FEDERAL RESERVE BANK of NEW YORK

Monetary Authority of Singapore

# Project Cedar Phase II x Ubin+

## Improving wholesale cross-border multi-currency payments and settlements

The content of this report should not be interpreted to reflect any policies or directives of the Federal Reserve Bank of New York, the Federal Reserve System, or the Monetary Authority of Singapore. Any views expressed in this report are those of the authors and do not necessarily reflect the views of the Federal Reserve Bank of New York, the Federal Reserve System, or the Monetary Authority of Singapore.

# Table of Contents

# Table of Contents

# 1. Executive Summary

**Project Cedar Phase II x Ubin+ (Cedar x Ubin+)** is a research project exploring potential improvements for multi-currency wholesale cross-border payments. The project examined whether wholesale central bank digital currencies (CBDC) developed using distributed ledger technology (DLT) could improve the efficiency and transparency of cross-border payments involving one or more vehicle currencies. This collaboration brings together Project Cedar of the Federal Reserve Bank of New York's New York Innovation Center (NYIC), and Ubin+ of the Monetary Authority of Singapore (MAS).

Today, a vehicle currency may be used as a third currency within a foreign exchange trade to facilitate indirect conversion between illiquid currency pairs, as opposed to a direct trade. As market participants see value in transacting using major currencies due to their wide acceptance and relative price stability, these currencies often enjoy higher market liquidity. Although solutions that drive efficiencies, such as low risk and speed, exist today, illiquid currency pairs continue to face limitations, such as high costs, slow settlement times, lack of access to market solutions, and limited transparency. As the prevalence of transacting in emerging market economy (EME) currencies has increased in recent years, understanding the potential solution space has become an area of focus for central banks globally.[1]

Given the range of research currently underway in central banks, it is plausible that a future state-financial system may involve countries designing and deploying new technologies in distinct ways. Accordingly, the Cedar x Ubin+ collaboration investigated potential solutions to bridge heterogeneous networks implemented under separate governance and operating models, while maintaining the independence of the respective central bank infrastructures. In addition to interoperability, the collaboration – which builds off the findings from

[1] See Bank for International Settlements, "Facilitating increased adoption of payment versus payment (PvP),"July 2022, at https://www.bis.org/cpmi/publ/d207.pdf.

the Cedar and Ubin+ project portfolios – aimed to explore current limitations in wholesale cross-border markets such as high costs, slow settlement times, and limited transparency. The project also identified several important opportunities for future research in this space, including privacy limitations and liquidity optimization.

Ultimately, the experiment conducted under the Cedar x Ubin+ collaboration validated the hypotheses related to interoperability, speed, and atomic settlement, targeting known problem areas within multi-currency wholesale cross-border payments today. Hashed timelock contracts, a form of smart contract, were used to successfully bridge ledgers with distinct underlying DLT systems and execute simulated cross-border, cross-currency payments. This demonstrated that interoperability could be established across ledgers with different technical designs.[2] Atomic settlement was achieved as the claiming of funds by each member of the payment chain was conditional upon the ability of all participants to claim their respective funds, significantly reducing the counterparty risk associated with a given transaction. Settlement was achieved in under thirty seconds for all test scenarios, including payment chains requiring several cross-ledger currency exchanges. This could reduce the need for manual correspondence across time zones that can drive delays in these complex, cross-border transactions.

This report aims to contribute to a broad and transparent dialogue related to innovation in the financial sector. This report is not intended to advance any specific policy outcome, nor to signal that the Federal Reserve or the MAS will make any imminent decisions about the appropriateness of issuing a CBDC, nor to indicate how one would necessarily be designed. While DLT was explored as a potential solution in Cedar x Ubin+, alternative technical designs may also provide viable solutions. No decisions as to optimal technical design have been made by the Federal Reserve System and the MAS. This report is separate from the Federal Reserve Board's and MAS's evaluation of the potential benefits, risks, and policy considerations of a U.S. and Singapore CBDC respectively.

[2] Although the Cedar x Ubin+ experiment considered the interlinking of DLT systems, the solution concept could be applied to non-DLT systems as well.

The NYIC is a part of the Federal Reserve Bank of New York. Established in partnership with the Bank of International Settlements Innovation Hub (BISIH), the NYIC generates insights into high-value central bank-related opportunities through technical research, experimentation, and prototyping, to drive advancements in central banking and enhance the functioning of the global financial system.

# 2. Overview

## Current State

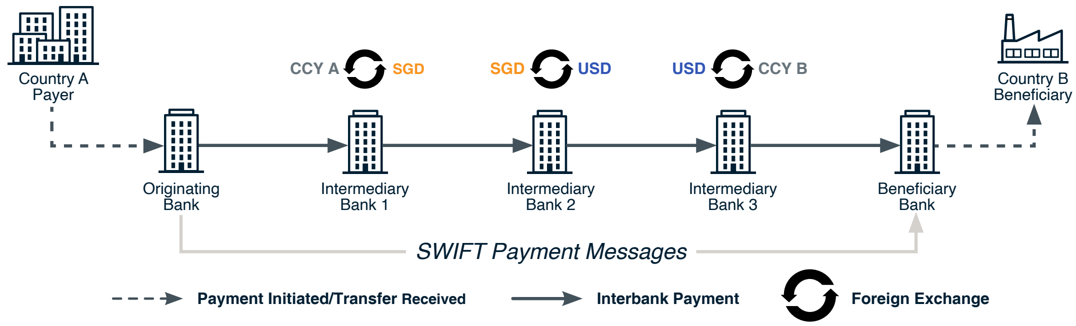
Cross-border payments involve the transfer of funds from an originator in one jurisdiction to a beneficiary in another jurisdiction.[3] These payments enable cross-border trade, commerce, and finance that support global value chains. Reliance on cross-border payments has increased amidst growing international trade and investment, as well as internationalization of production and value creation by multi-national firms.

Today, most cross-border payments flow through a network of correspondent banks and payment service providers that have access to domestic payment systems in the countries of both the originator and beneficiary. These payments are facilitated by instructions sent via SWIFT payment messages.[4] The figure below provides an overview of a typical cross-border payment chain.

[3] See, Bech, Morten, Umar Faruqui, and Takeshi Shirakami, "Payments Without Borders," BIS Quarterly Review, March 2020, at https://www.bis.org/publ/qtrpdf/r_qt2003h.pdf.

[4] SWIFT, the Society for Worldwide Interbank Financial Telecommunication, is the world's leading provider of secure financial messaging services supporting the execution of confirmations, clearing and settlement for international payments and foreign exchange. SWIFT is a trademark of S.W.I.F.T. SC. More information is available at https://www.swift.com.

**Figure 1.** Traditional Cross-Border Correspondent Payment Flow




## The Role of Foreign Exchange in Wholesale Cross-Border Payments

Many cross-border payments are also cross-currency payments. Cross-currency payments – which involve sending a payment in one currency and receiving of that payment in another currency – require a foreign exchange (FX) trade to convert the currencies and execute settlement processes in both the originating and beneficiary jurisdictions.[5] The over-the-counter (OTC) FX market facilitating these FX trades is the largest market in the global financial system with more than $7.5 trillion of daily turnover as of April 2022.[6] These FX transactions support activities such as hedging risk, payments for services outside domestic markets, and international trading and investment.[7] One or more intermediary banks in the payment chain will provide FX services to enable the delivery of a cross-currency payment in the intended currency.

[5] Settlement refers to the discharge of an obligation in accordance with the terms of the underlying contract. See Committee on Payments and Market Infrastructures, Glossary (bis.org).

[6] Bank for International Settlements, "OTC Foreign Exchange Turnover in April 2022," October 27, 2022, at https://www.bis.org/statistics/rpfx22_fx.pdf.

[7] GFMA Global FX Division, "First Steps Towards 24/7 FX Settlement Capabilities–Expanding Payment versus Payment (PvP) Opportunities," March 2020, at Expanding-pvp-opportunities-march-2020.pdf (gfma.org).

## Challenges in Cross-Border Payments

Cross-border payments face significantly greater challenges of cost, speed, access, and transparency than domestic payments.[8] These challenges vary by payment type and currency corridor. The figure below summarizes the challenges that exist in executing cross-border wholesale payments requiring FX conversion.

**Figure 2:** Key Challenges in Cross-Border Payments

| High Costs: | Low Speed: | Limited Access: | Low Transparency: |
|---|---|---|---|
| Holding liquidity buffers in multiple currencies can drive funding and opportunity costs.<br>When FX transactions are conducted to address funding needs, multiple intermediaries in the payment chain charge fees for payment processing, liquidity management, and settlement risk for each currency in the chain. | The time taken from initiation to reconciliation of a payment is lengthened by: 1) a lack of alignment in operating hours of key payment systems and correspondents across jurisdictions and time-zone differences, and 2) complex compliance processes due to differing regulatory requirements across jurisdictions, particularly in AML and sanctions screening. | Cross-border payments rely on systems developed for domestic or regional use and are not often interlinked with infrastructures of other countries.<br>Access to these infrastructures is limited and necessitates reliance on local agents in both originator and beneficiary jurisdictions. | The status of the payment from initiation to reconciliation is often not visible to the originator or the beneficiary.<br>The involvement of multiple intermediaries and networks in the end-to-end payment chain and systems that are not interlinked reduces the ability to determine the status of the payment prior to final settlement. |

These challenges in cross-border payments are partly driven by a few key frictions in existing processes for executing and settling wholesale FX transactions, described in the sections below.

[8] Financial Stability Board, "Enhancing Cross-Border Payments–Stage 1 Report to the G20," April 9, 2020 at https://www.fsb.org/wp-content/uploads/P090420-1.pdf.

