BIS Innovation Hub

Project Rialto – Technical report

Improving instant cross-border payments using central bank money settlement

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Executive summary

Project Rialto was a collaboration between the BIS Innovation Hub, the Bank of France, the Bank of Italy, the Bank Negara Malaysia (Central Bank of Malaysia) and the Monetary Authority of Singapore.

The experiment targeted foreign exchange (FX)- and settlement-related frictions in retail cross-border payments (see the interim report in BISIH et al (2025)). The goal of the project was to demonstrate the technical feasibility of connecting non-tokenised payment systems with tokenised FX and settlement. The proof of concept (PoC) presented in this report integrated retail cross-border payments using interlinked instant payment systems, automated FX scheme leveraging automated market makers (AMMs) and tokenised central bank money (CeBM) as a safe settlement asset.

The PoC successfully tested a direct transaction between senders and receivers in different jurisdictions and in different currencies. It also successfully tested a transaction with a vehicle currency to address cases that involve low-liquidity currency corridors or cases in which a third currency is needed to facilitate the exchange. These two types of transactions constituted the main scenario for the PoC. In addition, variations from the successful transaction path were analysed to ensure that, even in cases of errors, malicious activity or disruption events, the integrity and resilience of the Rialto architecture were maintained.

This technical report also describes the principles and key trade-offs that need to be considered to evaluate the viability of AMM in combination with tokenised CeBM from an economic perspective vis-à-vis existing arrangements in the retail cross-border payments market segment. The key economic dimensions that would determine the viability of using AMM in an operational context are its fee structure and overall transaction costs, its performance under different market conditions, the potential impact on transparency and market integrity, and the impact on market liquidity and efficient capital utilisation by financial institutions.

The Rialto experiment proved that it is possible for retail market operators to access a technical solution that combines payment versus payment (PvP), automatic FX and settlement in tokenised CeBM with only minimal changes to current arrangements.

Acronyms, abbreviations and definitions

AMM	Automated market-maker. Decentralised exchange using a bonding curve and a liquidity pool to price and exchange tokenised assets
AML/CFT	Anti-money laundering and combating the financing of terrorism
API	Application programming interface
CeBM	Central bank money
CEX	Centralised exchange
DAO	Decentralised autonomous organisation
DCA	Dedicated cash account
DeFi	Decentralised finance
DEX	Decentralised exchange
DLT	Distributed ledger technology
EUR	Euro
FSB	Financial stability board
FX	Foreign exchange
FXP	Foreign exchange provider
Gas fee (network fee)	A fee required to successfully conduct a transaction on a blockchain platform
GDP	Gross domestic product
IPS	Instant payment system
Liquidity pool	A smart contract with the ability to hold and transfer tokenised assets based on a pre-defined logic
On-chain, off-chain	On-chain (off-chain) usually refers to data that are stored and processed on (outside) a blockchain
PoC	Proof of concept
PSP	Payment service provider
PvP	Payment versus payment
P2P	Person to person
SAP	Settlement access provider
SGD	Singapore dollar
Smart contract	A program stored on a distributed ledger technology (DLT) platform that executes based on a pre-defined logic
SO	Settlement orchestrator
State machine	A computational model that defines a set of states and specifies how the system transitions from one state to another in response to inputs or events
TIPS	TARGET Instant Payment Settlement
Tokenisation	The process of recording claims on real or financial assets that exist on a traditional ledger onto a programmable platform
XDN	Cross-border DLT network used for the exchange of tokenised central bank money in different currencies

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1. Introduction

What is the potential of automated FX technology, such as AMM, to reduce the costs of low-value cross-border payments? Project Rialto assessed how such technologies could underpin existing private sector infrastructures. The experiment targeted foreign exchange- and settlement-related frictions in retail cross-border payments. It demonstrated the technical feasibility of private sector retail cross-border payments using interlinked instant payment systems (IPS) together with an automated FX market using tokenised CeBM as the safe settlement asset.

Project Rialto was a collaboration between the BIS Innovation Hub, the Bank of France, the Bank of Italy, the Bank Negara Malaysia and the Monetary Authority of Singapore.

> *"Project Rialto demonstrated the technical feasibility of retail cross-border payments using interlinked IPS together with automated FX market using tokenised central bank money as the safe settlement asset."*

More than $800 billion worth of transactions take place every year in the retail cross-border payments market. Despite their growing size and importance, retail cross-border payments lag domestic ones in terms of cost, speed, access and transparency because of the complex processes they involve (FSB (2020)).

Rialto focused on low-value use cases such as remittances and other person-to-person payments executed via the traditional private sector banking system. Despite ongoing efforts to reduce the inefficiencies associated with such payments, FX and settlement remain key frictions (FSB (2024)). This is especially true in those transactions that involve less liquid currency corridors and those that are executed using traditional payment means such as bank transfers. Both types of remittance transactions are in fact characterised by relatively high average costs, according to recent estimates (World Bank (2024)). As the market strives to look for more efficient options, there has been an increasing focus on same-day or even instant payment-versus-payment (PvP) solutions that allow for fast and reliable access to liquidity in foreign currency (CPMI (2023)).

Rialto's technical experiment combined PvP with CeBM settlement in a simulated cross-border payment infrastructure by building on previous works conducted by the BIS Innovation Hub.[1] The PvP mechanism for FX transactions could help reduce the need for pre-funding to cover asynchronous settlement legs. Settling these PvP obligations in tokenised CeBM enhances finality by using the safest form of settlement asset. The Rialto PoC successfully integrated simulated interlinked IPS together with a cross-border DLT network for automated FX and settlement in tokenised CeBM. The goal of the experimental architecture was to reduce FX- and settlement-related frictions through an improved transaction chain that could help private market operators reduce the costs associated with these frictions in the future retail cross-border payments market.

1. Project Nexus (BISIH et al (2023b)) experimented with multilateral interlinking of domestic instant payment systems. Project Mariana (BISIH et al (2023a)) demonstrated tokenised CeBM and AMM on a cross-border DLT network. Project Rialto combines these concepts, enabling instant cross-border payments by interlinked domestic instant payment systems (as in Nexus) and automated FX using a safe settlement asset (as in Mariana). For more details, see the Rialto interim report (BISIH et al (2025)).

While the project's interim report (BISIH et al (2025)) described the background, scope and initial technical and policy considerations, this technical report describes the Rialto PoC, its technical architecture and design (sections 2 and 3) as well as the economic considerations arising from the experiment that determine the viability of the Rialto technical approach (section 4). Section 5 concludes.

2. Project overview

Project Rialto focused on two types of transactions: (i) a direct person-to-person (P2P) transaction operated by private sector payment service providers (PSPs) in different jurisdictions and in different currencies; and (ii) a transaction involving a vehicle currency addressing low-liquidity currency corridors and other cases in which a vehicle currency is needed to facilitate the exchange. These two types of transactions constituted the main scenarios. In addition, variations from the successful transaction path were analysed to ensure that, even in cases of errors, malicious activity or disruption events, the integrity and resilience of the architecture are maintained.

The Rialto architecture involved two integrated technical blocks. The first block included the domestic or regional IPS systems and the IPS interlinking mechanism (IPS link) where transactions were processed, cleared and settled in fiat money (block 1). The second block included an experimental cross-border DLT network (XDN)[2] where the FX trading and conversion and the related settlement in tokenised CeBM took place (block 2).

> *"A cross-border DLT network was used by settlement access providers for the exchange of tokenised central bank money in different currencies."*

2.1. Expected benefits

The key frictions targeted in Rialto are FX- and settlement-related frictions. The conceptual setup of Project Rialto promises several benefits in these two domains by using PvP, settlement in tokenised CeBM and an innovative handling of the FX trading and conversion processes.

