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# Blockchain application for central bank digital currencies (CBDC)

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**Abstract**
Central Bank Digital Currency (CBDC) is a digital version of domestic currency with a unit of account equivalent to its domestic currency. Blockchain or Distributed Ledger technology (DLT) can be used to implement CBDC to execute and settle peer-to-peer transactions. With the emergence of private money, such as cryptocurrencies and stablecoins, and the growing use of digital payments to lessen the global pandemic spread, CBDC is an active research area among central banks worldwide. Many central banks started their CBDC projects by building DLT proofs of concept (PoCs) to replicate wholesale payment systems and expand their investigation into other use cases, such as delivery versus Payment (DvP) and cross-border remittance. Many large economies like the United States have projects exploring CBDC. The People's Bank of China (PBoC), China Central Bank, has already started a pilot testing of their digital retail currency. This paper discusses the application of blockchain for CBDC by presenting CBDC projects by central banks. Moreover, this paper analyses issues, identify challenges and discusses future works in this rapidly evolving field.

**Keywords** Central bank digital currency · CBDC · Digital currency

## 1 Introduction

This section has two subsections. The first subsection highlights the digital transformation of currency from exchange of things to physical token then evolve to be digital data in ledger and digital token today. The second subsection describes the organization and contribution of this paper.

### 1.1 Digital transformation of currency

Before the invention of "Currency," humans exchange goods and services directly using the barter system. For example, a farmer may want to barter a bowl of rice for kilograms of meat. However, this arrangement takes time and suffers at least three significant issues. First, the parties must find each other to make the trade. Second, they must agree on the unit, such as how many bowls of rice would be for those kilograms of meat third, once the exchange is done. People cannot store the value of goods for a long time since most goods traded using this method are perishable. Slowly, a currency was developed over the centuries using traded goods such as salt or weapons as the medium of exchange, a unit of account, and a store of value. However, those traded items used as currencies were similar but not identical in every unit. Humans solve this problem by minting metal coins that already have intrinsic value and are standardized in every unit of coinage. The first official currency was the Lydian coins made from electrum, a mixture of silver and gold that occurs naturally. The coins were stamped with pictures that acted as denominations. The use of government-minted metal coins continued until today.

With the lighter weight of paper currency, which can easily be transported, China's Yuan dynasty was one of the first to move from coins to paper money. However, some of Europe still used metal coins as their only currency until the sixteenth century. This is because European acquisitions of the new colonies provided new sources of precious metals and enabled nations to keep minting more coins. However, bank depositors and borrowers started using paper banknotes to carry around in place of metal coins.

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People can take those notes to the bank at any time to exchange for their face value in metal—usually silver or gold—coins. These paper notes could also be used to buy goods and services like today's currency. However, it was privately issued by banks and private institutions, not the governments. To create more trust in these notes, many governments issued this paper currency by having assets such as gold to back up the value of each banknote issued, so only a limited number of banknotes could be printed. Hence, this provides more stability in previously unbacked currency.

Mobile payment and virtual currency are the two innovative forms of currency in the twenty first century. People can use their portable electronic devices, such as smartphones or tablets, to pay for their goods or services and send money to friends or family members. In 2009, Bitcoin, a new form of currency which is a virtual currency, was released. Virtual currencies have no physical coinage but are in digital format. It is operated using a decentralized system, unlike fiat currency, centralized and controlled by government-issued currencies.

CBDC is a digital version of domestic currency with a unit of account equivalent to its domestic currency. The holder of this CBDC has a direct claim on the Central Bank balance sheet. With the emergence of private money, such as cryptocurrencies and stablecoins, and the growing use of digital payments to lessen the global pandemic spread, CBDC is an active research area for most central banks worldwide. More than a quarter of them are now developing or running concrete pilots, as reported by Bank for International Settlements (BIS) [1]. In [1], BIS updates earlier surveys that asked central banks for their CBDC engagement. This shows that more than two-thirds of central banks will likely issue a retail CBDC in the short or medium term. Many are exploring a CBDC ecosystem that involves private sector collaboration and interoperability with existing payment systems.

### 1.2 Organization and contribution

This paper is organized as follows: (together with the highlight of our contribution.)

- *Section 2* provides related work from Blockchain or Distributed Ledger Technology (DLT), stablecoins, and Facebook Libra or Diem, which are fundamental for our CBDC studies.
- *Section 3* surveys wholesale and retail Central Bank Digital Currency (CBDC) projects worldwide.
- *Section 4* analyzes the technical platform and design issues for CBDC.
- *Section 5* posts challenges for CBDC.
- *Section 6* discusses future works and provides a conclusion.

## 2 Related works

### 2.1 Blockchain or distributed ledger technology (DLT)

DLT is a set of technologies or protocols that use distributed participants to collectively and securely maintain a decentralized digital database without a single central authority. Bitcoin, invented in 2008 and released in 2009 by an unknown person or group of persons named Satoshi Nakamoto [2], is the most famous application of DLT. Another example is Ethereum [3] which has programmable as its distinctive feature. Developers can use Ethereum as a platform to build many innovative cryptocurrencies or applications called decentralized applications (or "dapps"). Based on Bitcoin or Ethereum, many cryptocurrencies were created and are called "Altcoins."

Since only those involved in the transaction should see the transaction as the main requirement for financial transactions, "private" or "permissioned" DLT, which requires that nodes in the system must be permitted to join, emerges as the solution for this problem. Hence, many Central Banks choose this DLT platform to implement their CBDC. Corda [4] is an open-source "private" DLT platform that provides strict privacy for recording and managing contracts between mutually distrusting parties. Corda is unique among blockchain platforms that introduce the concept of "Notary," which stamps every transaction to avoid double-spending. Hyperledger Fabric [5] is another "permissioned" DLT foundation for application development or modular architecture solutions. Quorum [6] is a DLT based on Ethereum that combines the innovation of the public Ethereum community with enhancements to support enterprise needs. Hyperledger Iroha [7] is designed to be simple and easy to incorporate into projects that require DLT with a new crash fault-tolerant consensus algorithm called YAC [8]. Hyperledger Besu [9] is an enterprise-friendly Ethereum client for public and private permissioned networks. Hyperledger Besu includes several consensus algorithms and has comprehensive permissioning schemes explicitly designed for use in a consortium environment. Elements [10] is an open-source, sidechain-capable blockchain platform providing access to community-developed features such as Confidential Transactions and Issued Assets. Interledger [11] is an open protocol for sending payments across various ledgers, enabling interoperability for any value transfer system. Bitt [12] is a company that has expertise in digital currency and provides a solution for central banks to develop and implement digital currency for a central bank using blockchain or DLT technologies.

### 2.2 Stable coins

Stablecoins are cryptocurrencies designed to minimize the price volatility relative to some "stable" asset or basket of assets. This is a significant problem for cryptocurrencies to be used as payment instruments. A stablecoin can be pegged to assets such as fiat money or exchange-traded commodities (Asset-Backed), a cryptocurrency (Crypto-Backed), or does not peg to anything but has a mechanism to stabilize its value (Algorithmic).

### 2.3 Facebook Libra or Diem

In June 2019, Libra formally published its white paper [13]. After the announcement, many regulators, central banks, and politicians strongly criticized and opposed the project causing a few members to leave the associations. The main concerns are the threat to countries' monetary sovereignty, financial stability, and systemic financial risks, consumer protection, the potential for marketing dominance abuse, privacy concerns resulting from Facebook's dubious reputation given the previous scandal, and lack of explicit compliance undermining global regulatory efforts, especially in money laundering. With the "Libra 2.0" blueprint [14], the Libra association hopes to address concerns from regulators and opposition groups.