## Risks in FX Settlement

Settlement of FX trades involves two parties exchanging full notional amounts in the underlying currencies on the value date. In the absence of an arrangement ensuring that final settlement of one currency is conditional upon final settlement of the second currency, one party to an FX trade faces the risk of paying the currency it sold without receiving the currency it bought. This FX settlement risk has a credit risk dimension (for example, the risk of losing the full principal value of a transaction), and a liquidity risk dimension (for example, the shortfall in the currency bought).

Settlement risk in FX is mitigated by payment-versus-payment mechanisms. Payment-versus-payment, or PvP, is a legal construct that ensures final settlement of a payment in one currency takes place only if final settlement of the payment in the other currency occurs. PvP mechanisms can take the form of settlement services, such as CLSSettlement, or links between the payment systems of two currencies.[9] However, these settlement services are not universally available, resulting in increased frictions for certain FX transactions, such as conversion between EME currencies.

Where these arrangements are not available, accessible, or practical, transactions settle in the bilateral market through correspondent banks. Participants may rely on controlled settlement, however, this only reduces counterparty exposure for one party. Participants may also attempt to manually synchronize transactions, which can be operationally intensive. Alternatively, banks may settle 'on-us', which internalizes settlement on the books of a single entity but does not necessarily ensure settlement of one payment leg is conditional on settlement of the other payment leg.[10]

---

[9] Currently, CLSSettlement provides PvP settlement for deliverable FX transactions in eighteen currencies (AUD, CAD, EUR, JPY, CHF, GBP, USD, DKK, NOK, SGD, SEK, HKD, HUF, KRW, NZD, ZAR, ILS, and MXN). CLS also operates the CLSNow service for same-day transactions (CAD, EUR, GBP, and USD). Other systems providing PvP settlement include the B3 Foreign Exchange Clearinghouse in Brazil (B3) settling BRL/USD, the Clearing Corporation of India Limited's Forex Settlement (CCIL) providing INR/USD settlement, and the CHATS system in Hong Kong (HKD, CNH, IDR, MYR, THB, EUR, USD). The PvP mechanisms in these arrangements either rely on central clearing with net settlement or simultaneous gross settlement.

[10] Basel Committee on Banking Supervision, "Supervisory Guidance for Managing Settlement Risk in Foreign Exchange Transactions," September 2000, at https://www.bis.org/publ/bcbs73.pdf.

Notwithstanding the benefits of PvP settlement, it is estimated that, as of April 2022, $2.2 trillion worth of FX turnover is not settled with PvP mechanisms on a daily basis.[11] There are two primary drivers of this occurrence:

- **Ineligibility:** Many EME currencies remain ineligible for existing PvP mechanisms despite growing market activity in these currencies. Some EME jurisdictions have not implemented the requisite legal basis for settlement finality, which is integral to achieving PvP. Settlement finality relies on laws that support the finality of discharge of a payment, transfer instruction, or other obligation between the financial market infrastructure and system participants, or between participants generally.[12]

- **Limited availability**: Existing payment and settlement system operating hours may not offer sufficient flexibility to meet the institutions' needs for time-sensitive transactions that otherwise miss system cutoffs or deadlines.[13]

The risks described above often materialize as increased costs for cross-border transactions, as pricing for cross-currency payments is driven in part by the cost of managing the associated settlement risk.

---

[11] See Glowka, Mark and Thomas Nilsson, "FX Settlement Risk: an Unsettled Issue," at, https://www.bis.org/publ/qtrpdf/r_qt2212i.pdf.

[12] See Bank for International Settlements, "Principles for Financial Market Infrastructures (PFMI)," at https://www.bis.org/cpmi/info_pfmi.htm.

[13] Committee on Payments and Market Infrastructures, "Facilitating Increased Adoption of Payment versus Payment (PvP)," Bank for International Settlements, July 2022, at https://www.bis.org/cpmi/publ/d207.pdf.

## Time Lags in Cross-Border Cross-Currency Payments

Settlement processes take longer for cross-border cross-currency transactions, as most FX spot trades settle on a T+2 basis (for example, two days after transaction date).[14] Prior to settlement, participants in the payment chain rely on correspondent banks to provide liquidity in the underlying currencies and manage time-based pre-settlement processes such as confirmations, intraday controls, and liquidity management. As part of the settlement process, banks conduct necessary regulatory checks (for example, Anti-Money Laundering (AML) and Know Your Client (KYC) processes).

Time zone differences and limited operating hours narrow the window of time for settlement and reconciliation across jurisdictions on the settlement date, potentially resulting in the delay of reconciliation until the next business day.[15] These factors contribute to the lack of available options to move funds on a PvP basis with sufficient flexibility to facilitate time-sensitive transactions, such as fund movements on the same day and or at a specific point within the day.

## Lack of Interlinking Arrangements in Existing Payment Systems

Execution of cross-border payments relies on domestic or regional infrastructures unique to a given jurisdiction, and access to these infrastructures is often limited to specific institutions. Such systems are typically designed for domestic use and oftentimes are not interlinked directly or indirectly to execute cross-border payments.

Multi-currency settlement systems provide centralized infrastructure to enable participants to settle FX transactions but, as mentioned above, these services do not extend to all currencies. This necessitates reliance on intermediary banks to access the domestic systems in both originator and beneficiary jurisdictions to complete settlement on a bilateral basis. Longer transaction chains can reduce

[14] The U.S. dollar-Canadian dollar currency pair is the most notable exception, which settles on a T+1 basis.

[15] GFMA Global FX Division, "First Steps Towards 24/7 FX Settlement Capabilities–Expanding Payment versus Payment (PvP) Opportunities," March 2020, at [Expanding-pvp-opportunities-march-2020.pdf](Expanding-pvp-opportunities-march-2020.pdf) (gfma.org)

transparency of a transaction's status, and increase both costs and counterparty risk. Overcoming differences in technologies across systems can be among one of the biggest challenges facing interlinking initiatives.

These challenges in executing and settling certain cross-border cross-currency payments could therefore be improved by solutions that:

1. Enable simultaneous settlement of FX transactions in currencies that are ineligible for existing PvP arrangements, particularly for FX transactions requiring time-sensitive execution.

2. Enable near real-time end-to-end settlement of cross-border cross-currency payments.

3. Achieve technical interoperability in payment infrastructures to enable the interlinking of systems across countries. This could shorten cross-border payment chains, decrease costs and enhance transparency.

The concept of interoperability can take on different meanings in different contexts. For the purposes of Cedar x Ubin+, interoperability is defined as technical, semantic, and business system compatibility that allows payment systems to be interlinked so that end users can seamlessly clear and settle payments with each other across systems without needing to be direct participants of multiple systems.[16]

[16] See Committee on Payments and Markets Infrastructures, "Report to the G20, Interlinking Payment Systems and the Role of Application Programming Interfaces: A Framework for Cross-Border Payments," July 2022, at https://www.bis.org/cpmi/publ/d205.pdf.

## Global Initiatives to Overcome Challenges in Cross-Border Payments

In support of the G20-led, multi-stakeholder effort to address challenges in cross-border payments, several public sector-led initiatives have been launched to bilaterally link real-time payment systems between countries to enable instantaneous transfer of funds between users. One such example is Project Nexus, the BISIH multilateral solution to link countries' real-time payment systems.[17]

Further, around 90 percent of the world's central banks are exploring how CBDC could increase the efficiency of settlement systems.[18] Cross-border payments are a key area of interest amongst industry participants and central banks looking into this topic. Examples of collaborative projects in this space include Project Dunbar, a project led by the BISIH to investigate shared platforms for international CBDC settlement, and France's and Luxembourg's provision of wholesale CBDC as a settlement asset in their Venus initiative.[19,20] Much of the research to date has focused on bilateral atomic settlement to achieve PvP or delivery-versus-payment (DvP). Atomic settlement, discussed in greater detail in the Solution Concept section below, is a technical construct ensuring that all counterparties in each transaction receive payment or, in the event of a failure,

---

[17] See Bank for International Settlements, "Project Nexus: Enabling Instant Cross-Border Payments", at https://www.bis.org/about/bisih/topics/fmis/nexus.htm.

[18] This figure is based on responses from 81 central banks (representing close to 94% of global economic output), to a survey conducted by the BIS in 2021. See Kosse, Anneke and Ilaria Mattei, "Gaining Momentum – Results of the 2021 BIS Survey on Central Bank Digital Currencies," Bank for International Settlements, May 2022, at https://www.bis.org/publ/bppdf/bispap125.pdf.

[19] See Bank for International Settlements, "Project Dunbar: International Settlements Using Multi-CBDCs," at https://www.bis.org/about/bisih/topics/cbdc/dunbar.htm.

[20] The Venus initiative consisted of a 100-million-euro digital native bond issuance by the European Investment Bank under Luxembourg law and settled using a tokenized representation of euro central bank money. The Banque de France and the Banque centrale du Luxembourg assisted in the Venus initiative by providing a safe settlement asset in the form of a tokenized representation of euro central bank money that can be described as an experimental CBDC.

no counterparty receives payment. Research into atomic settlement has focused on its ability to address the four key problems of high costs, low speed, limited access, and low transparency.

For example, Phase I of Project Cedar focused on enabling near real-time, atomic settlement in an FX spot transaction through settlement in wholesale CBDC based on DLT. The project successfully demonstrated settlement in under fifteen seconds on average across a simulated network of eight distinct currency ledgers.

Through the Ubin+ initiative, the MAS is exploring cross-border FX settlement with wholesale digital currencies in collaboration with international partners. A key area of the exploration covers different models of digital currency connectivity across borders.