The Rialto architecture can increase efficiency by automating and securing the orchestration of the currency exchange in an atomic transfer. Furthermore, the use of CeBM as a safe settlement asset significantly reduces credit and liquidity risks.[3] Contrary to the complexity of nostro and vostro accounts[4] in correspondent banking, in Project Rialto intermediaries only send or receive CeBM directly across all jurisdictions involved via the XDN. Additionally, as a result of the atomic transfer, settlement risk may be mitigated because the technical orchestration of the FX ensures safe settlement processing through PvP.

The FX mechanism in Rialto was designed as a modular component that interacted with specialised intermediaries operating within the Rialto architecture (foreign exchange providers (FXPs)). This modular approach broadens private sector participation, keeps central bank operational involvement minimal, and supports interoperability. It enables incremental adoption, lowering barriers for both large and small financial institutions.

2. The concept of a XDN or transnational network was introduced in Project Mariana (BISIH et al (2023a)) and subsequently referenced in the Rialto interim report (BISIH et al (2025)).
3. PFMI Principle 9 requires that "an FMI should conduct its money settlement in central bank money, where practical and available, to avoid credit and liquidity risks". See also footnote 19.
4. Nostro and vostro accounts are wholesale bank accounts used by financial intermediaries in the context of remittances and foreign exchange transactions.

When combined, the above characteristics of the Rialto architecture provide the possibility to reduce the costs of retail cross-currency payments by reducing FX- and settlement-related frictions.

2.2. Project scope

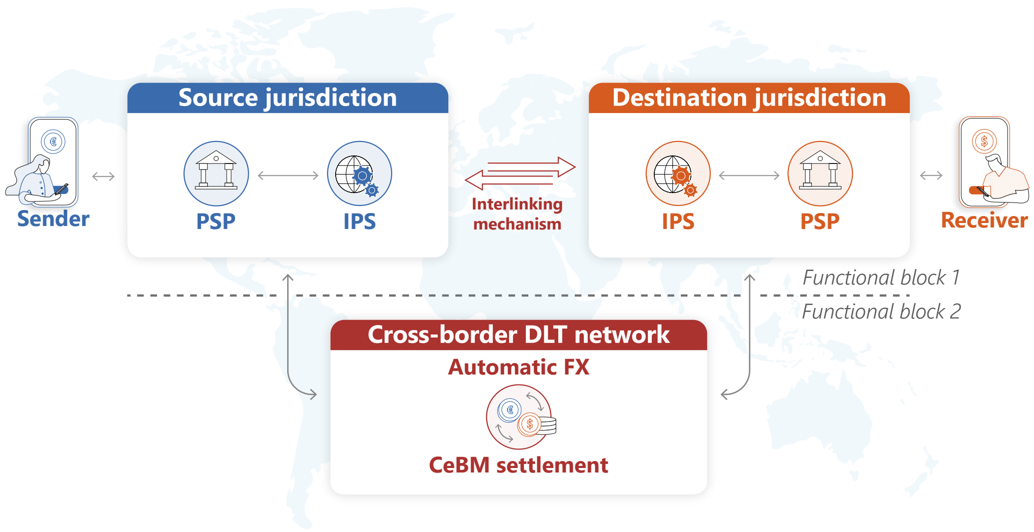
As part of the project scoping, the following functional requirements were identified for the technical solution:

- Enabling end-to-end transaction settlement in near real time on a PvP basis, minimising potential reconciliation efforts that might arise if certain processes fail.
- Providing the sender with a transparent view of the offered exchange rate and service fees. The sender can either specify an exact amount to be sent or an exact amount to be received with full transparency over the equivalent amount.
- Adopting the standard practices of instant payment schemes globally for the involved IPS, with the communication flow across jurisdictions aligned to international standards for cross-border payments (eg TARGET Instant Payment Settlement (TIPS) cross-border services).[5] Intermediaries should communicate based on the ISO 20022 payment, clearing and settlement (pacs) message standards, mainly pacs.008 and pacs.002 messages, to orchestrate payment instructions and accept, reject or provide further reports, respectively.[6]
- Integrating Rialto's automatic FX layer with an instant payment interlinking mechanism, developed based on the hub design of Project Nexus (BISIH et al (2023b)). While the project experimented with this model, the design could theoretically be expanded to support bilateral IPS connections. Key features include the fee model for PSPs, message specifications, quote validation and message transformations between IPSs across jurisdictions.
- Ensuring the approach works with existing PSPs without requiring them to connect to the XDN or to have a wallet.[7]

The overall architecture was designed for robustness, security and flexibility, accommodating potential discrepancies or interoperability challenges between the conventional instant payments market infrastructures and the next-generation XDN. Graph 1 shows a high-level representation of the Rialto architecture, with its two main blocks: block 1 (which includes the IPS link) and block 2 (which includes the XDN).

5. More information on TIPS and Eurosystem cross-border payments initiatives is available at www.ecb.europa.eu/paym/target/tips/crossborder/html/index.en.html.
6. For the PoC, the message versions pacs.008.001.13 and pacs.002.001.15 were adopted, together with common usage guidelines specifying mandatory data elements and validation rules.
7. In the Rialto architecture, PSPs can access an IPS either directly or via an SAP.

Rialto high-level functional architecture – Graph 1



The transaction flow assumed that the sender and receiver of a payment are retail customers of different PSPs, each located within their own jurisdiction. To facilitate instant cross-border payments, Project Rialto required at least one intermediary to operate on both the domestic IPS and the XDN infrastructure. Payment messages exchanged between the sender's PSP and the receiver's PSP were routed through an IPS link of the hub type, resembling the Nexus architecture. The IPS link supported the clearing and settlement of instant payment messages and respective instructions.

The introduction of the XDN was required for the efficient exchange of currencies at the wholesale level. The XDN leveraged distributed ledger technology (DLT), enabling intermediaries to exchange tokenised CeBM. Accordingly, the FX settlement did not occur directly on any central bank's balance sheet but was instead facilitated through an automated FX module. This effectively eliminated the operational overheads of settling transactions for any central bank.[8]

8. Central banks would eventually be involved in the redemption of CeBM tokens used by financial intermediaries in the Rialto technical approach.

3. Technical solution design

This section provides an overview of the key design decisions taken during the development of the PoC. It further describes the main transaction scenarios tested and related robustness checks. Finally, the section includes considerations related to the main lessons learned from the experiment from a technical perspective.

3.1. Key design decisions

The functional requirements were translated into the following key design decisions.

On- and off-ramping

SAPs were introduced to serve as access points to the XDN for PSPs. Since small and mid-sized financial institutions are often restricted from offering DLT operations due to high implementation costs, the SAPs provided PSPs with access to the XDN. Particularly, the SAPs provided on- and off-ramping services to PSPs by being credited on their dedicated cash account (DCA) and exchanging tokenised CeBM within the XDN.[9]

> *"The SAPs provided on- and off-ramping services to PSPs by being credited on their dedicated cash account and exchanging tokenised central bank money within the XDN."*

AMM currency exchange

The decision to adopt an AMM model over DLT-based central limit order books (CLOBs) or hybrid venues was driven by the AMM model's operational simplicity and robust security.[10] In fact, AMMs offer continuous liquidity to a single counterparty, that settles on the ledger in near real time, eliminating the need for specialised matching engines and high-availability infrastructure. Additionally, widely audited, open-source AMM frameworks enable rapid integration while providing secure and reliable FX functionality.