In Libra, the Libra Association is a trusted entity as "a de facto central bank." Hence it is not decentralized. Unlike bitcoin, which uses "public" or "permissionless" blockchain and relies on cryptocurrency mining, Libra processed transactions only by members of the Libra Association via the permissioned blockchain. At first, Libra would transition to a "permissionless" proof-of-stake system within five years, but this idea was later dropped. Calibra, now renamed "Nuvi," is a digital wallet for Libra. "Nuvi" will be a standalone app in Messenger and WhatsApp. The association also changed its name from "Libra" to "Diem" in December 2020 to be the new beginning for its launch of single currency stablecoin in 2021 which never materialized as it sold the Diem Group's Assets to Silvergate in 2022 [15].

### 2.4 Blockchain application for central banks

With the disruptive potential of Blockchain or Distributed Ledger Technology (DLT), many central banks are interested in adapting this technology with many use cases [16] utilizes a systematic mapping study approach to this field of study, presents an in-depth assessment of research maturity and the types of researchers, and found that the most research-intensive use-cases for the central banks are Central Bank issued Digital Currency (CBDC, Regulatory Compliance, Payment Clearing and Settlement Systems (PCS). [17] analyzes requirements of CBDC design, make a literature review on blockchain based CBDC schemes, and provide guidelines for blockchain based CBDC design.

## 3 Central bank digital currency (CBDC)

CBDC is a digital version of domestic currency with a unit of account equivalent to its domestic currency. CDBC can be classified as retail or wholesale. Retail CBDC is issued for general use, such as person-to-person or person-to-business payments. For more efficient interbank payments, wholesale CBDC is issued only by financial institutions and clearinghouses. With the emergence of private digital currencies such as Bitcoin [2], Ethereum [3], Diem, or Libra [13], CBDC often assumes to be implemented by using blockchain or DLT. However, CBDC can be implemented using centralized architecture. This section discusses the case for CBDC and surveys both wholesale and retail CBDC as define in the Tables 1 and 2.

### 3.1 Case for CBDC

In a world where cash use is decreasing, and private e-money is ubiquitous and currently controlled by a few large companies, such as in China or Sweden, CBDC can bring many people who use private money back to use public money in a financial system. CBDC can also enable the domestic payment system to be more resilient.

Since digital penetration, such as a smartphone, is more significant than a bank account in many countries, CBDC could provide financial inclusion for the unbanked who access smartphones. In addition, CBDC can help users access current digital payment tools at considerably lower or zero costs without a bank account.

Utilizing CBDCs can help financial institutions or fintech companies experiment with DLT on its programable money features, encouraging competition and innovation in the financial sector. Newcomers can build on CBDC programable money features to enter the payments market and offer solutions that reduce smaller institutions' need to execute their payments through larger banks. Using advanced digital features like smart contracts and programmable money, innovators can utilize these as the basis of innovative new financial services or platforms.

A domestically issued CBDC would help lessen or fend off privately issued currency adoption. Central Banks can retain sovereignty over monetary policy. CBDC can be used to enhance monetary policy transmission. Some academics also argue that CBDC that pays interest would increase the economy's response to changes in the policy rate. CBDC that pays negative interest rates can break the

**Table 1** Wholesale CBDC projects

| Project | Abbreviation | Country |
|---|---|---|
| Jasper | J | Canada |
| Ubin | U | Singapore |
| Steller | S | EU and Japan |
| Khokha | K | South Africa |
| Inthanon | I | Thailand |
| mCBDC Bridge | M | BIS, Thailand, Hongkong, China, UAE |

**Table 2** Retail CBDC projects

| Project | Abbreviation | Country |
|---|---|---|
| e-CNY or China DECP | C | China |
| Bahamas Sand Dollar | B | The Bahamas |
| e-Krona | K | Sweden |
| Nigeria eNaira | N | Nigeria |
| Bakong | B | Cambodia |
| More of an all-in-one mobile payment and banking app than retail CBDC | | |
| Project Hamilton | H | USA |
| Thailand Retail CBDC | TH | Thailand |
| e-Peso | P | Uruguay |
| Hryvnia | U | Ukrane |

"zero lower bound" constraint to make holding cash costly during a prolonged crisis.

While there are some definite benefits and advantages, there are also challenges and disadvantages of CBDC, which can be mitigated by the appropriate design of CBDC. The challenges and issues are discussed in Sect. 4.

## 3.2 Wholesale CBDC

This section provides surveys of wholesale CBDC project worldwide as summaries in Table 1.

### 3.2.1 Project Jasper

Launched in March 2016, Project Jasper [18] primary objective is to understand how DLT could transform the payments in Canada. The project is a collaborative effort between Payments Canada, its member financial institutions, the Bank of Canada, and other market participants. The project has 3 Phases which are Phase I: Platform allows for Central Bank-Issued Digital Receipt for Deposited Fund [19], Phase II: New DLT Platform [20], Phase III: Securities Settlement using Distributed Ledger Technology [21]. Project Jasper focused on clearing and settling high-value interbank cash payments using DLT in phases I and II. However, phase III explored integrated payments and securities (Delivery versus Payment, DvP).

### 3.2.2 Project Ubin: Singapore's central bank digital money using distributed ledger technology

Project Ubin [22] results from the collaboration between the Monetary Authority of Singapore (MAS) and the industry to better understand Blockchain and DLT potential benefits through practical experimentation by developing more easy-to-use and efficient alternative payments and securities clearance and settlement systems based on CBDC. The project has five phases: Phase I: Tokenize SGD [23], Phase II: Re-Imagine RTGS [24] and the source-codes [25], Phase III: Delivery versus Payment (DvP) [26] to develop tokenized assets settlements across various blockchain platforms Phase IV: Cross Border Payment versus Payment (PvP) [27] produced the report, Cross-border interbank payments, and settlements: Emerging opportunities for digital transformation [28], and Phase V: Enabling Broad Ecosystem Collaboration [29], developed prototype by MAS with J.P. Morgan and Temasek that enables payments to be executed in various currencies on the same network and seamlessly connect and interface with other blockchain networks. The network also supports use cases such as securities trading asset DvP clearing and settlement, private exchanges settlement, conditional payments, escrow for trade, and trade finance payment commitments [30]. Phase V also considers DLT payments network commercial viability and value beyond technical experimentation.

### 3.2.3 Project Stella

In December 2016, Project Stella was a joint research project of the European Central Bank (ECB) and the Bank of Japan (BOJ). This project has three phases and produces reports. Published in September 2017, Phase 1 [31] analyzed large-value payment processing using DLT. Published in March 2018, phase 2 [32] investigated securities delivery versus payment (DvP) in a DLT environment. Published in June 2019, phase 3 [33], DLT-related technologies could improve cross-border payments, especially

in terms of safety. Like other CBDC study projects, Project Stella analysis and experimental results are not meant to replace or complement existing arrangements. The scope of the project does not include legal and regulatory aspects. [34]

#### 3.2.4 Project Khokha

Early in 2018, Project Khokha [35] was formally initiated by the South African Reserve Bank (SARB). This project was a collaborative effort that involved many partners: a consortium of banks, ConsenSys as the technical partner, and PricewaterhouseCoopers Inc. (PwC) as the support partner. Khokha is a Zulu word meaning 'pay.' Project Khokha is an Enterprise Ethereum solution to increase transaction volume and network resilience while maintaining confidentiality requirements for real-time gross settlement. Managed by the SARB Fintech Unit, the project planning started late in 2017, with execution running for 14 weeks from January to April 2018.