Cedar x Ubin+ therefore builds on existing wholesale CBDC research by exploring a new possible solution: end-to-end atomic settlement for cross-border cross-currency payments that leverage one or more vehicle currencies.[21]

[21] Atomicity in this context means a transaction either entirely succeeds or completely fails. PvP ensures that the final transfer of a payment in one currency occurs if and only if the final transfer of a payment in another currency takes place. As mentioned above, PvP settlement is enabled by a clear legal basis regarding when settlement finality occurs to define when transactions are irrevocable. Legal considerations relating to PvP settlement were out of scope for this experiment.

# 3. Solution Concept

**Cedar x Ubin+** explores the technical feasibility of a hypothetical DLT-enabled wholesale CBDC prototype to address the challenges of speed, cost, transparency, and access in cross-border, cross-currency payments not eligible for PvP settlement mechanisms today. Cedar x Ubin+ hypothesizes that these benefits can be realized through addressing underlying frictions tied to FX settlement risk, time delays in conducting an end-to-end payment and the lack of interoperability in existing mechanisms.

## Opportunity Areas and Hypotheses

To design the Cedar x Ubin+ experiment, opportunity areas and corresponding hypotheses were established. The hypotheses center on the assumption that emerging technology, specifically, DLT, has the potential to solve for known problems in certain cross-border, cross-currency payments. Although alternative technologies may also provide such benefits, the Cedar x Ubin+ experiment focused on understanding the potential value of DLT within the identified problems.

**Opportunity 1:** Establish technical **interoperability** and multi-network **connectivity** across national payment systems and infrastructures.

**Hypothesis 1:** Wholesale CBDC systems developed using DLT can be technically interoperable with other payment systems across different jurisdictions. Although central banks may implement a range of technical solutions to support the exchange and settlement of their respective wholesale CBDCs, these single-currency ledgers can enable participants in one jurisdiction to transact with participants of another without the need for each participant to gain access to each ledger, or without participants relying on a central party to discharge obligations on a common multi-currency ledger.

**Opportunity 2:** Reduce FX **settlement risk** when using vehicle currencies across illiquid currency corridors.

**Hypothesis 2:** Vehicle currencies are used to facilitate cross-border payments across illiquid currency corridors. Wholesale CBDC systems developed using DLT can provide currency-agnostic models for atomic settlement of cross-currency payments and enable synchronous settlement across multiple transaction legs (for example, PvPvPvP). This potentially reduces the need to acquire less liquid currencies before the settlement window to mitigate the risk of non-delivery.

**Opportunity 3:** Reduce **delays** in clearing and settlement of cross-border, cross-currency payments.

**Hypothesis 3:** Wholesale CBDC systems, which may operate 24x7, can shorten the end-to-end processing time of cross-border, cross-currency payments initiated between participants in different jurisdictions by enabling atomic settlement of all underlying transactions across interoperable networks. Settlement does not have to be broken up into different stages across the operating hours of FX intermediaries in different time zones.

## Potential Solutions

Cedar x Ubin+ investigated two approaches for designing networks supporting multiple wholesale CBDCs. The concepts, benefits, and limitations of both approaches were considered:

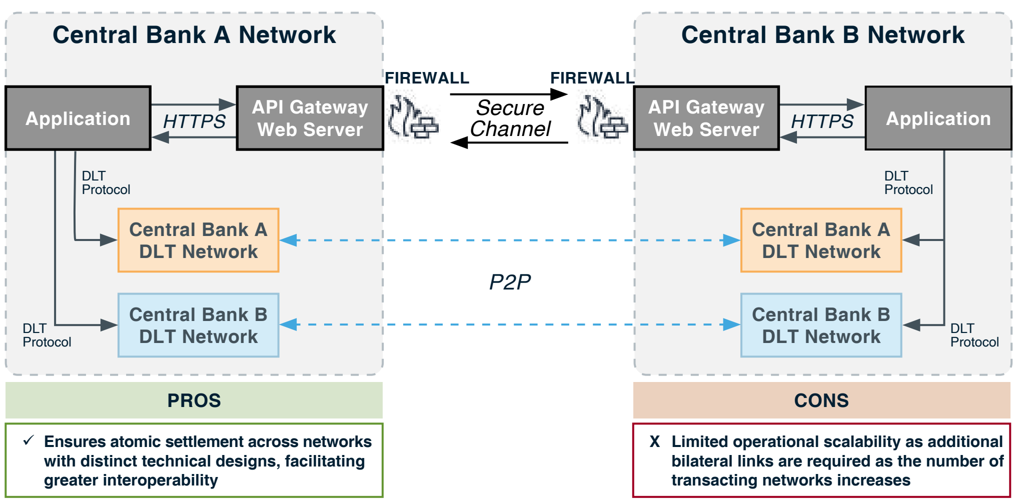
**Approach 1:** Interlinking distinct CBDC networks via bridges
**Approach 2:** A multi-CBDC common platform

**Approach 1: Interlinking Distinct CBDC Networks via Bridges**
Interlinking distinct CBDC networks typically relies on a shared technical interface or clearing mechanism. One such mechanism is a hashed timelock contract (HTLC). In this approach, the networks require compatible application programming interfaces (APIs) to provide input data and compute necessary components for transactions to be executed across networks via HTLCs. The

cryptographic primitives of HTLCs facilitate atomic settlement across networks without the need for all parties to be onboarded to a single network, allowing individual parties to operate the networks on which their digital assets are issued.

HTLCs are time-bound smart contracts that act as bridges between ledgers based on distinct technologies, allowing for atomic settlement of digital assets that are maintained on different ledgers and/or are operated by distinct parties. In the case of a CBDC network, when a payment leg is initiated, the initiating party's CBDC tokens (for example, CBDC A) are locked for a predetermined amount of time using a hashed secret generated by the counterparty. This allows for the initiation of the second payment leg on a separate network where the operator of that network similarly locks CBDC tokens (for example, CBDC B) on behalf of the counterparty. The second leg is linked to the first by the same hashed secret. The party who initiated the first leg can claim the CBDC tokens (for example, CBDC B) it is owed after the secret is revealed by the counterparty, which enables its counterparty to claim the CBDC tokens (for example, CBDC A) locked in the first leg.[22] This process is illustrated in the figure below.

**Figure 3.** HTLC Model[23]



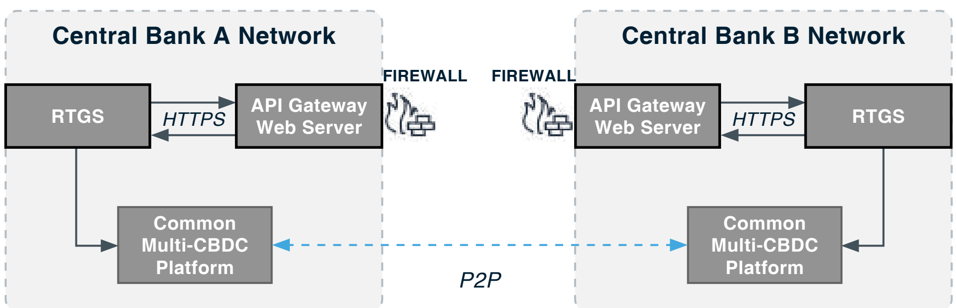

[22] Further details on the execution of cross-border cross-currency settlement via HTLCs is given in the description of the technical solution.

[23] References throughout this report to central bank digital currency ledgers or DLT systems operated by a central bank are included for the purpose of simulation and experimentation and do not imply any reference to production systems.

### Approach 2: A Multi-CBDC Common Platform

Networks with multiple CBDCs could be designed based on common infrastructure, whereby participants hold and settle CBDCs on a jointly operated platform. Common platforms enable central banks to exercise control over their respective currencies by limiting access of CBDC to participating commercial banks and institutions within the platform. For instance, a central bank could restrict the ability of commercial banks to acquire CBDC in the network based within its jurisdiction. Smart contracts on the common platform can enable atomic settlement by earmarking the first leg of the settlement, waiting for confirmation of the second leg being earmarked, and triggering an exchange once both legs are committed. However, assets in the common platform model would likely be required to meet a common set of technical and governance standards, which could limit the range of design options for central banks.

**Figure 4.** Common CBDC Platform Model




| PROS | CONS |
| --- | --- |
| ✓ Shared network facilitates settlement between CBDCs of distinct jurisdictions, while preserving the central bank's control of its internal ledger | X Establishing multi-party governance structure for a common network while maintaining independence is non-trivial<br>X Requires agreement and alignment to a common technical stack and standards |

Aside from faster settlement and removal of intermediaries, centralizing common processes (for example, screening processes by banks) on a common CBDC platform can provide efficiency gains from a time and cost perspective. The incorporation of smart contracts can also reduce costs from use of intermediaries. Another potential benefit of a common platform is to enable direct conversion between currencies in a way that does not require the security exposure of bridges. However, the common platform approach poses three challenges:

1. Market participants' access requirements for using CBDC in payments and settlement could differ by jurisdiction, making it difficult to synchronize the ruleset for a common platform.
2. Differing accounting requirements and payment regulations across jurisdictions may present similar challenges in developing a single, common rulebook.
3. A risk of dilution in the efficacy of governance by central banks could occur when CBDCs are used on a shared platform.

## Choice of Model

Central banks globally are exploring wholesale CBDC design and financial infrastructure enhancement through experimentation with a range of technology, design, and policy choices. This suggests that if there were a future wholesale CBDC landscape, the supporting infrastructures could be disparate, as central banks and authorities in different jurisdictions will adjust policy and design choices within their own systems to suit domestic priorities and context.

Consequently, interoperability between future financial infrastructure could require bridging between financial networks with different designs. This assumption drove the choice to explore Approach 1 in Cedar x Ubin+, the interlinking of distinct CBDC networks via HTLCs as a bridge, rather than an approach that would require most activities to occur on a singular international system.