For the automated FX module, a tick-based constant product AMM (Uniswap v3) was chosen to leverage its capital-efficiency advantages and support dynamic liquidity management. By enabling market-makers to allocate liquidity within self-defined price ranges, the AMM decentralises concentration decisions – allowing the market, rather than a central operator, to determine the optimal distribution of liquidity along the bonding curve. Its fee tier structure provides a flexible mechanism to model different spreads, which can be layered in later without modifying the core smart contracts. In essence, the

9. The experiment focuses on instances in which a PSP needs the on- and off-ramping services provided by SAPs. In principle, it is also possible that certain PSPs might have these capabilities and act as SAPs. Similarly to Project Nexus (BISIH et al (2023b)), to be an SAP a financial institution must be a member of the local IPS. Therefore, all SAPs are also PSPs by definition (but not all PSPs are SAPs).
10. See Table 1, Project Rialto interim report (BISIH et al (2025)).

AMM delivers the right balance of concentrated liquidity, market-driven flexibility and low governance costs for the PoC.

Rate slippage coverage

Given the algorithmic calculation of quotes based on an AMM's liquidity pool, there may be a mismatch between the rate provided and the rate executed for currency exchange.[11] Since, by their nature, AMMs cannot guarantee a specific exchange rate, an FXP was introduced for Rialto to cover such rate slippage and provide a quote to the IPS link. The FXP serves as a critical intermediary with two primary functions. First, it manages FX quotes by receiving quote requests from the IPS link, by retrieving exchange rates from the AMM and providing binding quotes to the IPS link. Upon doing so, the FXP commits to honouring this quote. Second, during the atomic transfer, if negative slippage occurs, ie the AMM cannot fulfil the agreed rate, the FXP covers the shortfall with its own reserves to ensure the receiver gets the exact committed amount. In compensation, the FXP can keep additional exchanged currency if the AMM slips to the benefit of the exchanged currency. This mechanism not only guarantees price certainty but also shifts the burden of slippage risk from the SAP to the FXP. In return, the FXP adds a spread and/or charges a fee for managing quotes and absorbing the associated exchange risk. This design reinforces reliability and predictability in cross-border currency exchanges within the system.

Earmarking funds

Due to the separation of the functional blocks and the absence of a single intermediary with full end-to-end visibility, there could be a risk that payments may be initiated without assurance that the entire transaction can be successfully processed. This risk could lead to considerable reconciliation efforts, particularly in case of reverting the AMM FX conversion. Since the AMM cannot guarantee a quote, reverting the transaction may be impractical.

To mitigate this risk, an earmarking mechanism at the S-IPS was introduced to block the necessary funds before initiating the transfer on the XDN. Using this earmarking scheme, the transaction proceeds only if all preconditions are met: the transaction on the XDN is successfully executed and the D-IPS settles the corresponding transfer on the destination side. If the transaction on the XDN fails, the earmarked funds are released, and no settlement occurs. This mechanism ensures settlement integrity across multiple independently settled components and enables prevalidation before initiating the on-chain transfer. It also supports automatic rollback in case of rejections or timeouts, executing settlement only when all conditions are fulfilled. Given the short execution time of instant payments, the impact of blocked liquidity was deemed less disruptive than the operational complexity associated with reconciliation errors.

11. The functioning of AMMs in the context of wholesale cross-border payments is discussed in Project Mariana (BISIH et al (2023a)).

Two-phased DLT settlement

To mitigate unilateral debit risk, source and destination SAPs (abbreviated as S-SAP and D-SAP, respectively)[12] must provide consent before any funds are moved. The process begins with the S-SAP initiating settlement by supplying the amounts, currency addresses and a unique end-to-end transaction reference (UETR) that identifies the Rialto transfer. The D-SAP must then validate this record; if either party disagrees, no CeBM is transferred. Once validated, the FXP receives the source funds and triggers the FX swap and subsequently the transfer of destination CeBM to the D-SAP.

Finality

Given the hybrid architecture involving traditional IPS and DLT-based currency exchange, settlement processes are tightly interlinked and require precise coordination. The successful exchange and transfer of tokenised CeBM from the S-SAP to the D-SAP constitutes an irreversible transaction recorded on the XDN. Finality was achieved when the D-SAP confirms the receipt of funds on the XDN.[13] As a consequence, subsequent payments are initiated only after settlement on the XDN was successfully completed. Establishing finality at the point of interaction between the D-SAP and D-IPS ensures both transaction certainty and orderly sequencing across the two infrastructure layers.

Vehicle currency integration in the atomic transfer

In corridors with limited FX liquidity, direct currency exchanges can incur high costs, wide spreads and increased settlement risk. To address these challenges, Rialto's technical experiment demonstrated how vehicle currencies can also be used in an AMM mechanism to facilitate FX transactions. Instead of relying on direct conversions between illiquid currency pairs, trades were executed in two legs via a more liquid intermediary currency. This approach enhances rate stability, improves execution reliability and expands corridor coverage – while minimising dependence on direct FX markets and avoiding additional complexity when transacting with less liquid currencies.

> *"In corridors with limited FX liquidity, direct currency exchanges can incur high costs, wide spreads and increased settlement risk. To address these challenges, Rialto's technical experiment demonstrated how vehicle can also be used in an AMM mechanism to facilitate FX transactions."*

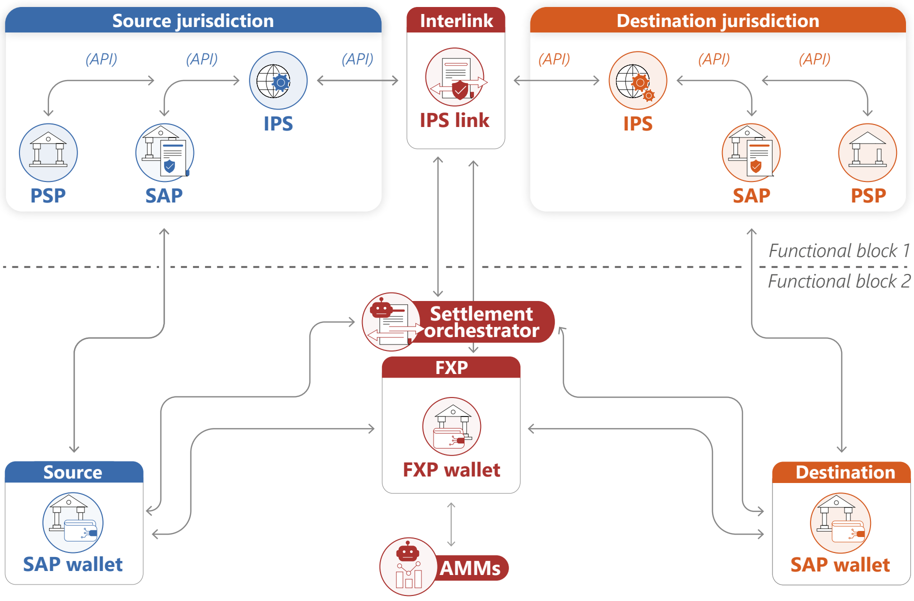
12. Similarly, we refer to PSP or IPS in the source (destination) jurisdiction as S-PSP (D-PSP) and S-IPS (D-IPS).
13. While the absence of an earmarking mechanism at the destination side may introduce counterparty risk on the D-SAP, this is considered to have limited impact given the retail nature of the transaction.

3.2. Functional architecture

The functional architecture of the experiment is illustrated in Graph 2. In this architecture, both PSPs act as the entry and exit points of the payment flow. interface with end users, initiate and receive payment instructions, handle compliance checks and ensure that funds are blocked/debited (source) or credited (destination) based on the success of the precedent transactions.

SAPs provide on- and off-ramping services to PSPs and prepare and execute settlements on behalf of PSPs within their jurisdiction. They act as key orchestrators between the traditional payment infrastructure and the DLT layer since they offer DLT access to PSPs that might lack it. In this sense, SAPs serve as the trusted bridge between tokenised CeBM settlement and traditional domestic clearing. The S-SAP prepares the on-chain transaction, while the D-SAP validates it to trigger the atomic transfer. Once the D-SAP receives tokenised CeBM, it confirms finality – initiating subsequent instant payments.

