer of cash transactions on the LVTS.
- *LVTS-Member node*: Responsible for extending on-ledger credit to non-LVTS CDS members (such as broker-trader in the case of Jasper Phase III) for transaction settlement.
- *CDS node*: Responsible for the tokenization of equity. Additionally, it performs the role of central counterparty (CCP) in Jasper III in accordance with its legal mandate in Canada's financial services industry.
- *Broker-Trader node*: Participant in securities settlement transactions.

Overall, one node each were established for the Bank of Canada, Payments Canada and CDS respectively in accordance with the operational requirements of each entity. Additionally, fourteen broker-trader nodes and one LVTS-member node were established. The cumulative nodes established depict the relevant roles in Canada's equity settlement process [93]. Each node was hosted on a separate Microsoft Azure virtual machine.

Jasper Phase III created role-based permissions and restrictions for a number of processes required for securities settlement to reflect participants access rights in a real-world securities settlement scenario. These included processes for: *creating, pledging, transferring and redeeming* equity or cash tokens.

Collectively, cash and equity tokens are referred to as DDRs. Individually, cash DDR refers to cash tokens and equity DDR refers to equity tokens respectively.

Jasper Phase III included the development of the following deliverables:

- Tokenized cash asset issued by the Bank of Canada and tokenized equity asset issued by the CDS for delivery-versus-payment (DvP) settlement. Tokenized cash represents a claim on central bank money held at the Bank of Canada. Analogously, tokenized equity represents a claim on equity held at the CDS.
- Corda-based integrated settlement platform for the settlement of tokenized equity and cash assets.
- Capabilities for DvP settlement of tokenized equity assets against cash assets on the integrated securities settlement system (SSS) with the CDS acting as the CCP.
- Capabilities for credit extension to broker-dealer by the LVTS-member participant.

The process for *pledging*, *transferring*, *redeeming* and *archiving* cash and equity DDRs follows a similar pattern as in Jasper Phase I and II.

The happy path for the tokenization of cash in Jasper Phase III is presented in Figure 11 and described as follows:

- *Step 1*: Bank1 initiates an on-ledger transaction to *pledge* cash to the Bank of Canada for cash DDR.
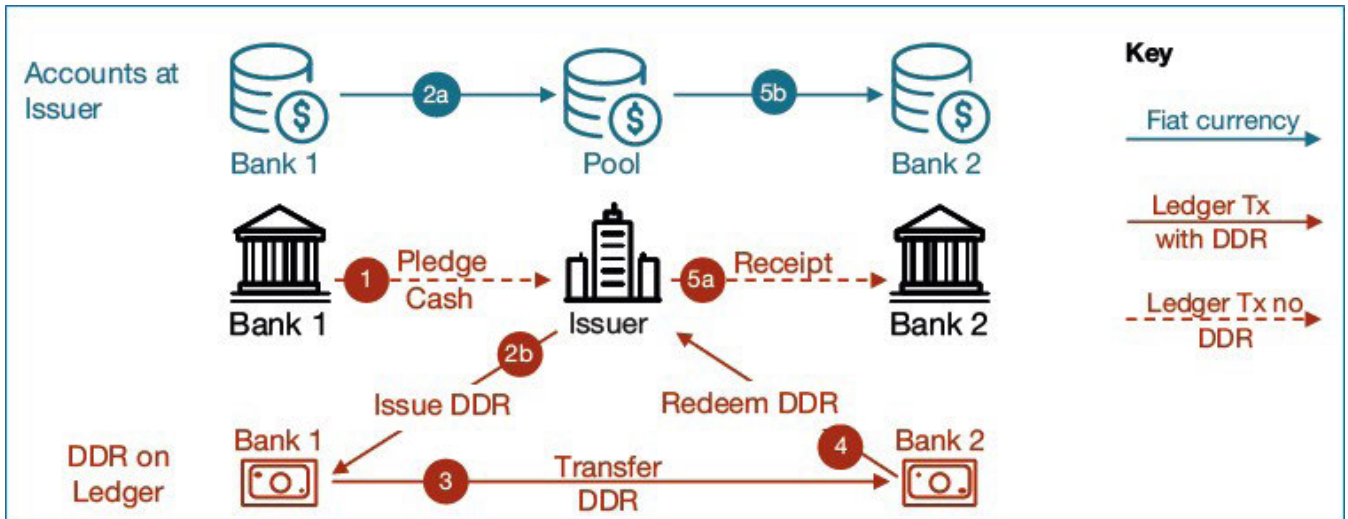
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FIGURE 11. Project Jasper Phase III asset tokenization process [93].
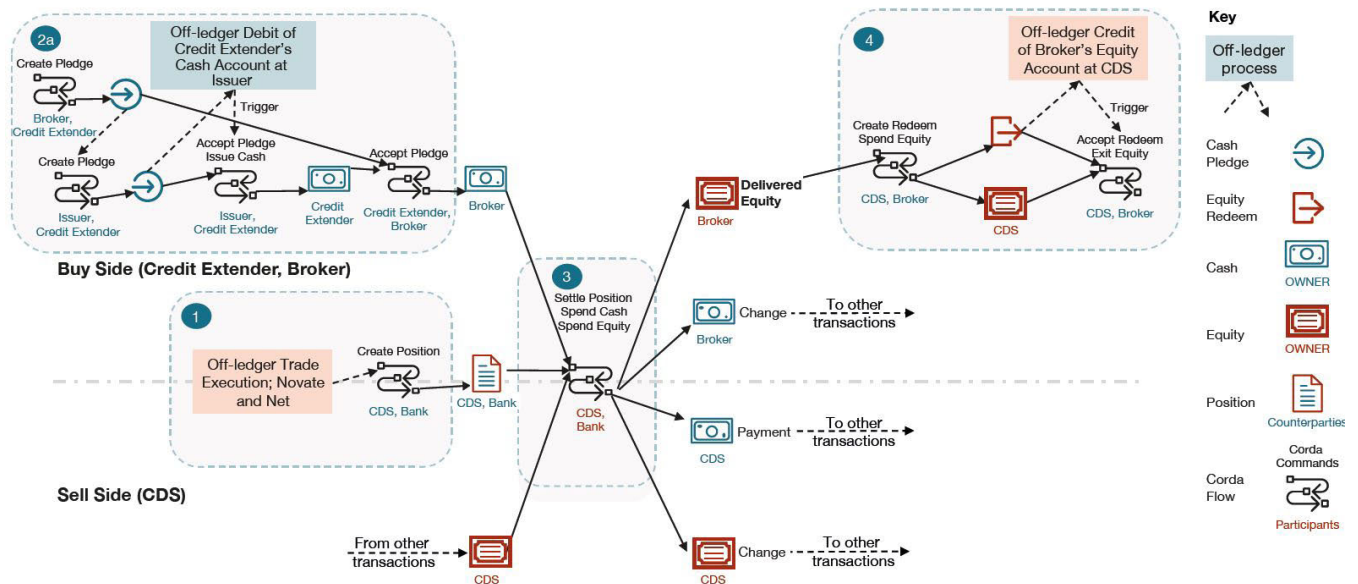

FIGURE 12. Project Jasper Phase III end-to-end security settlement process [93].

- *Step 2a*: The Bank of Canada reviews Bank1's on-ledger *pledge* request and verifies if Bank1 has sufficient funds in their off-ledger accounts. On successful verification, the Bank of Canada *transfers* the pledged amount from Bank1's off-ledger accounts on the Bank of Canada's books into an off-ledger "pool" account.
- *Step 2b*: The Bank of Canada *transfers* the corresponding cash DDR amount to Bank1's on-ledger wallet.
- *Step 3*: Bank1 *transfers* its on-ledger cash DDR to Bank2. Bank2 receives cash DDR in its on-ledger wallet.
- *Step 4*: Bank2 initiates a cash DDR *redeem* request and sends cash DDR to the Bank of Canada for redemption.
- *Step 5a*: The Bank of Canada verifies the cash DDR redemption request and issues an on-ledger receipt to Bank2 to confirm receipt of cash DDR.

- *Step 5b*: The Bank of Canada *transfers* the corresponding cash DDR amount in Bank of Canada money from the off-ledger pool account to Bank2's off-ledger account held at the central bank.

We present Jasper Phase III's end-to-end equity and cash settlement process in Figure 12.

Following the development of the Jasper Phase III prototype, the platform was integrated with both the LVTS and the CDSX.

Further, system testing was conducted for the integrated FMIs from three efficiency perspectives: technical efficiency, operational efficiency and cash efficiency. The observations from each efficiency perspective are presented as follows:

- *Technical Efficiency*: a) Using DLT enabled the integration of the LVTS and CDSX FMIs for securities

settlement without a large increase in the number of LVTS transactions processed per day and without Payments Canada and CDS losing control and ownership of their respective FMIs. b) The shared ledger DvP settlement approach adopted for Jasper Phase III enabled a better cash-equity interactions among transaction parties compared to the existing securities settlement arrangement in Canada. c) A cloud-hosted non-enterprise version of Corda was used to implement the Jasper Phase III integrated SSS prototype with a minimal set of functions in order to quickly evaluate the applicability of DLT for securities settlement functions in Canada. As a result, a detailed assessment of system performance, resiliency, availability and security were out of scope for the project. However, the platform was used to settle 35,000 trade positions in a timely manner.

- *Operational Efficiency*: Due to the scope limitation of the Jasper Phase III experiment, cost savings related to the use of DLT for an SSS deployment could not be examined.
- *Cash Efficiency*: The atomic settlement functionality built into Jasper Phase III brought about immediate settlement finality in the securities settlement process, thereby enabling the reuse of equity and cash DDRs once a transaction was completed.

The Jasper Phase III platform did not implement capabilties for posttrade activities.

Due to the limited scope and functionality of the Jasper Phase III integrated SSS prototype, a number of open questions on scope, business models and production readiness of DLT for FMIs remain that needs to be explored in future CBDC research.

B. PROJECT BLOCKBASTER

Motivated by advancements in emerging technologies and their applicability to the financial services industry, the Deutsche Börse Group and Deutsche Bundesbank started Project BLOCKBASTER [24] in March 2016 to explore the possibility of leveraging blockchain to improve back office services in Germany's securities settlement FMI.

Deutsche Bundesbank is the central bank of Germany [101]. Deutsche Börse Group is one of the world's largest securities exchange centers [100]. It is the owner and operator of Clearstream, a securities clearinghouse based in Luxembourg.

The goal of Project BLOCKBASTER was to create a DLT-based SSS prototype for the settlement of securities for cash.

Project BLOCKBASTER implemented a full interbank bond issuance and lifecycle management prototype on two DLT platforms: Hyperledger Fabric and Digital Assets.

The securities settled on Project BLOCKBASTER were tokenized bond and cash assets.

In order to enable rapid prototyping and assessment of the applicability of DLT for securities settlement, the scope of Project BLOCKBASTER was limited to the DLT-based settlement of matched trades in cash or securities only.

Capabilities for interest rate payments to users (banks) were also built into the BLOCKBASTER platform.

Capabilities for bond pricing, market making and LSM settlement options were out of scope for Project BLOCKBASTER.

Project BLOCKBASTER established five key entities with the following responsibilities within the PoC prototype:

- *Coin Providing Authority* - The CPA was responsible for the issuance of *digital coins* used for settlement in Project BLOCKBASTER. Only the CPA could issue digital coins in Project BLOCKBASTER.
- *Coin Distributor* - The CD was an entity (bank) with capabilties to *pledge* and *transfer* money to the CPA in exchange for digital coins. CDs could transfer their digital coins to banks or back to the CPA for redemption for cash.
- *Bond Providing Authority* - The BPA was a central securities depository with responsibility for the issuance of *digital bonds* used for settlement in Project BLOCKBASTER. Only the BPA could issue digital bonds in Project BLOCKBASTER.
- *Bond Distributor* - A BD was an entity (bank) with capabilties to receive digital bonds issued by the BPA. BDs could transfer their digital bonds to banks or back to the BPA for redemption for actual securities.
- *Corporate Action Executor* - The CAE was an entity responsible for executing a corporate action such as interest payment in Project BLOCKBASTER.

