BIS Innovation Hub

Project mBridge

Connecting economies through CBDC

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1. Executive summary

Project mBridge experiments with cross-border payments using a common platform based on distributed ledger technology (DLT) upon which multiple central banks can issue and exchange their respective central bank digital currencies (multi-CBDCs). The proposition of mBridge is that an efficient, low-cost and common multi-CBDC platform can provide a network of direct central bank and commercial participant connectivity, greatly increasing the potential for international trade flows and cross-border business at large. To test this proposition, a new native blockchain – the mBridge ledger – was custom-designed and developed by central banks for central banks, to serve as a specialised and flexible platform implementation for multi-currency cross-border payments. Particular attention was paid to modular functionality, scalability, and compliance with jurisdiction-specific policy and legal requirements, regulations and governance needs. The platform design ensures that mBridge adheres to the five overarching CBDC principles emphasised by the CPMI/BIS Innovation Hub/IMF/World Bank report to the G20[1]: *do no harm, enhancing efficiency, improving resilience, assuring coexistence and interoperability with non-CBDC systems* and *enhancing financial inclusion*.

Over the course of six weeks, the mBridge platform was put to the test through a pilot involving real-value transactions centred around the chosen use case of international trade. Significant groundwork was laid prior to the pilot, including extensive coordination within and among central banks and commercial banks, and tailored legal agreements and dress rehearsals, which ultimately led to its success. Between 15 August and 23 September 2022, 20 commercial banks from Hong Kong SAR, Mainland China, the UAE and Thailand conducted payment and foreign exchange (FX) payment versus payment (PvP) transactions on behalf of their corporate clients using the CBDCs issued on the mBridge platform by their respective central banks. The pilot advances multi-CBDC experimentation by settling real value directly on the platform and on behalf of corporate customers. Over US$12 million was issued on the platform, facilitating over 160 payment and FX PvP transactions totalling more than US$22 million in value.

The pilot's real-world setting also brought to light a range of policy, legal and regulatory considerations of a multi-CBDC, cross-border payments platform such as mBridge. Extending access to central bank money directly to foreign participants and conducting transactions on a shared ledger requires further exploration of policy, data privacy and governance considerations. A new, digital form of currency and a multi-CBDC platform also raise challenging legal questions that depend on each participating jurisdiction's standing rules and regulations and may require regulatory changes to achieve full legal certainty and clarity. While some of these considerations can be addressed by the platform's current design, others require further development and exploration.

[1] BIS et al (2022).

Equipped with the lessons from earlier phases of the project, the pilot and policy, legal and regulatory analysis, Project mBridge will continue the technology-build and testing. This includes improving on existing functionalities and adding new functionalities to the platform, as it continues to progress towards a minimum viable product (MVP) and, eventually, a production ready system.

2. Acronyms and abbreviations

AED	United Arab Emirates dirham
AML	anti-money laundering
API	application programming interface
BFT	Byzantine fault tolerance
BIS	Bank for International Settlements
BOT	Bank of Thailand
CBDC	central bank digital currency
CBUAE	Central Bank of the United Arab Emirates
CLS	continuous linked settlement
CNY	Chinese yuan
CPU	central processing unit
CTF	counter-terrorist financing
DLT	distributed ledger technology
EMDEs	emerging markets and developing economies
e-AED	United Arab Emirates dirham CBDC
e-CNY	Chinese yuan CBDC
e-HKD	Hong Kong dollar CBDC
e-THB	Thai baht CBDC
FX	foreign exchange
GDP	gross domestic product
HKC	Hong Kong Centre
HKD	Hong Kong dollar
HKMA	Hong Kong Monetary Authority
KYC	know your customer
mBL	mBridge ledger
MVP	minimum viable product
PBC	People's Bank of China
PBCDCI	Digital Currency Institute of the People's Bank of China
PoC	proof of concept
PvP	payment versus payment
RTGS	real-time gross settlement
SaaS	software as a service
THB	Thai baht
UAE	United Arab Emirates
UAT	user acceptance testing
UI	user interface

3. Introduction

The G20 has made enhancing cross-border payments a global priority and has identified CBDC as a potential way forward to improving such payments.[2,3] A "holy grail" solution for cross-border payments is one which allows such payments to be immediate, cheap, universally accessible and settled in a secure settlement medium.[4] For wholesale payments, central bank money is the preferred medium for financial market infrastructures.[5] A multi-CBDC platform upon which multiple central banks can issue and exchange their respective CBDCs is a particularly promising solution for achieving this vision, and mBridge is a wholesale multi-CBDC project that aims to advance towards this goal. It builds on previous work done in Inthanon-LionRock Phases 1 and 2 (Bank of Thailand and Hong Kong Monetary Authority (2020) and BIS Innovation Hub et al (2021a)). It also applies the lessons learnt from other cross-border CBDC projects such as Jasper-Ubin (Bank of Canada and Monetary Authority of Singapore (2019)), Stella (European Central Bank and Bank of Japan (2019)), Aber (Saudi Central Bank and Central Bank of the United Arab Emirates (2020)), Jura (BISIH et al (2021b)) and Dunbar (BISIH et al (2022)).

Project mBridge tests the hypothesis that an efficient, low-cost, real-time and scalable cross-border multi-CBDC arrangement can provide a network of direct central bank and commercial participant connectivity and greatly increase the potential for international trade flows and cross-border business at large. More specifically, it seeks to build an MVP, and move towards a production setting that:

i. Improves solutions for the key pain points of international payments.

ii. Advances cross-border settlement in central bank money.

iii. Supports the use of local currencies in global transactions.

iv. Creates opportunity for new and innovative payment products and services.

All the while safeguarding currency sovereignty and monetary and financial stability by appropriately integrating policy, regulatory and legal compliance, and privacy considerations.

To achieve this, mBridge adopts a single-platform, direct-access CBDC model – a common technical infrastructure hosting multiple CBDCs, on which local

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2 Cross-border payments refer to payments that take place between a payer and a payee who are residents of different jurisdictions and may be made in the currency of the payer's jurisdiction or in another currency. They form a subset of international payments, which also include offshore payments and domestic payments made in foreign currency. See BISIH (2022).

3 In October 2020, the G20 endorsed a roadmap to enhance cross-border payments, comprising of the necessary elements of a globally coordinated response in the form of a set of 19 building blocks (BBs). BB 19, in particular, is tasked with factoring an international dimension into CBDC design to explore how CBDCs could potentially enhance cross-border payments. See FSB (2020) and BIS et al (2022).

4 See Bindseil and Pantelopoulos (2022) and BIS (2021).

5 See CPMI-IOSCO (2012).

and foreign financial institutions can directly hold and transact in CBDCs issued by central banks, irrespective of jurisdiction. The platform's design adheres to five important overarching criteria for assessing cross-border CBDC arrangements based on CBDC principles developed in BIS et al (2020) and G7 (2021) – namely, *do no harm, enhancing efficiency, increasing resilience, assuring coexistence and interoperability with non-CBDC systems and enhancing financial inclusion*.[6] mBridge uses custom-built DLT to support real-time, peer-to-peer, cross-border payment and foreign exchange (FX) transactions through a payment versus payment (PvP) arrangement[7] using CBDCs. Thereby, it offers potential improvements in terms of speed, transparency, efficiency, resilience, access, costs and settlement-risk reduction compared with the existing correspondent banking model. Given its common platform, mBridge also achieves, by design, interoperability between domestic traditional clearing systems as participants from multiple jurisdictions can directly reach each other on a single, integrated technical platform.[8] Access to CBDC and modules for connecting to existing payment systems can also foster greater financial inclusion for jurisdictions that are experiencing a decrease in active correspondent banking links or decreased transaction flows.[9]

mBridge is a joint project between the BIS Innovation Hub Hong Kong Centre (HKC), and four participating central banks in Asia and the Middle East – the Hong Kong Monetary Authority (HKMA), the Bank of Thailand (BOT), the Central Bank of the United Arab Emirates (CBUAE) and the Digital Currency Institute of the People's Bank of China (PBCDCI). These five entities make up the Steering Committee for Project mBridge, which is chaired by the BIS Innovation Hub HKC and supported by four subcommittees – Technology, Legal, Policy and Business – chaired by the PBCDCI, HKMA, BOT and CBUAE, respectively. Steering Committee members have decision-making and voting rights on the project and jointly lead the platform design and development.

Individual experimentation with CBDCs by the HKMA, BOT, CBUAE and PBCDCI date back several years. mBridge, in particular, is the third phase of a cross-border multi-CBDC project that began in 2019 (Graph 1). The first phase, Inthanon-LionRock Phase 1, was launched in 2019 when the HKMA and BOT joined their CBDC efforts together to produce a proof of concept (PoC) single-corridor network built on Corda, designed to allow Hong Kong SAR and Thailand commercial banks to conduct fund transfers and FX transactions on a peer-to-peer basis in Hong Kong dollar (HKD) and Thai baht (THB) wholesale CBDCs. This was followed by Inthanon-LionRock Phase 2 in 2020–21, during which a prototype built on Hyperledger Besu was developed and a third hypothetical jurisdiction was added.

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[6] As a single-system, direct-access CBDC model with a flexible modular framework to accommodate jurisdiction-specific policy, legal and regulatory considerations, mBridge offers potential benefits in respect of all five criteria compared with other CBDC frameworks. See BIS et al (2022) for a detailed discussion of the five overarching CBDC criteria and different access and interoperability options of CBDC systems to facilitate cross-border payments.

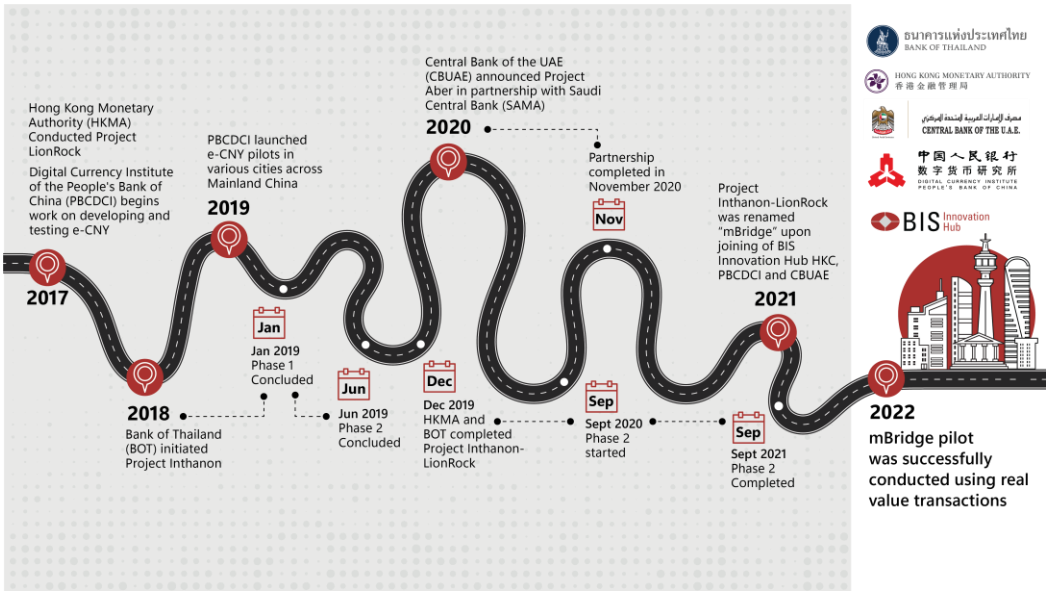
[7] PvP is a settlement mechanism that ensures that the final transfer of a payment in one currency occurs if and only if the final transfer of a payment in another currency or currencies takes place. See Committee on Payments and Infrastructure, *Glossary*, October 2016, https://www.bis.org/cpmi/publ/d00b.htm.

[8] See Boar et al (2021).

[9] See Rice et al (2020).

These early phases demonstrated the potential of a substantial improvement in cross-border transfer speed and cost compared with the correspondent banking model.[10,11]

mBridge journey Graph 1



When the BIS Innovation Hub HKC, the PBCDCI and the CBUAE joined in 2021, the project entered Phase 3 and was renamed "mBridge". Although earlier phases of mBridge showed the potential of using CBDCs built on DLT for delivering 24/7, real-time, cost-effective and secure cross-border payments and settlements, moving out of a simulated environment to a more real-world setting was needed for a multi-CBDC platform to become an MVP. As a result, a new, fit-for-purpose private permissioned blockchain was developed – the mBridge ledger – built by central banks, for central banks.[12] Special attention was paid to modular functionality, scalability and compliance with jurisdiction-specific policy and legal requirements, regulations and governance needs.