#### 3.2.5 Project Inthanon

The Bank of Thailand (BOT) collaborated with eight commercial banks to initiate Project Inthanon. The project's primary goal is to explore the potential of DLT for improving efficiencies in financial market infrastructure. Project Inthanon is divided into three phases, starting with the study of DLT as a mechanism for managing and settlement of wholesale payments between banks (Real-time Gross Settlement, RTGS) in phase I, continuing with the study of DLT smart contracts in phase II, and the study of cross border payments in phase III.

**3.2.5.1 Project Inthanon phase I: real-time gross settlement (RTGS)** Project Inthanon Phase I [36] focused on building a decentralized RTGS prototype with important payment functionalities: tokenization of cash and bond, decentralized bilateral transfer, queuing mechanisms, gridlock resolution (GR), and automated liquidity provision (ALP). The GR and ALP design and implementation were innovative and significant additional contributions to other central bank studies. A decentralized payment network prototype was built using the Corda platform. BOT nodes and bank nodes are in this network. The BOT node is the only node that can mint and destroy Thai Baht cash tokens. Other bank nodes can convert their RTGS balance into cash tokens through the cash tokenization process. Once the bank nodes have cash tokens, they can use them for peer-to-peer payment to other nodes.

**3.2.5.2 Project Inthanon phase II: smart contracts** This phase was built upon RTGS PoC from Phase I and continues to collaborate, design, develop, and test a PoC as in phase I. Aiming to improve settlement efficiency and solve business use cases' pain points, Phase II [37] investigates two key areas. The first area is the interbank bond trading and repurchase life cycle. The second area is regulatory compliance and data reconciliation for third-party funds transfers. Phase II illustrated that DLT, with smart contract implementation, could help enhance bond trading and repurchasing activities. This bond life cycle includes coupon payments, interbank trading, and repurchase transactions. Using smart contracts for process automation, Post-trade can operate more efficiently, and liquidity management can be improved. Moreover, the redesigned third-party fund's transfer workflow could avert fraudulent transactions by letting senders verify beneficiary information before submitting the transactions and allowing involved parties to track the status of the transactions for more transparency.

**3.2.5.3 Project Inthanon-Lion rock: cross-border settlement** As the Hong Kong Monetary Authority (HKMA) and the Bank of Thailand (BOT) signed the Memorandum of Understanding in May 2019, the two authorities continue to work together and initiate Project Inthanon-Lion-Rock to study CBDC application to cross-border payments. In January 2020, they announced the outcomes [38] and published a report [39]. As a result, the THB-HKD cross-border corridor's network prototype was developed successfully with ten participating banks from both countries. This network enables participating banks in Hong Kong and Thailand to conduct peer-to-peer funds transfers and foreign exchange transactions. This reduces settlement layers and eliminates intermediaries such as corresponding banks, which is the current practice.

**3.2.5.4 Central bank digital currency: the future of payments for corporates** With the exploration of CBDC for corporates in this project, the BOT expands its CBDC research and development to businesses. This project demonstrates that DLT can increase payment efficiency for businesses. By allowing users to set various conditions on the CBDC, such as specific conditions for payments for specified invoices in supply chain financing, CBDC can enhance flexibility in handling business activities. However, the project found some limitations in scaling to support a high volume of transactions and preserving the privacy of the transactions, which needs to be explored further.

**3.2.5.5 Cross border payment or multiple CBDCs** The Multiple CBDC (mCBDC) Bridge [40] is a wholesale CBDC project first bilaterally initiated by HKMA and BOT in 3.2.5.3. The project was renamed mCBDC Bridge after

the BIS innovation hub, the People's Bank of China Digital Currency Institute, and the Central Bank of the United Arab Emirates joined. By developing a prototype that provides instant cross-border payment versus payment (PvP) in multi-currency cross-border payments, the project participant can investigate DLT potential and issues such as scalability, interoperability, privacy, governance, and significant challenges in the design of CBDC application for multi-currency cross border CBDC.

The project Dunbar [41] is the collaborative work by the Reserve Bank of Australia, Bank Negara Malaysia, the Monetary Authority of Singapore, and the South African Reserve Bank with the Bank for International Settlements Innovation Hub. Project Dunbar's objective is to develop prototype shared platforms for cross-border transactions using multiple CBDCs that enable financial institutions to directly conduct transactions in digital currencies, eliminating intermediaries and reducing transaction time and cost. Hence, this could make cross-border payments cheaper, faster, and safer. The report [42] published in March 2022, provides a broad overview of the multi-CBDC, key benefits and challenges, describes the design, and identifies and categorizes across the areas of policy, business, and technology. The report also identifies key milestones and next steps that represent problem statements that need further exploration in the multi-CBDC space and constitutes an open call for collaboration to the central banking, banking and payment, and broader technology ecosystem.

**3.2.5.6 Retail CBDC** Early in 2020, there was a growing interest in retail CBDC due to three major trends: the announcement of global stablecoins such as Libra or Diem, the People's Bank of China testing of the digital currency electronics payment (DCEP) or e-CNY, and the COVID-19 pandemic which encourages digital payment. Table 2 summaries the project surveyed in this section.

**3.2.5.7 PBoC DCEP or China e-CNY or digital Yuan** Digital Currency DCEP (Digital Currency Electronic Payment, DCEP) [43, 44] or e-CNY [45] is a proposed digital version of China cash issued only by the People's Bank of China (PBoC). e-CNY is backed by reserves and has properties like paper money but only in digital form. Following the Facebook announcement of Libra, PBoC accelerates its effort to test and plan to launch its digital currency to guard against the effect of other private or public digital currencies on its monetary sovereignty and currency (CNY). This could be considered the world's first retail CBDC as PBoC issues it, and it is not listed on cryptocurrency exchanges and will not be for speculation of value.

For issuance and redemptions, e-CNY would be based on a "two-tier system." PBoC would issue and redeem China's CBDC via commercial banks or other financial institutions on the first layer. Commercial banks would redistribute this CBDC to retail customers on the second layer. However, this design has a "blockchain as an option" as the technical roadmap has not been released yet. In addition, e-CNY would allow fund transfers without requiring bank accounts or a "loosely-coupled" design. e-CNY would also have an "offline" fund transfer feature. With e-CNY, the PBoC hopes to conduct a more effective monetary policy while having a broader view of all businesses and individuals across China. However, individual financial privacy abuses are still potential risks and remain serious concerns. Further, China can increase its CNY circulation and global reach with the hope that CNY will be a global currency like the US Dollar in the digital world.

**3.2.5.8 Project sand dollar by central bank of The Bahamas** Project Sand Dollar [46] is the Central Bank of The Bahamas' initiative to issue its digital Bahamian dollar (B$) and implement the digital payments system infrastructure to support the operation of a digital currency ecosystem.

**3.2.5.9 The Riksbank's e-krona pilot** In Sweden, private e-money payments have increased, and cash is declining. Since cash is the only possibility for the general public to hold and pay with central bank-issued money, Riksbank, Sweden Central Bank, has decided to study CBDC. This works as a complement to cash and is named "e-krona." The project aims to increase the Riksbank knowledge of a central bank-issued digital krona and show how the general public could use an e-krona in a test environment. This technical solution [47] will be based on DLT. However, there is no decision on issuing an e-krona.

**3.2.5.10 Nigeria's eNaira** In early 2021, Nigeria's government and the Central Bank of Nigeria (CBN) issued crypto transactions ban within the banking sector in response to the rise of cryptocurrency. Then, a few months later, Nigeria announced the plans to introduce the retail CBDC for Nigeria named eNaria. Like cash or coin, the eNaira is also a liability of the CBN and complements Nigeria's physical currency. In October 2021, CBN launched eNaira [48, 49]. Draws substantial international interest, especially the other economy's central banks.