Rialto functional architecture – Graph 2



The IPS in each jurisdiction functions as the domestic clearing and messaging layer, ensuring real-time processing and finality of instant payments. IPSs route messages, using XML-based ISO 20022 message, manage the DCAs of PSP and SAP, and provide instant settlement. Additionally, they interface with the IPS link for cross-border coordination, ensuring that transactions are processed securely and coherently across jurisdictions.

All messages between intermediaries in functional block 1 are transmitted via custom API and pacs messages.[14] The communication between PSPs and SAPs are always routed via their domestic IPS, supporting a standardised approach for message exchange.

14. A detailed description is available in the Functional annex.

While the IPS link has the main responsibility of allowing the transfer and conversion of payment messages between the S-IPS and the D-IPS, it also holds two key auxiliary responsibilities. For one, the IPS link forwards requests for quotes to an FXP and calculates all necessary fees, exchange rates and interbank settlement amounts, supporting the S-PSP to populate pacs messages.[15] Second, the IPS link validates the pacs message sand transforms pacs messages into the other jurisdiction's expected format. As the Rialto architecture uses two distinct settlement layers, the IPS Link verifies, upon receipt of the payment instruction, that the transaction details match the settlement record created on-chain.

The FXP acts as a specialised intermediary responsible for facilitating the foreign exchange component of a cross-border payment. It has access to multiple tokenised CeBM currencies. Its core responsibilities include the generation and provision of binding FX quotes in response to payment requests and coverage of potential rate slippage. The FXP ensures that the correct amount of destination currency is delivered according to the agreed quote, supporting price certainty and stability in the transaction.

On top of the XDN layer is a neutral, trusted settlement orchestrator (SO) smart contract that ensures all settlement steps follow a common transparent set of rules. By removing bilateral dependencies, the SO significantly reduces counterparty risk and strengthens overall confidence in the system. The SO transmits standardised events at each critical step, thus allowing synchronisation across the distinct infrastructure layers.

"On top of the XDN layer is a neutral, trusted settlement orchestrator (SO) smart contract that ensures all settlement steps follow a common transparent set of rules."

The AMM is an on-chain liquidity mechanism that facilitates real-time currency exchange between tokenised CeBM of different jurisdictions. It uses predefined algorithms and liquidity pools to calculate and execute FX conversions without requiring a centralised order book or manual pricing. When a cross-border transaction is requested, the AMM determines an exchange rate based on current pool balances and later executes a swap. The AMM enables continuous, algorithmic price discovery and efficient currency conversion within the DLT infrastructure, compared with more cost-intensive traditional FX exchanges.

15. Compared with Project Nexus, in which FXPs regularly push quotes to the IPS link, in Rialto the IPS link pulls quotes from the FXP on demand.

3.3. Transaction sequence

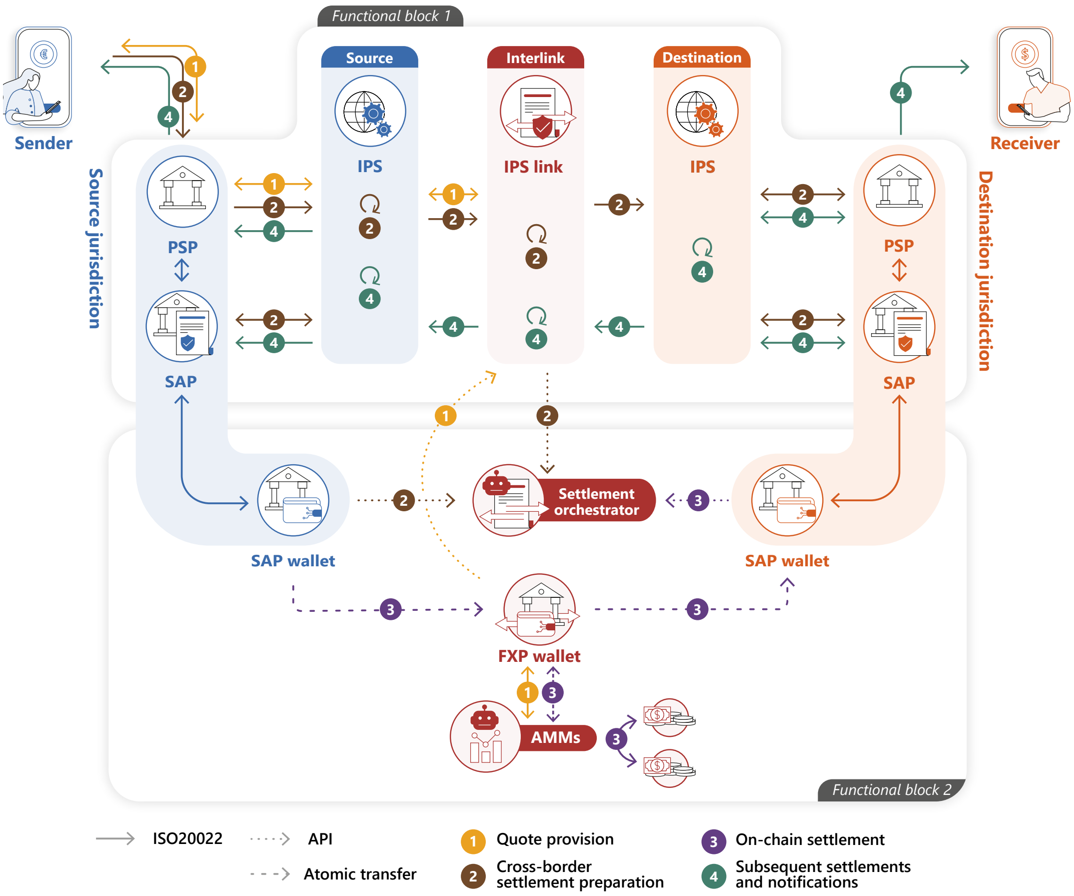
A Rialto cross-border payment transaction can be divided into four segments. These are (1) quote provision; (2) cross-border settlement preparation; (3) on-chain settlement; and (4) the subsequent settlements and notifications (Graph 3).

Segment 1: Quote provision

- Before initiating a payment, the sender provides necessary transaction details, including the receiver's bank account, destination country, currency and amount. Also, a proxy resolution leveraging phone numbers can extract receiver specifications. The sender may specify either the amount to be sent in their local currency or the exact amount to be credited to the receiver in its respective currency. With this input, the S-PSP has sufficient data to request a quote via the IPS link. This request is sent as a custom message via the S-IPS, streamlining communication between intermediaries and the IPS link.

- Upon receipt, the IPS link queries the FXP to retrieve a binding quote. The FXP leverages the AMM to provide a quote, given the requested parameters. The quote, along with relevant information such as a transparent view on service fees, the D-SAP, FXP and their associated DLT addresses, is returned to the S-PSP via the S-IPS. With this information, the S-PSP can present the full payment specification to the sender.

Direct transaction sequence diagram – Graph 3



Segment 2: Cross-border settlement preparation

- Once the sender accepts and instructs the Rialto payment, the S-PSP blocks the intended amount on the sender's balance and constructs a pacs.008 message, embedding the full end-to-end transaction data. The message is then transmitted through the S-IPS to the S-SAP.[16] Upon reviewing and accepting the transaction conditions, the S-SAP prepares the atomic cross-currency transaction on the XDN by following the SO's orchestration guidelines. Once the setup is successful, the S-SAP sends a pacs.002 confirmation to the S-IPS. At this stage, no settlement occurs, but the S-IPS is informed that its participants have accepted the payment conditions.