To maximise the value to the central banking community and project transparency, other central banks were invited to join the project as observers. To date, Project mBridge has welcomed observing members from around the world including Bangko Sentral ng Pilipinas, Bank Indonesia, Bank Negara Malaysia, Bank of Israel, Bank of Korea, Sveriges Riksbank, and staff of the Eurosystem Centre of the

10 There are various stages of a project starting from ideation to when it is brought to production comprising of PoC, prototype, pilot and MVP; the boundaries between each phase are often fluid and subjective with subtle differences. For more details, see Giblin et al (2021) and the appendix on project stages.

11 See Bank of Thailand and Hong Kong Monetary Authority (2020) and BIS Innovation Hub et al (2021a) for the detailed central bank journeys and project overview of Phases 1 and 2.

12 This distinguishes mBridge from other multi-CBDC projects, in which the underlying technology was built by non-central bank entities.

BIS Innovation Hub and of the New York Innovation Centre at the Federal Reserve Bank of New York.

4. Cross-border payments

4.1 The state of cross-border payments

Recent decades have witnessed rapid growth in global economic integration. At the same time, the system of cross-border financial flows underpinning this integration has not kept pace.[13] Cross-border payments are typically made through a global network of correspondent banks involving multiple intermediaries that are fragmented across different time zones and operating hours. In addition, the current corresponding banking network has yet to cover some less developed markets. While correspondent banks play a critical role in cross-border payments, due to duplicated processes and steps in the correspondent banking chain, cross-border payments exhibit high costs, low speed, operational complexities, limited access and low transparency. These inefficiencies also introduce settlement risk into the system, to the detriment of both financial intermediaries and end users.

Moreover, the bulk of settlement in correspondent banking occurs in commercial bank credit, representing a liability of the commercial bank. As such, it carries the associated credit and liquidity risks where settlement funds may not be available in the event of illiquidity or insolvency. Although the foregoing risk rarely materialises, it becomes significant when aggregated over large values and long settlement periods. Settlement in central bank money, the safest settlement asset, eliminates this risk; however, it is typically restricted to interbank domestic payments on access-controlled central bank real-time gross settlement (RTGS) systems.[14] One exception is Continuous Linked Settlement (CLS), a specialist institution that settles FX transactions on a PvP basis and maintains an account at each of the central banks whose currencies it settles; however, to date only a limited number of currencies are supported.[15] The costs associated with the correspondent banking model are substantial – private sector estimates suggest that, in 2020, for nearly $23.5 trillion in cross-border transactions flows, transaction charges amounted to around 0.5%, or approximately $120 billion (excluding FX costs),[16] roughly equivalent to the nominal GDP of Morocco. Furthermore, adverse secondary effects not captured in this figure, such as settlement delays and risks, likely amount to far greater costs.

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13 Innovation in the payments space has been concentrated mostly in the domestic arena, with cross-border payments often left on the sidelines. While incumbent payment providers and private sector players have pursued various initiatives to alleviate longstanding challenges in international payments (SWIFT global payments innovation, Visa business to business connect and continuous linked settlement system are some examples), they are limited in scope and high operational costs persist.

14 See Casu and Wandhofer (2017), Board of Governors of the Federal Reserve System (2022) and Bech et al (2020).

15 See CPMI (2012) and Bank of International Settlements, *BIS Quarterly Review*, December 2019.

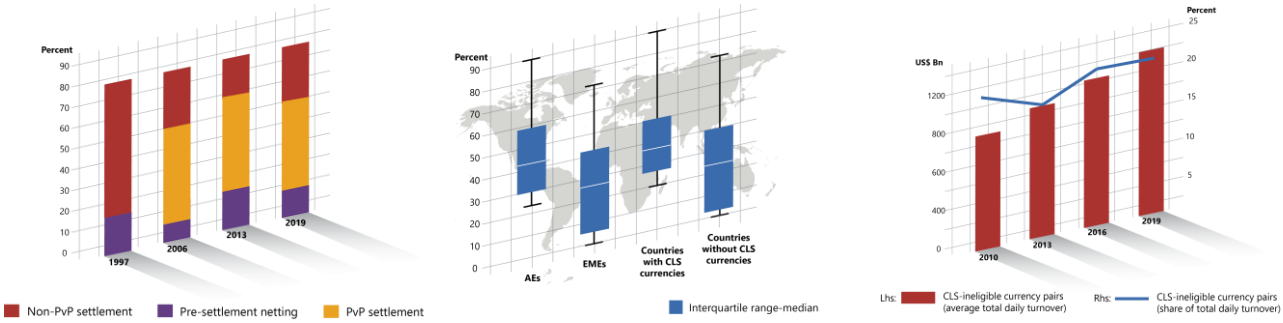
16 See Oliver Wyman and JP Morgan (2021).

This traditional model of cross-border payments presents even more challenges for emerging market and developing economies (EMDEs). Banks started paring back their correspondent networks and services after the Great Financial Crisis, with smaller economies likely experiencing a greater decline, leaving many without sufficient or affordable access to the global financial system.[17] Furthermore, cross-border transactions are often settled in a handful of dominant currencies and FX trading involving non-dominant currency pairs remains limited.[18] This exposes EMDEs to spillover effects from the monetary policies of jurisdictions from which the foreign currency originates, as well as associated financial stability risks, such as credit cycles. The limited international role of many local EMDE currencies also raises the issue of access to liquidity for these economies in times of global financial turbulence.[19]

FX settlement risk has also risen in recent years on the back of a declining share of global settlements using PvP mechanisms, owing in part to the fact that existing arrangements such as CLS do not support many EMDE currencies in which trading volumes have increased substantially (Graph 2).[20] By providing a shared platform on which participants can conduct peer-to-peer payments directly in the safety of the CBDCs of multiple jurisdictions, mBridge has the potential to alleviate many of the aforementioned challenges in international payments, extend PvP protection to currencies beyond those covered by existing systems and support the use of local currencies in cross-border settlement.

FX settlement risk: increasing and global — Graph 2

FX settlement methods[1] | Proportion of settlements with PvP protection[2] | CLS-ineligible currency pairs



[1] "PvP settlement" includes CLS and settlement through systems such as Hong Kong's CHATS. [2] The median value is represented by a horizontal line, with 50% of the values falling in the range shown in the box. The highest and lowest values are represented by the upper and lower end points of the vertical lines.

Source: Bech and Holden (2019).

[17] See Rice et al (2020).

[18] See Bank for International Settlements, https://www.bis.org/statistics/rpfx19_fx.pdf.

[19] See Asian Development Bank (2021).

[20] See Bech and Holden (2019) and CPMI (2022).

4.2 International trade as mBridge's first business use case

Prior to the pilot, the project team engaged extensively with the private sector to identify business use cases for the platform. Private sector participants comprising financial institutions, banking associations and exchanges from all four participating jurisdictions identified 15 potential cross-border use cases in which mBridge could provide significant value. These included diverse areas of opportunity such as international trade settlement, remittances, tokenised bond issuance, e-commerce and more.[21] International trade settlement was chosen as the first business use case to be piloted on mBridge given the sheer size of trade value in the four participating jurisdictions and the importance of trade to the region (Box A).[22] By supporting the development of local FX markets, extending the safety of central bank money to international settlements and alleviating many of the aforementioned pain points of cross-border payments, mBridge has the potential to facilitate trade in the region and, in turn, support trade-driven economic growth.

21 See BISIH et al (2021c).

22 While this phase of the project seeks to concretely demonstrate international trade settlement, mBridge holds the promise of an array of additional functionalities to be explored in future phases.

Box A

Regional trade

Intragroup trade between Mainland China, Hong Kong SAR, Thailand and the UAE amounted to US$563.6 billion in 2021, with important trading relationships between each of the four jurisdictions (Graph 3). Trade also plays a crucial role in each jurisdiction; for example, merchandise exports represented 18%, 46%, 93% and 159% of GDP in 2020 for Mainland China, Thailand, the UAE and Hong Kong SAR, respectively, according to World Bank data.[23] Including top players in global supply chains and commodity markets, these four jurisdictions are also important trading partners to the rest of the world. Together, they accounted for around US$8.7 trillion of merchandise trade in 2021, representing 19% of all such trade worldwide, according to World Bank data. As such, mBridge has the potential to support significant global trade flows as more jurisdictions join the platform.

Trade in the region continues to be settled predominantly in foreign currencies, despite the deepening intra-regional economic ties and supply chain integration over recent decades. Local currencies play limited roles in international trade, owing in part to the relatively high transaction costs associated with most Asian currencies compared with those of major currencies.[24] This dependence on foreign currencies for cross-border payments could inadvertently impact monetary sovereignty through monetary policy spillovers from the currency-originating jurisdiction, and adds more intermediaries and steps to the overall process. For example, a payment between a Thai corporate (the payer) importing goods from a Mainland Chinese corporate (the payee) using a foreign currency as the invoicing currency would involve the Thai payer's local bank, the Mainland Chinese payee's local bank, and the payer and payee's correspondent banks (Graph 4). Additional complexities are involved if the Thai and Mainland Chinese corporates' banks are small, local banks with no direct correspondent network, in which case even more intermediaries and steps are required.[25] With multiple banks along the payment chain, transaction fees can be charged and know your customer (KYC)/anti-money laundering (AML)/counter-terrorist financing (CTF) checks can be undertaken at each bank, and numerous break points can arise.[26]

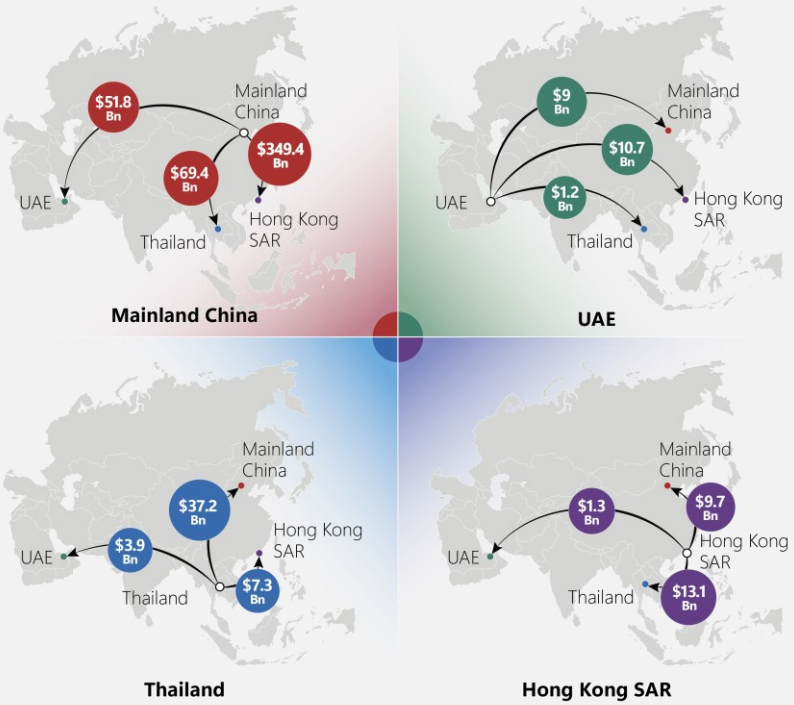
[23] See World Bank Open Data, https://data.worldbank.org/.

[24] See Shimizu (2019).

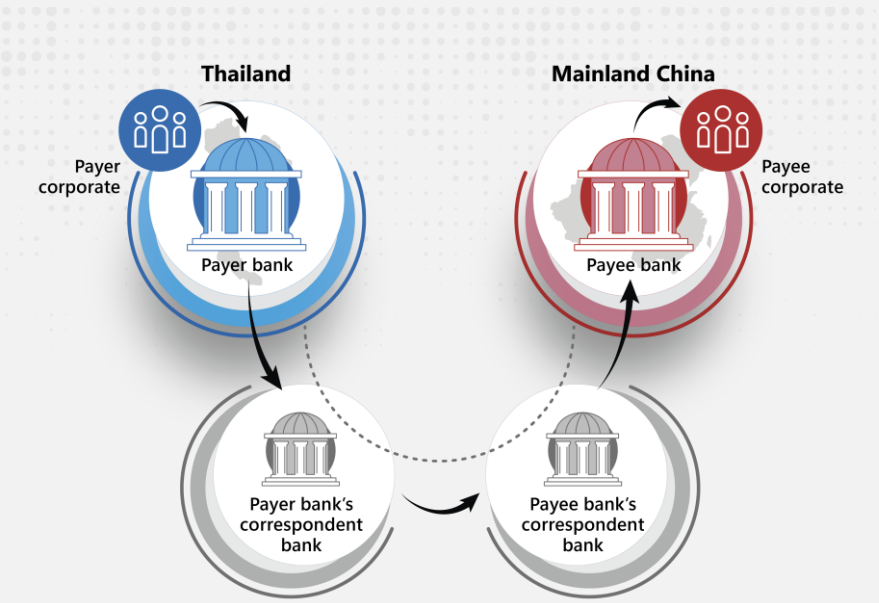
[25] See Oliver Wyman and JP Morgan (2021).