Compared to the multi-CBDC common platform approach, the interlinking model enables each central bank to practice governance and control over its CBDC and ledger. This circumvents the challenges of ownership/operating rights, security concerns, and achieving policy consensus on a common multiple CBDC platform for central banks. The interlinking model provides a greater level of autonomy to central banks to make policy, governance, and technical decisions related to their respective wholesale CBDC.

To test the viability of this model, a use case was selected to reflect current, real-world challenges as well as challenges that may arise in a future CBDC landscape. The use case, described in greater detail in the section below, assumes that intermediary banks have access to more than one currency ledger to facilitate the cross-border payment by internalization of the FX.[24] This assumption mirrors the existing correspondent banking model by assuming a continued role of intermediary banks, and use of commonly traded currencies as vehicle currencies for illiquid currency corridors.

## Reference Use Case

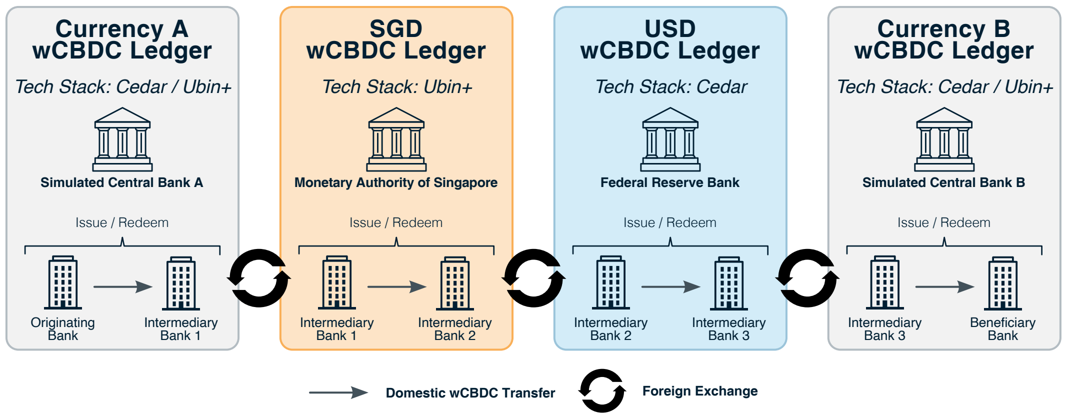
The Cedar x Ubin+ use case considers an end-to-end payment chain consisting only of settlement in central bank money in the form of wholesale CBDCs. This allowed for focus on enablement of PvP settlement through technical solutions, such as atomicity. The wholesale CBDC as simulated in Cedar x Ubin+ is assumed to maintain the characteristics of the digital balances of central bank reserves held by commercial banks today, in that the central bank liability is limited in access and used to facilitate large-value wholesale payment and settlement transactions. For this reason, the ultimate payment to the end beneficiary (for example, a large corporate client of a commercial bank in the beneficiary's jurisdiction) was not simulated, as this leg of the transaction would occur in commercial bank money.

In the Cedar x Ubin+ use case, commercial banks maintaining accounts with multiple central banks act as intermediaries to facilitate atomic settlement across an end-to-end payment chain for an illiquid currency corridor.

---

[24] Internalization refers to the process in which dealers attempt to match offsetting client flows on their own books rather than immediately hedging them in the inter-dealer market; see BIS Quarterly Review, December 2016.

**Figure 5.** Cedar x Ubin+ Reference Use Case




## Solution Assumptions

The following assumptions related to the simulated central bank ledgers were made for the purposes of the Cedar x Ubin+ experiment:

1. All currency ledgers operate on a 24x7 basis.
2. Each central bank owns and operates its own single currency ledger and manages access requirements for its own ledger.
3. Commercial banks act as intermediaries throughout the payment flow, leveraging the current correspondent banking model.
4. The wholesale CBDC is only intermediated by commercial banks that are licensed and approved by the central banks to hold and transfer the wholesale CBDC on a given ledger.

The experiment also makes the following assumptions about the use case:

5. Intermediary banks leverage USD and SGD as vehicle currencies to achieve better FX spreads in the transaction as it may be more cost-effective than direct conversion for some payment corridors.

6. The originator bank makes the initial payment in its local currency, and the beneficiary bank receives funds in its local currency. The originator bank does not have direct access to the beneficiary bank's currency (for example, an account with the central bank of the foreign currency, Currency B), and the beneficiary bank does not have direct access to the originator bank's currency (for example, an account with the central bank of the local currency, Currency A).[25]

7. The originator and beneficiary banks do not have a direct relationship with each other and rely on intermediary banks to support the payment.

8. The currencies within the transaction are traded OTC (for example, through a network of dealers quoting prices to their customers).

9. FX rates are internalized by each intermediary.

10. The experiment assumes all parties are executing transactions with known and predetermined counterparties and correspondents. The map of participants and transaction flow is established prior to payment initiation and execution, leveraging pre-existing correspondent relationships.

11. The experiment solely focuses on settlement processes in post-trade operations and excludes all other activities in the FX trade and post-trade lifecycle. Market making, price discovery, rate optimization and route discovery are excluded from the experiment. Processes tied to OFAC sanctions screening and BSA/AML/KYC requirements were also considered out of scope.

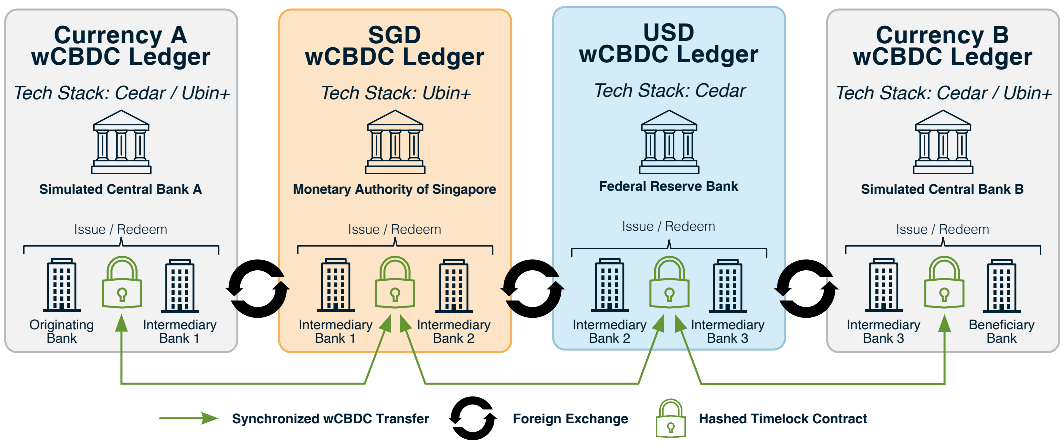
12. Legal considerations relating to PvP settlement, settlement finality, or cross-border cross-currency payments were out of scope.

[25] Assumptions 5-9 were made to reflect current FX market and cross-border payments dynamics in the experiment design.

## End-to-End Payment Process Flow

The end-to-end payment process for the reference use case is depicted at a high-level in the figure below. In this example, the payment traverses four distinct wholesale CBDC currency ledgers: Currency A ledger; SGD ledger; USD ledger; and Currency B ledger. Each intermediate transaction is a transfer from one party to another within a single wholesale CBDC ledger. These intermediate transactions are linked together using HTLCs to form the end-to-end payment. Accordingly, the total liabilities of the respective central bank balance sheets remain unchanged in this use case.

**Figure 6.** Cedar x Ubin+ Solution Concept, High Level




- **Currency A ledger:** The Originating Bank and Intermediary Bank 1 have access to the Currency A ledger. The Originating Bank initiates the outgoing payment in its local currency (Currency A) to Intermediary Bank 1.

- **SGD ledger:** Intermediary Banks 1 and 2 have access to the SGD ledger. Intermediary Bank 1 internalizes the FX conversion between Currency A and SGD, and transfers SGD to Intermediary Bank 2.

- **USD ledger:** Intermediary Banks 2 and 3 have access to the USD ledger. Intermediary Bank 2 internalizes the FX conversion between SGD and USD, and transfers USD to Intermediary Bank 3.

- **Currency B ledger:** Intermediary Bank 3 and the Beneficiary Bank have access to the Currency B ledger. Intermediary Bank 3 internalizes the FX conversion between USD and Currency B and transfers the foreign currency (Currency B) to the Beneficiary Bank, completing the cross-border cross-currency payment.

## Payments versus Transactions

Given that the Cedar x Ubin+ use case relies on linking several transactions to facilitate a payment, it is important to define those concepts when describing the experiment setup.

In the experiment, a payment refers to the entire end-to-end sequence of events.

Correspondingly, a transaction refers to a single leg within the longer end-to-end payment (for example, the transfer of funds from one participant to another).

For a payment to be considered complete, each intermediary leg of the transaction needs to be settled, including the final payment to the end-beneficiary.

## Technical Solution

The Cedar x Ubin+ prototype uses a form of smart contract, HTLCs, to execute the transaction as defined in the Reference Use Case section above.[26] This design enables settlement across multiple currency ledgers by breaking down the end-to-end payment flow into discrete but connected transactions. Within the Cedar x Ubin+ solution, the HTLCs comprise the following components:

- The **payment amount** and **currency**.
- A random and unique payment **hash h(S)** and **secret S** generated by the beneficiary bank; the payment hash is embedded into the HTLC, while the secret is kept by the end beneficiary bank.[27]

[26] HTLC is a protocol leveraged from the cryptocurrency domain; it is a protocol implemented in popular cryptocurrency networks such as the Lightning Network.

[27] The secret is a randomly generated series of characters used in HTLCs to verify that only the intended recipient of the funds is able to claim them. The secret is also sometimes referred to as the "preimage".

- A **timelock** that specifies the amount of time within which the payee of a given HTLC must claim the payment. After the timelock expires, the payer of the HTLC is allowed to reclaim the payment amount with its (that is, the payer's) signature.