With a digital currency management system (DCMS) from the fintech company Bitt, the technology behind the eNaira is blockchain-like in crypto-assets. However, the eNaira is not as open as crypto-assets because the central bank controls its access. The eNaira is stored in digital wallets, transferred digitally to anyone with its wallet at no

cost, and used for payment. CBN expects that the eNaira will gradually bring multiple benefits with a robust regulatory system as the eNaira becomes more widespread. Key benefits are increased financial inclusion, remittance facilitation, and reduced informality.

With about half of the population with a mobile phone [50], the eNaira will expand to the unbanked population, allow financial access with a mobile phone, and support more direct transfer for government or social programs. Hence, increasing financial inclusion. With remittance receipts amounting to $17 billion in 2020 [51], Nigeria is one of the significant remittance destinations. With the high cost per transaction using traditional remittance services, the eNaira will make it easier for Nigerians in foreign countries to remit funds to Nigeria using eNaira wallet-to-wallet transfer with lower remittance transfer costs. With exchange rate reforms, including a unified market-clearing rate, remittance using eNaira would enhance the invention by reducing the gap between official and parallel market exchange rates. With transactions over half of the GDP and equivalent to 80% employment, Nigeria has significant informal economy employment. Moreover, the eNaira is account-based which makes it traceable. As a result, the eNaira makes informal payments more transparent and enhances consumption through greater financial inclusion with greater adoption and widespread usage.

**3.2.5.11 Cambodia: project Bakong** Bakong [52] is more of an all-in-one mobile payment and banking app than retail CBDC. Cambodians can quickly receive and transfer funds using their personalized QR code or mobile phone number using the system they registered with a National ID card/Passport and local valid phone numbers instead of using a bank account.

**3.2.5.12 Digital dollar and project Hamilton** There are two projects involving digital dollars. The first project is a partnership between Accenture and the Digital Dollar Foundation called the "Digital Dollar Project." The project issued its white paper [53] detailing a plan and considerations for developing a US CBDC. It proposes a tokenized US digital dollar champion model, outlines US. CBDC benefits, and offers potential use cases and pilots.

The second project is Project Hamilton [54], the collaboration project between the Federal Reserve Bank of Boston and the Massachusetts Institute of Technology's Digital Currency Initiative. This exploratory research project tries to understand the opportunities and limitations of promising CBDC technologies [55]. Project Hamilton explores the design of CBDC and gets a practical understanding of the technical challenges and opportunities for CBDC. The primary goal for phase 1 was to design a core transaction processor with extensive retail payment system requirements of robust speed, high throughput, and fault tolerance. The secondary goal was to create a flexible platform for collaboration, data gathering, comparison with multiple architectures, and future research. With this intention, the project publicly releases all software from the study under the MIT open-source license [56]. Since phase 1 focuses on the feasibility and performance of transactions, Phase 2 aims to create a foundation for more complex functionality, such as time to the finality of fewer than five seconds, the throughput of 100,000 transactions per second, and wide-scale geographic fault tolerance. Various topics are also left to Phase 2. These include questions around high-security issuance, systemwide auditability, programmability, balancing privacy with compliance, technical roles for intermediaries, and denial of service attacks resiliency.

**3.2.5.13 Thailand's retail CBDC** After exploring Wholesale CBDC in Project Inthanon, the Bank of Thailand (BOT) announced Field [53] for its study, survey results, and pilot test plan.

The study [57], the paper [58], and surveys show that retail CBDC design and development must not harm the transmission of monetary policy and financial institutions or the overall stability of the financial system to reach its full benefits. Accordingly, there are three characteristics of retail CBDC. The first characteristic is that it should be like cash and pay no interest. The second is that the distributors of retail CBDC to the public should be intermediaries such as financial institutions. The third characteristic is the establishment of conditions or limits for converting CBDC. With these characteristics, the central bank can be more confident that retail CBDC would not affect deposits at financial institutions or cause bank runs during a crisis. These will also preserve the intermediaries' role in collecting deposits, providing credits, and managing liquidity in the financial system. With a prediction that retail CBDC demand will gradually increase, it can become an alternate payment method to cash and e-money in the future.

From the feedback from the public survey and discussion in a focus group, the respondents view that retail CBDC has benefits as an infrastructure that is open to access and competition. There is also a potential to foster significant and safe financial innovation. As generally agreed on by respondents, the CBDC design guidelines from the study can also help mitigate the effects caused by retail CBDC on the Thai financial sector. The respondents also suggested promoting consumer education to have more knowledge and understand benefits and use cases, notably how retail CBDC differs from current electronic payment options.

Based on survey results and the study, the Retail CBDC Pilot Test guidelines are established for developing and testing in the real-life environment under the Foundation and Innovation track. Expect to begin testing in 2022. The Foundation Track tests and evaluates retail CBDC uses in cash-like activities within a limited scale. For example, the use cases accept, convert, or pay for goods and services. Considering the format and criteria for participation, the Innovation Track tests and evaluates how the private sector and technology developers can develop innovative use cases for retail CBDC. By assessing all results and associated risks from this Pilot test, the BOT will ensure that the public can benefit from retail CBDC and that it does not harm economic and financial stability.

**3.2.5.14 e-Peso Uruguay** In November 2017, the Central Bank of Uruguay began a pilot program called called to issue, circulate and test unique digital banknotes in several denominations called "e-Peso." The digital banknotes were issued for distribution to a non-DLT platform named "e-note manager platform," the registry of digital banknotes ownership. In this system, users can instantly transfer e-Peso peer-to-peer via mobile phones using text messages or the e-Peso app. The e-Peso pilot was successful and closed in April 2018. All e-Pesos were canceled. However, this project is in an evaluation phase, and several questions are being considered before the central bank decides on further trials and potential issuance in the future.

**3.2.5.15 Ukraine** The National Bank of Ukraine, the country's central bank, has been working on a pilot project [59] to test the usefulness of a digital version of its currency, the Hryvnia. In 2019, the National Bank of Ukraine announced completing a two-month-long pilot involving central bank employees [60].

### 3.2.6 Request for proposal/solutions and study groups for CBDC

**3.2.6.1 Request for proposal/solutions** Several countries choose to request proposals or solutions to study and test CBDC. South African Reserve Bank: Request for expression of interest from prospective solution providers in anticipation of a feasibility project to issue electronic legal tender [61]. Banque de France calls for applications [62] to experiment using digital euro for interbank settlements. The Bank of Korea (BOK) launched a pilot test program [63] to assess the logistics of issuing a CBDC and recently took another step toward developing a CBDC with plans to build a pilot platform. BOK said it intends to select a technology supplier through an open bidding process to research the practicalities of a CBDC. The test will run from August to December 2021 and involve simulations of banks and retailers, including mobile phone payments, funds transfers, and deposits. BOK's research into the issuance of a CBDC was published in February 2021 and determined that it could be treated like fiat currency, not a crypto asset, and could therefore be exchanged freely with cash.

### 3.2.7 Study groups

Six central banks from Canada (BoC), England (BoE), Japan (BoJ), the European Central Bank (ECB), the Sveriges Riksbank, and the Swiss National Bank, together with the Bank for International Settlements (BIS), joined in a group to share experiences as they investigate CBDC potential in their home jurisdictions [64]. Central Banks in this group have published numerous noteworthy papers. For example, BoE's Central Bank Digital Currency: opportunities, challenges, and design [65], BIS's Central bank digital currencies [66], and the technology of retail central bank digital currency [67].

International Telecommunications Union (ITU) also established a Focus Group on Digital Currency, including Digital Fiat Currency ITU [68] with Stanford University [69]. In addition, the World Economic Forum (WEF) publishes the Central Bank Digital Currency Policy-Maker Toolkit [70] to help countries systematically study CBDC.