Three types of settlements were supported on the Project BLOCKBASTER platform: payments (only transfer of digital coins), Free-of-Payment (FoP) security settlement (only transfer of digital bonds) or DvP security settlement (concurrent exchange of digital bonds and digital coins).

Digital coins circulating on the BLOCKBASTER platform were returned to the CPA's account at the end of the business day, therefore there was no increase in money circulating in the German banking system.

Digital bonds on the BLOCKBASTER platform, however remained there until they were consumed in subsequent transactions or returned to the BPA for redemption [24].

We present a high-level overview of Project BLOCKBASTER in Figure 13.

We discuss the experimental results of the Fabric and Digital Asset prototypes developed in Project BLOCKBASTER in the subsequent subsections.

1) FABRIC-BASED PROTOTYPE

The Fabric-based BLOCKBASTER prototype was initially developed on Fabric v0.6, the current version of Fabric at the time of the prototype development. The prototype was later reconstructed on Fabric v1.0 as that version became available.

Fabric provides for a pluggable consensus mechanism (Section IV-C3), therefore the PBFT-based consensus mechanism in Fabric was replaced with a proof-of-authority (PoA) [97] consensus mechanism in the BLOCKBASTER Fabric-based prototype.
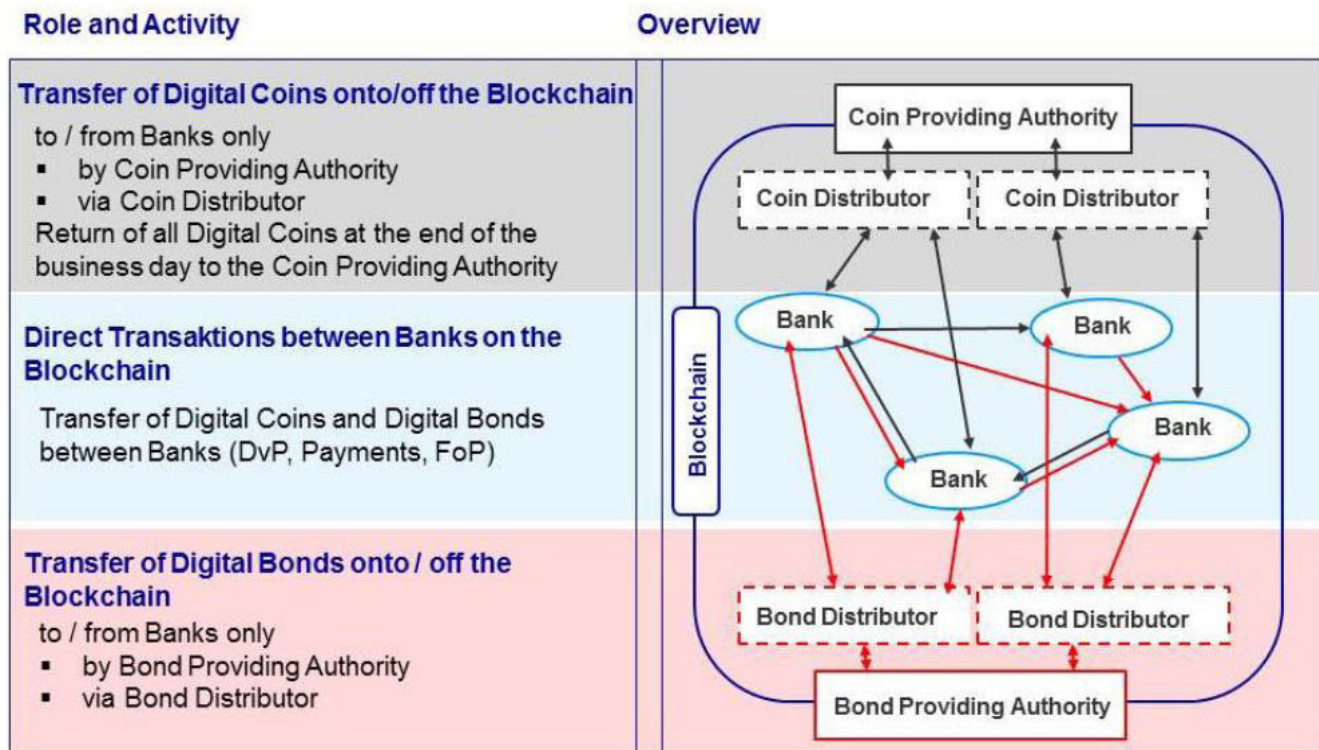
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FIGURE 13. Project BLOCKBASTER high level overview [24].

Leveraging the PoA consensus mechanism, transactions in the Fabric v0.6 BLOCKBASTER prototype were validated by only the CPA and BPA nodes, providing for high transaction scalability. The Fabric v1.0 BLOCKBASTER prototype adopted Fabric's endorsement policy and ordering service to further improve transaction performance.

Both Fabric prototypes implemented two types of nodes: validator nodes and non-validator nodes. Validator nodes were the CPA and BPA nodes with responsibility for validating transactions and preventing double spending. Non-validator which were the CD and BD nodes were responsible for publishing transactions onto the shared ledger.

Nodes for the Fabric v1.0 prototypes were individually deployed in an EC2 instance hosted within one Availability Zone on AWS.

Subsequently, the performance of the Fabric v1.0 prototype was evaluated from the *throughput* and *latency* perspectives using the following base dataset:*1,000 bank-user profiles*, *500 bond instruments* and *200,000 transactions*. The 200,000 transactions were broken down into *100,000 DvP transactions*, *50,000 FoP transactions* and *50,000 cash transactions*.

The Fabric-based prototype was instantiated with the base dataset and allowed to ran for 35 minutes with the following key observations:

- *Throughput*: Transaction throughput and latency were functions of the chaincode. The simpler the chaincode, the higher the throughput and the lower the latency.

The more complex the chaincode the lower the transaction throughput and the higher the latency.

- *Transaction Conflicts*: Significantly high throughput and minimal latency were recorded for all the transactions. However, several transaction conflicts were observed due to architectural changes between the Fabric v0.6 and v1.0 platforms. These conflicts were rectified in future versions of Fabric.

2) DIGITAL ASSET-BASED PROTOTYPE

Project BLOCKBASTER was rebuilt on the Digital Asset [98] (DA) DLT platform to evaluate the performance of the SSS prototype on a different DLT platform. The DA-based prototype was hosted on a DA in-house production environment hosted on AWS [24].

The DA DLT platform is made up of three layers; the application layer, the business logic layer, and the distributed ledger (DL) layer. The platform also comprises of two key roles; the operator role and the participant role.

A high-level overview of the DA platform is presented in Figure 14.

In Figure 14, the *application layer* provides capabilities for user-defined software interaction with other layers of the DA platform.

The *business logic layer* contains the business rules and smart contracts defined for a given DA network.

The *DL layer* stores transaction data in a DA network. It is made up of a *private contract store* (PCS) and a
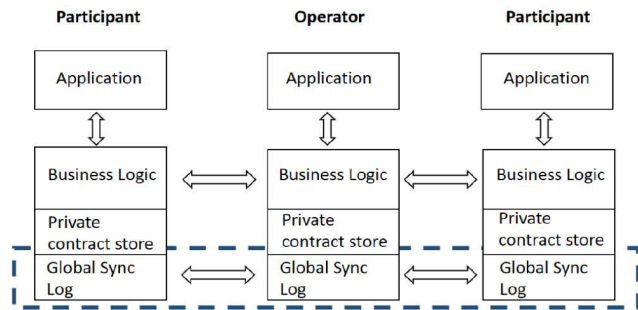
FIGURE 14. Digital asset DLT platform high level overview [99].

global sync log (GSL). The PCS is used to store all validated transaction data for which a given DA participant is counterparty to. The GSL records commitments and notifications across the entire DA network to guarantee platform auditability and integrity [99]. The GSL is the shared ledger in a given DA network.

The *operator* role in the DA DLT platform is responsible for defining, implementing and enforcing the rules of the DA network. In Project BLOCKBASTER, the operator function was performed by a special node called the *commiter node*. The committer node was responsible for verifying and writing all transactions to the GSL shared ledger.

The *participant* role refers to any entity that participates in activities on the DA DLT network. The CPA, BPA, CD, BD and CAE roles were all participant roles in the DA network.

Overall, three types of nodes were deployed for the DA-based BLOCKBASTER prototype: an *application node* that facilitates interactions between user-defined applications and the DA platform; a *participant node* which corresponds to DA platform's *participant role*; and a *committer node* which corresponds to the *operator role*.

An application node has a one-to-one relationship with a participant node.

In addition to the three types of settlements supported in the Fabric prototype, the DA-based prototype supported one more settlement type, *coupon payment*.

Following the rebuild of the DA-based BLOCKBASTER prototype, a functional assessment of the prototype was conducted from the throughput, latency and resource utilization perspectives using 30 different test scenarios and a varied number of bank-user profiles for each scenario.

All tests were ran for 30 minutes each with the base scenario ran over a 20 hour period to examine the platform performance consistencies over the period.

The node composition of the DA prototype experimental setup was as follows:

- *Operator node setup*: three DA nodes deployed on an in-house cloud environment hosted on AWS.
- *Participant node setup*: one CPA node; one BPA node; one CAE node; three CD nodes; three BD nodes; and 150 bank-user nodes.
- *Dataset*: 2,500,000 DvP transactions; 1,000,000 FoP transactions; 250,000 payment transactions; and 10,000 coupon payment transactions.

The following evaluation results were recorded for the functional testing of the DA prototype:

- *Throughput*: An increase in the number of transactions resulted in an increase in transaction throughput with a less than proportional increase in latency and memory usage.
- *Network Size*: An increase in participant nodes resulted in a less than proportional increase in latency and memory usage per node.
- *Scalability*: The DA-based prototype was able to meet stress testing and scalability benchmarks defined for the project.

C. PROJECT SALT

The Banco Central do Brasil initiated Project SALT [20] in September 2016 with the objective to identify central bank use cases that could be implemented on DLT.

The Bank identified four potential use cases and elected to implement one of the use cases, the *Alternative System for Transactions Settlement* (SALT) on multiple DLT platforms as a backup to Brazil's RTGS system.

Participants of Project SALT included the Central Bank of Brazil and a selected number of CMBs.

Phase I of Project SALT included the use case identification and the PoC implementation on BlockApps, a fork of the Ethereum platform over a sixty day period beginning September 2016 [20].

Phase II of Project SALT implemented SALT on Fabric and Quorum over a forty-five day period beginning January 2017 [20].

Additionally, Project SALT implemented a tokenized Brazilian Real (BRL) W-CBDC asset. We refer to the tokenized BRL asset as BRL-DDR.

1) SALT PHASE I

Having identified and selected one use case for implementation, the Central Bank of Brazil implemented Phase I of Project SALT, a backup RTGS system for wholesale interbank payment settlement with a minimal set of functionalities on BlockApps [20].

In SALT Phase I, both the central bank node and the CMB nodes were validating nodes. Consequently, both node types were equally responsible for achieving transaction consensus [20]. As it was implemented on BlockApps, the consensus mechanism used in SALT Phase I was the PoW consensus mechanism.

The SALT prototype had capabilities (smart contracts) that enabled CMBs to exchange BRL-DDR in a decentralized manner and achieving transaction consensus without relying on a central authority. Smart contracts implemented on SALT provided mechanisms to prevent double-spending by system participants. The Ethereum prototype is hosted at the Central Bank of Brazil's GitLab page [103].

Following the development and instantiation of the BlockApps prototype, the Central Bank of Brazil node generated the full quantity of BRL-DDRs to be transacted on SALT

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as well as digital wallets with corresponding balances for each CMB node [20]. All BRL-DDRs on the SALT Phase I platform were returned to the central bank once the system was terminated.

Testing and evaluating the SALT Phase I prototype, it was observed that the platform could not fully provide for system participants' requirements for data privacy.

The central bank adopted an inefficient mechanism to address the data privacy challenge which introduced further bottlenecks into the SALT Phase I platform. Adopting an alternative mechanism to resolve the data privacy limitation rendered the system inefficient in mitigating against double-spending. Additionally, transaction key protocol arrangements in SALT Phase I lacked strong forward secrecy unless keypairs were changed periodically [20].