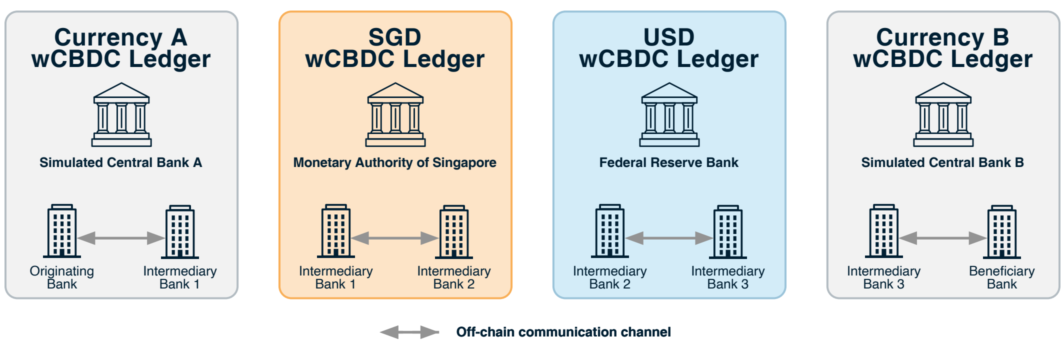
- A **claim key** belonging to the payee of a given HTLC (for example, the beneficiary bank's public key).

- A **reclaim key** belonging to the payer of a given HTLC, allowing the payer to reclaim the payment after the timelock expires (for example, the originator bank's public key).

- A **payment reference**, generated and sent by the initial HTLC creator to act as a reference to the discrete HTLCs.

The diagrams below depict the technical process that enables linked HTLCs across distinct wholesale CBDC ledgers to settle cross-border cross-currency payments.

**Figure 7.** Cedar x Ubin+ Technical Process - Step One



**1. Information is Exchanged Through an Off-Chain Messaging Channel:**

a. The Beneficiary Bank generates a random and unique secret, denoted as S, and hashes the secret, denoted as h(S). Execution of an atomic payment across multiple ledgers using HTLCs requires a common hashed secret.[28]

b. The Beneficiary Bank, as the recipient of Currency B, provides its direct counterparty (Intermediary Bank 3) with its claim key, the hashed secret h(S), and the desired timelock parameters.[29]

c. Intermediary Bank 3, as the payer of Currency B, will respond to the Beneficiary Bank by sending its reclaim key (for example, the reclaim key of Intermediary Bank 3). When the payer, Intermediary 3 in this case, shares its reclaim key with the beneficiary of the payment it is sending, the payer ensures that it will be able to reclaim its funds should the end-to-end payment fail.

d. Intermediary Bank 3 is also the recipient of a payment occurring on the USD Ledger, and will therefore provide its claim key, the hashed secret h(S), and desired timelock parameters to its direct counterparty, Intermediary Bank 2.

e. Intermediary Bank 2 will respond to Intermediary Bank 3 with its (Intermediary Bank 2's) reclaim key as the payer of USD.

f. These steps will repeat for Intermediary Banks 2 and 1, and the Originator Bank. Intermediary Bank 2 is the recipient of a payment on the SGD ledger and provides information to Intermediary Bank 1, which responds with its (Intermediary Bank 1's) reclaim key.

---

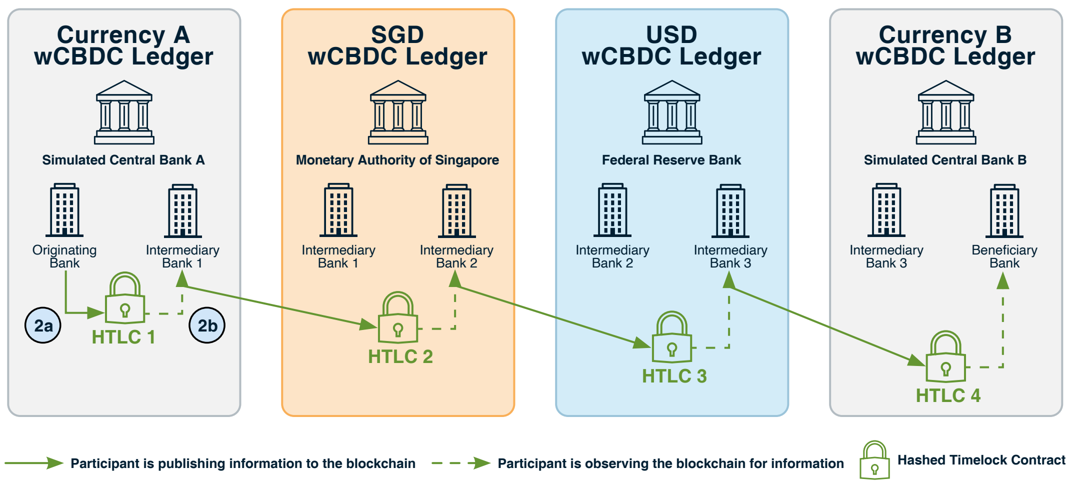
[28] Due to the importance and sensitivity of the information being exchanged, it is important for any production solution to establish a secure messaging channel.

[29] Typically in an HTLC, h(S) is shared directly from Beneficiary to Originator. In the Cedar x Ubin+ construct, h(S) is shared between neighboring parties to ensure they are able to observe the creation and execution of the HTLC on the relevant ledger.

g. Intermediary Bank 1 is the recipient of Currency A sent by the Originator Bank and therefore provides its (Intermediary Bank 1's) claim key, the hashed secret h(S), and desired timelock parameters, receiving the Originator Bank's reclaim key in return.

h. After the steps above have been completed, all parties have the payment hash, timelock parameters, claim key and reclaim key of the legs of the payment they are involved in.

**Figure 8.** Cedar x Ubin+ Technical Process - Step Two




## 2. HTLC Creation and Submission:

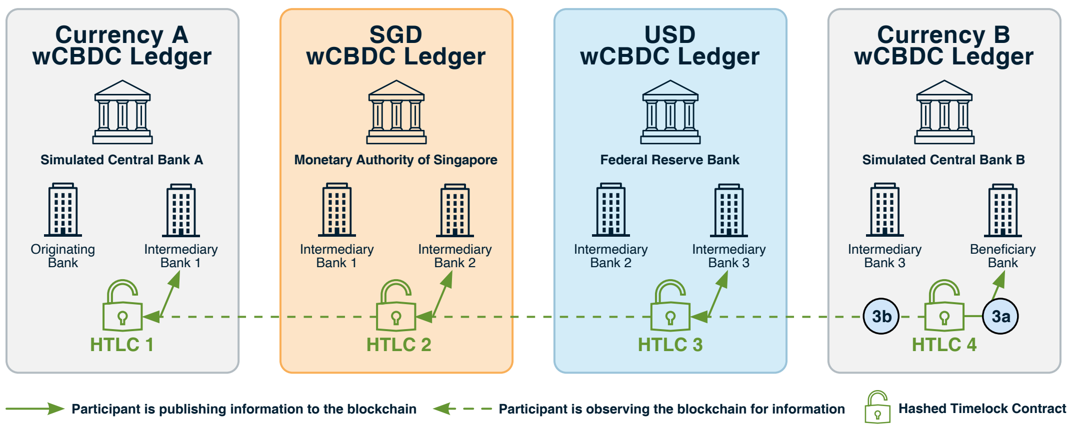
a. Participants that are payees of an inbound HTLC (for example, Intermediaries 1, 2, 3 and the Beneficiary Bank) will begin observing the currency ledger where they expect payment to identify when the inbound HTLC is published on the blockchain.[30]

[30] The term payee here signifies any party in the HTLC sequence receiving a payment, distinguished from the end beneficiary, who is the party receiving a one-way commercial payment in the end-to-end transaction.

b. Each payer in the transaction (for example, Intermediaries 1, 2, 3 and the Originating Bank) will create an outbound HTLC and submit it to the appropriate currency ledger. If the payer is also the payee of an earlier payment leg, the payer will wait to detect the inbound HTLC before submitting an outbound HTLC.[31,32]

c. Each ledger operator will validate the HTLC submission for its respective currency ledger and, if the HTLC is valid, they will include the HTLC into a block and publish the block to all nodes on the network.[33]

**Figure 9.** Cedar x Ubin+ Technical Process - Step Three




### 3. HTLC Claim Process

a. Once all HTLCs are successfully created on each currency ledger, the HTLC claim process begins. The Beneficiary Bank creates a transaction claiming the inbound HTLC; HTLC 4 in the diagram above. This HTLC claim transaction consists of the secret S and is signed by the Beneficiary Bank with its private key. The Beneficiary Bank submits this transaction to the currency ledger on which this inbound HTLC was published; the Currency B ledger in the diagram above.

[31] The term payer here signifies any party in the HTLC sequence making a payment, distinguished from the originator, who is the party making a one-way commercial payment in the end-to-end transaction.

[32] The creation and submission of outbound HTLCs to currency ledgers is sequenced from originator to beneficiary, following a typical cross-border cross-currency payment flow.

[33] The different roles of nodes within the network are discussed in greater detail in the Test Scenarios section of this report.

b. The Currency B ledger operator will validate the transaction ensuring that the hash of the provided secret in the claim matches the stored h(S) in the HTLC. Additionally, the operator will confirm that the signature is valid for the payee of the HTLC. If both validations are successful, the transaction is included in a block and published to all nodes on the network. The transaction will reveal S, which unlocked h(S), and this particular transaction leg is considered operationally settled.

c. Since the beneficiary bank of a payment creates the secret, and is initially the only party in the payment chain to know it, they claim the payment first and the subsequent claims of funds are executed by the parties in reverse order until Intermediary Bank 1 claims its payment.

d. Each payer of an HTLC will detect when their outbound HTLC is claimed. This subsequently allows the payer to extract S, which they can use to claim their respective inbound HTLC.[34] All payers will in turn extract S and claim their respective inbound HTLCs until all HTLCs used for this cross-border cross-currency payment are claimed. The payment is operationally settled once the final participant in the chain, Intermediary Bank 1 in the figure, claims its funds as evidenced by a corresponding update to the relevant currency ledger (for example, Currency A).