## 4 Technical platform and design issues for CBDC

CBDC would be widely available at a basic level, local electronic money, and issued by the central bank that must have several high-level features such as scalability, confidentiality, resilience, and security. This section discusses design issues and the technical platform for CBDC.

### 4.1 Centralized or distributed

Since many private-issued digital currencies such as Libra or Diem [71] or Bitcoin [2] use blockchain or DLT to ensure that the transaction is immutable, this often leads to the assumption that CBDC might be implemented using blockchain or DLT as discussed in the article [72]. However, it could also be a centralized digital fiat currency, such as in eCurrency [73].

### 4.2 Immutability of transactions or consensus

In a Centralized system, the consensus has no problem because it relies on the central trusted party to confirm the system's state. Bitcoin [2] was designed to reach consensus

in a trustless environment without the need to trust a single centralized party. However, the Central bank is at least one trusted central party in the CBDC environment. Hence, many design features, such as proof-of-work (POW), would be optional and desirable. In "permissioned" or "private" DLT, the Practical Byzantine Fault Tolerance [74] consensus mechanism can be used and is more straightforward because all the validators are known and authorized. However, applying them to a CBDC would need further studies of the risk and challenges.

### 4.3 Resiliency and availability

Widely available CBDC needs to have a high level of operational resilience. DLT has this advantage over the centralized system with its distributed nature, which has a single point of failure disadvantage. CBDC that uses DLT can continuously operate without interruption, even when any validators stop working or the central bank is temporarily down. This is the fundamental difference to the existing centralized financial architecture. However, this DLT resiliency is optional in every scenario. For example, when all nodes execute the same flawed "buggy" code, that causes the system to stop operation. Centralized systems can operate by using multiple backups to achieve high resiliency. However, DLT offers potentially better efficiency and cost-effectiveness to an increased level of resilience.

### 4.4 Privacy and security

Providing full resilience and security benefits, the system must allow multiple parties to help verify transactional data. However, this compromises privacy for parties that transact because others will also know the transactional data. By using pseudonyms or addresses rather than real-world identities, DLT systems still have privacy issues. Many studies found that hackers can determine various information by analyzing pseudonyms or addresses. Consequently, this is not offering true privacy. Instead, a few broad approaches to tackle this privacy of DLT: Permissioned DLT, No sensitive data included on the shared ledger, data encryption, and cryptographic protocol such as Zero-knowledge proof [75].

### 4.5 Scalability and operation efficiency

Blockchain and DLT systems today are still relatively slow. For example, with about 10 min for bitcoin or around 15 s for Ethereum for transactions to be confirmed, DLT CBDC must scale to meet the requirement of a few seconds for transaction confirmation in a high peak load in thousands of transactions per second. However, the latest research paper from Project Hamilton [76] shows that retail CBDC systems can provide high throughput, as high as one hundred thousand transactions per second.

With widely used CBDC, more CBDC payments will increase the number of transactions compared to existing payment systems. Therefore, central banks will have to decide to expand their computing or operational capacity to handle this. However, by using DLT, central banks can set the rules and requirements for CBDC and let various vendors in the ecosystem provide on-demand computing capacity. Hence, only necessary for the central bank to operate some infrastructure.

### 4.6 Cybersecurity

With distributed nature of DLT, there is an increased cybersecurity risk as more parties can access and participate in the system's protocol. However, DLT can also offer cybersecurity benefits. For example, when a single party is compromised, the consensus mechanism can ensure that other participants in the network will reject any deceptive transactions.

### 4.7 Distribution models for CBDC

Another critical design feature is how the Central Bank will distribute the CBDC. In BIS the technology of retail central bank digital currency [67] proposes potential retail CBDC architectures: Direct CBDC, Hybrid CBDC, Indirect or synthetic CBDC.

#### 4.7.1 Direct CBDC

In this model, Central Banks distribute CBDC themselves. As a result, they will have to expand their computing and operational capacity, such as Know Your Customer (KYC) for all accounts. They will also have to allow many direct claims on the Central Bank ledger.

#### 4.7.2 Hybrid CBDC

In this model, Central Banks can have some intermediaries to help distribute CBDC. Many central banks are working with the private sector using this collaborative approach. The only entity allowed to create or destroy a token in the 'core ledger' is the Central Bank. While private-sector interacts with end-users, maintains KYC checks, and provides customers with additional 'overlay services.' This model can also be called the "Two-Tier Model," as explained in Sect. 3.2.5.7 PBoC DECP or e-CNY.

**Table 3** Techincal solutions for CBDC projects

| Name | Type | WholeSale CBDC | | | | | | Retail CBDC | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | J | U | S | K | I | M | C | B | K | N | B | H | TH | P | U |
| Corda | Private DLT | 1,2,3 | 2 | 2 | | 1,2,3 | | | | | | | | | | |
| Hyper Ledger Fabric | Private DLT | | 2 | 2 | | | | | | | | | | | | |
| Quorum | Private DLT | | 3,4,5 | | | | | | | | | | | | | |
| #STACS | Private DLT | | 5 | | | | | | | | | | | | | |
| Elements | Blockchain | | | 2 | | | | | | | | | | | | |
| Interledger | DLT InterOp | | | 1 | | | | | | | | | | | | |
| Special Purpose Library | Crypto | | | 4 | | | | | | | | | | | | |
| Privacy/Zero Knowledge Proof | Protocol | | | 4 | | | | | | | | | | | | |
| DECP or e-CNY | Hybrid | | | | | | | | | | | | | | | |
| Bitt | DLT | | | | | | | | | | | | | | | |
| Hyperledger IROHA | Private/DLT | | | | | | | | | | | | | | | |
| e-note manager platform | Centralized | | | | | | | | | | | | | | | |
| N/A | | | | | | | | | | | | | | | | |
| DLT | DLT | | | | | | | | | | | | | | | |
| Hybrid | Hybrid | | | | | | | | | | | | | | | |

#### 4.7.3 Indirect CBDC

There are separate responsibilities between the private and public sectors in hybrid proposals, such as the central bank, asset issuance, and network governance. The indirect CBDC model gives more responsibilities to the private sector. 'Synthetic CBDC' (sCBDC) [77] is recently coined by researchers at the IMF. In this model, Central Banks can have a non-central bank institution or private sector intermediary that issues a stablecoin backed by central bank reserve. That sCBDC held by retail participants is a liability of the private sector intermediary, not the central bank, as in previous models.

### 4.8 Technical solutions for CBDC projects

Table 3 summarizes technical solutions for CBDC projects, with the number in each cell denoting the phase of each project. Most wholesale CBDC projects use private or permissioned DLT because of privacy concerns that public blockchain such as Bitcoin has nodes in the system verified transactions. Corda [4] was chosen as the platform for most wholesale CBDC projects. Project Khokha [35] uses Ethereum enterprise as the platform. Elements [10] (bitcoin derived) are used in Project Stella with the use of many other libraries for a specific function such as interledger [11, 78], cryptography, and privacy [79]. Hyperledger Fabric [5] was one of Project Ubin Phase 2, and Quorum [6] was used as the primary implementation for Project Ubin in subsequence phases.

For Retail CBDC, Sweden has published a technical solution based on Corda [47]. China DCEP [43] is implemented on a hybrid system with a possible DLT platform developed in China. Bahamas Sand Dollar and Nigeria's eNaira use the Bitt digital currency management system [12].