- Next, the S-IPS forwards the pacs.008 message to the IPS link. The IPS link validates whether the quote initially communicated for the quote provision matches the quote of the pacs message. Additionally, it must also ensure that the pending DLT-based exchange constitutes the same amounts. Therefore, it retrieves the values from the SO and validates whether the amounts on the DLT match the pacs.008 message. After validation, the IPS link transforms the pacs message in a way that is readable for the destination side intermediaries and sends the transformed pacs message to the D-IPS.

- After receiving the transformed pacs.008 message the D-IPS forwards this message to the D-SAP. If the D-SAP accepts the condition of the payment, it can generate its own pacs.008 message to instruct an instant payment from the D-SAP to the D-PSP. After the D-SAP sends the newly constructed pacs.008 message to the D-IPS, the D-IPS forwards it to the D-PSP. If the D-PSP accepts the condition of the Rialto payment, it sends back a confirmation pacs.002 message to the D-IPS. Finally, after all participants have agreed to the conditions of the Rialto payment, the D-IPS forwards the confirmation of the D-PSP to the D-SAP.

Segment 3: On-chain settlement

- Now that all participants have agreed to the Rialto transaction conditions, the D-SAP can trigger the atomic transfer on the XDN by sending a validation transaction to the SO. The SO subsequently orchestrates an atomic transfer in which tokenised CeBM is moved from the S-SAP's wallet to the FXP's wallet, then sent to the AMM smart contract, which takes on the source currency CeBM and sends back an ad hoc calculated amount of destination currency CeBM. If this equals the agreed exchange amount, the FXP keeps a small spread and forwards the newly received tokenised CeBM further to the D-SAP wallet. While there are sequential steps involved, the SO orchestrates these steps in an atomic way, so that either all steps process successfully or none of them are processed.

- When a direct corridor is unavailable or yields uncompetitive rates, the smart contract automatically selects the most cost-effective route – potentially via vehicle currencies – without requiring manual input from intermediaries. Project Rialto extends its atomic transfer logic to support vehicle currencies, preserving PvP benefits even in the absence of direct FX corridors. A second AMM with a distinct liquidity pool enables dual-currency exchanges within a single atomic transaction. This design ensures pricing efficiency and reduces operational complexity in

16. *For the PoC, it is assumed that the PSPs are direct participants of the IPSs.*

low-liquidity corridors.

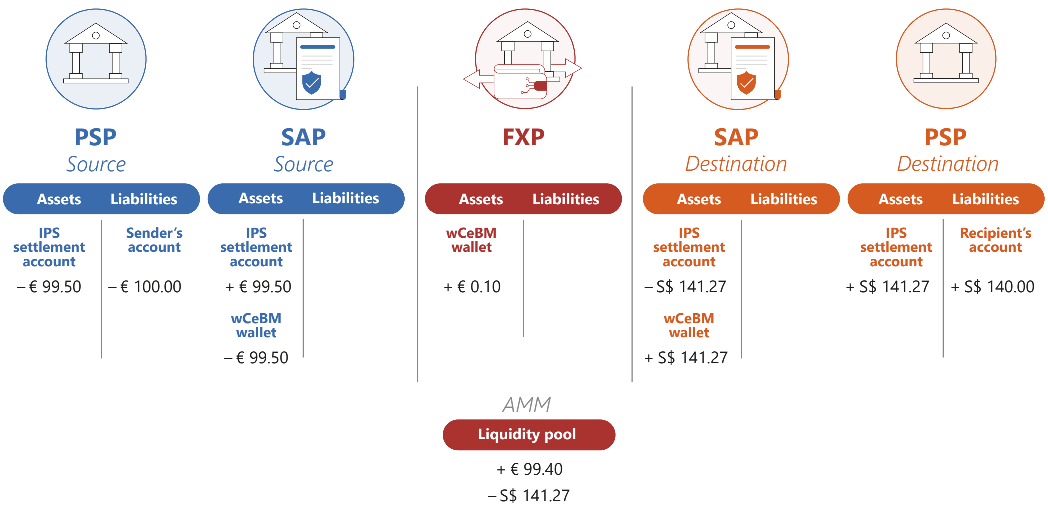
Segment 4: Subsequent settlements and notifications

- After the successful DLT transaction, the D-SAP has received an agreed amount in its wallet and is now obliged to trigger a payment in the same amount to the D-PSP. To trigger this, the D-SAP sends the confirmation of funds received on the DLT to the D-IPS via pacs.002 message. As a result, the D-IPS can now effectively settle and adjust the ledger balance of the D-SAP and D-PSP DCAs. Afterwards, the D-PSP is notified by the D-IPS of its DCA crediting. Accordingly, the D-PSP credits the receiver. Once successfully credited, the D-PSP confirms to the D-IPS that the receiver of the end-to-end transaction has been credited via a pacs.002 message.

- The D-IPS now forwards the confirmation of the successful crediting of the receiver to the D-SAP and the IPS link. For the source side of intermediaries to read the confirmation, the IPS link transforms the pacs.002 message in the expected format and forwards the newly transformed message to the S-IPS.

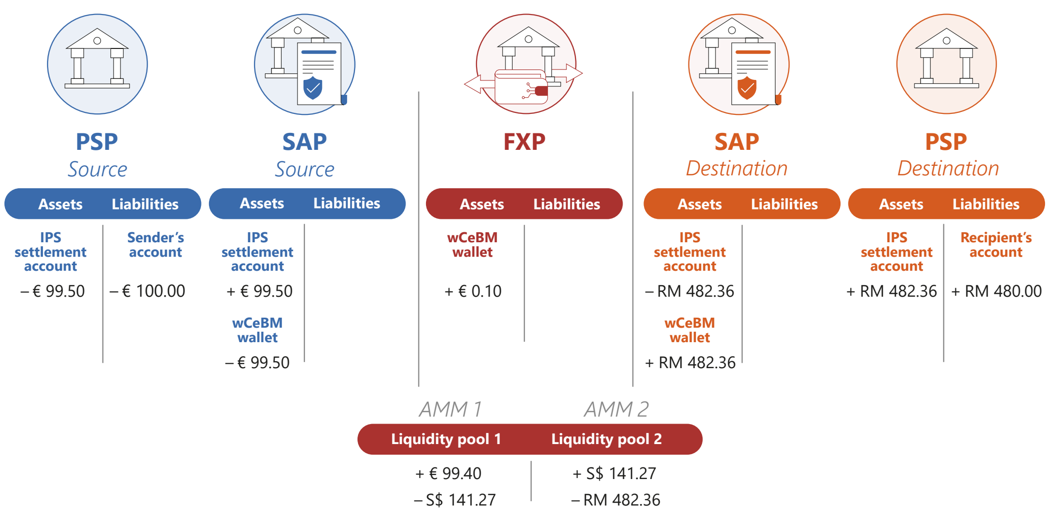
- Upon successful crediting of the receiver, the S-IPS ultimately receives confirmation of the final condition to trigger the settlement between S-PSP and S-SAP in their respective DCAs. Once successfully processed, the S-IPS notifies both the S-PSP and the S-SAP with a pacs.002 message. Subsequently, the S-PSP can now unblock the withheld amount and effectively debit the sender, resulting in the end of the direct transfer for a successful Rialto payment.

Direct transaction balance sheet analysis – Graph 4



Within the four segments described above, certain key moments are identified for the settlement of the end-to-end transaction. First, an atomic transfer on the DLT ensures that currency is exchanged via the AMM, the S-SAP is debited, and the D-SAP is credited. Second, an instant payment is settled between the D-SAP and the D-PSP. Third, after the receiver has been credited, the successful actions are communicated to the S-IPS where the final settlement between the S-PSP and the S-SAP takes place. At last, the S-PSP unblocks the amount and debits the sender. Graph 4 summarises the flows in the balance sheets of the various entities involved. Graph 5 looks at the case of a vehicle currency transaction.