2) SALT PHASE II

The Central Bank of Brazil began Project SALT Phase II in January 2017 to examine the suitability of alternative DLT platforms for the selected SALT use case scenario implemented in Phase I. Additionally, SALT Phase II sought to address the data privacy challenge encountered in Phase I [20].

SALT Phase II was implemented on Fabric and Quorum.

a: FABRIC

The first iteration of SALT Phase II was implemented on Fabric v0.6.

Consensus on the Fabric prototype [104] was achieved using the PBFT consensus mechanism. Overall, two types of nodes were supported on the Fabric prototype: validating nodes and non-validating nodes. Validating nodes were responsible for achieving transaction consensus while non-validating nodes only maintained a copy of the shared ledger.

The Fabric prototype had data privacy challenges similar to the BlockApps implementation in SALT Phase I.

The central bank attempted an implementation of SALT on Corda but discontinued the effort due to immaturity of the Corda platform at the time. Instead, the central bank implemented a Quorum prototype as part of SALT Phase II [20].

b: QUORUM

The second iteration of Project SALT Phase II was implemented on Quorum.

The consensus mechanism used in the Quorum implementation was QuorumChain.

A major advantage with the Quorum implementation was code reuse from the BlockApps-based prototype as both BlockApps and Quorum are a fork of the Ethereum DLT platform.

The Quorum implementation provided stronger guarantees for data privacy and weaker guarantees for double-spending prevention.

D. PROJECT UBIN

Project Ubin [17], Singapore's CBDC initiative has been implemented over multiple phases by MAS, Singaporean PSPs and industry collaborators since November 2016 to explore the potential benefits of DLT and its applicability to Singapore's FMIs.

MAS is the central bank and financial regulator in Singapore. MAS is the owner and operator of Singapore's RTGS system, the MAS Electronic Payment System (MEPS+). MEPS+ is the FMI used for domestic wholesale interbank payments settlement in Singapore as well as the settlement of Scriptless Singapore Government Securities (SGS) between MEPS+ participants [105].

Project Ubin Phase I [105] implemented a W-CBDC for domestic wholesale interbank payments settlement on the Ethereum DLT platform while Phase II [106] rebuilt the Phase I prototype with additional functionalities on Corda, Fabric and Quorum to address data privacy and settlement finality challenges encountered in Phase I.

In Phase III [107], Project Ubin implemented DvP capabilities for interbank securities and payments settlement on multiple DLT platforms.

The ultimate goal of Project Ubin was to provide capabilities for the exchange of a tokenized Singapore Dollar (SGD) asset or SGD depository receipt (SGD-DR) on DLT and to evaluate the implications of such an exchange on Singapore's FMIs. We use the term tokenized SGD asset and SGD-DR interchangeably.

1) UBIN PHASE I

Project Ubin Phase I began in November 2016 through the collaboration of MAS, eight Singapore-based CMBs, the Singapore Exchange (SGX), Deloitte, R3 and BCS Information Systems [105].

The goal of Ubin Phase I was to implement an RTGS PoC prototype on Ethereum for the exchange of SGD-DR among Project Ubin participants.

To achieve the objectives of Project Ubin in a timely manner, Ubin Phase I was divided into two workstreams; a *technical workstream* responsible for implementing Project Ubin's DLT-based RTGS prototype for domestic interbank payment settlement; and a *research workstream* responsible for concurrently analyzing and documenting the implications of DLT on Singapore's FMIs in a production environment.

The Phase I prototype developed by the technical workstream included capabilities for the: issuance of SGD-DR by MAS; creation of wallets by MAS for CMBs; pledging and transferring of SGD-DR among Ubin Phase I participating CMBs and redemption of SGD-DR for central bank money on the Ethereum DLT platform.

The DLT-based RTGS prototype was further integrated with MEPS+ to examine its implications for Singapore's FMIs.

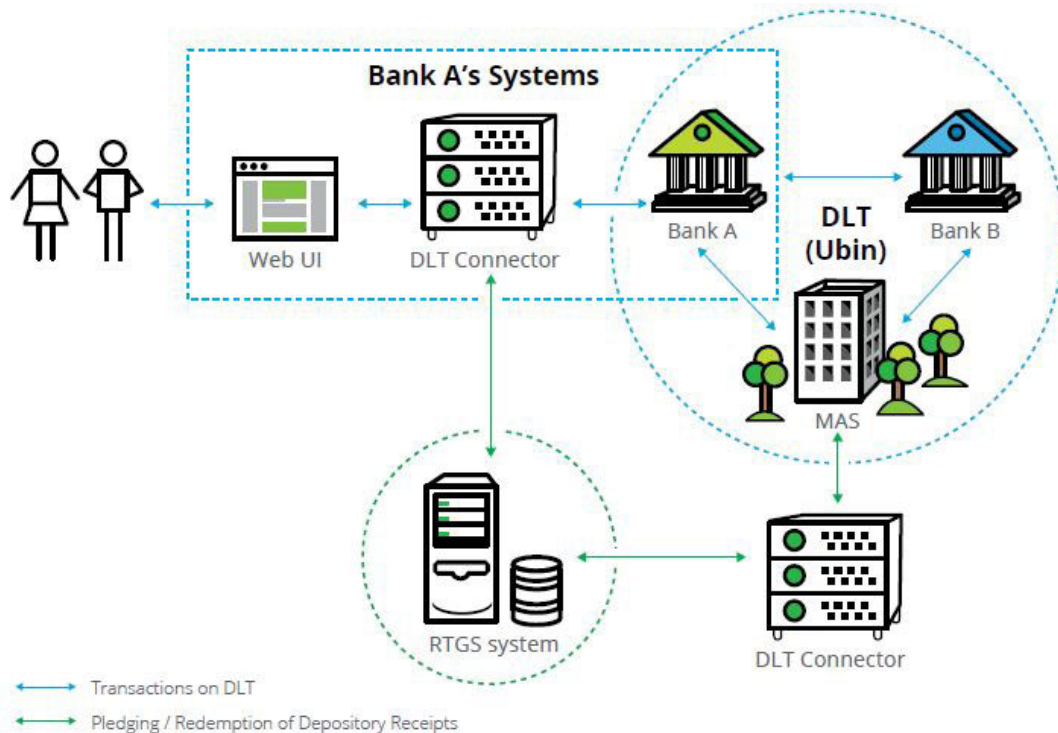The consensus mechanism used in the Ubin Phase I prototype was the PoW consensus mechanism.

FIGURE 15. Project Ubin Phase I high level architecture [105].

We present the high level architecture for Project Ubin Phase I in Figure 15.

In order for participating CMBs to pledge central bank money in their RTGS accounts held at MAS in exchange for SGD-DR, a special *DR Cash Custody* account was created by MAS. Pledged central bank money were stored in the DR Cash Custody accounts and the corresponding SGD-DR issued to the *pledging CMB*. Unlike Project Jasper which used "pool" accounts to store pledged central bank money, individual DR Cash Custody accounts were created for each participating CMB.

SGD-DR issued to a pledging CMB could be held on-ledger overnight [105] unlike Project Jasper which required the redemption of all DDRs intraday [15]. By holding on-ledger SGD-DR balances overnight, Project Ubin participants could conduct interbank transactions 24/7, independently of the operating hours of MEPS+ [105].

Project Ubin Phase I was completed with the achievement of the following deliverables:

- Development of an SGD-DR for domestic interbank payments settlement on an Ethereum network.
- Implementation of an Ethereum-based RTGS prototype for settlement of domestic wholesale interbank transactions.
- Development of a new Smart Contract codebase and an evolution of Project Jasper's monetary model to allow for overnight storage of SGD-DR on the DL network.
- Successful end-to-end integration of the Ethereum-based RTGS prototype with MEPS+ in a test environment for the transfer of funds from participating CMBs'

RTGS accounts to DR Cash Custody accounts and vice versa.

As it was implemented on Ethereum, Ubin Phase I could not provide for participants requirements for data privacy. Additionally, settlement finality could not be achieved on the Ethereum prototype as the PoW consensus mechanism is probabilistic.

2) UBIN PHASE II

Project Ubin Phase II [106] was launched in July 2017 by MAS, the Association of Banks in Singapore (ABS), a consortium of eleven PSPs and five technology providers.

The goal of Project Ubin Phase II was to leverage alternative DLT platforms to address the data privacy and settlement finality challenges encountered in Ubin Phase I and to extend the functionality of the Phase I prototype to include capabilities for *gridlock resolution* and *LSM settlement* options [106].

Consequently, Ubin Phase II was concurrently developed on Corda, Fabric and Quorum with a detailed design specification document for each prototype published on MAS' GitHub page [108]. All three prototypes were deployed on the Microsoft Azure cloud infrastructure. Overall, forty-one DLT-based nodes were deployed in VMs hosted on Microsoft Azure [106].

Project Ubin Phase II's codebase has been publicly released by MAS under Apache License Version 2.0. and hosted at [109].

A basic design concept employed in Ubin Phase II was the tokenization of cash assets (SGD-DR) to be settled
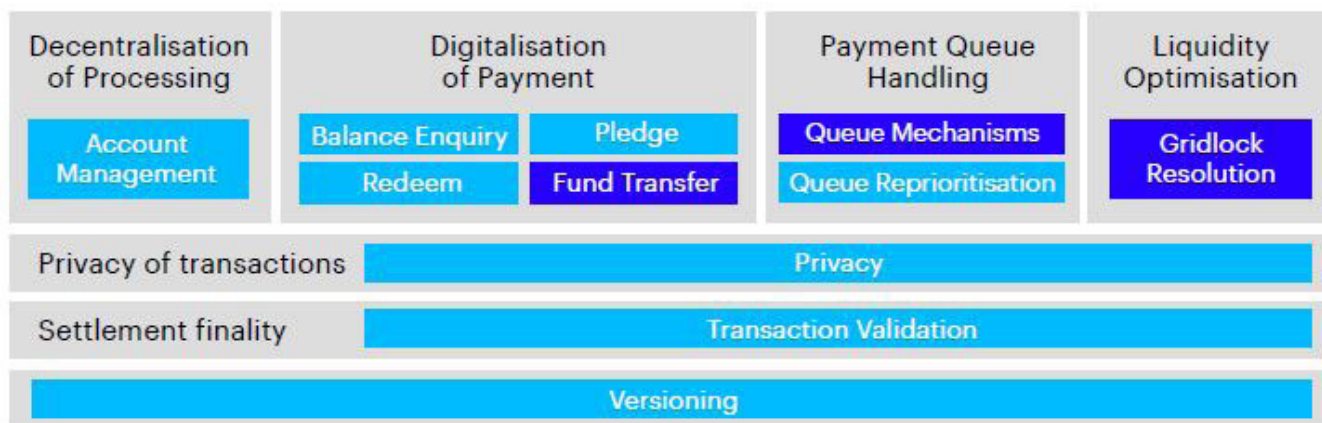
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FIGURE 16. Project Ubin Phase II functional architecture [106].

immediately and the tokenization of *obligations* assets (OBL-DR) to be settled in cash in the future.

Project Ubin Phase II's functional architecture is presented in Figure 16.

Overall, core capabilities implemented in Ubin Phase II were organized under six functional categories: *Decentralization of Processing, Digitization of Payment, Payment Queue Handling, Liquidity Optimization, Privacy of Transactions and Settlement Finality*. The six functional categories were further decomposed into eleven epics or capabilities and implemented in each DLT prototype.

Ubin Phase II focuses on the assessment and evaluation of the *Fund Transfer, Queue Mechanisms and Gridlock Resolution* epics built into each of the three DLT-based prototypes via smart contracts.

a: QUORUM
The Ubin Phase II Quorum prototype was implemented on Quorum v1.5.

Transaction consensus was achieved in the Quorum prototype using Quorum's Raft consensus mechanism.

Transaction privacy was achieved using a combination of Quorum Constellation and zero knowledge proofs (ZKP).

b: CORDA
The Ubin Phase II Corda prototype was implemented on Corda v1.0.

Double spending prevention on the Corda platform was achieved through the use of a notary node, similar to other Corda prototype implementations examined in this paper.