**Table 4** Business use cases for wholesale CBDC projects

| Use cases | Wholesale CBDC Projects | | | | |
|---|---|---|---|---|---|
| | Jasper | Ubin | Stella | Khokha | Inthanon |
| Tokenized currency | 1 | 1 | 1 | 1 | 1 |
| RTGS | 1,2 | 2 | 1 | 1 | 1 |
| DvP | 3 | 3 | 2 | 1 | 2 |
| Smart contracts | 4 | 5 | 2 | 1 | 2 |
| Cross border (PvP) | 4 | 4 | 3 | | 3 |
| Data privacy | 1 | 1 | 4 | 1 | 2 |
| Board ecosystem collaboration (different assets) | | 5 | | | 2 |

## 5 Challenges

### 5.1 Appropriate use cases

The business use cases for the CBDC project are shown in Table 4, where the number in the cell indicates the phase of the particular project.

All wholesale CBDC projects start from tokenized currency and build RTGS as a platform to continue their studies. Then many projects progress further to study Delivery versus Payment, DvP and Payment versus Payment, PvP, or cross-border payment. Project Stella took a unique approach to learning data privacy approaches and Project Inthanon but with different techniques. Using the cryptographic library in Project Stella, Project Inthanon explores data privacy using smart contracts and necessary data.

### 5.2 Economics financial markets implications

In issuing CBDC, Central Banks [80], IMF Working Paper [81], and academics [82] have published various research questions considering the impact of CBDC on monetary policy and financial stability. For example, depositors, especially in times of crisis, trust that the central bank is more stable than the commercial banks. Hence, the central bank can be a deposit monopolist attracting all deposits away from the retail banking sector. Another effect of CBDC is that it can theoretically charge negative interest rates and directly inject or "helicopter drop" to individuals, introducing a new and innovative way to implement monetary policy.

### 5.3 Law and regulations

Since the issuance of CBDC will affect societies and the way of life of its citizen, representatives of the people should be consulted. For example, in Sweden, the Riksbank partition to Riksdag (Parliament) [83] proposes that the Riksdag supports the Riksbank's request to inquire into the payment market in a cashless digital economy, the roles of the central government and the private sector in such a market.

### 5.4 Data privacy and AML/CFT

Once in electronic form, transaction data can be collected and traced. This is good for Anti-Money Laundering and Combating the Financing of Terrorism (AML/CFT). However, the data privacy that people enjoy from using physical paper money is compromised. CBDC design and implementation must consider this issue and develop solutions to balance the two groups' needs.

## 6 Conclusions and future works

Since current interest now shifts to explore more in the area of retail CBDC, there will be interesting to follow developments and lessons learned from the testing of retail CBDC such as China's DCEP, Project Hamilton [54], Sweden's e-krona [47], South Africa digital tender [61], South Korea [63]. However, wholesale CBDC is still developing, such as Digital Euro in France [62] and Project Ubin Phase 5 [84]. In addition, increased scalability and interoperability issues in blockchain are active areas of research that can be beneficially upgraded to the existing platform that numerous CBDCs have already implemented.

The main contribution of this paper is the discussion on the application of blockchain or DLT to Central Bank Digital Currency.

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## Declarations

**Conflict of interest** The first author, Mr. Vijak Sethaput, was a senior developer and participated in project Inthanon, Thailand's CBDC mentioned in Sect. 3.2.5)

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## References


1. a., C.B., Wehrli, A.: "Ready, steady, go?—Results of the third BIS survey on central bank digital currency," 1 2021. [Online]. Available: https://www.bis.org/publ/bppdf/bispap114.pdf. Accessed 1 May 2021
2. Nakamoto, S.: [Online]. Available: (2008). https://bitcoin.org/bitcoin.pdf. Accessed 15 May 2020
3. Buterin, V.: "Ethereum White Paper: A next-generation smart contract and decentralized application platform," 2014. [Online]. Available: https://github.com/ethereum/wiki/wiki/White-Paper. Accessed 15 May 2020
4. R3:, "Corda Enterprise–a next-gen blockchain platform," R3, [Online]. Available: https://www.r3.com/corda-platform/. Accessed 15 May 2020
5. Foundation, L.: "Hyperledger Fabric," [Online]. Available: https://www.hyperledger.org/use/fabric. Accessed 15 May 2020
6. "Quorum," [Online]:. Available: https://www.goquorum.com/. Accessed 15 May 2020
7. Foundation, L.: "Hyper Ledger Iroha," [Online]. Available: https://www.hyperledger.org/use/iroha. Accessed 15 May 2020
8. N. I. B., A.L., Fedor Muratov, N.M.T.: "YAC: BFT Consensus Algorithm for Blockchain," 3 9 2018. [Online]. Available: https://arxiv.org/pdf/1809.00554.pdf. Accessed 15 May 2020
9. Foundation, L.: "Hyper Ledger Besu," [Online]. Available: https://www.hyperledger.org/use/besu. Accessed 15 May 2020
10. "Elements," [Online]:. Available: https://elementsproject.org/. Accessed 15 May 2020
11. "Interledger," [Online]:. Available: https://interledger.org/. Accessed 15 May 2020
12. Bitt: "Digital Currency Management System | Bitt," [Online]. Available: https://www.bitt.com/. Accessed 31 March 2022
13. Association, L.: "White Paper: An Introduction to Libra," 2019 6 18. [Online]. Available: https://sls.gmu.edu/pfrt/wp-content/uploads/sites/54/2020/02/LibraWhitePaper_en_US-Rev0723.pdf. Accessed 1 December 2022
14. Association, L.: "Libra White Paper v2.0," 4 2020. [Online]. Available: https://wp.diem.com/en-US/wp-content/uploads/sites/23/2020/04/Libra_WhitePaperV2_April2020.pdf. Accessed 1 December 2022
15. Diem, "Statement by Diem CEO Stuart Levey on the Sale of the Diem Group: 's Assets to Silvergate," 1 1 2022. [Online]. Available: https://www.diem.com/en-us/updates/stuart-levey-statement-diem-asset-sale/. Accessed 1 December 2022
16. Dashkevich, G.D.N.: "Blockchain application for central banks: a systematic mapping study". IEEE Access **8**, 139918–139952 (2020)
17. Tao Zhang, Z.H.: Blockchain and central bank digital currency. ICT Exp. **8**(2), 264–270 (2022)
18. Bank of Canada: "Project Jasper," [Online]. Available: https://www.bankofcanada.ca/research/digital-currencies-and-fintech/projects/#project-jasper. Accessed 22 October 2020
19. Payments Canada, "Project Jasper Primer," Payments Canada, 2017. [Online]. Available: https://www.payments.ca/sites/default/files/project_jasper_primer.pdf. Accessed 22 October 2022
20. Payments Canada, "Project Jasper: A Canadian Experiment with Distributed Ledger Technology for Domestic Interbank Payments Settlement," Payments Canada, 2017. [Online]. Available: https://payments.ca/sites/default/files/2022-09/jasper_report_eng.pdf. Accessed 22 October 2022
21. Payments Canada, "Jesper Phase III Securities Settlement using Distributed Ledger Technology," Payments Canada, Canada, October, 2018. [Online]. Available: https://payments.ca/sites/default/files/2022-09/jasper_phase_iii_whitepaper_EN.pdf. Accessed 22 October 2022
22. Monetary Authority of Singapore (MAS):, "Project Ubin: Central Bank Digital Money using Distributed Ledger Technology," [Online]. Available: https://www.mas.gov.sg/schemes-and-initiatives/Project-Ubin. Accessed 19 April 2020
23. Monetary Authority of Singapore (MAS) and, Deloitte: "Project Ubin: SGD on Distributed Ledger," 3 2017. [Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Project-Ubin–SGD-on-Distributed-Ledger.pdf. Accessed 19 April 2020
24. Monetary Authority of Singapore (MAS): and Associatiation of Bans in Singapore (ABS), "Project ubin phase 2 report: re-imagining RTGS," 9 2017. [Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Project-Ubin-Phase-2-Reimagining-RTGS.pdf. Accessed 19 April 2020
25. Ubin, P.: "Project Ubin," [Online]. Available: https://github.com/project-ubin. Accessed 19 April 2020
26. Monetary Authority of Singapore (MAS), " Delivery versus Payment on DLT," Monetary Authority of Singapore (MAS) and Singapore Exchange (SGX), Singapore, 11 November 2018.[Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Project-Ubin-DvP-on-Distributed-Ledger-Technologies.pdf. Accessed 10 December 2022
27. The Bank of Canada (BOC) and the Monetary Authority of Singapore (MAS):, "Jasper-Ubin Design Paper: Enabling Cross-Border High Value Transfer using DLT," 2 5 2019. [Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Jasper-Ubin-Design-Paper.pdf?la=en. Accessed 19 April 2020
28. The Bank of Canada:, [Online]. Available: (2018). https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Cross-Border-Interbank-Payments-and-Settlements.pdf. Accessed 1 May 2021
29. Monetary Authority of Singapore (MAS):, "MAS helps develop blockchain-based prototype for multi-currency payments," 2019 11 11. [Online]. Available: https://www.mas.gov.sg/news/media-releases/2019/mas-helps-develop-blockchain-based-prototype-for-multi-currency-payments. Accessed 19 April 2020
30. #STACS, D.L.T.: Integrations with payment systems," [Online]. Available: https://stacs.io/dlt-integrations-with-payment-systems/. Accessed 15 May 2020
31. "STELLA - a joint research project of the European Central Bank and the Bank of Japan,": [Online]. Available: (2017). https://www.boj.or.jp/en/announcements/release_2017/data/rel170906a1.pdf. Accessed 19 April 2020
32. STELLA - a joint research project of the European Central Bank and the Bank of Japan:, [Online]. Available: (2018). https://www.boj.or.jp/en/announcements/release_2018/data/rel180327a1.pdf. Accessed 19 April 2020
33. the European Central Bank (ECB) and the Bank of Japan (BOJ):, "Synchronised cross-border payments.," 4 6 2019. [Online]. Available: https://www.boj.or.jp/en/announcements/release_2019/data/rel190604a1.pdf. Accessed 19 April 2020
34. Project Stella, a joint research project of the European Central: Bank (ECB) and the Bank of Japan (BOJ), "Balancing confidentiality and auditability in a distributed ledger environment.," 12 2 2020. [Online]. Available: https://www.boj.or.jp/en/announcements/release_2020/data/rel200212a1.pdf. Accessed 19 April 2020