Vehicle currency transaction balance sheet analysis – Graph 5



3.4. Operational resilience

The Rialto's technical design was cross-validated by analysing a number of special cases in addition to the ideal transaction flow. In what follows, some of these special scenarios are described, demonstrating the solution's robustness in the face of events such as compliance failure or a technical disruption.

Compliance failure

This scenario considers the event of a payment rejection due to a negative compliance check at the D-PSP. Reasons for rejection might be based on sanctions screening, anti-money laundering (AML) checks or other types of rejections, such as fraud detection, by the D-PSP.

After receiving the payment instruction, the D-PSP notices a compliance issue and instantly rejects the payment instruction. The pacs.002 rejection messages are sent by the D-IPS to the D-SAP and the IPS link. As no payment has been made yet, blocked liquidity can be unblocked at the D-IPS and the S-IPS level by releasing the withheld balance. The S-SAP will then cancel the initialised settlement.[17] Rejected payments should be immediately notified to the sender.

Rialto's robustness in the case of compliance failure was a direct consequence of the design choices of earmarking funds and two-phased DLT settlement. The transaction sequence flow was designed in a way that no settlement proceeds before all parties agree to the settlement instructions to minimise the reconciliation efforts needed in case of a compliance issue.

Disruption event

This scenario refers to a situation in which the end-to-end Rialto payment fails due to a major disruption event such as a natural disaster, severe conflict, outage, failure, incident or participant default. Under this scenario, three principal situations were identified, and functional solutions were provided for each situation:[18]

1. Disruption event happens before the atomic transaction in XDN was successfully executed. In this situation, any Rialto payment can be rejected or cancelled for any of the mentioned major disruption events.

2. Immediately after the atomic transfer on the XDN successfully occurred, the disruption event happens.

   Since disruptions at this particular time of an end-to-end transaction hinder further processing that lead to settlement obligations, a new atomic transaction in the opposite direction, using the reverted FX currency pair was needed. The sender should not be financially impacted by the disruption: the withheld balance in the sender's account should be unblocked and a transaction failure notification issued. Any positive or negative rate slippage resulting from the reversal should be absorbed by the FX provider's business model, assuming sufficient system liquidity.

17. The D-SAP also has the same capabilities
18. Detailed functional specifications are not included in this report.

3. Disruption happens right after settlement finality has been established at the D-IPS.

   Finality is a foundational concept in a payment scheme because it defines the exact point at which a payment becomes irrevocable and binding, that is, when the transfer of funds is legally completed and cannot be reversed. For this reason, if a Rialto transaction reaches a timeout before the disruption event resolution and, thus, is cancelled, in-flight reconciliation messages should offset the open payment obligations, without taking the timeout into consideration.

In parallel, to minimise reconciliation and dispute impacts, the use of a payment status request (pacs.028) might be considered, as it supports intermediaries to retrieve further information. In turn, this can lead to more complex implementation efforts for intermediaries to adhere to disruption event requirements.

3.5. Lessons learned

Project Rialto's experiment successfully demonstrated the technical feasibility of retail cross-border payments using interlinked IPS together with an automated FX wholesale conversion layer that allows the use of CeBM as a safe settlement asset.

Achieving this result required settlement across two functional blocks with fundamentally different payment and settlement flows to support end-to-end PvP. For this purpose, the experiment has explored a way to integrate existing and next-generation payment infrastructure based on the role played by hypothetical financial intermediaries that have access to both blocks of the architecture (SAPs).

The modular design architecture of Rialto demonstrated that retail market operators can access a solution that combines PvP, automated FX and tokenised CeBM settlement while mitigating key risks, with minimal changes to existing systems. Furthermore, the technical solution has proved that it is possible to minimise reconciliation efforts by allowing settlement to occur only after the involved intermediaries have accepted the payment conditions and the enforcement points have validated the clearing messages.

"The modular design architecture of Rialto demonstrated that retail market operators can access a solution that combines PvP, automated FX and tokenised central bank money settlement while mitigating key risks, with minimal changes to existing systems."

On the side of FX-related frictions, the Rialto PoC uncovered the potential for automated solutions based on smart contracts (and especially a tick-based constant product AMM) to provide instant FX services in the context of retail transactions involving two or three different currencies. The experiment also explored how different AMMs can interact to provide FX trading and conversion services in transactions in which a vehicle currency is needed for the exchange.

AMMs in their current form are unable to commit to a quote; hence, each trade risks experiencing small price deviations from the quoted price (slippage). Retail payment systems, such as the Nexus-based one explored in Rialto, require a guaranteed exchange rate between quote and execution of the trade. To bridge the two systems, the Rialto architecture needed to re-introduce FX providers that guarantee an exchange rate and hence take on the risk of price deviation.

While AMMs proved useful for atomic on-chain FX conversion and reduced liquidity requirements were lower in AMMs with concentrated liquidity, in Rialto architecture, they still require prefunding which introduces new costs and inefficiencies and can impede real application of the approach. CLOBs operated on-chain might be an alternative solution to be explored in future experiments.

Rialto's technical experiment used the testnet of a public layer 2 blockchain to simulate a neutral cross-border DLT. Future experimentation could explore how Rialto's technical approach could be used with other tokenised assets, for example tokenised private money, or other types of DLT networks, and how such an arrangementt could be linked to off-chain settlement in CeBM.

Although the project primarily focused on technical feasibility, it also considered compliance-related aspects. An important additional feature of the Rialto architecture was the possibility for intermediaries in functional block 1 to monitor the real-time state of DLT in functional block 2 by capturing relevant events emitted by on-chain transactions. This finding could be relevant for monitoring the exchange of CeBM tokens on the side of central banks or other regulatory authorities with a payment systems oversight mandate.

4. Economic considerations

This section outlines the economic, legal and governance considerations related to the key trade-offs that determine the viability of the Rialto technical approach. The focus was especially on how such a system based on an automated FX mechanism can be practicable to FX market operators, payment services providers and end users in terms of economic, legal and governance matters.

Compared with current solutions based on over-the-counter (OTC) relationships, the automatic FX solution used in Rialto's technical experiment can provide existing market participants with an additional marketplace for currency exchange in the XDN. In an operational context the performance of this component is determined by different factors, namely its fee structure and transaction costs, its performance under different market conditions, the potential impact on transparency and market integrity, and the impact on market liquidity and efficient capital utilisation on the part of financial intermediaries involved in the payment chain. From an economic viability perspective these four dimensions provide the principles under which the solution proposed in Project Rialto can be assessed vis-à-vis the existing market arrangements.

In Project Rialto, FX services are provided by hypothetical FXPs, which are regulated entities in their specific jurisdiction and are allowed to hold domestic and foreign CeBM for the purposes of multilateral wholesale exchanges with other regulated entities in their respective jurisdictions. Crucially, in Rialto, FXPs work with the support of a hypothetical decentralised exchange (DEX), specifically an AMM,[19] to provide the necessary liquidity and the determination of exchange rates needed for clearing P2P cross-currency transactions.

As described above, several dimensions underpin the economic viability of the Rialto technical solution in the context of this market segment. These dimensions can be viewed as affecting both the demand (senders and receivers of payments) and the supply of cross-border payment services (financial intermediaries). This section looks at the principles that could make the Rialto approach viable from an economic standpoint vis-à-vis the existing arrangements in the retail cross-border market segment.

Two main questions arise. First, how can the introduction of a DEX for the trading of currency pairs in the Rialto model impact consumer welfare? Second, how can such a solution be economically viable in the context of the chosen FMI (interlinked IPS) and specifically how does it affect the profitability of PSPs and FXPs that operate within the system? To answer these questions this section draws on a growing academic literature that studies the efficiency of innovative decentralised exchanges compared with traditional electronic venues[20] and outlines four main areas for further research.