Exchange of value between counterparties were initiated through the use of *confidential identities* [110] to guarantee counterparty transaction privacy. Using confidential identities, only the parties involved in a transaction were aware of the details of the transaction.

Each Corda node was allocated a vault where SGD-DR and OBL-DR states were stored. The UTXO model was used to represent SGD-DR and OBL-DR states in the Corda implementation of Ubin Phase II.

c: FABRIC
The Ubin Phase II Fabric-based prototype was implemented on Fabric v1.0.1.

Double-spending prevention on the Fabric-based prototype was achieved through the use of endorsement policy, similar to previous Fabric-based prototype implementations examined in this paper.

Transaction privacy on the Fabric-based prototype was achieved through the use of channels which were provisioned by the ordering service.

3) UBIN PHASE III
Project Ubin Phase III [107] commenced in August 2018 through the partnership of MAS, ABS, SGX, Anquan Capital, Deloitte and Nasdaq.

The goal of Ubin Phase III was to extend the experience gained in Project Ubin Phase I and II to implement DvP settlement capabilities for the cross-ledger settlement of tokenized securities in Singapore.

The securities settled were tokenized cash assets (SGD-DR) issued by MAS and tokenized SGS assets (SGS-DR) also issued by MAS.

The SGD-DR and SGS-DR assets were exchanged on a trade-by-trade basis over DLT-based SSS' implemented on multiple DLT platforms [107].

The DLT platforms used to implement the Ubin Phase III prototypes were Ethereum, Fabric, Quorum, Chain and Anquan permissioned blockchain.

Overall, three interledger prototypes for cash and securities comprising of Quorum-Anquan, Ethereum-Fabric and Fabric-Chain were developed by Anquan Capital, Deloitte and Nasdaq respectively.

The prototypes were developed to fulfil Ubin Phase III's objectives to leverage DLT to:

- Facilitate interledger trading of tokenized securities in Singapore.
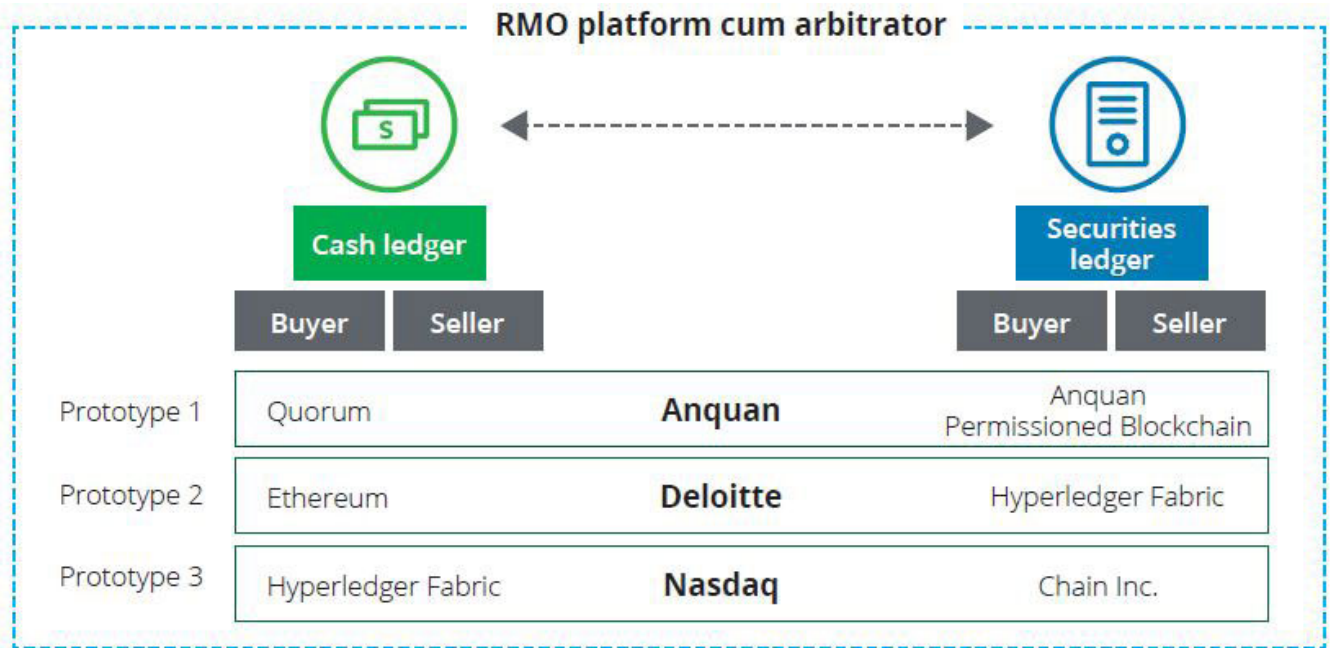- Guarantee investor confidence in trading MAS-issued securities.

FIGURE 17. Project Ubin Phase III high level architecture [107].

- Minimize counterparty risks in trading MAS-issued securities through the use of smart contracts to fulfil DvP trade obligations.
- Achieve DVP settlement finality.

In order to achieve Ubin Phase III's defined objectives, each cash-securities prototype implemented five core capabilities, namely *contract locks, account controls, secure secrets, dispute resolution* and *time boundaries*.

The *contract locks* capability provided mechanisms to *lock* SGD-DR and SGS-DR involved in an ongoing transaction (*Tx1*) so that they were not used in new transactions (*Tx2*) until *Tx1* was completed, thus, preventing double-spending and minimizing counterparty risks.

The *account controls* capability provided mechanisms to achieve settlement finality through the use of signatures under the ownership of the seller, buyer and MAS.

The *secure secrets* capability provided an extra layer of security for posttrade activities to achieve DvP finality. Secure secrets were generated by the RMO and sent separately off-chain to each of the transacting parties as a PDF file. Secure secrets were a function of the digital signatures of the counterparties involved in a given transaction.

The *dispute resolution* capability provided mechanisms for MAS in its role as *Arbiter* to autonomously arbitrate counterparty trade issues, thereby guaranteeing investor protection and confidence in trading MAS-issued securities.

The *time boundaries* capability provided mechanisms for trades to be concluded within pre-defined time windows as a way to minimize counterparty risks and achieve settlement finality.

We present the high-level architecture of Project Ubin Phase III in Figure 17.

Five key entities were established for the Ubin Phase III platform. The entity composition of the Ubin Phase III prototypes were as follows:

- *Recognized Market Operator (RMO)* - The RMO role was the owner and operator of the Ubin Phase III platform. This role was responsible for the smooth and efficient operation of the Ubin Phase III platform. At all times, the RMO was able to view all transactions on the Ubin Phase III platform and also act as an Arbiter for dispute resolution among system participants. The RMO holds one keypair each for the cash ledger and securities ledger. In Ubin Phase III, MAS performed the RMO role.
- *Cash Ledger* - The cash ledger was used for the issuance, storage and transfer of SGD-DRs. This ledger was managed by MAS.
- *Securities Ledger* - The securities ledger was used for the issuance, storage and transfer of SGS-DRs. This ledger was managed by SGX.
- *Buyer* - The buyer role was an exchange-registered trader who held accounts on both the cash and securities ledger as well as one keypair for each ledger.
- *Seller* - The seller role was an exchange-registered trader who held accounts on both the cash and securities ledger as well as one keypair for each ledger.

Having completed the development of the Ubin Phase III prototypes, the following DLT-based DvP securities settlement scenarios were executed and evaluated.

- *Scenario I*: Successful settlement.
- *Scenario II*: Failed settlement with automatic recovery.
- *Scenario III*: Failed transaction requiring arbitration.
- *Scenario IV*: Failed transaction with arbitration.

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The Ubin Phase III prototype was able to successfully confirm the above scenarios.

We highlight some of the characteristics of the solutions developed by Anquan Capital, Deloitte and Nasdaq in the subsequent subsection.

a: ANQUAN SOLUTION
Anquan Capital implemented its Ubin Phase III DLT prototypes using Quorum for the cash ledger and the proprietary Anquan [78] permissioned blockchain platform for the securities ledger respectively.

The Anquan DLT platform is a permissioned implementation of ZILLIQA [112], a high-throughput DLT platform developed from the ground up to address the limitations of the Ethereum DLT platform.

The consensus mechanism used on the securities ledger was the PBFT consensus mechanism while transaction privacy on the cash ledger was achieved through the use of ZKP.

Interledger exchange of value and transaction scalability was achieved through the use of the sharding technique and atomic swaps. Leveraging atomic swaps enabled the efficient exchange of the underlying securities across ledgers without the need for an Arbiter [106].

Additionally, the Anquan solution was integrated with the Ubin Phase II prototype.

b: DELOITTE SOLUTION
Deloitte implemented its Ubin Phase III DLT prototypes using Ethereum for the cash ledger and Fabric for the securities ledger respectively.

Transaction privacy on the securities ledger was achieved by leveraging channels, similar to the Fabric-based prototype examined in Section VI-D2.c.

The Fabric prototype also provided a centralized key management service that allowed buyers and sellers to store their private keys in an escrow. The centralized key escrow service was provided by MAS. MAS would then use its digital signature to sign transactions on behalf of system participants using its key management service.

To enable transaction arbitration, the Deloitte solution leveraged smart contracts to implement a semi-centralized DVP settlement process.

c: NASDAQ SOLUTION
Nasdaq implemented its Ubin Phase III DLT prototypes using Fabric for the cash ledger and the Chain Core DLT platform for the securities ledger respectively.

Chain Core [79] is an financial services industry-focused DLT platform developed from the ground up to enable a secure and efficient transfer of tokenized financial assets.

Nasdaq decoupled the DvP settlement processes from the underlying DLT platforms using smart contracts. The DvP settlement capability in the Nasdaq solution was therefore DLT-neutral, allowing it to be integrated with different DLT platforms other than the platforms leveraged by Nasdaq in its Ubin Phase III solution.

Transaction privacy in the Nasdaq solution was achieved through a combination of multi-level encryption mechanisms, one-time addresses and channels.

Nasdaq's Ubin Phase III solution provided capabilities for:
- A *smart contract engine* that enabled the creation and execution of DLT-agnostic smart contracts;
- A modular, containerized, elastic and configurable infrastructure that could be securely deployed on a variety of cloud platforms;
- *Role-based APIs* for the DvP settlement process. Role-based application programming interfaces (APIs) enabled Ubin Phase III system participants to initiate and execute multiple interledger transactions using a single API interface.

E. PROJECT STELLA
The Bank of Japan and the ECB initiated Project Stella in December 2016 to assess the applicability of DLT to FMIs in both jurisdictions [41].

The ECB is responsible for the administration of monetary policy within the Eurozone [84]. TARGET2, the high-value interbank settlement system in the euro area is used to perform monetary policy operations in the Eurozone [114]. The Eurosystem, which comprises of the ECB and National central banks of all EU Member States, is the owner and operator of TARGET2 [113].

The Bank of Japan, Japan's central bank is responsible for administering monetary policy in Japan. It is the owner and operator of the BOJ-NET, Japan's wholesale LVTS [41].

Project Stella has been implemented in three phases using multiple DLT platforms.

Project Stella Phase I [41] implemented a W-CBDC and core RTGS functionalities on the Fabric DLT platform.

Project Stella Phase II [42] implemented DvP functionalities for the settlement of tokenized securities on Corda, Elements and Fabric.

Project Stella Phase III [43] focused on the potential of improving the efficiency of cross-border transactions using DLT. Stella Phase III was implemented on Fabric.

In all three phases of Project Stella, fictitious virtual CMBs were created to test the developed prototypes.

Additionally, IBM, DG Labs and R3 provided technical advice for Stella Phase II.

1) STELLA PHASE I
Project Stella Phase I began in December 2016 through the partnership of the Bank of Japan and the ECB.

Project Stella Phase I evaluated the potential of DLT to deliver specific RTGS functions for domestic wholesale interbank payments settlement in the Eurozone and Japan.

In Stella Phase I, two separate DLT-based RTGS prototypes with LSM settlement capabilities were developed on Fabric v0.6.1 [41]. One prototype satisfied core RTGS functional requirements of TARGET2 as defined by the ECB while the other satisfied key requirements of BOJ-NET as defined by the Bank of Japan.