35. Consensys, “Project Khokha: : blockchain case study for central banking in South Africa,“ [Online]. Available: https://consensys.net/blockchain-use-cases/finance/project-khokha/. Accessed 19 April 2020
36. the Bank of Thailand (BOT):, “Inthanon phase I: an application of distributed ledger technology for a decentralised real time gross settlement system using wholesale central bank digital currency,“ 29 1 2019. [Online]. Available: https://www.bot.or.th/Thai/PaymentSystems/Documents/Inthanon_Phase1_Report.pdf. Accessed 15 May 2020
37. the Bank of Thailand (BOT):, “Inthanon Phase 2,“ 18 7 2019. [Online]. Available: https://www.bot.or.th/English/FinancialMarkets/ProjectInthanon/Documents/Inthanon_Phase2_Report.pdf. Accessed 15 May 2020
38. the Bank of Thailand and (BOT) the Hong Kong Monetary Authority (HKMA):, “The outcomes and findings of Project Inthanon-LionRock and the Next Steps,“ 22 1 2020. [Online]. Available: https://www.bot.or.th/English/AboutBOT/Activities/Pages/Inthanon_LionRock.aspx. Accessed 15 May 2020
39. the Bank of Thailand (BOT) and Hong Kong Monetary Authority (HKMA):, “Inthanon-LionRock: Leveraging Distributed Ledger Technology to Increase Efficiency in Cross-Border Payments,“ 22 1 2020. [Online]. Available: https://www.bot.or.th/English/FinancialMarkets/ProjectInthanon/Documents/Inthanon-LionRock.pdf. Accessed 15 May 2020
40. BIS, “Multiple: CBDC (mCBDC) Bridge,“ [Online]. Available: https://www.bis.org/about/bisih/topics/cbdc/mcbdc_bridge.htm. Accessed 20 May 2021
41. BIS, “Project Dunbar: ” 9 [Online]. Available: (2021). https://www.bis.org/about/bisih/topics/cbdc/wcbdc.htm. Accessed 9 2021
42. BIS Innovation hub:, “Project Dunbar International settlements using multi-CBDCs,“ March 2022. [Online]. Available: https://www.bis.org/publ/othp47.pdf. Accessed 31 March 2022
43. Michael, “China’s National Digital Currency DCEP:/CBDC Overview,“ 13 5 2020. [Online]. Available: https://boxmining.com/dcep/. Accessed 15 May 2020
44. Binance Research: (Jinze & Etienne), “First Look: China’s Central Bank Digital Currency,“ 28 7 2019. [Online]. Available: https://research.binance.com/analysis/china-cbdc. Accessed 15 May 2020
45. Working Group on E-CNY Research and Development of the People’s Bank of China, “Progress of Research & Development of E-CNY in China,“ 7 [Online]. Available: (2021). http://www.pbc.gov.cn/en/3688110/3688172/4157443/4293696/2021071614584691871.pdf. Accessed 15 September 2021
46. Central Bank of The Bahamas:, “Digital Bahamian Dollar,“ 2021. [Online]. Available: https://www.sanddollar.bs/. Accessed 20 May 2021
47. SVERIGES, R.I.K.S.B.A.N.K.: “The Riksbank’s e-krona pilot,“ 2 [Online]. Available: (2020). https://www.riksbank.se/globalassets/media/rapporter/e-krona/2019/the-riksbanks-e-krona-pilot.pdf. Accessed 15 May 2020
48. Ree, J.: “Five Observations on Nigeria’s Central Bank Digital Currency,“ 16 11 2021. [Online]. Available: https://www.imf.org/en/News/Articles/2021/11/15/na111621-five-observations-on-nigerias-central-bank-digital-currency. Accessed 1 February 2022
49. Crawley, J.: “Nigeria’s eNaira CBDC Goes Live,“ 25 10 2021. [Online]. Available: https://www.coindesk.com/policy/2021/10/25/nigerias-enaira-cbdc-goes-live/. Accessed 2 February 2022
50. statista: “Nigeria mobile internet user penetration 2026|Statista,“ 7 [Online]. Available: (2021). https://www.statista.com/statistics/972900/internet-user-reach-nigeria/. Accessed 31 March 2022
51. The World Bank:, “Personal remittances, received (current US$),“ 2020. [Online]. Available: https://data.worldbank.org/indicator/BX.TRF.PWKR.CD.DT?locations=NG. Accessed 31 March 2022
52. National Bank of Cambodia, "បាគង | “ Bakong—the next-generation mobile payments,“ [Online]. Available: https://bakong.nbc.org.kh/. Accessed 15 May 2020
53. Digital Dollar Foundation and Accenture:, [Online]. Available: (2020). https://static1.squarespace.com/static/5e16627eb901b656f2c174ca/t/5ecfc542da96fb2d2d5b5f15/1590674759958/Digital-Dollar-Project-Whitepaper_vF.pdf. Accessed 6 2020
54. Federal Reserve Bank of Boston and Massachusetts Institute of Technology Digital Currency Initiative:, “Project Hamilton Phase 1 Executive Summary,“ 3 2 2022. [Online]. Available: https://www.bostonfed.org/publications/one-time-pubs/project-hamilton-phase-1-executive-summary.aspx. Accessed 22 February 2022
55. The Federal Reserve Bank of Boston:, “The Federal Reserve Bank of Boston announces collaboration with MIT to research digital currency,“ 2020 8 13. [Online]. Available: https://www.bostonfed.org/news-and-events/press-releases/2020/the-federal-reserve-bank-of-boston-announces-collaboration-with-mit-to-research-digital-currency.aspx. Accessed 22 February 2022
56. Federal Reserve Bank of Boston and Massachusetts Institute of Technology Digital Currency Initiative:, “GitHub - mit-dci/opencbdc-tx: A transaction processor for a hypothetical, general-purpose, central bank digital currency,“ 2022. [Online]. Available: https://github.com/mit-dci/opencbdc-tx. Accessed 22 February 2022
57. Bank of Thailand, “Retail Central bank digital currency: : implications on monetary policy and financial stability in Thailand,“ 8 2021. [Online]. Available: https://www.bot.or.th/Thai/PressandSpeeches/Press/News2564/n6064t_annex.pdf. Accessed 22 February 2022
58. Bank of Thailand, “The way forward for retail central bank digital currency in: Thailand,“ 4 2021. [Online]. Available: https://www.bot.or.th/Thai/digitalcurrency/documents/bot_retailcbdcpaper.pdf. Accessed 22 February 2022
59. CCN.com, “Not a cryptocurrency: Ukraine completes national digital currency Ppilot,“ 26 2 2019. [Online]. Available: https://www.ccn.com/ukrainian-central-bank-completes-national-digital-currency/. Accessed 15 May 2020
60. COINTELEGRAPH, “Ukraine completes pilot scheme for E-Hryvnia national digital: currency,“ 25 2 2019. [Online]. Available: https://cointelegraph.com/news/ukraine-completes-pilot-scheme-for-e-hryvnia-national-digital-currency. Accessed 15 May 2020
61. South African Reserve Bank:, “Request for expression of interest from prospective solution providers in anticipation of a feasibility project for the issuance of electronic legal tender,“ 26 4 2019. [Online]. Available: https://www.resbank.co.za/AboutUs/Departments/FinancialServices/ProcNew/Pages/Publications.aspx?sarbweb=9f333ff2-bf64-4708-a361-076bd6802ff4&sarblist=fdf9-dae8-3990-44d4-b89a-c87649f22461&sarbitem=40. Accessed 15 May 2020
62. BANQUE DE FRANCE, “CENTRAL BANK DIGITAL CURRENCY EXPERIMENTS WITH THE BANQUE DE FRANCE: CALL FOR: APPLICATIONS,“ 30 3 2020. [Online]. Available: https://www.banque-france.fr/sites/default/files/media/2020/03/30/fact_sheet_-_central_bank_digital_currency_30_march_2020.pdf. Accessed 15 May 2020
63. Bank of Korea:, “Bank of Korea, Central Bank Digital Currency (CBDC) pilot test,“ 6 4 2020. [Online]. Available: http://www.bok.or.kr/portal/bbs/P0000559/view.do?nttId=10057475&menuNo=200690. Accessed 15 May 2020
64. Bank for International Settlements (BIS):, “Central bank group to assess potential cases for central bank digital currencies,“ 21 1