[26] See Casu and Wandhofer (2017).

2021 intra-group trade among the four jurisdictions (in US$ billions) Graph 3



Typical correspondent banking payments process Graph 4



5. Pilot

The mBridge pilot[27] moves the needle in the multi-CBDC space in terms of the nature of transactions, the number and value of transactions and the number of participants. Over the course of six weeks, Project mBridge conducted a large-scale pilot settling real-value transactions in CBDC from each of the four participating jurisdictions directly on the mBridge ledger. It represented the largest cross-border CBDC pilot to date, with over US$ 12 million of CBDCs issued onto the platform, over US$ 22 million of payments and FX PvP instantly settled across borders, and the greatest number of direct pilot participants. Twenty of the region's largest commercial banks participated in the pilot (Graph 5), settling real value on behalf of their corporate clients, focusing primarily on settlement for international trade as well as between interbank groups. Where the pilot differs from other multi-CBDC projects is in the final settlement of real-value transactions directly on the platform (as opposed to on the domestic payment systems) and the fact that it included paying and receiving banks conducting transactions directly on behalf corporate clients (as opposed to interbank transfers). By providing a shared platform on which participants conducted peer-to-peer payments directly in the safety of central bank money across multiple jurisdictions, the pilot successfully demonstrated the platform's ability to improve cross-border payment speed and efficiency, and to reduce settlement risks in a real-world setting.

Participating commercial banks in the pilot — Graph 5

[27] For more details on what constitutes a pilot, see Giblin et al (2021). See also the appendix on project stages.

5.1 Preparation and setup

The mBridge pilot required extensive coordination and engagement both within and among central banks and commercial banks to be successfully completed. First, as CBDC represented a new digital form of central bank money in many of the participating jurisdictions, significant interdepartmental coordination across Payment, Legal, Risk, Financial Stability, Monetary Policy and Treasury teams (among others) took place within each central bank and each commercial bank to facilitate both the availability of CBDC (from a central bank perspective) and the ability to transact in CBDC (from a commercial bank perspective) over the course of the pilot. Second, due to the cross-border nature of transactions, extensive cross-jurisdictional synchronisation also took place among the four central banks and 20 commercial banks to ensure the appropriate operational and legal jurisdictional requirements were met. For example, central banks needed to ensure sufficient liquidity was available in the local currency for transactions between each jurisdiction pair, while commercial banks needed to coordinate among each other, as well as with their corporate clients, which transactions to route through the platform.

To provide the legal certainty needed to conduct a real-value pilot, three important legal documents tailored for the pilot were drafted and executed by the participants:[28]

i) **Pilot participation agreement**: outlined central banks' role and provision of services under the pilot scheme along with the rights and responsibilities of the commercial bank participants.

ii) **Platform operating terms**: provided overarching principles and procedures for commercial banks on the use of mBridge; notably, it included the circumstances under which CBDC payments and exchanges on the platform are deemed made, completed, irrevocable and final, achieving legal certainty for settlement finality on the platform.

iii) **Terms and conditions**: outlined currency-specific rules governing the use of local CBDCs by foreign commercial banks; for example, it outlined the terms of use of the CBDCs and rights of holders of the CBDCs on mBridge. The terms and conditions were embedded as a clickthrough agreement on the platform.

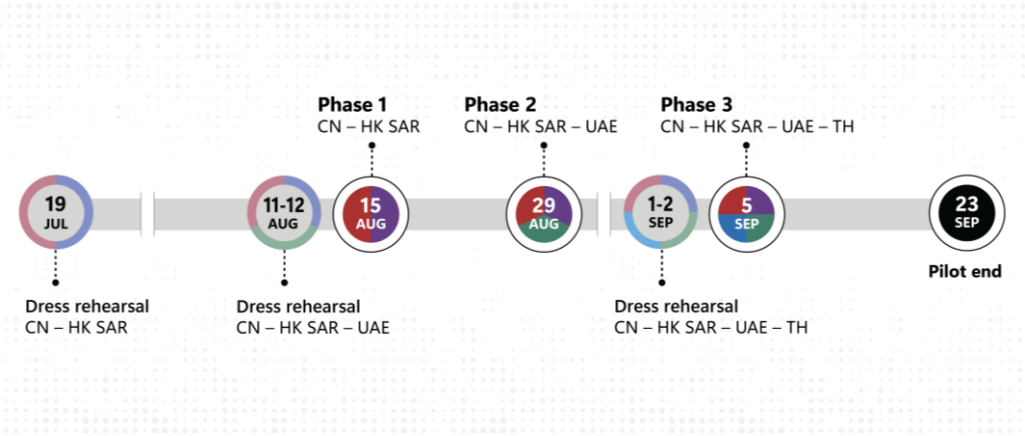
To simplify the technical operation of the platform for the purposes of the pilot, the mBridge ledger was deployed and operated in a high-security, centralised cloud based in Hong Kong SAR. This enabled participants to access the platform as a software as a service (SaaS) offering though a convenient front-end, web-based user interface (UI). In future pilot phases, however, the project team will explore further distributing the deployment and operations of the platform among the

[28] In certain jurisdictions, additional documents were drafted on top of these three documents, such as a business continuity plan.

participants for data privacy and governance reasons (see subsection 7.1.3 for more details).

With all the necessary groundwork laid, the pilot then took place over a period of six weeks between 15 August and 23 September 2022. It was conducted in three consecutive phases, detailed in Graph 6, with each phase increasing the number of jurisdictions involved. The first phase included only transactions between banks in Hong Kong SAR and Mainland China. The second phase saw the addition of UAE banks, and the final phase included Thai banks. A series of "dress rehearsals" also took place in a parallel user acceptance testing (UAT) environment prior to the start of each phase, to get banks acquainted with the platform and ensure smooth operations.

Pilot timeline — Graph 6



5.2 Transaction types and functional requirements

Transaction types that feature prominently in the context of international trade and that facilitate cross-border settlement in local currency were explored in the pilot. More specifically, the pilot tested the following three transaction types (Graph 7):[29,30]

i. Issuance and redemption of CBDC between central banks and their domestic commercial banks.

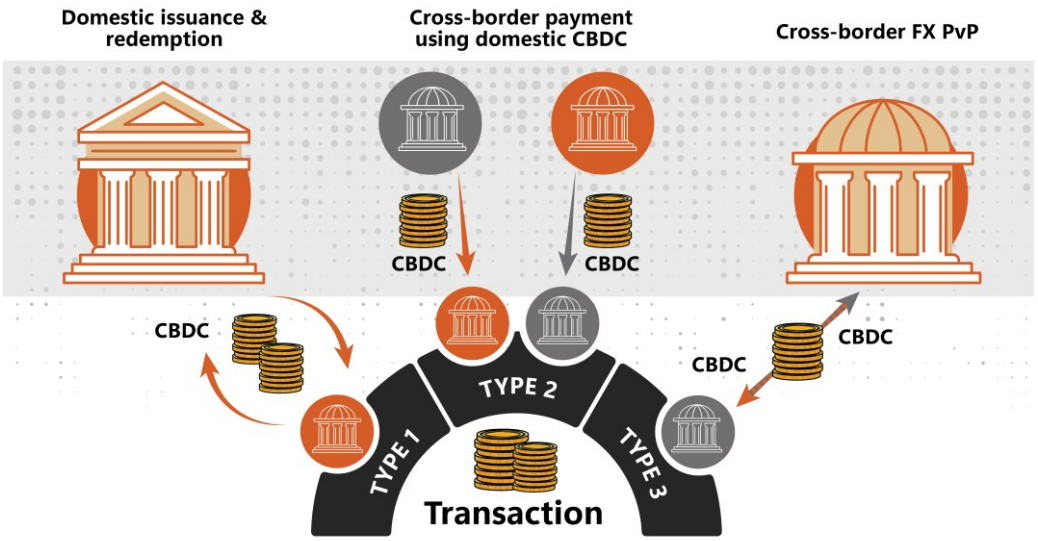
ii. Cross-border payment between commercial banks in local CBDC (for example, a UAE corporate paying a mainland Chinese corporate in e-CNY through their commercial banks participating on the platform).

[29] Since the pilot was conducted between more than two jurisdictions, other transaction permutations were possible, such as cross-border transactions denominated in a third-jurisdiction currency. For the pilot, these additional transaction types were considered out of scope (see subsection 7.1.2 for more details).

[30] For the purpose of this report, all references to e-CNY, e-THB, e-AED and e-HKD refer to the wholesale use of CBDC of each currency.

iii. Cross-border PvP FX between commercial banks in local CBDC (for example, a Thai bank exchanging e-THB for e-HKD with a Hong Kong SAR bank on the platform)

Transaction types tested on the platform — Graph 7



These three transaction types are underpinned by the core functionality of the platform, which is split between the two primary participant types – central banks and commercial banks.

A central bank participant has the widest set of functions on the platform. Central banks are the exclusive issuers and redeemers of CBDC on mBridge, effectively providing fungibility between M0 reserves and CBDC through RTGS on- and off-ramps to the platform or automatic connectivity to domestic CBDC systems. They also have the sole authority to onboard and offboard their domestic commercial banks and set parameters for what currencies their banks can hold, how much they can hold of each currency and what currency pairs they can conduct FX PvP with. Additionally, central banks can view the necessary transaction information of their domestic banks, and foreign banks using their domestic CBDC, to meet supervisory needs without compromising data privacy (see subsection 6.4 for more details).

Meanwhile, commercial banks have a more limited set of functionalities. They can request issuance and redemption of CBDCs on the platform from their domestic central bank in exchange for a debit or credit of their reserve accounts or equivalent accounts in their domestic CBDC systems.[31] They can also initiate peer-to-peer push payments in any currency on the platform with any commercial-bank

[31] See more on manual and automatic issuance and redemption in Section 6.

counterparty on the platform.[32] Furthermore, commercial banks can initiate PvP transactions or respond to similar transactions initiated by another commercial bank to conduct atomic FX transactions in local currency pairs. Lastly, each participating commercial bank can query the platform to view their past transactions and current holdings on-bridge.

The platform will also strive to facilitate non-functional requirements that are in many ways prerequisites to their functional counterparts. These include, but are not limited to, data integrity, transaction privacy, platform scalability, transaction throughput and transparent system monitoring. These attributes are all essential components of a well-functioning platform and often present optimisation challenges during implementation. For example, security, scalability and decentralisation lead to implementation tradeoffs that need to be carefully evaluated.[33] More on how some of these features are supported can be found in Section 6.

5.3 Pilot statistics

Table 1 presents pilot transaction statistics. Over the course of six weeks, HK$ 8.5 million in e-HKD, ¥11.8 million in e-CNY, 31د.إ million in e-AED and ฿32.1 million in e-THB were issued onto mBridge as M0 central-bank-issued CBDC. Across all four currencies, issuance amounted to US$ 12.1 million of liquidity on the platform. This, in turn, facilitated 164 cross-border payment and FX PvP transactions totalling US$ 22.1 million, suggesting that the CBDCs issued on mBridge during the pilot facilitated nearly double the amount in cross-border value.

Breaking down payment and FX PvP values transacted on the platform by currency, HK$13.2 million was in e-HKD, ¥23.6 million in e-CNY, 60.1د.إ million in e-AED and ฿23.5 million in e-THB. Payment and FX PvP transactions were mostly comprised of underlying corporate payments for the international settlement of goods and services. Furthermore, a number of interbank transactions also took place, paving the way for additional use cases to be settled on mBridge.