The Cedar x Ubin+ prototype requires participants entering a cross-border multi-wholesale CBDC payment to lock their funds within an HTLC for a designated amount of time, referred to as the timelock. For each HTLC used to facilitate an atomic payment, the time required to lock funds increases. Establishing these time increments provides a safeguard for exposure to principal loss. Determining the appropriate timelock is dependent on a number of factors, discussed in greater detail in the Design Learnings and Considerations section of this report.

---

[34] Unlike the HTLC creation process and typical sequential cross-border cross-currency payments, HTLCs are claimed from beneficiary to originator.

**Figure 10.** Incremented Timelocks

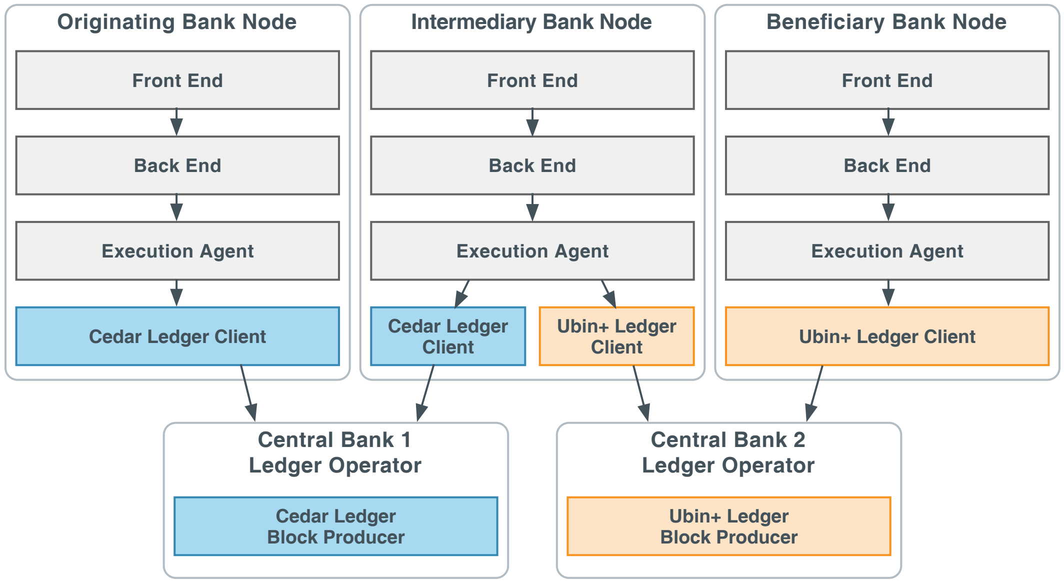

## Architecture Overview

A key assumption of Cedar x Ubin+ was that, should central banks develop their own wholesale CBDCs, they would make distinct choices in their design and implementation of CBDCs. Because of this, it was important that the solution test interoperability between ledgers with distinct designs. In the Cedar x Ubin+ experiment, the Cedar ledger, which uses an unspent transaction output data model and is written in Rust, executed transactions in coordination with the Ubin+ ledger. The Ubin+ ledger uses an account-based data model and is written in Java.

Although both the NYIC's Cedar ledger and MAS's Ubin+ ledger leverage DLT, the solution design does not necessitate all participants to implement a DLT-based ledger. The HTLC only requires each participant ingest and execute the cryptographic primitives that support the hashing and exposure of the shared secret. Experimentation with a non-DLT based ledger was not within the scope of Cedar x Ubin+ but may be an interesting topic for future research.

The figure below provides a high-level overview of the architecture linking these two currency ledgers between organizations, which underpins the Cedar x Ubin+ use case. Cedar x Ubin+ tested multiple scenarios, detailed in the Experiment Design section below, where ledgers were arranged in different topologies to simulate a variety of test cases.

**Figure 11.** Cedar x Ubin+ Architecture




The components of the architecture are as follows:

**Block producer:** For each ledger (for example, the simulated USD Cedar ledger or simulated SGD Ubin+ ledger), a block producer was deployed along with a node for each participant. Each party in the system has its own node, which is not used by any other party in the system.

**Front end user interface:** For each participant, an instance of the front-end is deployed serving a web-based user interface. This instance would theoretically serve as a user interface (UI) for the relevant party, allowing that party to manually create and authorize incoming payments.

**Back end infrastructure:** For each participant, an instance of the back end is deployed that handles messaging between participants, receives payments from the payment generator, serves data to the front end user interface, and performs any additional coordination with the execution agents. To execute the automated test scenarios, the back end automatically authorizes all payments as soon as they arrive.

**Execution agent:** An instance of the execution agent is deployed for each participant to facilitate the sending and receiving of transactions and transaction statuses to the underlying ledgers. The execution agent is responsible for translating the differences between the underlying ledger technology. There is one back end for each execution agent and each execution agent is connected to each of the unique ledgers for which a simulated participant maintains access. Agents can communicate with each other via a secure messaging channel.

**Payment generator:** A payment generator is deployed to receive information from the back ends relating to their ability to send and receive payments. Based on the available participants, the payment generator will construct routes that adhere to the parameters of the test scenario and generate payments to send to the involved participants in the system.

# 4. Experiment Design

To validate the solution concept, an experiment was designed to assess the success of the prototype against existing challenges of establishing interoperability, reducing settlement risk, and minimizing delays in the settlement process. To do this, success criteria and a set of test cases were developed to test hypotheses related to each of these goals.

## Success Criteria

Success criteria for the Cedar x Ubin+ experiment were developed to test the hypotheses described in the Opportunity Areas and Hypotheses section above. The criteria are as follows:

1. **Interoperability:** Establish interoperability between wholesale CBDC ledgers with distinct technical designs, as demonstrated by successful simulation of a payment traversing multiple, distinct wholesale CBDC ledgers from originator to beneficiary.

2. **Atomic settlement:** Settlement of each transaction within the end-to-end payment must be irreversible and linked to the irreversible settlement of all other transactions in the end-to-end payment.[35]

3. **Near real-time settlement:** Complete the end-to-end payment settlement across linked obligations in under thirty seconds on average.

### Primary Metrics

Two primary metrics were established to measure the prototype's performance against the success criteria. These metrics are described in the table below.

**Table 1:** Key Performance Metrics

| # | METRIC | DEFINITION |
|---|---|---|
| 1 | PAYMENTS PER SECOND | The number of end-to-end cross-border payments completed per second over the course of a given test run. Each payment may consist of several transactions depending on the test scenario. |
| 2 | PAYMENT LATENCY | The time in seconds between the payment authorization from the final participant and completion of payment settlement. |

Supplementary metrics were captured to provide additional insight into performance of the prototype. These metrics are outlined in the Appendix.

[35] See Principle 12 of the Principles for Financial Market Infrastructures, which states that "an exchange-of-value settlement system should eliminate principal risk by linking the final settlement of one obligation to the final settlement of the other through an appropriate DvP, DvD, or PvP settlement mechanism," such that final settlement of one obligation occurs if and only if the final settlement of the linked obligation occurs. Principle 12 also states that "DvP, DvD, and PvP do not require a simultaneous settlement of obligations. In some cases, settlement of one obligation could follow the settlement of the other." As noted earlier, legal considerations related to settlement finality were out-of-scope in this experiment.

## Test Scenarios

Test scenarios were developed to execute simulations on the prototype and measure performance. Each scenario is characterized by a set of parameters, which have been set to obtain specific insights about the prototype's performance. These parameters are described in the table below.

**Table 2:** Test Scenario Parameters

| # | PARAMETERS | DEFINITION |
|---|---|---|
| 1 | ACTIVE CURRENCY LEDGERS | The number of distinct currency ledgers on which transactions are initiated and executed in each scenario.<br>• The number of ledgers indicates the scale of a given test scenario. Theoretically, as the number of active ledgers increases, the number of payments settled per second across the system should increase as well.<br>• The number of ledgers does not indicate the length of the payment chain, as not all active ledgers need to be involved in each end-to-end payment in the scenario. |
| 2 | PARTICIPANTS | The number of transacting parties (for example, simulated commercial banks) present across all ledgers for a given scenario.<br>• A participant can transact on one or two of the active ledgers.<br>• Only participants active on two ledgers can play an intermediary role to route payments across ledgers.<br>• A participant may not necessarily be active in all transactions for a given test run. |
| 3 | CROSS-LEDGER EXCHANGE | The number of exchanges linking payments across two distinct ledgers (such as, currency conversion).<br>• For example, if the originator pays in Currency A and the intermediary converts Currency A to USD and then pays the beneficiary in Currency B, there are a total of two different currency conversion transactions (in other words, Currency A -> USD and USD -> Currency B). |
| 4 | LEDGER COMPOSITION | The division of the total active ledgers in a scenario based on their underlying ledger technologies (for example, Cedar and Ubin+) |

In order to test technical interoperability across networks, eight scenarios, described below, were designed to simulate cross-ledger spot currency exchanges across two distinct ledger technologies. These scenarios are differentiated by the number of active currency ledgers, intermediaries, and participants. The payment paths in the test scenarios assume both the originator and the beneficiary have access only to their respective domestic currency and require intermediaries on each ledger to facilitate the end-to-end payment and underlying FX transactions. The vehicle currencies in the scenario, either USD or SGD or both, are liquid currencies that serve as media of exchange to enable lower transaction costs than would otherwise be possible with a direct trade between the originator and beneficiary currencies. These were simulated in the test scenarios by ensuring all intermediary legs in the pre-determined payment paths included either or both the USD and SGD.