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The Stella Phase I ECB prototype was developed to meet TARGET2's daily transaction volume requirement of 343,729 payments per day (PPD) while the Bank of Japan prototype was developed to meet BOJ-NET's daily transaction volume requirement of 67,326 PPD. On the average, the ECB and the Bank of Japan process between 10 and 70 transaction requests per second (RPS) daily.

Transaction consensus in Stella Phase I was achieved using the PBFT consensus mechanism.

To test the performance of the Stella Phase I prototypes, the Bank of Japan and the ECB created simulated data which were used as experiment inputs.

Participant nodes for the ECB DL network were deployed on VMs in an in-house network infrastructure hosted at the ECB while Bank of Japan participant nodes were deployed on a commercial cloud platform.

Performance tests for the Stella Phase I prototypes were conducted in parallel by the ECB and the Bank of Japan with the following evaluation results:

- *LSM Settlement*: Generally, LSM functionalities performed as required.
- *Latency*: Transaction latency increased as the number of nodes on the network increased.
- *Throughput*: Both prototypes met the ECB and the Bank of Japan's daily RTGS PPD requirements; however, increasing transaction volumes to 250 RPS led to an overall decrease in system performance.
- *Distance*: Network performance was enhanced the closer the nodes required to achieve transaction consensus were to each other. However, an increase in distance between *consensus nodes* resulted in a decreased system performance.

The ECB and the Bank of Japan further tested the reliability and resiliency of the Stella Phase I prototypes using three base scenarios.

- *Scenario I*: Temporary failure of an authoritative node used to authenticate and approve transaction requests.
- *Scenario II*: Temporary failure of one or more validating nodes.
- *Scenario III*: Sending incorrect data formats.

In *Scenario I*, a single-point of failure problem was encountered when the authoritative node responsible for transaction authentication and approval was temporarily unavailable.

In *Scenario II*, it was observed that system availability and performance were not impacted as long as the number of validating nodes required for achieving consensus were operational.

In Scenario III, the system was able to accurately detect and eliminate transactions with incorrect data formats, therefore system performance was not impacted.

2) STELLA PHASE II
The Bank of Japan and the ECB launched Project Stella Phase II in November 2017 to examine the potential of using

DLT for interledger DvP settlement of tokenized financial assets [42].

Stella Phase II defined three DLT-based DvP settlement approaches. They were; *single-ledger DvP settlement*, *cross-ledger DvP settlement with connection between ledgers* and *cross-ledger DvP settlement without connection between ledgers* [42].

The three DLT-based DvP settlement approaches are presented in Figure 18.

Stella Phase II implemented DvP settlement prototypes for two of the approaches: the *cross-ledger DvP settlement without connection between ledgers* and the *single-ledger DvP settlement* on Fabric, Elements and Corda.

To achieve interledger asset transfer without a direct interaction between the underlying ledgers, Stella Phase II leveraged cross-chain atomic swaps [111] using hashed timelock contract (HTLC) [115].

In this paper, we refer to the cross-ledger DvP settlement prototype without connection between ledgers as *HTLC-based cross-ledger DvP settlement* prototype.

The atomic swap protocol enables the transfer of assets between multiple ledgers without the need for a trusted third-party [111].

In HTLC-based cross-ledger DvP settlement, HTLC uses hashlocks to conditionally block the transfer of assets and timelocks to deliver the assets when settlement conditions are satisfied. Analogically, timelocks recovers the assets back to the sender if settlement conditions are not satisfied.

HTLC works as follows: firstly, counterparties to a transaction must each generate a secret *S*. Secondly, counterparties generate a hash digest for their respective secrets, *S*, that is *H(S)*. Counterparties then send *H(S)* and *S* to each other off-chain in accordance with pre-determined securities settlement conditions.

The ECB and Bank of Japan established two base scenarios to test both the single-ledger and the HTLC-based cross-ledger DvP settlement prototypes. The base scenarios examined the viability of DLT for DvP settlement of securities between two counterparties, *Bank A* and *Bank B*. In the base scenarios, *Bank A* was the seller of securities and *Bank B* was the buyer of securities. The base scenarios were as follows:

- *Scenario I*: Successful settlement.
- *Scenario II*: Failed settlement due to one counterparty not satisfying settlement conditions.

We highlight the experimental results of the HTLC-based cross-ledger DvP settlement prototype. All tests were conducted in a non-production environment.

- *Scenario I*: Tokenized financial assets could be transferred between ledgers using HTLC. Using, cross-chain atomic swaps with HTLC, settlement finality could be achieved if all asset transfer conditions were satisfied.
- *Scenario II*: The experiment identified a major limitation with HTLC. DvP settlement requires time asymmetry for the settlement of one leg (obligation) of the transaction, usually the cash leg before the securities leg. During the simulation of *Scenario II*, *Bank B* did not
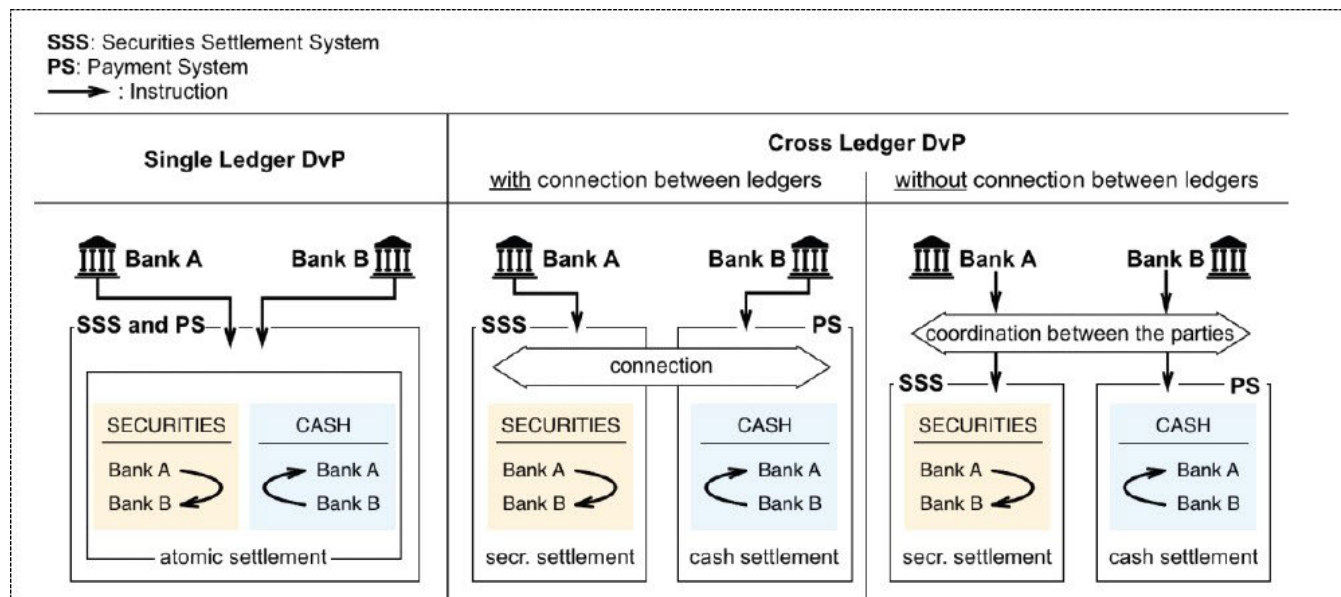
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FIGURE 18. Project Stella Phase II DLT-based DvP settlement approaches [42].

submit its transfer instructions within the specified *time-lock* leading to *Bank A* retaining its securities asset and still receiving cash payment for the securities from *Bank B*. This HTLC design flaw exposed *Bank B* to principal risk.

We present a summary of the DvP settlement prototypes developed on Elements, Corda and Fabric in the next subsection.

a: ELEMENTS
Stella Phase II implemented one single-ledger DvP settlement prototype on Elements as well as one Element-Element HTLC-based cross-ledger prototype.

Additionally, one Element-Fabric HTLC-based cross-ledger prototype was implemented.

b: CORDA
Stella Phase II implemented one Corda-based single-ledger DvP settlement prototype. A Corda-Corda HTLC-based cross-ledger prototype was also implemented.

No HTLC-based implementations were made between Corda and other DLT platforms.

c: FABRIC
Lastly, Stella Phase II implemented one single-ledger DvP settlement prototype on Fabric as well as a Fabric-Fabric HTLC-based cross-ledger prototype.

3) STELLA PHASE III
The value of cross-border payments and settlements is expected to reach USD 30 trillion by the year 2022 [45]. However, existing cross-border payments settlement arrangements are complex, expensive and inefficient, thereby affecting the safety and security of such payments [43].

Figure 19 depicts a simplified cross-border payments settlement credit risk scenario that arises upon intermediary *Entity B* failing (e.g. going bankrupt) after receiving €1 million from *Entity A* meant for onward transmission to *Entity C* in Japanese Yen. *Entity B* goes bankrupt before it could fulfil the transfer obligation to *Entity C*, thereby exposing *Entity A* to principal risk.

The report on Project Stella Phase III [43] published in June 2019 by the ECB and the Bank of Japan examined the feasibility of synchronously improving cross-border payments settlement security and efficiency with and without DLT as well as with and without the use of the interledger protocol (ILP) [116].

In Stella Phase III, prototypes were developed to examine the following base scenarios:

- *Scenario I*: Non-DLT-based centralized interledger cross-border settlement with ILP.
- *Scenario II*: DLT-based ledger vs. non-DLT-based centralized ledger cross-border settlement with ILP.
- *Scenario III*: DLT-based interledger cross-border settlement with ILP.
- *Scenario IV*: DLT-based interledger cross-border settlement without ILP.

The DLT-based ledger prototype was developed on Hyperledger Fabric v.1.2.1.

The non-DLT-based centralized ledger used in Stella Phase III was the *Five Bells Ledger* [118].

In Scenarios I-III, *Interledger.js* [117], the open-source JavaScript implementation of ILP was leveraged.

To eliminate the credit risk scenario presented in Figure 19, an on-ledger escrow-lock mechanism with HTLC was implemented on the prototypes. The on-ledger escrow-lock mechanism provided capabilities to conditionally lock funds transferred by counterparty *Entity A* in an escrow until
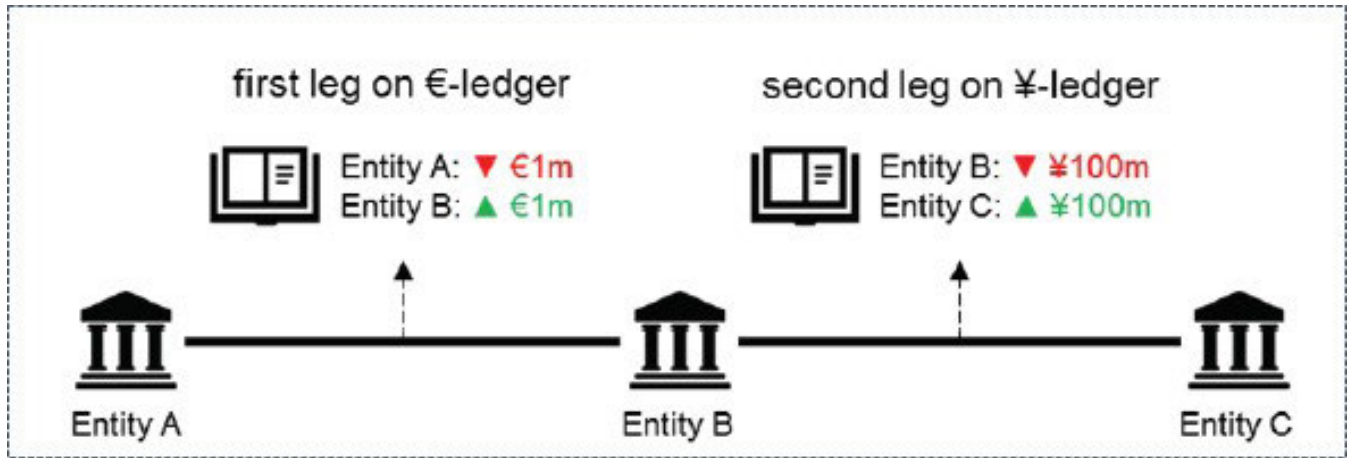
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counterparty *Entity C* satisfied the terms and conditions of the contract for which funds were being transferred.