As can be seen from Table 1, there are asymmetries across the four CBDCs both in terms of the number of transactions and their value, which reflect several factors. While the pilot consisted of real-value corporate transactions, it was also conducted in an orchestrated manner with the setup having implications for the activity of each CBDC. For example, as Hong Kong SAR and Mainland Chinese banks were the only commercial bank participants to start transacting in the first phase of the pilot, e-HKD and e-CNY were available on the platform for the full duration of the six weeks. On the other hand, e-AED was only available starting in Phase 2 when UAE banks joined the pilot, followed by e-THB starting in Phase 3 when Thai banks joined. This explains why e-HKD and e-CNY transactions greatly outnumbered those of e-AED and e-THB. Furthermore, differences in transaction values reflect different

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[32] While it is technically feasible to initiate push payments in *any* participating currency on the platform, only transaction types involving a currency that is local to one of the counterparties was tested in the pilot, as explained earlier in the subsection.

[33] See Hafid et al (2020).

rules and considerations set by the issuing central banks. For example, transaction values in e-AED were significantly higher relative to the other three currencies, owing in part to the fact that all e-AED-denominated transactions were interbank rather than corporate payments, and reflecting the scale and materiality of interbank transactions that typically occur between the UAE and the other three jurisdictions. Subsection 7.1 provides a more detailed discussion on why these different rules and restrictions were put in place.

Pilot transaction statistics — Table 1

Number of transactions	**e-HKD**	**e-CNY**	**e-AED**	**e-THB**	**Total**
Issuance	17	35	10	8	70
Payment and FX PvP	51	72	23	18	164
Of which payment	40	69	15	8	132
Of which FX PvP	11	3	8	10	32
Redemption	18	35	10	8	71
Total	86	142	43	34	305

Transaction value (local currency)	**e-HKD**	**e-CNY**	**e-AED**	**e-THB**	**Total (US$)**
Issuance	8,483,655	11,821,780	31,024,625	32,113,000	12,118,083
Payment and FX PvP	13,194,963	23,643,559	60,058,250	23,481,840	22,094,936
Of which payment	10,279,078	23,479,504	60,039,250	10,830,920	21,347,208
Of which FX PvP	2,915,885	164,055	19,000	12,650,920	747,728
Redemption	8,483,655	11,821,780	31,024,625	32,113,000	12,118,083
Total	30,162,272	47,287,119	122,107,500	87,707,840	46,331,101

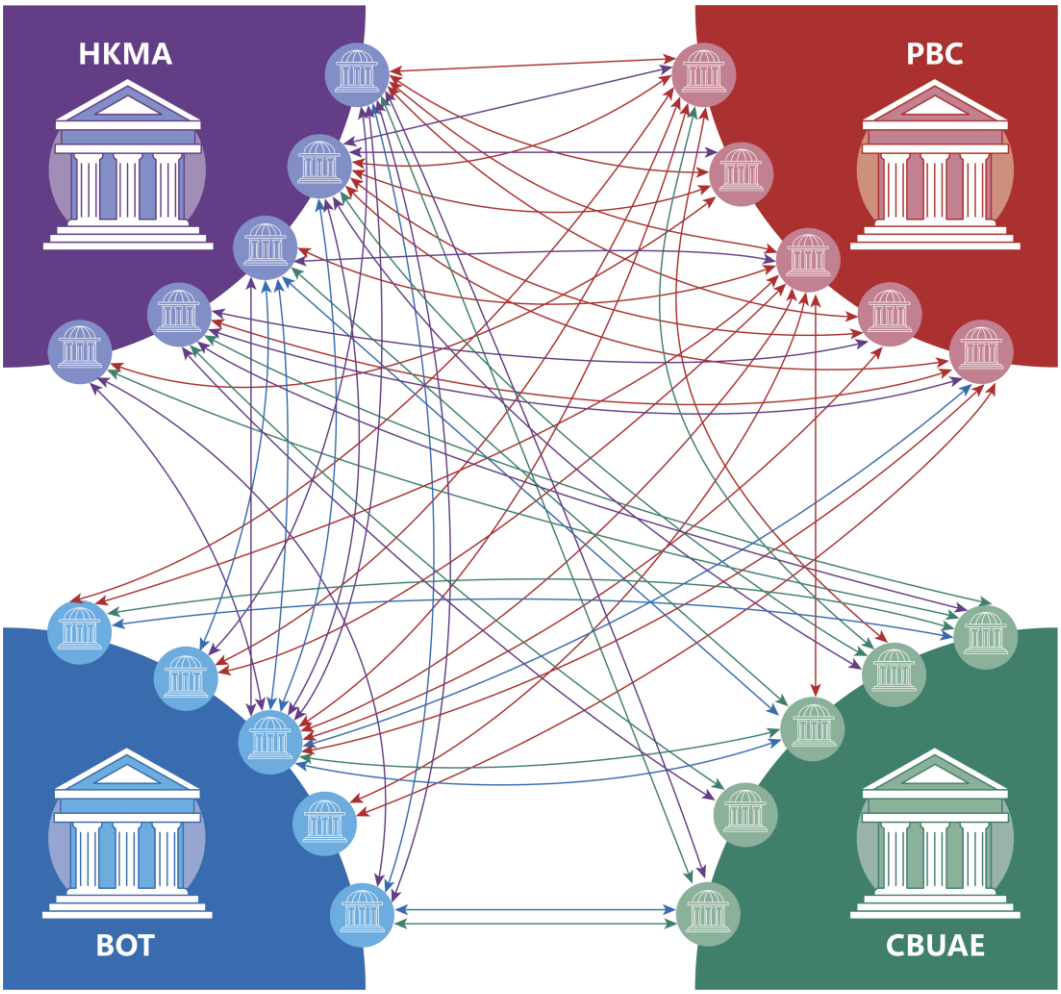
Transaction values in each currency are denominated in local currency, while transaction values in the "Total" column were converted to US dollars using average daily exchange rates between 15 August and 23 September 2022 taken from Bloomberg.

On the platform, a commercial bank can transact with any other commercial bank directly in a peer-to-peer manner. Among the 20 participating commercial banks, five from each jurisdiction, this connectivity enabled 150 different bilateral and direct potential connections.[34] Over the six weeks of the pilot, 41 unique, cross-border, peer-to-peer linkages were enacted, with each bank transacting on average with two banks in other jurisdictions in a currency that is local to at least one of the counterparties (Graph 8). This bilateral connectivity enabled by mBridge contrasts with payments routed through the correspondent

[34] Each of the 20 banks can connect to 15 banks in the other three jurisdictions; we then divide the multiplicative value of 300 (20x15) by two to not count each connection twice.

banking model, in which banks do not typically have the direct connections required to transmit cross-border payments across currencies and therefore require chains of linked correspondent institutions and routing through third-party currencies, adding time, friction and settlement risk. The peer-to-peer linkages between payee and payer banks offered by mBridge can significantly reduce the complexity of cross-border payments, and as such, tackle many of the associated pain points. Moreover, settlement on mBridge occurs in the safety of central bank money, reducing or even eliminating a key risk in correspondent banking payments.[35]

Pilot transaction linkages — Graph 8



Visual representation of the 41 unique, cross-border, peer-to-peer linkages enacted over the course of the pilot. Each unique linkage can involve two currencies – those local to the transacting counterparties. Colours of the arrows in the graph represent the currency of the jurisdiction in each corner with the same colour.

[35] mBridge also demonstrates the potential to settle transactions instantly, therefore reducing settlement risk compared with the correspondent banking model, in which there is currently a three- to five-day delay between payment and settlement for a typical cross-border transaction processed via correspondent banks. See BISIH et al (2021a) for details.

5.4 Key lessons

The pilot's real-world setting provided numerous lessons that will inform the development of future phases of the project. Platform design decisions, constraints imposed by incumbent systems and participant relationship dynamics all influenced how the platform was used, and consequentially will have an impact on shaping the roadmap.

One important observation is the limited number of FX PvP transactions which were conducted during the pilot compared with one-way payments (see Table 1). This reflected in part the relatively short window of time banks had to off-load their foreign CBDCs due to the requirement set by some central banks to clear balances of their CBDCs at the end of the day, along with the limited overlapping RTGS hours between the four jurisdictions. FX rates were also determined off-bridge before FX PvP transactions took place on the platform, and thus the lack of an efficient FX price-discovery mechanism on-bridge added time and complexity to the workflow. As a result, many banks relied on requesting foreign currency against pre-existing balances in nostro accounts, instead of making use of the FX PvP function on mBridge.[36] Given the need to rely on existing correspondent banking relationships for liquidity, the real-value nature of transactions and the short time span of the pilot, transactions took place, for the most part, between banks with pre-existing business and service relationships. To fully benefit from the direct bilateral connectivity offered by mBridge and its FX PvP functionality, it is therefore important that liquidity provision and management functions, along with measures to facilitate FX dealing on-bridge, are appropriately integrated into the platform in the future.

Finally, an additional finding from the pilot was that the ease with which mBridge integrates with domestic wholesale payment systems can save time for participants and allow for straight-through processing. The modular framework of the platform allowed for both manual and automatic integration with domestic payment systems. It is likely no coincidence that, with the PBC integrating the platform into their live e-CNY domestic system using the automatic issuance and redemption features, issuance and redemption transactions were highest in e-CNY.[37] With the intention to move towards automatic integration in the future, the other central banks in the interim made use of the manual issuance and redemption function on mBridge. The manual process added time and friction to the processes, although any control and coordination issues were quickly resolved during the pilot. Seamless integration by central banks of the platform with domestic CBDC and payment infrastructures and automation of the CBDC issuance and redemption processes are therefore crucial for the future success of mBridge.

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[36] For example, while ICBC (Thailand) was not a pilot participant, as the CNY clearing bank in Thailand, they provided e-CNY liquidity assistance to the Thai commercial banks participating in the pilot. Through their access to ICBC Head Office in Mainland China, ICBC (Thailand) was able to assist Thai banks in converting e-CNY on and off mBridge.

[37] That being said, the relatively high number of e-CNY issuances and redemptions could also reflect greater demand for e-CNY-denominated transactions given the relatively high share of regional trade accounted for by Mainland China.

5.5 Participant feedback

Upon completion of the pilot, participating commercial banks from each jurisdiction were asked to provide their feedback through a structured questionnaire covering the functional features of the platform, business use cases, compliance and legal considerations, platform operations and input on the future directions of Project mBridge. In general, most respondents found the platform intuitive and easy to use. They found taking part in the pilot useful in understanding how a CBDC platform can integrate into their workflow and all expressed interest in participating in future pilots. The majority of respondents acknowledged the benefits of switching from existing cross-border payment frameworks to the mBridge platform in terms of speed, intermediary reduction, transparency, cost, availability and risk reduction, as well as the excellent potential of the platform in its current form to be developed into a production-ready system.

Post-pilot commercial bank feedback — Table 2

Feedback included:	**Suggestions for improvement included:**
• Platform was intuitive and easy to use • Taking part in the pilot was useful in understanding how a CBDC platform can integrate into commercial bank workflows • Interest in taking part in future mBridge pilots • Benefits of using mBridge compared with existing systems in terms of speed, transparency, cost, availability and risk reduction	• Introducing FX market makers/liquidity providers to facilitate FX dealing on-bridge • Interoperability with domestic systems and API connectivity to enable end-to-end execution and straight through processing • Maker-checker mechanisms • More jurisdictions and currencies • More use cases • More comprehensive set of terms and conditions and overarching legal and governance structure as platform moves towards production

Respondents also provided valuable insight into areas in which mBridge features can be enhanced or added to for banks to be able to use the platform at scale and to avoid putting undue pressure and risk on their operations. These included, for example, liquidity management tools, interoperability with domestic systems and application programming interface (API) connectivity, and transaction reporting/statements, among other UI improvements. Respondents also welcomed the idea of testing more use cases and adding more jurisdictions and currencies to the platform. Finally, banks noted the need for a more comprehensive set of terms and conditions, and overarching legal and governance structure, as the platform moves towards production stage. A detailed list of feedback is outlined in Table 2. These suggestions are instrumental in shaping the future roadmap for mBridge (see Section 8 for more details).

6. Technical platform design

Central bank money is the safest form of money in any currency area and plays a fundamental role in the financial system and overall economy.[38] It is therefore natural for a CBDC platform to be designed and built by central banks, for central banks. After experimenting with different technology architectures in earlier phases, the project team developed a new native blockchain for mBridge, the mBridge ledger (mBL), to meet the needs of the central bank and commercial participants. Under the Steering Committee structure, platform requirements are first discussed by subcommittees chaired by the four central banks before being implemented by the development team. The code is open and available to all central bank project members for input and review.