**Scenario Descriptions:**

**Scenario 1 - Bilateral Cross-Border Payment:** Scenario 1 covers a bilateral trade (one cross-ledger exchange) across two active ledgers (Cedar and Ubin+) and tests technical interoperability for the simplest and most common commercial use case, a spot trade between two currencies. There are no vehicle currencies in the scenario as one participant initiates a payment on the USD ledger (Cedar) and there is a linked obligation exchanged on the SGD ledger (Ubin+).

**Scenario 2 - Bilateral Cross-Border Payment with Expanded Network:** Scenario 2 simulates the same use case as Scenario 1 but expands the number of active ledgers in the simulation. This simulates a slightly larger financial ecosystem, where there are four distinct currency ledgers and eight participants across those ledgers. Similar to current cross-border payments, several banks have access to multiple currency ledgers and those banks are executing payments in parallel across the ledgers on which they maintain a relationship.

**Scenario 3 - Illiquid Currency Corridor:** Scenario 3 simulates a use case for an interbank payment where one vehicle currency (for example, USD or SGD) may be required in an illiquid currency corridor. For any given payment, two intermediaries facilitate two cross-ledger exchanges across three distinct ledgers.

**Scenario 4 - Interoperability Validation:** Scenario 4 simulates the use case depicted in Figure 5, in which a commercial payment from originator to beneficiary requires FX trades with two vehicle currencies (such as USD and SGD) to complete the payment. This scenario tests three cross-ledger exchanges of linked obligations across four active ledgers of differing technical design. Intermediaries 1, 2 and 3, as both receivers and senders in the underlying transactions, support the three cross-ledger exchanges as parties to the FX trades.

**Scenarios 5-8 - Increasing Network Scale:** Scenarios 5 through 8 all test the intermediated vehicle currency use case with an increasing number of active ledgers and participants to demonstrate scalability of the use case and test performance. Increasing the number of active ledgers does not add to the length of the payment chain or affect the role of the vehicle currency (or currencies) used to support each payment. Rather, increasing the number of active ledgers reflects an increased capacity to process transactions and facilitate end-to-end payments across the entire network. Scenario 8 is an exception, as it assumes three vehicle currencies to support one payment.[36]

[36] This scenario is unlikely to occur but is included to test performance.

**Table 3:** Primary Test Scenarios

| # | SCENARIO DESCRIPTION | ACTIVE LEDGERS | PARTICIPANTS | CROSS-LEDGER EXCHANGES |
|---|---|---|---|---|
| 1 | Bilateral FX spot trades with two active ledgers | 2 | 4 | 1 |
| 2 | Bilateral FX spot trades with four active ledgers | 4 | 8 | 1 |
| 3 | Intermediated FX payment with one vehicle currency and four active ledgers | 4 | 8 | 2 |
| 4 | Intermediated FX payment with two vehicle currencies and four active ledgers | 4 | 8 | 3 |
| 5 | Bilateral FX spot trades with eight active ledgers | 8 | 16 | 1 |
| 6 | Intermediated FX payment with one vehicle currency and eight active ledgers | 8 | 16 | 2 |
| 7 | Intermediated FX payment with two vehicle currencies and eight active ledgers | 8 | 16 | 3 |
| 8 | Intermediated FX payment with three vehicle currencies and eight active ledgers | 8 | 16 | 4 |

Three additional scenarios, scenarios 9A-9C, were designed to mirror scenarios in Project Cedar Phase I to provide comparability against a benchmark. Given the different nature of the use case in Project Cedar Phase I (FX spot trade, which involves an agent paying one currency and receiving another), the payments in scenarios 9A-9C were designed to be circular to provide this comparability. In these scenarios, the payment paths include a payment originator that makes a payment in one currency and ultimately receives a payment in another currency.

Scenarios 9A-9C are described in the table below.

**Table 4:** Project Cedar Benchmark Scenarios

| | # | ACTIVE LEDGERS | PARTICIPANTS | CROSS-LEDGER EXCHANGES |
|---|---|---|---|---|
| PHASE I CEDAR BENCHMARKS | 9A | 2 | 4 | 1 |
| | 9B | 4 | 8 | 1 |
| | 9C | 8 | 16 | 1 |

## Test Execution

To verify that the simulation would operate within a realistic computing environment, the Cedar x Ubin+ prototype was deployed in Amazon Web Services (AWS). This deployment strategy enabled fast and repeatable testing with reproducible results across multiple configurations.

For execution of the tests, the OpenCBDC Test Controller, which was used in Project Cedar Phase 1, was modified to support the components and architecture in Cedar x Ubin+.[37] The Test Controller enables large-scale benchmarking of complex multi-machine systems in realistic network environments.

[37] OpenCBDC Test Controller was developed to enable large-scale multi-machine benchmarks in a realistic network environment; see: https://github.com/mit-dci/opencbdc-tctl

For each test run, a simulated network is established according to the parameters of the test scenario and containing the components as illustrated in the Architecture Overview section above. Once each of the roles in the system is active, the system runs for ten minutes, the test is closed, and the results are captured.

# 5. Results

## Success Criteria Validation

The experiment ultimately met the three success criteria for Project Cedar x Ubin+ by validating each of the three corresponding hypotheses.

1. **Interoperability:** HTLCs successfully bridged two or more distinct ledgers with differing underlying DLT systems in this experiment. All test scenarios were successfully load tested for ten minutes across the Cedar and Ubin+ ledgers. An HTLC was successfully deployed across each transaction whenever a new payment was initiated by the payment generator.

2. **Atomic Settlement:** The tests demonstrated atomic settlement for the end-to-end payments across multiple transaction legs through HTLCs and DLT-based ledgers. Under Scenario 3, which depicts a typical FX trade with a vehicle currency (such as USD), all trades settled atomically for all transactions across ledgers of differing technology with an average of 6.48 payments per second and a peak of 47 payments per second. End-to-end payments were completed without the need for a central party to discharge obligations for the transacting parties and without the need for any participants to have access to all ledgers.

3. **Near Real-Time Settlement:** All primary scenarios satisfied the condition of average end-to-end payment latency of fewer than thirty seconds, successfully validating the third success criterion of near real-time settlement. In the most complex scenario, which employed three vehicle currencies, the Project Cedar x Ubin+ solution design achieved an average end-to-end payment latency of seventeen seconds.

Beyond the success criteria, the results indicate evidence of scalability. When keeping the length of the end-to-end payment chain constant (in other words, the number of cross-ledger exchanges), increasing the number of active ledgers in the system resulted in a proportional increase in payments per second. System payment performance increased by an additional 50 percent when introducing multiple route options for bridge currency ledgers. While scalability was not a focus of Cedar x Ubin+, these results could inform future research in this area.

Additionally, the system metrics (included in the appendix of this report) indicate that the prototype was able to execute the test scenarios effectively while operating below system performance limits. Like scalability, optimization of system performance was not a focus of Cedar x Ubin+ but may benefit from future research.

These results should be interpreted solely in the context of this particular experiment, which focused on implementations of DLT. This research does not reflect any decision to implement DLT, HTLCs, CBDCs, or any particular technology stack. Other solutions may be equally or more viable. Future research could investigate whether existing systems or frameworks could be adapted to solve for the cross-border payment issues contemplated in this report.

### Project Cedar Phase I and Phase II Comparison

System performance and enhancements between Phase I and Phase II of Project Cedar were assessed. Scenarios 9A, 9B, and 9C were designed to offer direct comparison by creating a circular payment path for multi-leg, cross-border, cross-currency swaps. While optimizing for speed or throughput was not a success criterion for Cedar x Ubin+, there was an interest in maintaining system performance which was commensurate with previous tests. This was ultimately validated by the test results. A few specific observations were made:

- Payment latency was largely consistent across the two phases, with two and four ledger scenarios settling slightly faster, and eight ledger scenarios settling slightly slower.
- Payments per second improved across all three scenarios, including a significantly higher peak throughput for the eight-ledger scenario, settling approximately twice as many payments per second.
- Evidence of scalability was similar across both phases, with the payments per second scaling proportionately to the number of active ledgers.

## Primary Results

Results were generated through execution of the test scenarios described above. Each of the results shown below is the averaged figure across three runs with these configurations. Each run simulated the test scenario for ten minutes.

**Table 5:** Primary Results

| SCENARIO | PAYMENT LATENCY (mean) (s) | PAYMENT LATENCY (peak) (s) | PAYMENTS PER SECOND (mean) | PAYMENTS PER SECOND (peak) |
|---|---|---|---|---|
| 1 | 9.00 | 21.44 | 7.77 | 81.00 |
| 2 | 8.98 | 25.59 | 13.31 | 59.00 |
| 3 | 11.72 | 26.90 | 6.48 | 47.00 |
| 4 | 14.61 | 23.99 | 5.48 | 48.00 |
| 5 | 10.22 | 35.73 | 22.90 | 94.00 |
| 6 | 14.53 | 44.37 | 10.33 | 75.00 |
| 7 | 16.32 | 38.30 | 7.27 | 41.00 |
| 8 | 16.93 | 27.50 | 5.17 | 25.00 |
| 9A | 7.54 | 12.93 | 15.76 | 114.00 |
| 9B | 7.63 | 12.72 | 33.26 | 121.00 |
| 9C | 10.31 | 25.12 | 52.67 | 183.00 |

# 6. Design Learnings and Considerations

The Cedar x Ubin+ solution employed DLTs and HTLCs to successfully deliver cross-border settlement. The following section highlights some of the benefits and drawbacks of the solution concept.