We present the experimental results of the cross-border settlement scenarios involving the DLT-based prototype, that is Scenarios II-IV in the subsequent subsection.

Entity B, which held accounts on both the Euro and Yen ledgers acted as an intermediary in all the given scenarios.

- *Scenario II*: Funds transfer from counterparty *Entity A* which held an account on the Fabric-based ledger to counterparty *Entity C* which held an account on the Five Bells Ledger was successful, demonstrating the viability of ILP.
- *Scenario III*: Synchronized cross-border payments settlement between two Fabric-based ledgers with ILP was successful.
- *Scenario IV*: DLT-based interledger payments settlement without ILP was achieved. Using the Euro ledger and Yen ledger analogy in Figure 19, funds on the Euro ledger were locked between *Entity A* and *Entity B* using the on-ledger escrow with HTLC service. The same mechanism was used to lock funds on the Yen ledger between *Entity B* and *Entity C*. Funds on the Euro ledger and funds on the Yen ledger were synchronized and released to *Entity B* and to *Entity C* respectively once all settlement conditions were met.

Stella Phase III confirmed that ILP is ledger-agnostic as the protocol was successfully leveraged on both DLT and non-DLT-based ledgers.

F. PROJECT KHOKHA

Project Khokha [21], South Africa's W-CBDC experiment was launched in January 2018 by the SARB, seven South African CMBs, PricewaterhouseCoopers and ConsenSys to explore the use of DLT for domestic wholesale interbank payments settlement in South Africa.

The Khokha participant ecosystem is presented in Figure 20.

The goal of Project Khokha was to build a DLT-based RTGS prototype for interbank payments settlement using a tokenized South African Rand asset. The prototype was built on the Quorum DLT platform.

The RTGS system in South Africa is called the South African Multiple Option Settlement system (SAMOS). SAMOS, which is owned and managed by the SARB is used to process high-value interbank payments, interbank retail payment obligations and securities settlement in South Africa.

SAMOS processes 70,000 wholesale interbank payments intraday on RTGS basis with capabilities to process a whole day's transaction within two hours in the event that the system is unable to operate in the course of the day due to system outage [21].

In order to compare the functionality and performance of the DLT-based RTGS prototype to the existing SAMOS FMI, the following performance metrics were defined for the Khokha prototype.

- Except the SARB, counterparty transaction data in the DL network should be fully confidential to all system participants.
- The system should adhere to the settlement finality (Principle 8), money settlement (Principle 9) and operational risk (Principle 17) requirements of the PFMIs.
- The system should settle up to 70,000 wholesale interbank payments intraday.
- The system should scale and settle up to 200,000 wholesale interbank payments intraday.
- In emergency situations, the system should settle up to 70,000 interbank payments within two hours.
- At least 95% of blocks containing transactions should be propagated throughout the entire DL network under one second.
- At least 99% of blocks containing transactions should be propagated throughout the entire DL network within two seconds.
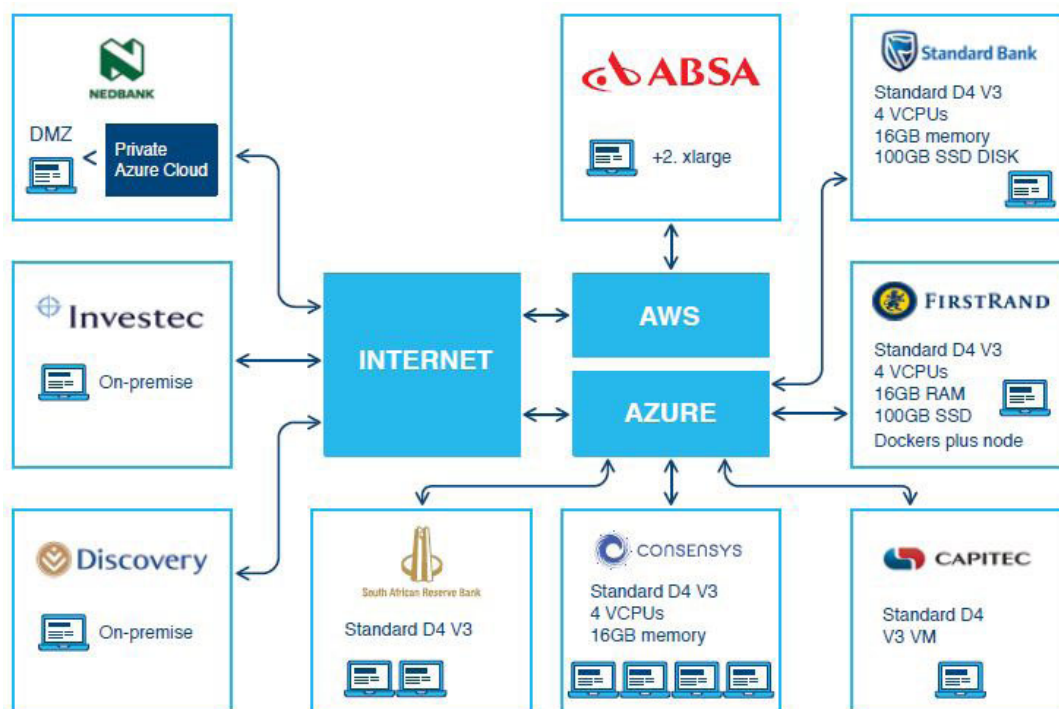
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FIGURE 20. Project Khokha participant ecosystem [21].

In Project Khokha, participating entities deployed Quorum-based distributed nodes using a combination of VMs, on-premise private and public cloud hosting platforms with varying network resources as shown in Figure 20. The SARB was responsible for issuing tokenized Rand assets and creating wallets for each participating CMB to hold tokenized Rand assets.

Transaction consensus on the Khokha platform was achieved using the IBFT consensus mechanism. Additionally, Pedersen commitments and range proofs were leveraged to guarantee transaction privacy, settlement finality, scalability and system resiliency in Khokha [21].

Capabilities to pledge, transfer, redeem and track tokenized Rand balances were built into the Khokha platform.

At all times, the SARB node had full visibility of transactions on the Khokha platform.

Khokha was implemented over four iterations as follows:
- *Iteration 1*: Capabilities for the issuance of tokenized Rand assets and the creation of on-ledger wallets by the SARB were implemented. Capabilities for CMBs to pledge, transfer and redeem tokenized Rand assets for central bank money were also implemented in this iteration.
- *Iteration 2*: Capabilities for transaction approval by the SARB without guarantees for data privacy were implemented.
- *Iteration 3*: Mechanisms for the exchange of keypairs among counterparties as well as capabilities for data privacy and settlement finality using Pedersen commitments were implemented.

- *Iteration 4*: Mechanisms to achieve system resiliency were implemented through a combination of Pedersen commitments and range proofs. Capabilities for counterparties to verify and validate transactions were also implemented in this iteration.

Following the development of the Khokha platform, the prototype was tested in a non-production environment against the defined performance metrics with the following results. The platform:
- Settled a minimum of 70,000 transactions intraday.
- Achieved the scalability requirement of up to 200,000 transactions intraday.
- Settled 70,000 transactions in two hours in line with the emergency performance metric.
- Achieved 95% block propagation throughout the entire DL network in one second and up to 99% block propagation throughout the entire network within two seconds.
- Adequately provided for counterparty data privacy requirements.
- Adhered to the defined settlement finality, money settlement and operational risk requirements of the PFMIs.

G. PROJECT INTHANON

The Bank of Thailand together with R3 and eight Thai CMBs initiated Project Inthanon [26] in August 2018 to examine the potential of DLT for Thailand's FMIs. Project Inthanon has been implemented over two phases.

Project Inthanon Phase I [26] implemented a DLT-based distributed RTGS prototype for domestic wholesale interbank payments settlement in Thailand.
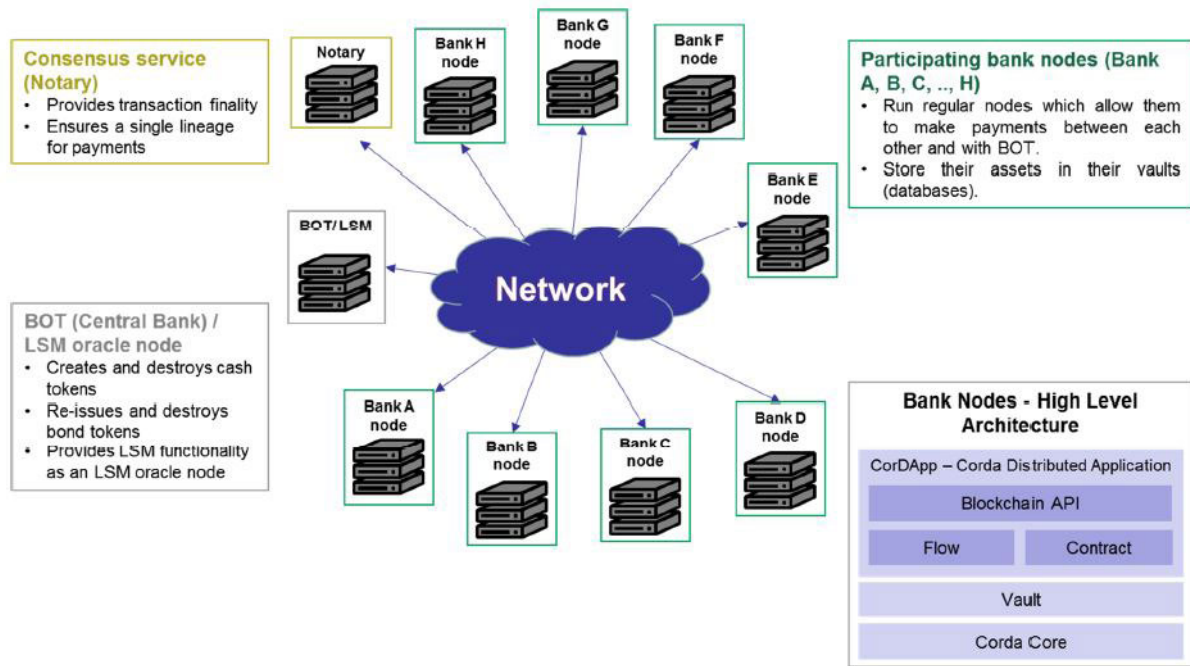
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FIGURE 21. Project Inthanon Phase I design architecture [26].

Project Inthanon Phase II [126] focused on the implementation of a securities settlement platform for the issuance, management and settlement of Bank of Thailand-issued tokenized bond and tokenized cash assets.

1) INTHANON PHASE I

Project Inthanon Phase I [26] commenced in August 2018 through the collaboration of the Bank of Thailand, eight Thai CMBs and R3.

Project Inthanon Phase I [26] implemented on Corda, a distributed RTGS prototype with LSM settlement options for domestic wholesale interbank payments settlement in Thailand. Inthanon Phase I was implemented on Corda v3.2.

We present the design architecture of Inthanon Phase I in Figure 21.

Key deliverables in Inthanon Phase I included the development of a Corda-based distributed RTGS prototype with LSM settlement capabilties and the issuance of tokenized Bank of Thailand-issued bond and cash assets.

Similar to previously examined CBDC experiments, capabilities for pledging central bank money for Bank of Thailand-issued tokenized securities were implemented in Inthanon Phase I. Analogically, mechanisms for the transfer and redemption of tokenized assets (e.g. Section VI-A3) for central bank money were implemented in the Inthanon Phase I prototype.

Three types of nodes were deployed in Inthanon Phase I, namely *supervisory node*, *notary service node* and *participant nodes*.

Similar to previous Corda implementations examined in this paper, the supervisory node and notary node functions were performed by the Bank of Thailand whiles CMBs were assigned participant nodes.

All nodes in Inthanon Phase I were deployed on separate Microsoft Azure cloud-hosting platforms.