The mBL aims to serve as a specialised, flexible and scalable implementation for multi-currency cross-border payments. To maximise the accessibility, adaptability and extendibility of the platform for current and future users, the platform implements a modular design that provides users and developers with a familiar service-oriented architecture. In this approach, different modules such as payment, foreign exchange, capital management and compliance are decoupled and modularised to accommodate the evolving needs from different jurisdictions. This allows participating central banks to validate, adapt and extend functionality according to their technical, business and regulatory requirements, and aims to support each jurisdiction's autonomy in implementation and adoption of the platform.

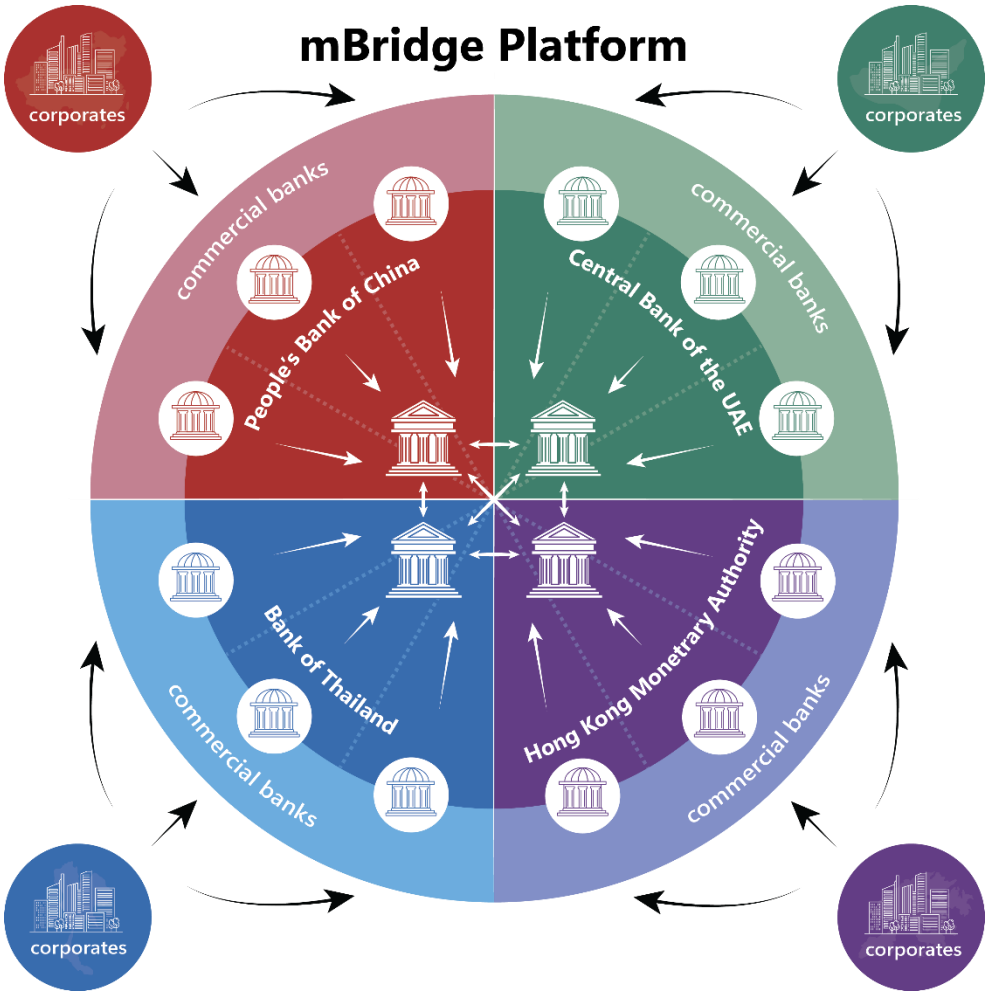
6.1 Network topology

At the core of the mBL are the central banks, who each run a validating node that operates the mBL consensus protocol. As shown in Graph 9, central bank validating nodes form a complete, connected graph with a link between every pair of nodes.[39] Each central bank can onboard its domestic commercial banks onto the platform, and the commercial banks of each jurisdiction are all connected to the onboarding central bank and hence to the validating core of the mBL. Once onboarded, commercial banks can transact on behalf of their clients, extending the reach of the platform.

[38] See Carstens (2021).

[39] In the mathematical field of graph theory, a complete graph is a simple, undirected graph in which every pair of distinct vertices is connected by a unique edge. See Bang-Jensen and Gutin (2018).

High-level network topology Graph 9



6.2 Functional architecture

As shown in Graph 10, the mBridge platform can be broken down into the following five distinct layers, with each layer encapsulating multiple functional modules:

1. **Access layer**: supports different ways to access the platform. For the pilot, a web-based front-end was developed that enabled pilot participants to directly use the platform through a web browser without requiring technical integrations. This layer also supports an API module, against which participants can directly integrate with their core banking payment systems. Lastly, a gateway module provides request authentication controls and load balancing.
2. **Application layer**: includes a wide range of local back-end services. Wallet management provides encryption and decryption services based on self-hosted private keys, while privacy protection provides local key generation and management services for the pseudo-anonymous key pairs. The transaction engine executes business logic on the underlying blockchain and data layers.

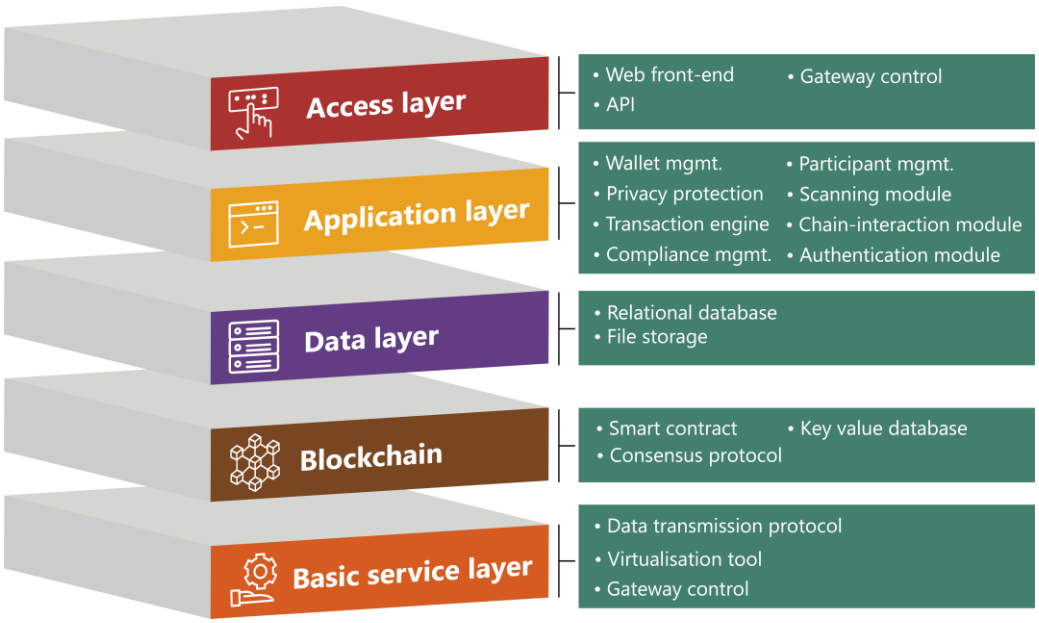
Meanwhile, compliance management enforces controls such as value limits and currency types, and participant management offers access management and supervisory functions for the central banks. Finally, the scanning module is responsible for the monitoring and parsing of on-chain data, while the authentication module authenticates actions against the underlying blockchain and data layers.

3. **Data layer**: encapsulates local data storage and supports relational databases and file storage functions.

4. **Blockchain layer**: as the core of the platform, it consists of smart contracts and consensus protocols and enables the technical settlement of all transactions. It also includes a key-value database (KV database) to store data that is essential to the operations of mBridge. For details on the blockchain API interface, see the appendix on technical design.

5. **Basic service layer**: as the lowest level of the technical stack (see the appendix on technical design for more details), this layer provides the necessary software and hardware facilities for the system, such as data transmission protocols, CPU virtualisation, network resources and server hardware.

mBridge platform layers — Graph 10



6.3 Consensus protocol

At the heart of the mBridge platform is a private,[40] permissioned[41] distributed system. Validating the ledger is the process of accepting or rejecting proposed

[40] Private refers to the fact that a participant needs to be onboarded by a representative central bank on to the ledger in order to participate.

[41] Permissioned refers to the fact that validation of the ledger is reserved to permissioned entities, ie the central banks.

transactions to the ledger and is done through the consensus mechanism which lies at the core of any DLT platform.[42] There are many types of consensus mechanism, the most familiar of which are proof-of-work and proof-of-stake used in the public, permissionless Bitcoin and Ethereum ledgers, respectively. The trade-offs and economic incentives in private, permissioned ledgers, however, are different from those in public, permissionless ones, as private, permissioned ledgers do not need to provide economic incentives for public validators. One desirable property of consensus mechanisms is Byzantine fault tolerance (BFT),[43] or resilience to malfunctioning components that provide conflicting information to different parts of the system.

The mBL uses a consensus mechanism named HotStuff+, which is a variation of HotStuff first introduced in Yin et al (2019). HotStuff has numerous desirable properties, notably that its runtime, a measure of the computational complexity of an algorithm, scales linearly with respect to the number of validating nodes. This contrasts with most other BFT and practical-BFT protocols that are quadratic with respect to the number of validators and therefore require greater runtime for the same number of validating nodes.[44]

For future consideration, a new consensus mechanism named Dashing is being tested by the development team. Dashing is a dynamic-threshold blockchain consensus protocol for permissioned blockchain, and achieves higher efficiency and robustness than HotStuff+ does. It uses triple certificate security, a process in which three certificates with different thresholds are used under different network circumstances. As a result, both higher efficiency and robustness can be achieved. Additionally, a decoupling of block proposals from the consensus achieves greater scalability under a high concurrency of transactions.[45]

6.4 Privacy controls

When designing CBDC platforms, choices concerning privacy are often top of mind for policymakers. Design choices should be considered in terms of privacy of what and from whom. It is also important to keep in mind that privacy is not a binary choice between anonymity and full disclosure, and there are many subtleties involved. For example, in the case of cash transactions, only the counterparties to the transaction know of its existence, while the issuer of the currency does not. However, if the cash transaction was large and for the purpose of a real estate title

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42 This can be generalised as the problem of State Machine Replication, a method for implementing a fault-tolerant service coordinating user interactions over a set of replicated servers. See Lamport (1978).

43 See Lamport et al (1982).

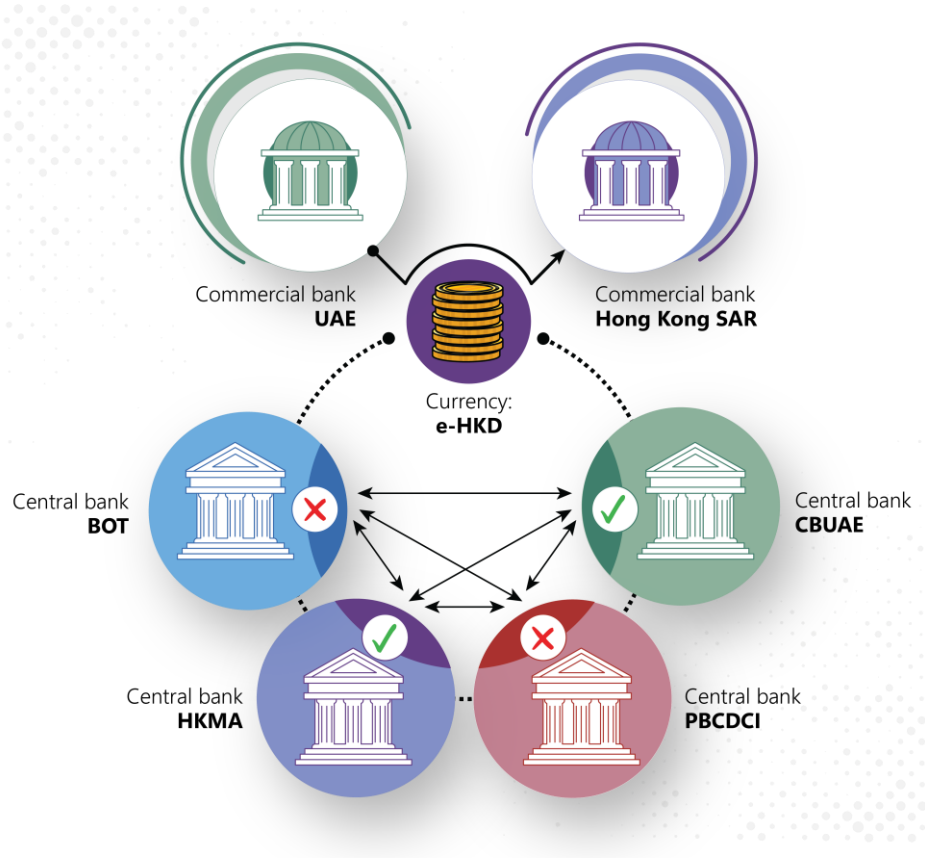
44 The HotStuff consensus algorithm can be broken down into four distinct phases – prepare, pre-commit, commit and decide – which are executed sequentially in the original HotStuff implementation. HotStuff+ adds an asynchronous implementation to the validation process and supports dynamic switching and adding validator nodes; as a result, it increases the performance and resilience.