## Solution Benefits

1. **Enforcement of Atomic Settlement:** An HTLC protocol was used in the solution design for Cedar x Ubin+ to execute atomic settlement of transactions in this experiment. Atomicity was enforced by:

    - **Specifying Custody:** HTLCs leverage the blockchain's ability to support on-chain custody of funds by explicitly stating via public keys who can claim and reclaim payment; only the corresponding private keys can attempt to claim or reclaim payment.

    - **Conditions for Claiming or Reclaiming Funds:** For a beneficiary to claim payment, a unique secret must be revealed within the time window to unlock the corresponding hashed secret included in the HTLC. Otherwise, the sender can reclaim payment after the time window expires.

2. **Transparency:** Transparency is a key benefit that DLT may provide, as the immutable and visible nature of the data structure affords participants potentially richer, real-time, and more resilient data. However, transparency is also closely related to privacy, which could be considered a drawback of DLT systems. This is further discussed in the section below.

    Currently, access to different networks is provided by intermediaries who rely on confirmation of debits and credits and account statements to provide confirmation of settlement to their clients. In the Cedar x Ubin+ prototype, each participant hosts its own node and receives a copy of a currency ledger state. Participants do not need to rely on intermediaries to confirm whether a payment has been completed.[38] Participants can review their copy of the currency ledger to confirm whether a payment has processed or determine the amount of funds they hold.

While DLT allows for increased transparency compared to existing payment systems, the visibility of a given user is ultimately dependent on the access provisioned by the owner or operator of the network.

3. **Interoperability:** HTLCs were used in the solution concept because of their portability across distinct technical solutions. A core assumption of the Cedar x Ubin+ experiment was that the underlying technology systems for central banks' potential CBDC implementations would vary, given that central banks would likely make a range of design decisions to achieve their distinct operational, policy and technical goals. Atomic settlement of a cross-currency transaction would only be possible if these systems could interoperate despite those differences. HTLCs achieve interoperability between systems so long as the underlying system supports the cryptographic primitives coordinating the transfer of assets, such as wholesale CBDCs, within a specified time window and without the need for a central clearing authority. This may reduce barriers to access from a technical perspective by removing the need for a common ledger design or a shared platform.

## Solution Limitations

The Cedar x Ubin+ experiment focused on enabling interoperability across wholesale CBDC ledgers based on distinct DLT designs. Exploration of the solution concept exposed potential limitations that represent important considerations for central banks and other institutions weighing design alternatives.

[38] Within the current construct of payments, there are requirements, such as the Travel Rule, to provide certain messaging, information, and self-servicing capabilities. Such requirements were not contemplated as part of the Cedar x Ubin+ design.

1. **Absence of full visibility across the end-to-end payment:** Within the Cedar x Ubin+ design, transparency is addressed by significantly decreasing the time during which the originator or beneficiary of a payment does not have visibility into the status of the payment. This does not address the existing cross-border, cross-currency issue of end-to-end transaction visibility during the settlement of a payment. Although the current design allows for a scenario in which all participants in the chain have real-time visibility into the payment status, this comes at the cost of exposing data, such as information about non-neighboring parties in the payment chain. Advanced cryptographic techniques such as zero knowledge proofs (ZKPs) may support a solution in which the participants have real-time insight into the payment status without exposing sensitive information. ZKPs were not explored as part of Cedar x Ubin+ but may be an interesting topic in future research.

2. **Limitations to atomicity across the payment chain:** For a payment chain using HTLCs to link transactions, a situation can occur wherein some participants in the payment chain can claim the payment while others, due to possible technical or operational errors, are unable to do so within the allotted time. This creates scenarios where a participant may be exposed to settlement risk as they have made a payment but are unable to atomically receive the funds owed in return. The figure below depicts such a scenario.

**Figure 12.** Breakdown in Atomicity Across the End-to-End Payment


In this scenario, a technical or operational error occurring on the ledger of either Intermediary Bank 2 or Intermediary Bank 3 ledger prevents Intermediary Bank 3 from reclaiming the funds from the HTLC prior to expiration of the timelock. In such an instance, initiation of a new payment is required for Intermediary Bank 3 to reclaim its funds. While it is likely that, in an interlinking arrangement, policies and procedures would be in place so that Intermediary Bank 3 is made whole, this scenario highlights the limitations of the technical solution to enforce atomicity across the payment chain. Additionally, selection of an appropriate timelock could mitigate this issue such that payments could be claimed in the event of a technical or operational failure. Considerations for the timelock are discussed in greater detail below.

3. **Optimizing the timelock for liquidity management:** The duration set for the timelock in each HTLC determines how long the funds are locked to facilitate atomicity across the end-to-end payment. The timelock therefore has implications for liquidity management regardless of whether the transaction is successful, as participants are not able to access and redeploy locked funds until the timelocks expire. Determining the appropriate timelock should include considerations of the following factors to balance liquidity management goals with the allocation of sufficient time to facilitate the end-to-end payment:

    - **Processing time:** The time it takes to process a transaction on a given currency network.
    - **Internet latency:** The impact from executing transactions using the Internet; this influences the amount of time between submission of a transaction and when information is received from the currency network (in other words, via a verified block).
    - **Signing policies:** Differences across participant signing policies; such differences could increase the time required to claim a payment. The length of time required to sign a transaction can be influenced by several factors, such as the use of more complex key management solutions (KMS) like multi-signature, multi-party computation solutions.
    - **Internal service level agreements:** Any off-line services that participants must complete prior to claiming a payment.
    - **Other factors:** For example, expectations for restoring services should an outage occur.

# 7. Looking Ahead

In Cedar x Ubin+, the MAS and NYIC teams developed a solution that demonstrated the potential of using HTLCs to bridge distinct DLT systems and facilitate atomic, end-to-end cross-border cross-currency payments settlement. The project's three hypotheses related to establishing interoperability and multi-network connectivity, while significantly reducing FX settlement risk and the time required to clear and settle cross-border payments, were successfully validated.

While these initial results show potential, performance enhancements and optimization would be required to demonstrate the viability of this solution's architecture at a larger scale, including increased payments per second and the involvement of additional distinct currency ledgers.

Additionally, some of the topics that were out of scope for this project pose interesting considerations and possible areas for further study. These could include alternative models, such as integration with non-DLT ledgers, alternatives to HTLCs, such as point timelock contracts (PTLCs), and exploration of emerging privacy solutions, such as zero knowledge proofs.

Digital currencies may play an important role in a future-state financial system in which currencies are traded seamlessly and atomically. Future work exploring further capabilities of digital currencies could include incorporating smart contracts, optimizing price discovery, and investigating the feasibility of on-chain solutions for FX trading and settlement.

# 8. Appendix

## System Performance Metrics

**Table 6:** System Performance Metrics: 3-6

| # (NUMBERING CONTINUED FROM ABOVE) | METRIC | DEFINITION |
|---|---|---|
| 3 | CPU | The percentage of CPU time used by the system components at a given moment, reflected as a mean and peak.[39] |
| 4 | MEMORY | The memory used by the system components at a given moment, reflected as a mean and peak. |
| 5 | DISK READS | The amount of data read from disk by the system components at a given moment, reflected as a mean and peak. |
| 6 | DISK WRITES | The amount of data written to disk by the system components at a given moment, reflected as a mean and peak. |

## Virtual Machine Configuration

The virtual machines used to execute the test scenarios ran Ubuntu Server 20.04 LTS. The virtual machines were of type m5.large (2 vCPUs, 8GB RAM) with a 20GB Elastic Block Store (EBS) disk.

[39] This is measured in percentages of a single CPU. Since the Project Cedar x Ubin+ prototype runs the simulation on 2vCPU machines, this metric can reach up to 200%.

## System Metrics Test Results

**Table 7:** System Metrics Test Results – CPU and Memory

| SCENARIO | CPU (mean) | CPU (peak) | MEMORY (mean) (MB) | MEMORY (peak) (MB) |
|---|---|---|---|---|
| 1 | 9.46% | 86.84% | 494.85 | 1148.79 |
| 2 | 9.22% | 83.88% | 524.93 | 1204.85 |
| 3 | 8.31% | 81.97% | 512.80 | 1127.89 |
| 4 | 8.53% | 73.01% | 517.27 | 1226.49 |
| 5 | 9.06% | 87.03% | 593.96 | 1208.50 |
| 6 | 7.73% | 88.31% | 573.71 | 1127.13 |
| 7 | 7.61% | 77.62% | 578.47 | 1164.46 |
| 8 | 7.08% | 78.39% | 568.10 | 1209.27 |
| 9A | 11.61% | 75.24% | 352.69 | 698.09 |
| 9B | 12.79% | 75.34% | 380.04 | 730.00 |
| 9C | 13.10% | 82.46% | 389.92 | 980.10 |

**Table 8:** System Metrics Test Results – Disk Reads and Disk Writes

| SCENARIO | DISK READS (mean) (MB/s) | DISK READS (peak) (MB/s) | DISK WRITES (mean) | DISK WRITES (peak) |
|---|---|---|---|---|
| 1 | 0.10 | 21.07 | 0.30 | 31.02 |
| 2 | 0.10 | 21.57 | 0.34 | 32.40 |
| 3 | 0.10 | 24.56 | 0.30 | 37.44 |
| 4 | 0.10 | 24.60 | 0.30 | 31.85 |
| 5 | 0.10 | 21.14 | 0.34 | 34.85 |
| 6 | 0.09 | 21.14 | 0.28 | 33.20 |
| 7 | 0.10 | 24.33 | 0.27 | 42.69 |
| 8 | 0.09 | 22.22 | 0.26 | 39.64 |
| 9A | 0.12 | 20.97 | 1.09 | 47.37 |
| 9B | 0.11 | 25.11 | 1.19 | 39.32 |
| 9C | 0.11 | 21.14 | 1.10 | 44.56 |