Fee structure and transaction costs

A first key consideration is related to the fee structure and the overall transaction costs in the Rialto technical approach vis-à-vis the remittance market segment. Achieving an efficient balance between improving access and adopting a particular payment instrument for consumers while preserving adequate cost coverage for PSPs is a key trade-off that would need to be taken into account in an operational context. On the one hand, fees compensate intermediaries for the costs and provide them with a fair rate of return on the

19. For the PoC, the DEX chosen for the experiment is a tick-based constant product AMM. However, the interim report also surveys other types of DEX that could be applied in an operational context (BISIH et al (2025)). For an introduction to AMM, see Xu et al (2023) and BISIH et al (2023a).
20. This literature includes, for example, Lehar and Parlour (2021); Caparros et al (2023); Augustin et al (2022); Malinova and Park (2024); Capponi et al (2023); Capponi and Jia (2021); Barbon and Ranaldo (2024); Hasbrouck et al (2022); Gogol et al (2024). See also BISIH et al (2025) and references therein.

capital invested. On the other hand, fees have a direct impact on overall transaction costs and payment services demand in both domestic and cross-border transactions (Ardizzi and Cologgi (2025); Ahmed et al (2021); Kpodar and Imam (2024)).

From the consumer or demand side perspective, in the traditional remittance market, fees and FX margins make up the bulk of remittance services costs (World Bank (2024); FSB (2024)). Costs tend to be higher for less liquid currency corridors and transactions executed via the traditional banking channel; however, these costs can vary significantly depending on corridor-specific conditions and policy measures. (Box A).

Composition and determinants of remittance fees – Box A

When assessing the potential impact of experimental approaches that aim to reduce the costs of person-to-person cross-border payments like remittances, it is key to understand what the drivers of such costs are. In recent years, international policy institutions have been collecting information from market actors in the context of ongoing efforts to improve cross-border payments (see for example World Bank (2024)). The data have shown that remittance fees have been declining over the past decade but remain, on average, above the targets set by the G20 and the United Nations Sustainable Development Goals, reflecting cost- and risk-based constraints as well as factors related to market structure.

Fees vary depending on time, the currency corridor, the type of remittance service provider and also the type of payment instrument used. Despite the high level of heterogeneity, it is possible to refer to specific benchmarks used for policy monitoring purposes and distinguish two main cost components. According to the latest Financial Stability Board (FSB) estimates, on remittances in the sum of $200, average foreign exchange (FX) margins are approximately 2% of the value of transactions across regions and payment methods, whereas average fees are between 2.3 and 6% (FSB (2024)). The FSB also notes that the distinction between the fee and FX components may not reflect the true source of the costs but may simply be marketing information. This highlights an information gap on the determinants of fees in the remittance segment. Insights into what explains remittance fees can be found in empirical literature that studies the determinants of remittance costs and the potential impact of policy actions aimed at reducing them (eg Orozco (2006); Freund and Spatafora (2008); Beck and Martinez Peria (2011); Ardic and Natarajan (2021); Beck et al (2022); Kpodar and Imam (2024)).

To summarise, the available empirical evidence has associated lower fees with factors such as a higher GDP per capita in the sending countries, better access to financial institutions, a larger market for remittances and a shorter distance between sending and receiving countries. Market structure is also important as banks charge higher fees than money transfer operators (MTOs). However, a larger share of banks among remittance service providers has also been associated with higher fees charged by MTOs.

MTOs’ fees react to competitive pressures – a greater number of market players is associated with lower MTO fees, but not lower bank remittance fees. Institutional factors also play a role. In jurisdictions that have a pegged exchange rate regime, both banks and MTOs charge lower fees. In terms of payment instruments, cash payments attract higher fees, while digital channels are cheaper.

In terms of innovative solutions, centralised venues in the crypto asset market impose a tiered fee structure that depends on the trading volume. In addition to trading fees, users on centralised exchanges (CEXs) often incur withdrawal fees, deposit limitations and hidden costs, making transactions more expensive, particularly during high-volatility periods. By contrast, DEXs operate with more transparent fee structures, where fees are embedded directly into smart contracts.

In AMMs for example, swap and gas fees (or network fees) are the main explicit cost component for the end users and serve as compensation for implicit costs affecting liquidity providers. Implicit costs derive from the automatic changes to the value of the pool following each transaction as well as the maintenance and improvement of the network. Graph 6 summarises the main costs and rewards applied by AMMs.[21] In AMMs and other DEXs, lower fees have been associated with higher trading volumes, better incentives for liquidity providers and – perhaps surprisingly – a lower price impact of trades.[22] On the other hand, higher fees increase the explicit costs which directly affect consumer welfare, especially for smaller amounts transacted, for which users might be better off trading on CEXs rather than DEXs (Barbon and Ranaldo (2024)).

AMMs costs and rewards – Graph 6

Rewards

Liquidity rewards
Income for providing liquidity coming from swap fees
(affecting liquidity providers)

Other types:
Staking rewards, governance rights, security rewards

Explicit costs

Swap fees

Gas fees

Other types:
Liquidity withdrawal penalties

Implicit costs

Slippage
Income for providing liquidity coming from swap fees
(affecting liquidity providers)

Divergence loss
or impermanent loss:
Pool depreciation after trades
(affecting liquidity providers)

21. End users are especially exposed to swap fees, gas fees and slippage. Swap fees are distributed to liquidity pool shareholders to compensate for the supply of assets and for the divergence loss. Gas fees (or network fees) serve as a form of remuneration for validators who maintain and secure the network. Gas fees fluctuate based on supply, demand and network capacity, and may increase during periods of network congestion. Slippage is defined as the rate of variation between executed and intended exchange rate, Slippage = (Intended Price - Executed Price) / Intended Price. It affects all trades done via AMMs by design and it is borne by the FXP governing the AMM in the Rialto model. For low-value payments and sufficiently large liquidity pools, the price impact of slippage is negligible.

22. The leading mechanism is that an increase in trading fees lowers the marginal cost of trading with the DEX by increasing overall fee revenues for liquidity providers, incentivising liquidity provision and reducing the price impact of trades. In other words, an increase in fees endogenously increases investments in the DEX protocol which increases liquidity inventory and reduces the price impact of trading within the DEX platform (ie the implicit costs in Graph 6).

This finding is also relevant for the currency market in which different currencies face different levels of liquidity and price efficiency. Existing blockchain currency markets have been found to be generally efficient, with prices trading within arbitrage bounds and responding promptly to macroeconomic announcements. However, gas fees and market volatility have been identified as important factors reducing price efficiency in blockchain-based currency markets (Ranaldo et al (2024)). This is because market volatility heightens risk for traders holding wealth in crypto assets vis-à-vis more traditional asset classes, thus reducing arbitrage activity, while high gas fees increase transaction costs, hindering arbitrageurs from closing price gaps with traditional markets.[23]

On the side of profitability for operators involved in the system, in ongoing experiments on interlinked IPS like Project Nexus the profitability of PSPs and SAPs is guaranteed by a fee structure that provides source and destination PSPs with the necessary revenue to carry out their activities. Specifically, a PSP can charge the sender fees related to processing the payment. These fees can be explicit (or "invoiced"), meaning that they appear as a separate line item on the sender's account statement and must be made visible to the sender before they confirm the payment. Alternatively, fees can be implicit (or "deducted") when a PSP debits more from the sender's account than it transfers to the source SAP. This fee is thus included in the amount debited and is not explicitly visible to the sender. SAPs in turn, who are intermediaries offering access to the regional or domestic IPS to FXPs, can have a direct contractual relationship with FXPs and levy explicit charges from them for the services offered. In the context of Project Rialto, the fees charged by PSPs are also determined by the FX component and this interaction would be a key factor determining the overall viability of the Rialto technical approach.