45 See Duan et al (2022).

transfer, the recipient would likely require some degree of disclosure on the origin of the funds.

The mBridge platform implements privacy controls for core transaction data, which comprise payer and payee identities, the amount transacted and the details of the CBDC invoked. Through an implementation of pseudo-anonymous addresses using randomly generated self-issued key pairs – the flow of which is detailed in the appendix on technical design – the mBridge platform ensures that sensitive transaction details can only be viewed by the counterparties of the transaction, their respective central banks and the currency issuer. For example, consider a hypothetical scenario in which a UAE commercial bank makes a payment to a Hong Kong SAR commercial bank in e-HKD on mBridge; the details of the transaction would only be visible to the payer, the recipient, the CBUAE and the HKMA, while the BOT and the PBCDCI and other participants would not be able to see any sensitive transaction information (Graph 11). If, instead, the payment was in e-THB (note this transaction type was not within the scope of the pilot and is used purely for illustrative purposes), the BOT would also be able to see the transaction details. Without these controls in place, sensitive transaction details would be visible to any participant with access to the ledger, which in the case of mBridge is every participant on the platform.

mBridge privacy controls — Graph 11



6.5 Functional implementations

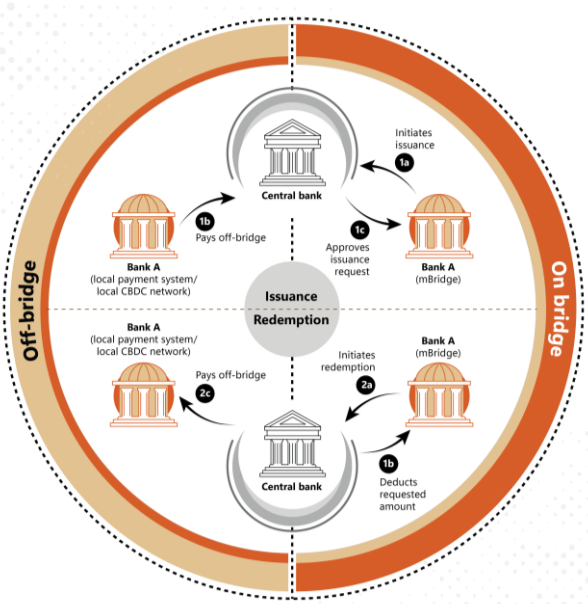
6.5.1 Issuance and redemption

Recognising that some jurisdictions may not yet have a CBDC system, and that API integration takes time, the platform supports a manual mode of integration in addition to an automated one. This supports interoperability and coexistence with domestic payment systems, as both CBDC and traditional payment systems can be easily connected to the platform. Nevertheless, a key lesson from the pilot (as described in subsection 5.4) is that as the platform moves closer to the production stage, automated integration with the standing systems of the participating central banks is important to reap the full benefits of mBridge. Specifically, the mBridge ledger enables two issuance and redemption models, manual and automatic, as shown in Graph 12.

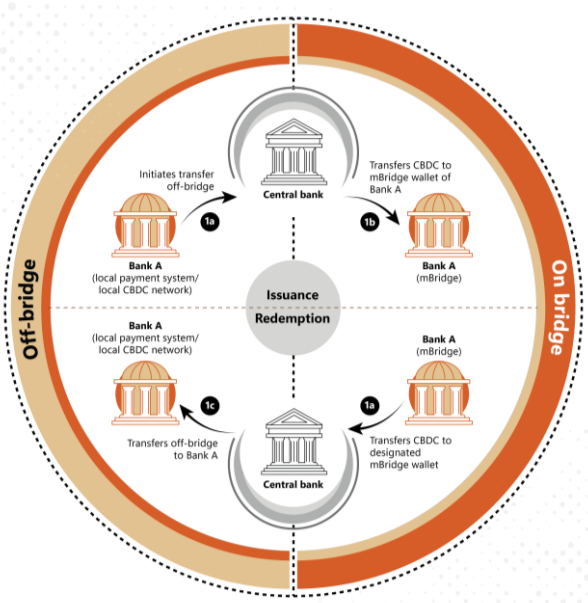
1. **Manual issuance and redemption**: under this model, central banks can issue and redeem their CBDCs on mBridge without needing to modify their existing payment arrangements. A commercial bank first submits an issuance request and conducts a manual off-bridge transfer of funds to the issuing central bank through the domestic payment system, which can be either a traditional payment system such as RTGS or a domestic CBDC system. Upon receipt of the funds and the completion of internal control checks, the central bank issues the equivalent amount of CBDC into the commercial bank's wallet on mBridge. Similarly, redemption is triggered by a commercial bank's request with the amount of CBDC to be redeemed being sent to the central bank on mBridge. The central bank then manually transfers the equivalent amount of funds to the commercial bank through the domestic payment system and completes the redemption transaction.
2. **Automatic issuance and redemption**: this model directly integrates the domestic payment system and/or CBDC network with the mBridge platform, allowing transactions between the two systems to be processed in a highly automated manner. The process involves a commercial bank sending money though the local payment system to a designated account/wallet which would then automatically trigger a CBDC issuance on mBridge. Similarly, a commercial bank initiating a redemption on mBridge would automatically trigger a payment to the commercial bank's account/wallet.

mBridge issuance and redemption Graph 12

A. Manual issuance and redemption



B. Automatic issuance and redemption



6.5.2 Payment and PvP

There are two types of payment that can be performed on mBridge (see the appendix on technical design for a more detailed flow):

1. **Simple one-currency push payments**: starts with the initiator selecting the currency, amount and counterparty. The initiator then conducts the appropriate off-bridge compliance checks, including AML/CTF/sanctions checks, and sends a payment request to the payee. Once the payee receives this request, it conducts its own off-bridge compliance check and, if appropriate, confirms the payment. Once received, the initiator will call the payment interface which invokes the contract to pay the specified currency amount to the receiving address.

2. **Dual-currency FX PvP transactions**: these transactions are atomic, meaning they are indivisible – either both legs of the transaction settle or neither settle. A PvP transaction involves three distinct phases: initiation, commit and execute. In the first phase, the initiator selects the currency pair, amount, FX rate (which is determined off-bridge) and a counterparty. Then, like a one-way payment, the initiator conducts the appropriate off-bridge compliance checks before sending a payment request to the counterparty. Once the counterparty confirms, the commitment phase will begin during which the first leg of the transaction is committed; the PvP contract then waits for the other transaction to be triggered and emits an event to the counterparty that the initiator is ready to make payment. Finally, in the execution phase, the counterpart commits the other leg of the transaction, triggering the atomic execution of the PvP contract.

7. Policy, legal and regulatory considerations

7.1 Policy considerations

A multi-CBDC common platform raises several policy, legal and regulatory considerations. The rich diversity of monetary systems and governance frameworks of the four participating jurisdictions enabled the development team to explore a platform design that can accommodate jurisdiction-specific nuances and maximise policy flexibility for individual jurisdictions, while at the same time adhere to a common set of principles that are critical for the functioning of the platform. Meanwhile, the pilot's real-world setting shone light on a range of policy and legal issues that need to be further explored on the path to a production-ready system.

7.1.1 Measures to preserve monetary sovereignty

Without the appropriate safeguards, cross-border use of CBDCs and broadening direct access to central bank money could hamper central banks' ability to maintain monetary and financial stability. For example, as the accessibility of domestic institutions to foreign currencies and of foreign institutions to domestic currency increases, heightened offshore demand for CBDCs can drive volatile capital flows, balances of domestic money offshore and substitution away from the domestic currency.[46] In designing a multi-CBDC platform, a key question for central banks to consider is whether commercial bank participants can access the CBDCs of jurisdictions where they are not themselves locally domiciled and regulated. If so, this broadens direct access to central bank money to foreign banks as compared with today's systems, in which access is often conditional on local supervision or licensing.[47,48]

On mBridge, both domestic and foreign commercial banks are permitted to directly hold and transact in CBDC, since this is a desirable condition to ensure seamless cross-border payments in central bank money. The platform's design follows the CBDC principle of "do no harm" – designing CBDC ecosystems that support public policy objectives and do not impede central banks' ability to carry out their mandates.[49] To ensure that mBridge fully respects the monetary sovereignty and policies of each participating central bank, it aims to provide central banks with the tools needed to allow this foreign access without compromising control of their currency. It does this through flexible control functions over CBDC issuance and redemption, transaction currencies and amounts, and visibility into usage. These controls can also be further customised to accommodate the evolving management needs of the jurisdiction.

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46 See IMF (2020) and CPMI (2018).

47 See BISIH (2022).

48 A related question concerning access policy is whether to accept non-bank participants as account holders, but this is out of the scope of the current phase of the project.

49 See BIS et al (2022).

While CBDCs can be held and used by foreign commercial banks, only domestic banks can be issued or redeem CBDC against reserve balances. This ensures that no changes are made to the monetary base through the exchange of reserves to CBDC. Measures limiting the circulation of CBDCs offshore, such as restrictions on which offshore entities can hold a central bank's CBDC and limits on amounts held, can also serve as useful tools to allow central banks to broaden access without compromising monetary sovereignty.[50] Central banks can also tailor the time frames during which their CBDCs are allowed to exist on the platform. For example, CBDCs can be restricted to intraday circulation, leaving no effects on the central bank's overnight balance sheet, or be permitted to be held overnight, with impacts on the balance sheet. Other arbitrary time periods (eg week-end or month-end) can also be set, giving central banks the tools to intervene periodically for other policy or supervisory purposes.[51]

As mBridge is still moving towards a production stage, most of the controls discussed above were implemented manually by each central bank during the pilot. Future phases will explore further integration of these controls into the technical platform. For example, CBDC smart contracts can be used to clear balances through an automated sweep at specified time intervals, and access and value controls can be automated depending on the jurisdiction of the user, demonstrating the flexibility of the platform. Furthermore, central bank dashboards and analytical tools can be developed to provide central banks with a more real-time, dynamic and comprehensive view of their CBDC on the platform.

7.1.2 Foreign and domestic use of CBDC

Certain transaction types were intentionally omitted from the scope of the pilot due to the potentially significant policy implications detailed below that need careful consideration and further discussion before conducting such transactions with a broader ecosystem.

(i) **Domestic transactions using a domestic currency**: could challenge and compete with existing local payment systems, such as the RTGS.

(ii) **Domestic transactions in a foreign CBDC**: raises the risk of displacing local currencies.

(iii) **Cross-border transactions using a currency which is foreign to both counterparties**: despite the prevalence of this in international trade, it raises similar concerns about displacing local currencies. This challenge is particularly salient for EMDEs.

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[50] See BISIH (2022).

[51] For example, the e-THB existed intraday during the pilot to ensure compliance with Thailand's foreign exchange regulations, which prohibit non-Thai banks from holding over 200 million THB at the end of each day to prevent currency speculation. As there was no automated aggregation mechanism during this phase of the project that would allow the aggregation of e-THB holdings of foreign banks on mBridge with off-bridge holdings, e-THB needed to be redeemed off the platform at the end of each day for simpler reconciliation. See Bank of Thailand (2021).