Tokenization of Bank of Thailand-issued cash assets in Inthanon Phase I follows a similar pattern as in Figure 11.

The consensus mechanism used in Inthanon Phase I follows previous Corda-based CBDC prototypes examined in this paper, such as in Section VI-D2.b.

A key difference between Inthanon Phase I and the other CBDC experiments with LSM capabilties (e.g. Section VI-A2, Section VI-D2 and Section VI-E1) examined in this paper was that, the Inthanon Phase I prototype enabled banks with liquidity shortages to pledge tokenized bond assets to the Bank of Thailand in exchange for tokenized Baht assets.

The Inthanon Phase I prototype was tested in a non-production environment with the following evaluation results:

- *Settlement Success*: Inthanon Phase I participants were able to exchange value among each other with guaranteed data privacy and settlement finality.
- *Enhanced LSM Capability*: The Inthanon Phase I platform implemented an enhanced LSM settlement option that enabled participating CMBs to pledge tokenized bond assets to the Bank of Thailand as collateral in exchange for tokenized cash assets.

2) INTHANON PHASE II

Project Inthanon Phase II [126] was launched in February 2019 through the partnership of the Bank of Thailand, R3 and eight Thai CMBs.

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Intermediaries Approach	Direct widened access	Direct multiple-currencies
• also known as asset swap via intermediary • needs intermediary for foreign exchange and transfer	• also known as direct access • does not involve an intermediary	• also known as asset transfer • allows for multiple currencies within the same network • still need intermediary (which could be the central banks) for transfer

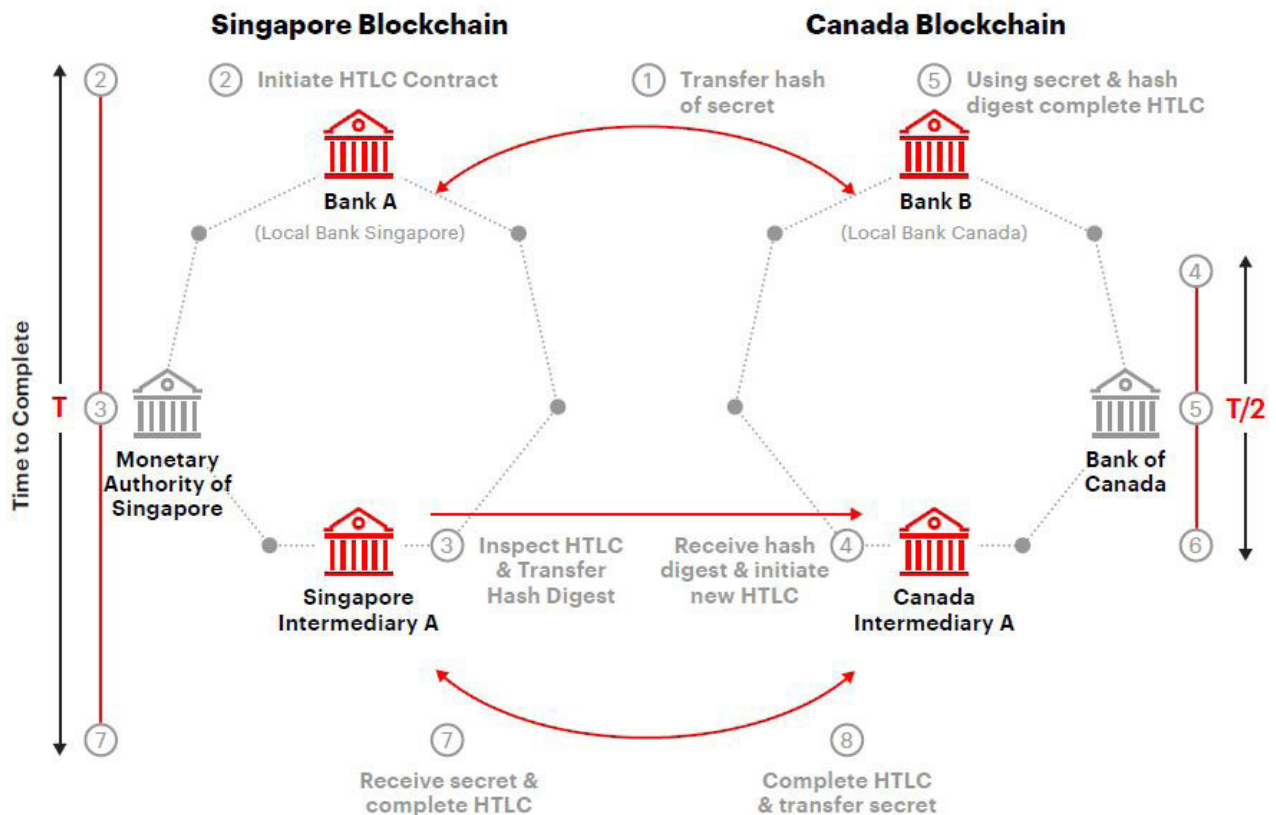**FIGURE 22.** Cross-border payments settlement approaches and characteristics [40].

FIGURE 23. Project Jasper-Ubin cross-border interledger value exchange transaction flow [40].

Project Inthanon Phase II [126] implemented on Corda, a securities settlement platform for the issuance, management and settlement of Bank of Thailand-issued tokenized bond assets and tokenized cash assets. Project Inthanon Phase II was implemented on Corda v4.0.

The securities settlement infrastructure implemented in Inthanon Phase II was an integrated single-ledger DvP settlement platform similar to the single-ledger DvP model presented in Figure 18.

Similar to Inthanon Phase I, three types of nodes were deployed in Inthanon Phase II, namely participant nodes,

supervisory node and notary node. Participating CMBs were each assigned participant nodes. The Bank of Thailand was responsible for the supervisory and notary node functions.

Tokenized cash and bond assets in Inthanon Phase II were represented on-ledger using Corda's UTXO state model.

The consensus mechanism used in Inthanon Phase II was similar to the mechanism used in Inthanon Phase I.

Key capabilities implemented in Inthanon Phase II included capabilities for:

• DvP settlement of Bank of Thailand-issued tokenized bond and cash assets;

TABLE 5. (a) CBDC experiment practices summary-A.

Experiment Name/Jurisdiction	Phase/Year	Goals	Stakeholders	Use Case	DLT used
Project Jasper (Canada)	Phase I (Mar - June 2016)	Build a DLT-based PoC prototype for domestic wholesale interbank payments settlement in Canada.	Payments Canada, Bank of Canada, R3, CIBC, TD Bank, Scotiabank, BMO and RBC.	UC2, UC3	E
	Phase II (Dec 2016 - Apr 2017)	Rebuild the Phase I PoC on an alternative DLT platform with extended RTGS functionalities.	Payments Canada, Bank of Canada, R3, CIBC, TD Bank, Scotiabank, BMO, RBC, NBC and HSBC	UC2, UC3	C
	Phase III (Oct 2017 - May 2018)	Implement a DLT-based PoC prototype for an integrated SSS that allows for the exchange of multiple asset types on a shared transaction ledger.	Payments Canada, Bank of Canada, TMX Group, Accenture and R3.	UC2, UC6	C
BLOCKBASTER (Germany)	Phase I (Mar - Nov 2016)	Evaluate the potential of blockchains for interbank securities settlement for DvP.	Deutsche Bundesbank, Deutsche Börse Group and Digital Asset.	UC2, UC6, UC7	D, F
Project SALT (Brazil)	Phase I (Sept - Nov 2016)	Explore central bank use cases that could benefit from the potential of DLT and implement a prototype for one of the identified use cases.	Central Bank of Brazil and selected CMBs.	UC2, UC3	B
	Phase II (Jan - Feb 2017)	Evaluate competing DLT platforms for their suitability for wholesale interbank payments.		UC2, UC3	F, Q
Project Ubin (Singapore)	Phase I (Nov - Dec 2016)	Explore the use and potential benefits of DLT for key RTGS functionalities.	MAS, Deloitte, Bank of America Merrill Lynch, Credit Suisse, DBS Bank Ltd, Hongkong and Shanghai Banking Corporation Ltd, J.P. Morgan, Mitsubishi UFJ Financial Group, OCBC Bank, SGX, UOB, BCS Information Systems and R3.	UC2, UC3	E
	Phase II (July - Nov 2017)	Rebuild the Phase I PoC on multiple DLT platforms with extended RTGS functionalities.	MAS, ABS, Bank of America Merrill Lynch, Citi, Credit Suisse, DBS Bank Ltd, HSBC Limited, J.P. Morgan, Mitsubishi UFJ Financial Group, OCBC Bank, SGX, Standard Chartered Bank, UOB, Accenture, R3, IBM, ConsenSys and Microsoft	UC2, UC3	C, F, Q
	Phase III (Aug - Nov 2018)	Evaluate the use of DLT for the development of an interbank SSS for the settlement of tokenized assets.	MAS, ABS, SGX, Anquan Capital, Deloitte and Nasdaq.	UC2, UC6	E, F, H, N, Q

Note: **B** - BlockApps, **C** - Corda, **D** - Digital Asset, **E** - Ethereum, **F** - Fabric, **H** - Chain, **L** - Elements, **N** - Anquan and **Q** - Quorum.

- Tokenized Bank of Thailand-issued bond and cash assets;
- Bond issuance and full lifecycle management;
- Multi-asset LSM settlement options; and
- Third-party funds transfer fraud prevention.

Following the development of the Inthanon Phase II prototype, the platform was tested in a non-production environment.

An evaluation of the Inthanon Phase II prototype demonstrated that:

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TABLE 5. *(Continued.)* (b) CBDC experiment practices summary-B.

Experiment Name/ Jurisdiction	Phase/Year	Goals	Stakeholders	Use Case	DLT used
Project Stella (EU & Japan)	Phase I (Dec 2016 - Sept 2017)	Implement a DLT-based RTGS prototype with LSM capabilites.	ECB, Bank of Japan and virtual CMBs	UC2, UC3	F
	Phase II (Nov 2017 - Mar 2018)	Implement DvP functions on multiple DLT platforms for interbank settlement of securities for cash.	ECB, BOJ, R3, IBM and DG Lab.	UC2, UC6	C, F, L
	Phase III (June 2019)	Explore the potential to improve the safety of crossborder transactions using DLT.		UC2, UC9	F
Project Khokha (South Africa)	Phase I (Jan - June 2018)	Explore the use of DLT for wholesale interbank payments settlement in South Africa.	SARB, Absa, Capitec, Discovery Bank, FirstRand, Investec, Nedbank, Standard Bank, ConsenSys and Pricewaterhouse Coopers Inc.	UC2, UC3	Q
Project Inthanon (Thailand)	Phase I (Aug 2018 - Jan 2019)	Implement a decentralized RTGS prototype with LSM functionalities on DLT for wholesale interbank payments settlement.	Bank of Thailand, Bangkok Bank, Krung Thai Bank, Bank of Ayudhya, Kasikornbank, Siam Commercial Bank, Thanachart Bank, Standard Chartered Bank, Hongkong and Shanghai Banking Corporation Limited and R3.	UC2, UC3	C
	Phase II (Feb - June 2019)	Implement a DLT-based DvP system for interbank bond trading and bond lifecycle management.	Bank of Thailand, Bangkok Bank, Krung Thai Bank, Bank of Ayudhya, Kasikornbank, Siam Commercial Bank, Thanachart Bank, Standard Chartered Bank, Hongkong and Shanghai Banking Corporation Limited and R3.	UC2, UC7	C
Jasper-Ubin (Canada & Singapore)	Phase I (Nov 2019)	Enable cross-border high value transfer between different DLT platforms that settle in different currencies.	Bank of Canada, MAS, Accenture and J.P. Morgan.	UC2, UC9	C, Q

Note: **B** - BlockApps, **C** - Corda, **D** - Digital Asset, **E** - Ethereum, **F** - Fabric, **H** - Chain, **L** - Elements, **N** - Anquan and **Q** - Quorum.

- DLT-based DvP settlement of securities for cash was feasible in Thailand.
- Inthanon Phase II enabled the on-ledger exchange of multiple tokenized assets in real-time.
- Multi-asset LSM capabilties implemented on Inthanon Phase II enabled the efficient use of liquidity across the Inthanon Phase II securities settlement infrastructure.