2020. [Online]. Available: https://www.bis.org/press/p200121.htm. Accessed 15 May 2020
65. Bank of England:, "Central bank digital currency: opportunities, challenges and design," 12 3 2020. [Online]. Available: https://www.bankofengland.co.uk/paper/2020/central-bank-digital-currency-opportunities-challenges-and-design-discussion-paper. Accessed 15 May 2020
66. BIS Committee on Payments and Market Infrastructures:, "Central bank digital currencies," 2018. [Online]. Available: https://www.bis.org/cpmi/publ/d174.pdf. Accessed 15 May 2020
67. Boehme, R.A.R.: "The technology of retail central bank digital currency," BIS Quarterly Review, 1 3 2020. [Online]. Available: https://www.bis.org/publ/qtrpdf/r_qt2003j.htm. Accessed 15 May 2020
68. ITU, "Focus Group on Digital Currency including Digital Fiat Currency:, " [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/dfc/Pages/default.aspx. Accessed 15 May 2020
69. News, I.T.U.: "ITU and Stanford University to launch new partnership supporting pilots of Digital Fiat Currency," 5 6 [Online]. Available: (2019). https://news.itu.int/itu-stanford-university-launch-new-partnership-supporting-pilots-digital-fiat-currency/. Accessed 15 May 2020
70. WORLD ECONOMIC FORUM (WEF):, "Central Bank Digital Currency Policy-Maker Toolkit," 1 2020. [Online]. Available: https://www.weforum.org/whitepapers/central-bank-digital-currency-policy-maker-toolkit. Accessed 15 May 2020
71. Association, D.: "Diem Association: Home Page". [Online]. Available: https://www.diem.com/en-us/. Accessed 1 December 2022
72. Scorer, S.: "Central Bank Digital Currency: DLT, or not DLT? That is the question," [Online]. Available: https://theotcspace.com/content/central-bank-digital-currency-dlt-or-not-dlt-question. Accessed 15 May 2020
73. eCurrency: "eCurrency - Central Bank issued Digital Currency (CBDC)," [Online]. Available: https://www.ecurrency.net/. Accessed 1 June 2020
74. Liskov, M.C.B.: "Practical Byzantine Fault Tolerance," in OSDI '99: Proceedings of the third symposium on Operating systems design and implementation, New Orleans Louisiana USA, (1999)
75. Wikipedia: "Zero-knowledge proof," [Online]. Available: https://en.wikipedia.org/wiki/Zero-knowledge_proof#cite_note-knowledgecomplexity-9. Accessed 1 June 2021
76. J. L. C. F. M. V. T. F. D. U. K. K. A. B. N. Narula, "A High performance payment processing system designed for central bank digital currencies," 2 2 2022. [Online]. Available: https://dci.mit.edu/s/HamiltonWhitepaper-2022-02-02-FINAL2.pdf. Accessed 22 February 2022
77. a., T.A., Griffoli, T.M.: "FinTech Notes: The Rise of Digital Money," 15 7 2019. [Online]. Available: https://www.imf.org/en/Publications/fintech-notes/Issues/2019/07/12/The-Rise-of-Digital-Money-47097. Accessed 15 May 2020
78. "GitHub: Five Bell Ledger," [Online]. Available: https://github.com/interledger-deprecated/five-bells-ledger. Accessed 15 May 2020
79. "fastecdsa: 2.1.2," [Online]. Available: https://pypi.org/project/fastecdsa/. Accessed 15 May 2020
80. a., D.S.L.S.: H. U. Jesús Fernández-Villaverde, "Central Bank Digital Currency: Central Banking for All?," 1 6 2020. [Online]. Available: https://www.philadelphiafed.org/-/media/research-and-data/publications/working-papers/2020/wp20-19.pdf?la=en. Accessed 7 June 2020
81. a., A.A., Itai Agur, G.D., "IMF working paper: : designing central bank digital currencies," International Monetary Fund (IMF), (2019)
82. Brunnermeier, M.K., Niepelt, D., "On the equivalence of private and public money," J. Monet. Econ. **106**, 27–41 (2019). [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0304393219301229. Accessed 10 December 2022
83. Riksbank, "Petition to the Swedish Riksdag:, The states role on the payment market," 2018/19. [Online]. Available: https://www.riksbank.se/globalassets/media/betalningar/framstallan-till-riksdagen/petition-to-the-swedish-riksdag-the-states-role-on-the-payment-market.pdf. Accessed 30 May 2020
84. TEMASEK and Monetary Authority of Singapore:, "Project ubin phase 5 enabling broad ecosystem opportunities," [Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Project-Ubin-Phase-5-Enabling-Broad-Ecosystem-Opportunities.pdf. Accessed 3 November 2021



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