During the pilot, while participating banks were able to directly transact in the CBDCs of other jurisdictions on the platform, foreign banks were limited in terms of how they could move CBDCs on mBridge. Excluding *domestic and cross-border transactions in a currency which is foreign to both counterparties* from the pilot meant that a domestic bank was always involved in at least one leg of any transaction with regard to the underlying currency. This ensures that significant amounts of domestic currency cannot accumulate offshore beyond the central bank's control, limiting opportunities for the currency to be used for speculative purposes.

Further in-depth analysis will be needed, and countermeasures implemented, to mitigate the policy risks associated with the excluded transaction types before they are included in future phases of mBridge. For example, considering *domestic transactions using domestic currency*, mBridge can be further developed to become an infrastructure for domestic CBDC, if desirable. Additionally, subject to the decision of the participating central banks, mBridge can enable *domestic and cross-border transactions in a currency which is foreign to both counterparties* after careful consideration by each central bank; for example, they can set parameters for what currencies their local banks are allowed to hold, the value limit for each currency they are allowed to keep under custody and what currency pairs they are allowed to conduct PvP transactions with, thereby mitigating some of the undesirable outcomes discussed above.

7.1.3 Data privacy and governance

With the involvement of numerous central and commercial banks from multiple jurisdictions on a shared ledger, data privacy and governance are important considerations for the success of mBridge. Considerations include how data and information are shared among the participants and where confidential data resides, both of which are influenced by the detailed technical architecture and network deployment.

For the pilot, existing features of the platform in its current stage ensured that data privacy concerns were adequately addressed. For example, on mBridge, sensitive data are stored off-chain. On the ledger, data are only shared on a need-to-know basis, with only transacting parties and their respective central banks being privy to the details of a transaction. This is implemented using self-generated key pairs for pseudo-anonymity that protect user identities and sensitive on-ledger transaction data. Certain transaction types were also excluded from the scope of the pilot to ensure compliance with existing data privacy protection laws.[52]

While the centralised deployment of the pilot provided easy use of the platform, it also resulted in data being located in a single cloud environment, heightening privacy concerns. Looking ahead to future pilots, the project team will explore distributed deployment. Under such a distributed approach, only a small amount of data is recorded on the blockchain and shared to all participants.

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[52] For example, non-corporate retail transactions involving Thai banks were prohibited as Thailand's Personal Data Protection Act (PDPA) requires end-to-end compliance.

Sensitive and confidential data are stored off-chain in each jurisdiction's local database, contained within the local jurisdiction. Even in cases in which such data need to be stored on the ledger, it would be properly encrypted. Additionally, the development teams are in the process of evaluating zero-knowledge proof methodologies to enforce stronger privacy against arbitrary central bank validators. All of this may serve to alleviate data confidentiality and governance concerns.

7.2 Legal and regulatory considerations

Given that each jurisdiction has different standing rules and regulations, a multi-jurisdictional CDBC platform raises different legal questions and challenges in each jurisdiction. During the course of 2022, the mBridge project team sought detailed legal advice from external counsel in an effort to assess whether, and if so which, regulatory changes are needed to enable jurisdictional participation in mBridge.[53] The legal advice focused on the following key areas:[54]

a. **Legal categorisation of CBDC:** this is the most pivotal and challenging area across jurisdictions. The typical question is whether CBDC on the platform would be classed as currency, a representation of funds on account with the central bank, a debt or something else. In some cases, local laws formally recognise currency in digital form; in other cases, although not formally recognised, a statutory framework for issuance of currency in such form can be achieved with modest upgrades. Where neither of these is the case, an alternative is to use a transferable digital receipt or certificate of funds held on account with the central bank.

b. **Central bank participation**: central bank powers are generally crafted in broad terms and are fundamentally focused on the core duties relating to the stability and integrity of financial systems and maintenance of financial infrastructure. This provides a useful foundation for central bank participation on a wholesale CBDC platform. Ancillary aims relating to international linkages can also help support the ability of central banks to participate on such a platform.

c. **Role of the platform operator**: multiple options are available for the platform operator. Conceptually, to comply with data governance requirements, each of the central banks could become a participant on the platform, host the platform on multiple nodes in a decentralised manner and play certain governance roles that the platform will define and agree on. Nevertheless, tasks that can best be performed centrally may be identified. In such a case, a decision will need to be made as to which party or structure is best positioned to perform those central tasks. In any event, governance of the platform requires a strong interplay

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53 External counsel was provided by King & Wood Mallesons, with the support of Al Tamini (as to the laws of the UAE) and Kudun & Partners (as to the laws of Thailand).

54 A detailed confidential analysis was provided to each jurisdiction with 43 targeted questions across 10 core areas, totalling over 200 pages. Based on the foregoing, a self-assessment matrix was derived that can be used by future members who wish to access the platform/become participants to evaluate whether they would be able to participate under their standing legal frameworks or would require regulatory change.

between platform standards and local rules, as they are fundamentally intertwined.

d. **AML/CTF/Sanctions**: mBridge offers an intermediated infrastructure, in which commercial banks transact payments in CBDC on behalf of their customers. Each commercial bank participant on the mBridge platform is obliged to comply with applicable laws and regulations in relation to AML/CTF/sanctions. To ensure the commercial participant has taken the necessary steps, the platform enables transaction-specific certification. This certification is provided after an off-bridge process, the result of which is translated into a pass/fail output and attached to the transaction itself. Central banks can also retain full discretion in relation to CBDC issuance and redemption to align with their domestic requirements and policies; any additional stakeholder, such as a platform administrator or operator, will need to factor in compliance – this will depend on the model adopted.

e. **Settlement finality**: in the pilot, settlement finality was achieved through specially developed legal agreements between each central bank and its respective commercial banks, further supplemented by operating terms of the platform tailored on a per-jurisdiction basis (recall subsection 5.1).[55] The legal advice also considered on a per jurisdiction basis whether regulatory changes would be needed.

f. **Privacy laws**: as explained in subsection 7.1.3, the pseudo-anonymity and privacy protection management functions of mBridge protect user identities and ensure that data are shared on a need-to-know basis, with only transacting parties and their respective central banks privy to transaction details. However, more work and exploration remain to be done to ensure that different data privacy and governance regulations across jurisdictions are adequately addressed.

g. **Ancillary areas** that may require further focus on the path to a production-ready system include contract, intellectual property, competition and anti-trust laws, general conduct of business requirements, record-keeping, cybersecurity and risk management requirements, liability considerations, and dispute resolution mechanisms and procedures.

With all of this in mind, given that central bank powers are crafted in broad terms incorporating core duties relating to the stability and integrity of financial systems and maintenance of financial infrastructure, wholesale multi-CBDC platform participation is generally achievable. Nevertheless, depending on the specific jurisdiction and the legal categorisation of the CBDC, regulatory changes may be required, or in certain cases preferred, to achieve full legal certainty and clarity. A strong contractual architecture will also support these aims.

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[55] Note that e-CNY was an exception. As the e-CNY is already classified as legal tender in Mainland China, the transfer of e-CNY takes effect from the time of delivery and is deemed final.

8. Conclusion and future roadmap

The work completed to date as part of Project mBridge demonstrates that a tailored multi-CBDC platform solution to tackling the limitations of today's cross-border payment systems is a realistic and achievable goal. By providing a shared platform on which participants can conduct peer-to-peer payments directly in the safety of central bank money across multiple jurisdictions, the mBridge pilot and accompanying analysis confirmed that a common multi-CBDC platform can improve cross-border payment speed and efficiency, reduce settlement risks and support the use of local currencies in international payments. All of this was accomplished while taking into careful consideration any potential policy, macroeconomic, regulatory and legal implications.

Equipped with the lessons from the pilot and earlier phases of the project, Project mBridge will continue its work. This includes the technology-build and testing – including improving on existing functionalities and adding new functionalities to the platform – in an effort to move from the current pilot phase towards MVP and eventually a production-ready system (see appendix on project stages).

In 2023 and 2024, the roadmap for mBridge will focus on the following:

- achieving automated interoperability with domestic payment systems;
- integrating FX price discovery and matching into the platform;
- introducing liquidity management tools such as transaction queueing and priority management;
- evaluating the role of central bank participants in providing liquidity;
- improving data privacy-preserving tools;
- continuing to develop the legal framework, and platform terms and conditions;
- taking further inventories of policy, regulatory and compliance considerations;
- evaluating decentralised deployment through a lens of data-privacy and legal considerations, and in tandem determining the remit and structure of a centralised governance role;
- testing and piloting more business use cases and transaction types;
- including additional jurisdictions and participants; and
- exploring more services that the private sector can add to the platform.

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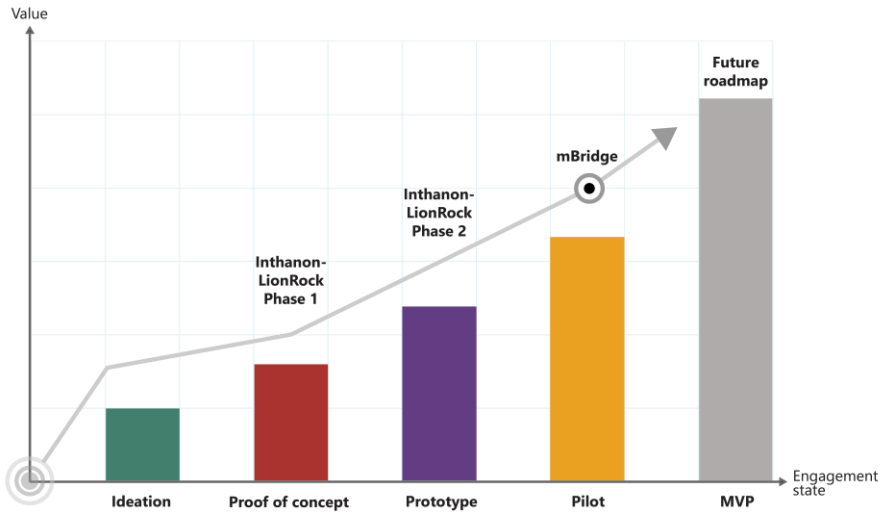
Appendix: Project stages

Proof-of-concept (PoC)**:** a method to test and validate a technology or approach within a limited time window. It typically has less functionality than a prototype. The experience and knowledge gained from a PoC informs on the feasibility of the product. A PoC is comparable to research when it is not clear whether an idea can be brought to life and whether to proceed with the development of the product.

Prototype: While a PoC focuses on one or just a few aspects of a product, a prototype is a working model of several aspects of the product. A prototype is comparable to a draft of a full product and is built to test the product's design, usability, and often functionality. While a PoC is typically used only internally, a prototype can also be used to attract users. Furthermore, it forms a basis for a minimum viable product. While the main goal of a prototype is testing, building a prototype helps to get a preview at how real people interact with a product. The development team can gather users' feedback and make changes to the prototype or create a new one. Prototyping is also useful for idea generation.

mBridge path towards a production setting — Graph A1



Source: Project team's adaption of Giblin et al (2021).

Pilot: Pilots are often used as the first stage of a new policy or service rollout. Rather than a test or experiment, pilots are a 'live' activity, usually with a small group of real users receiving the new service.

Minimum viable product (MVP): a minimum version of a final product and is delivered to the market right away. It is typically simple, appealing, and bug-free. An MVP is a version of a product that has just enough features to stay viable. It only has the core functionality. Delivering an MVP to the market allows for immediate feedback on the product's value. See BIS Innovation Hub et al (2021a) and Giblin et al (2021).

Appendix: Technical design

Blockchain API interface

The API interface described in Table A1 below is the API for the mBridge ledger. This API is the API between the application layer and the blockchain. These APIs invoke smart contracts on the blockchain. The ISO 20022 compliant API at the application layer is not detailed here.