H. JASPER - UBIN

The report on Project Jasper-Ubin [40], a cross-border CBDC experiment between the Bank of Canada, MAS, Accenture and JP Morgan was published in November 2019.

The goal of Project Jasper-Ubin was to examine the feasibility of a cross-border interledger payments settlement denominated in different currencies using DLT.

The Jasper-Ubin prototypes were developed on Corda and Quorum for the Bank of Canada and the MAS respectively.

The Jasper-Ubin prototypes were a DLT-based implementation of cross-border payments approaches proposed by the Bank of Canada, the Bank of England and the MAS in their joint CBDC research report on cross-border payments settlement [45].

In the Jasper-Ubin report [40], three cross-border settlement approaches were discussed, the *intermediary approach*, the *widened access approach* and the *multicurrency approach*.

In Project Jasper-Ubin, a prototype for only one approach, the *intermediary approach* was implemented. Figure 22 describes the characteristics of the three cross-border payments approaches discussed in the Jasper-Ubin report.

Similar to Project Stella Phase II, cross-chain atomic swaps with HTLC was used for the cross-border interledger exchange of value between the Jasper-Ubin prototypes.

The experimental setup for the Jasper-Ubin PoC consisted of one intermediary bank (*Intermediary A*) with accounts in both Canada and Singapore, one local bank (*Bank A*) in Singapore and one local bank (*Bank B*) in Canada respectively. *Intermediary A* and *Bank B* were assigned one node each in Canada while the same *Intermediary A* and *Bank A* were assigned two nodes each in Singapore.

We present the transaction flow of the cross-border interledger value exchange between the Jasper-Ubin prototypes in Figure 23.

Following the development of the Jasper-Ubin Quorum and Corda prototypes for Singapore and Canada respectively, a cross-border interledger high-value transfer denominated in SGD was executed from *Bank A* in Singapore to *Bank B* in Canada with the following results:

- *HTLC Transfer*: HTLC enabled a successful atomic transfer of SGD$ 105 from *Bank A* through *Intermediary A* to *Bank B*. *Bank B*'s account was credited with CAD$ 100 by *Intermediary A* in accordance with pre-agreed exchange rates between the transaction parties.
- *HTLC Limitation*: The HTLC protocol requires the exchange of hash digests and secrets off-chain. *Intermediary A* in Canada may incur a principal risk in the event that it loses the original secret it received from *Bank B* after crediting *Bank B*'s account.

We present a summary of the goals, stakeholders, use cases and DLT platforms used to implement each of the CBDC experiments surveyed in this paper in Table 5 and Table 5.

VII. CONCLUSION AND FUTURE WORK

In this paper, we discussed the technical feasibility and challenges of leveraging DLT to issue CBDCs. We examined best practice approaches that were adopted by a selected number of central banks for the issuance, transfer and exchange of DLT-based CBDCs across multinational financial infrastructures.

We identified key practices that enabled the success and key outcomes of the CBDC experiments examined in this paper. We group the key practices under three major themes: *well-defined goals*, *multistakeholderism* and *technology*; and discuss the identified practices in the subsequent section.

Subsequently after our discussion of the identified key practices, we discuss the practical implications for central banks with regard to leveraging DLT to issue CBDCs.

A. KEY PRACTICES
1) WELL DEFINED GOALS
Central banks established well-defined goals for their CBDC research from the onset, which enabled them to clearly iden-

tify the type of stakeholders to assemble for their CBDC experiments.

The goal clarity also enabled central banks to establish clear design considerations for their specific experiments along with the choice of technology most suitable to achieve the intended CBDC design requirements.

Central banks were particularly interested in examining the potential of DLT to achieve compliance with specific PFMIs requirements. The PFMIs requirements were translated into the design considerations of *security* (e.g. Jasper Phase I and II, Ubin Phase I and II, Khokha, Inthanon Phase I and II), *safety* (BLOCKBASTER, Inthanon Phase I, Stella Phase III, Jasper-Ubin), *efficiency* (Jasper Phase I-III, BLOCKBASTER, Inthanon Phase I, Stella Phase III, Jasper-Ubin), *scalability* (Jasper Phase I and II, BLOCKBASTER, Ubin Phase II, Stella Phase I, Khokha) and *resiliency* (Jasper Phase I and II, SALT Phase I and II, Ubin Phase I and II, Stella Phase I, Khokha, Inthanon Phase I and II).

Notable use cases for DLT being explored by central banks include the applicability of DLT for wholesale interbank payments settlement, securities settlement, bond issuance and management, trade finance and cross-border payments settlements.

2) MULTISTAKEHOLDERISM
Central banks emphasized the importance of close collaboration with domestic and international financial market participants, technology service providers, academia and other industry participants at the onset of a CBDC research effort.

Central banks indicate that the success or failure of a CBDC research lies in the strength of the collaboration between the research stakeholders as each stakeholder brings unique perspectives and experiences to bear in the development and execution of CBDC experiments.

3) TECHNOLOGIES
Overall, central banks' preferred choice of DLT platforms for DLT-based CBDC experiments were mainly the permissioned DLT platforms. Particularly, DLT platforms with capabilities for settlement finality and data privacy such as Corda, Quorum and Fabric dominated the CBDC experiment landscape. Other less popular but notable DLT platforms leveraged by central banks for their CBDC experiments included Digital Asset, Anquan, Chain Core and Elements.

The first wave of CBDC experiments focused mainly on tokenizing wholesale central bank money and implementing core RTGS functionalities such as LSM settlement options on DLT. Such CBDC experiments (e.g. Jasper Phase II, Ubin Phase II, Inthanon Phase I) leveraged DLTs exclusively for their PoC development.

A second wave of CBDC experiments focused on implementing SSS functionalities for DvP on DLT. With the exception of Stella Phase II, such experiments leveraged

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DLTs exclusively for their PoC development. Stella Phase II leveraged a combination of DLT and the atomic swap protocol with HTLC to exchange tokenized assets across multiple DLT-based PoC prototypes.

The third wave of CBDC experiments focused on implementing cross-border payments settlement functionalities on DLT. Such experiments (e.g. Stella Phase III, Jasper-Ubin) leveraged a combination of DLT platforms and the atomic swap protocol with HTLC to exchange tokenized assets across multiple DLT-based CBDC research prototypes. Additionally, Stella Phase III leveraged ILP for the exchange of value across DLT-based and non-DLT based cross-border interledger prototypes.

B. PRACTICAL IMPLICATIONS FOR CENTRAL BANKS

The practical implications for central banks in issuing CBDCs are in many folds. The implications we discuss in this subsection are non-exhaustive.

Firstly, the CBDC experiments examined in this paper demonstrated that it is technologically feasible to leverage DLT to issue CBDCs. Leveraging DLT did not only enable the issuance of CBDCs, it also provided mechanisms to improve central banks' operational efficiency both domestically (e.g. BLOCKBASTER) and across borders (e.g. Jasper-Ubin). Leveraging DLT can also enable central banks to implement more resilient and robust FMIs (as demonstrated in SALT, Jasper and others) thereby increasing the public perception and trust in the central bank. Although DLT platforms are yet to become fully mature, current platforms provide adequate capabilties for central banks to achieve their data privacy (e.g. Inthanon I), transaction scalability (e.g. Khokha), settlement finality (e.g. Ubin Phase II), and operational risk (e.g. Jasper Phase II) requirements within the constraints of the PFMIs.

Secondly, CBDC issuance have the potential to pose legal challenges for central banks [27]. We do not examine the specific legal hurdles central banks must overcome in order to fully adopt CBDCs as legal tender in this paper. However, in order for CBDC to become a legal tender in any given country, existing laws and regulations may need to be revised to accommodate the new CBDC payment instrument.

Thirdly, the financial system in a given country may be significantly impacted depending on the model of CBDC issued by a central bank. Issuance of GA-CBDCs for example will give the general public direct access to central bank accounts and will therefore obliterate the essence of intermediary banks such as CMBs in the given country. Central banks must therefore reason about the type of CBDC to issue carefully in order not to disrupt the stability of existing financial systems.

Lastly, issuance of CBDCs and their widespread adoption by end users will impact the implementation of monetary policy in many ways. We do not examine the implications of CBDC issuance on monetary policy in this paper.

Nevertheless, we posit that, central banks may need to carefully assess the potential impacts CBDC issuance may have on the implementation of monetary policy in order not to disrupt their underlying financial systems.

C. FUTURE WORK

Having identified and examined various best practice approaches for CBDC research, our future work will focus on the implementation of **Afkoin** [119], a quantum-resistant CBDC intended for use in the Economic Community of West African States (ECOWAS) as a solution to ECOWAS' quest to create a monetary union and issue a single currency for use by its Member States [121].

ECOWAS is a fifteen member West African regional bloc established in May 1975 by the Lagos Treaty to "*promote co-operation and development in all fields of economic activity*" among Member States [120]. ECOWAS is made up of eight French-speaking countries, five English-speaking countries and two Portuguese-speaking countries.

In July 1993, a revised ECOWAS Treaty [121] was signed in Benin to "*promote co-operation and integration, leading to the establishment of an economic union in West Africa through the adoption of common policies in the economic, financial, social and cultural sectors, and the creation of a monetary union*".

To achieve the creation of a monetary union in West Africa, ECOWAS Member States passed the Accra Declaration [122] in April 2000. The Accra Declaration established a common set of economic criteria known as the *Convergence Criteria* through which a single currency, to be known as the **ECO** was to be issued in West Africa in the year 2003.

ECOWAS Member States have been unable to meet the established convergence criteria and have therefore postponed the issuance of the ECO on multiple occasions [123]–[125].

We posit that, by leveraging DLT along with smart contracts and efficient consensus mechanisms, Afkoin can represent a first step to achieving the convergence criteria and ultimately the issuance of a single currency in ECOWAS.

APPENDIX
GLOSSARY

The following glossary of terms relating to payments and securities settlement used throughout this paper have been taken from: the *Principles for financial market infrastructures*, Bank for International Settlements and International Organization of Securities Commissions, April 2012; *A glossary of terms used in payments and settlement systems*, Committee on Payment and Settlement Systems, March 2003; *Glossary of terms related to payment, clearing, and settlement systems*, European Central Bank and Eurosystem, December 2009 and from other relevant sources including Investopedia.com.

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TABLE 6. Glossary of terms.

Term	Definition
Atomic settlement	A settlement that does not require reconciliation. Atomic settlements are akin to settlements on real-time gross basis.
Central bank money	Liabilities of a central bank that take the form of banknotes or of bank deposits at a central bank and which can be used for settlement purposes.
Counterparty	The opposite party to a financial transaction such as a securities trade or swap agreement.
Delivery versus payment	A securities settlement mechanism that links a securities transfer and a funds transfer in such a way as to ensure that delivery occurs if and only if the corresponding payment occurs.
Financial market infrastructure	A multilateral system among participating institutions, including the operator of the system, used for the purposes of clearing, settling, or recording payments, securities, derivatives, or other financial transactions.
Liquidity-saving mechanisms	Liquidity-saving mechanisms include frequent netting or offsetting of payments during the course of the operating day. A typical approach is to hold payments in a central queue and to net or offset those payments on a bilateral or multilateral basis at frequent intervals.
Large-value transfer system	A funds transfer system through which large-value and/or high priority funds transfers are made between participants in the system for their own account or on behalf of their customers. Although, as a rule, no minimum value is set for payments made in such systems, the average size of such payments is usually relatively large. Large-value funds transfer systems are sometimes known as "wholesale funds transfer systems".
Real-time gross settlement system	A settlement system in which processing and settlement takes place on a transaction by-transaction basis in real time.
Securities settlement system	A system which permits the transfer of securities, either free of payment (FOP) or against payment (delivery versus payment)
Settlement	The completion of a transaction, wherein the seller transfers securities or financial instruments to the buyer and the buyer transfers money to the seller. A settlement may be final or provisional.
Settlement finality	The irrevocable and unconditional transfer of an asset or financial instrument, or the discharge of an obligation by the FMI or its participants in accordance with the terms of the underlying contract. Final settlement is a legally defined moment.

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