API interface — Table A1

Use case	API ID	Function
Issuance mode 1: issuance initiated from mBridge	API-1.1	Issuance request
	API-1.2	Compliance check result
	API-1.3	Off-bridge payment system execution result
Issuance mode 2: issuance initiated from off-bridge payment system	API-2.1	Issuance request
Redemption mode 1: redemption initiated from mBridge	API-3.1	Redemption request
	API-3.2	Compliance check result
	API-3.3	Off-bridge payment system execution result
Redemption mode 2: redemption initiated from off-bridge payment system	API-4.1	Redemption request
	API-4.2	Institutional confirmation information
Cross-border payment	API-5.1	Payment request
Foreign exchange	API-6.1	PvP request
Onboarding	API-7.1	Add/modify onboarding request
Onboarding	API-7.2	Approve onboarding request

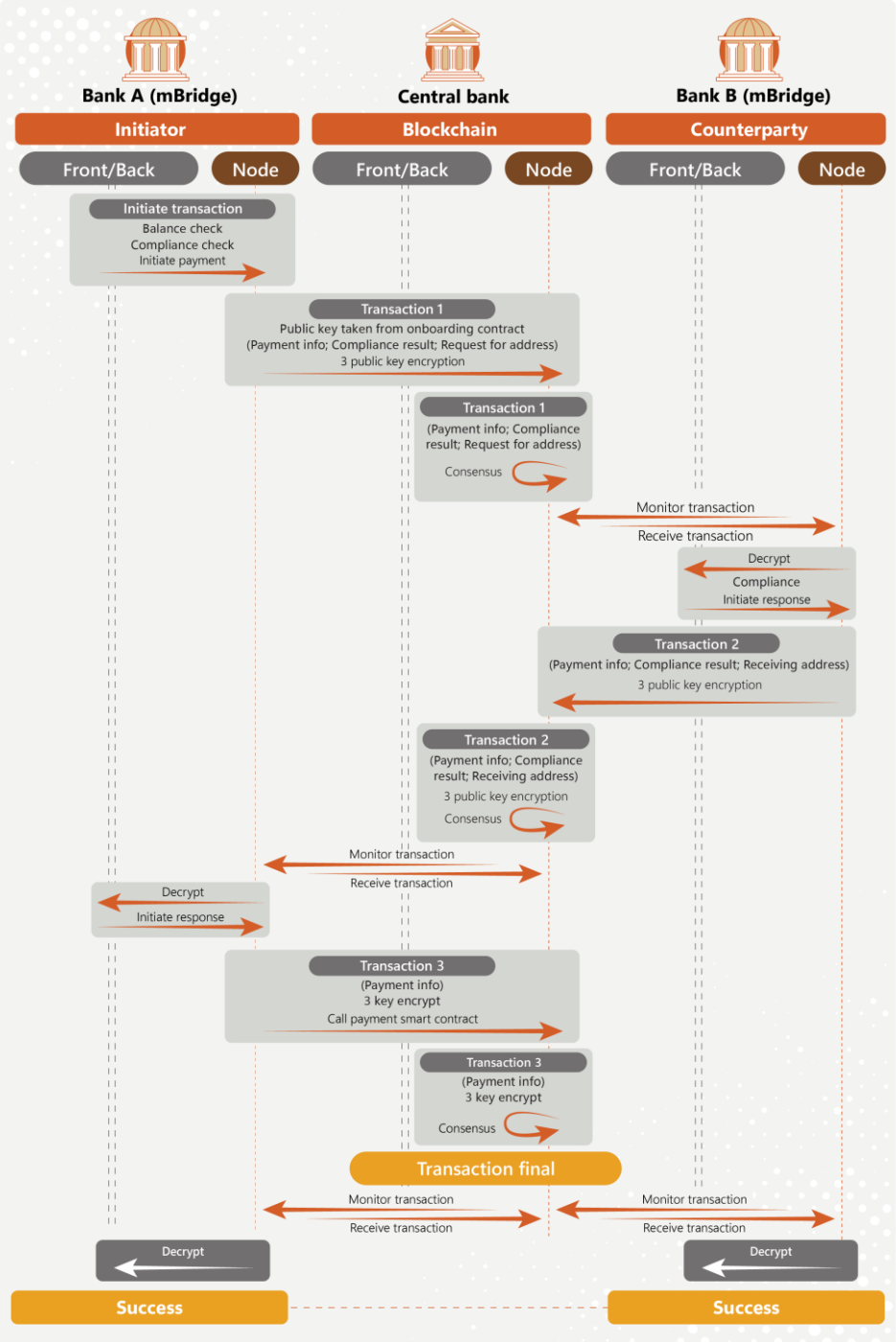
Technology stack

Technology stack — Table A2

Components	Implementation	Description
Core framework	Java Spring Boot	Mainstream Java frameworks
Microservices framework	Spring Cloud	Mainstream Microservices framework
Distributed task scheduling	Quartz	Open-source industry standard library
Service registry	Eureka	Spring Cloud registry
Operating system	CentOS	Mainstream server-side operating systems
Backend service database	MySQL	Mainstream relational database
JDK	OpenJDK8	Mainstream stable version of the JDK
Load balancing	Nginx	Mainstream web servers and software load balancers
Smart contract language	Solidity	Mainstream smart contract language
Blockchain virtual machine	EVM	Mainstream blockchain virtual machine engine
Blockchain consensus protocol	HotStuff+	Top performing O(n) consensus
Key-value storage	RocksDB	Mainstream data storage methods

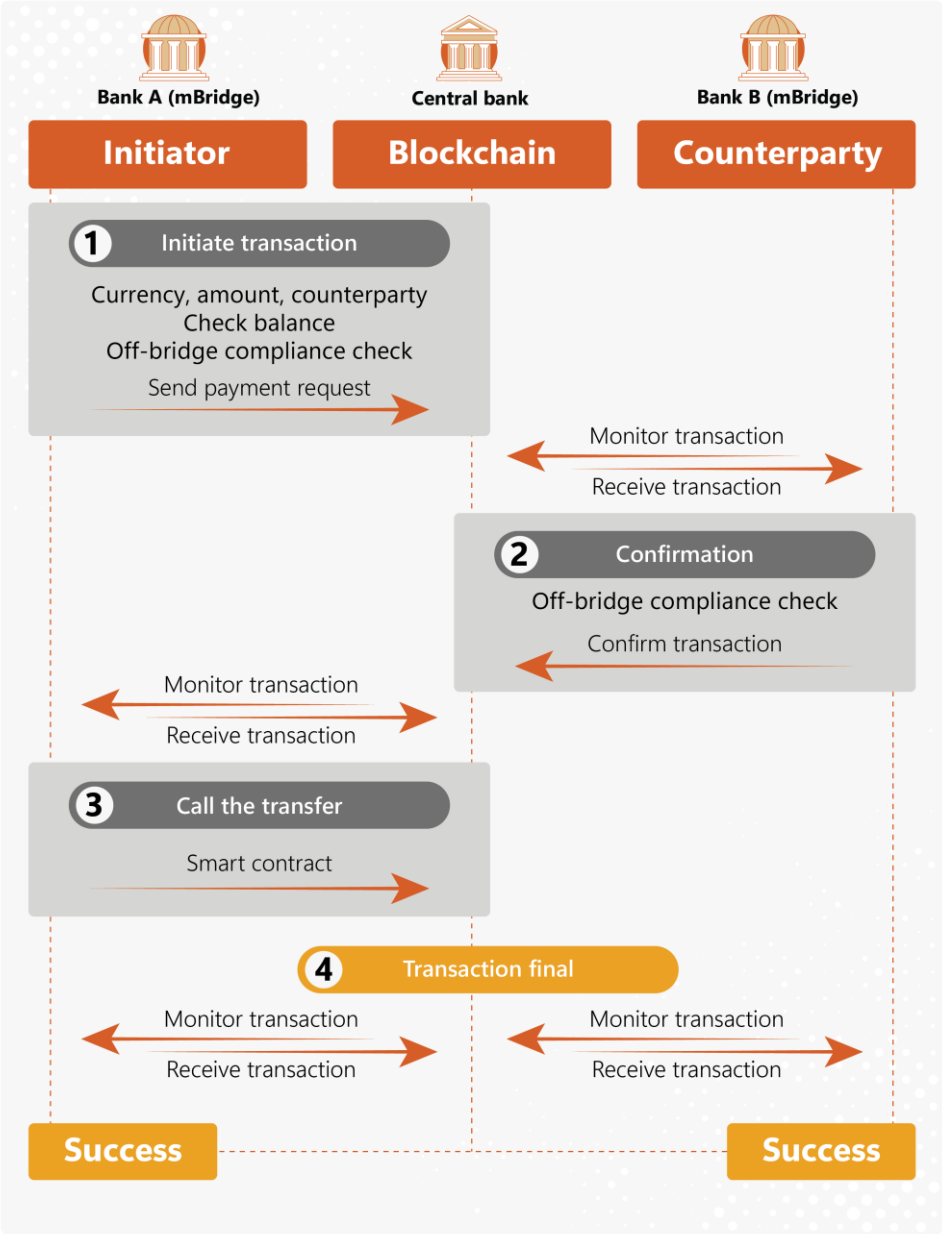
Pseudo-anonymous key pair signing

Pseudo-anonymous key pair signing — Graph A2

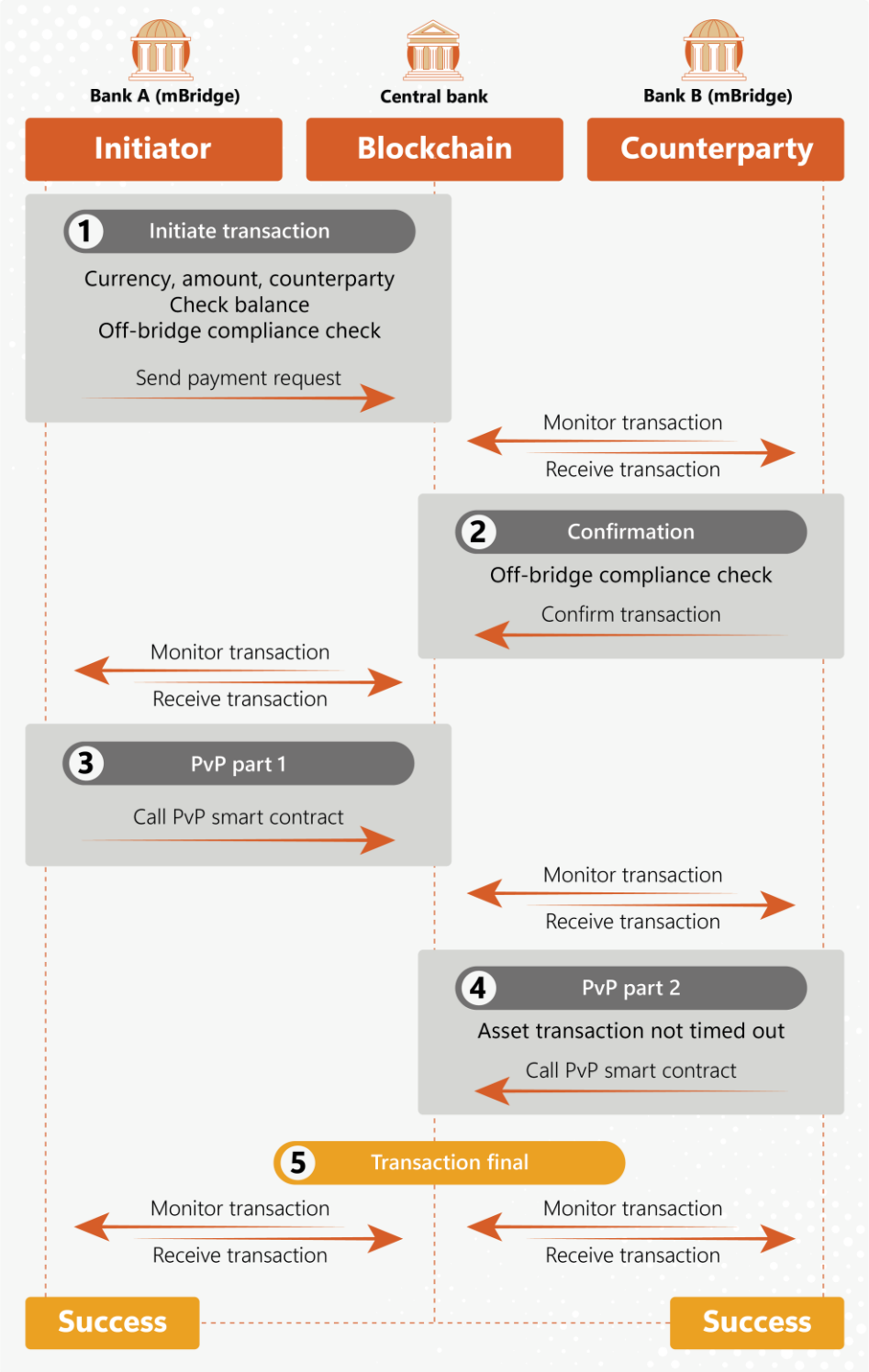


mBridge payment and FX PvP flow

Payment flow — Graph A3



FX PvP flow: Graph A4



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China Construction Bank

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