Within the FX dimension, the relationship between fees and the overall cost-effectiveness of automated decentralised platforms in the blockchain-based currency market compared with traditional venues could be an interesting avenue for future research and might offer insights into the economic viability of automated mechanisms for currency exchange like the one used in Project Rialto.

Performance under different market conditions

How do automatic FX solutions such as the one developed in Project Rialto perform under different market conditions? Recent evidence shows that AMMs are efficient if the price movements of the token pair are highly correlated or, in other words, if there is a stable exchange rate (Capponi and Jia (2021)). The explanation for this is that if the token exchange rate is too volatile, the expected fee revenue from providing liquidity is lower than the expected arbitrage loss plus the opportunity cost from holding the tokens as deposits in the AMM (ie the implicit costs in Graph 6). This result has two technical implications, namely that the curvature of the pooling function determines the severity of the arbitrage effect (divergence loss) and the fee revenues generated by the trades. It also implies that the liquidity pool should minimise the number of tokens traded since pooling multiple tokens not only increases the probability of arbitrage but also allows the arbitrageur to extract a larger portion of deposited tokens.

23. Recent research focused on equity trading also finds that optimally designed AMMs could improve the trading environment for investors, providing them with increased liquidity and substantially reduced trading costs, and that a higher trading fee would be required for small-cap stocks compared with large-cap stocks, akin to a higher opportunity cost of trading less liquid assets (Malinova and Park (2024)). This finding is also relevant for the currency market, where different currencies face different levels of liquidity and price efficiency.

Studies have also shown the potential shortcomings of AMMs under stressed market conditions. AMMs have the potential to be competitive with CEXs with respect to market quality in "normal" market conditions, when liquidity is high. For instance, certain DEXs that allow liquidity providers to provide concentrated liquidity can perform comparably to CEXs under normal trading conditions by efficiently adapting to market demand. However, they face challenges in non-equilibrium conditions, meaning in extreme events. For example, simpler AMMs which use static rules for liquidity, struggle to match the efficiency of CEXs during periods or higher market stress (Kirste et al (2024)).

In Rialto, the presence of FXPs holding additional liquid reserve balances could be a safeguard with respect to market turmoil events or liquidity issues with the automated mechanism. The interaction of traditional intermediaries and DEXs in the currency market and their joint performance has not been studied yet and could be an interesting topic for further research.

Transparency and market integrity

A crucial aspect affecting the economic viability of the Rialto technical model in the retail segment is how transparency and market integrity would be impacted by the automatic FX solution. In the Rialto context, transparency may refer to *pre-* and *post-trade* information affecting the exchange of currencies involved in a retail payment. *Post-trade* information refers to past trades and exchange rates in a given currency pair, while *pre-trade* information refers to quotes on future trades.

This information, albeit scarce in an OTC context, is important because it leads to improved liquidity, reduced execution risks and improved price discovery, as evidenced for example by the literature on the transparency of the securities trading process (Foucault et al (2010)) and the existing blockchain-based currency markets (Ranaldo et al (2024)). Furthermore, increased transparency on transactions can help reduce costs by reducing compliance costs and promoting competition among money transfer operators and banking institutions. This is especially critical in contexts in which AML/CFT regulations increase the cost of monitoring clients and their financial transactions. Such monitoring activities can lead to execution delays, price inefficiencies and hidden costs which particularly affect smaller financial institutions (Ahmed et al (2021)).

The interaction of DEXs and FXPs in Rialto could in principle improve transparency both pre- and post-trade thanks to the underlying technology (DLT) which ensures that the relevant information is available in real time to the intermediaries that have access to the ledger. As a concrete example, existing DEXs in the cryptoasset market provide fully auditable trade records. However, this information can sometimes expose AMMs to vulnerabilities associated with automated programs designed to exploit profit opportunities within blockchain transactions.[24] Technological advances have contributed to solving this problem. For example, certain DEXs now feature solutions to protect against this issue (Xu et al (2023)). An empirical investigation on the impact of DEXs on the transparency of the currency market would offer important insights into the viability of automated FX solutions and is an interesting avenue for future research.

24. So-called maximal extractable value (MEV) bots.

Liquidity and efficient capital utilisation

The Rialto technical approach can have a potentially positive impact on liquidity and efficient capital utilisation from an interbank perspective. In the context of the remittance segment, liquidity primarily has market and funding dimensions.

The *market* dimension relates to the possibility of trading currencies quickly and at a low cost which in turns enables cheap and fast payments between different jurisdictions. The automatic FX solution developed in Rialto's technical experiment can provide an additional marketplace for currency exchange that can help reduce frictions that may arise in traditional FX venues. In Rialto, by connecting to the AMM, FXPs can exchange currencies at predetermined rates and benefit from atomic settlement of transactions in CeBM and on a PvP basis. This in turns reduces liquidity, credit and settlement risks, as defined in the project's interim report (BISIH et al (2025)). The *funding* dimension instead relates more to counterparty risks which arise in the context of FX trading and affect the settlement stage of the payment – that is the necessity of banks to maintain a good level of reserves to be able to satisfy their payment obligations in a timely manner. In this domain, the use of multiple liquidity pools to fulfil an FX transaction using a vehicle currency as well as the introduction of two-phase settlement in Rialto are two unique features that can positively impact funding liquidity. Furthermore, since the transactions are settled in CeBM, in Rialto liquidity also has a *monetary* dimension. This is because in the PoC central banks are the sole issuers of the common settlement asset and steer its supply to authorised counterparties who operate within the system (PSPs, SAPs and FXPs).

In terms of efficient capital utilisation, the Rialto technical solution can have a positive impact on banks that are authorised to hold CeBM and who provide liquidity to the Rialto system. By depositing liquidity in the AMM, these intermediaries can earn returns and claims on the liquidity deposited that could in principle be used as collateral in other transactions (BISIH et al (2023a)). This enables a more efficient use of central bank reserves for intermediaries who participate in the system compared with traditional central bank reserve accounts as well as with the nostro and vostro accounts used in correspondent banking relationships today.

On the other hand, Rialto's AMM design necessitates the pre-funding of CeBM tokens within liquidity pools. Liquidity providers retain the unilateral ability to withdraw their funds at any time, a feature that introduces the potential for liquidity mismatches during periods of higher market volatility. Such mismatches may pose operational challenges, particularly if liquidity provision becomes concentrated in a few large providers or if AMM incentives are insufficiently robust during periods of stress (Aramonte et al (2021)).

Exploring the role of DEXs as liquidity-enhancing mechanisms in retail cross-border banking relations is an empirical question that has not been investigated and could inform the potential economic viability of such tools in the future retail payments market.

In addition to these economic considerations, there are also important questions regarding legal frameworks, governance models and emerging risks of the discussed architecture. For one, the legal status of decentralised components like AMMs and how they interact with current systems remains unclear; autonomous organisations (DAOs), in particular, are decentralised in nature and may be operating outside legal framework. Other issues that may need further discussion include accountability, access, ownership and claims, particularly when CeBM tokens are pooled in AMMs and thus held by a smart contract. Cross-border compliance also introduces added complexity due to varying rules on foreign exchange, data protection and financial crime prevention. Legal clarity on settlement finality is also essential, as it demands not only technical assurance that transactions are irreversible, but also legal recognition and enforceability across all participating jurisdictions, each with its own rules, contracts, and regulatory regimes. Additionally, potential cyber- and DeFi-related risks, such as smart contract vulnerabilities and protocol exploits, underscore the need for robust risk management controls, including strong legal and technical safeguards.

5. Conclusion

As efforts continue to reduce the inefficiencies associated with remittance payments, FX and settlement remain key frictions. This is especially true in those transactions that involve less liquid currency corridors and those that are executed using traditional payment means such as bank transfers. Both types of remittance transactions are in fact characterised by relatively high average costs, according to recent estimates. As the market strives to look for more efficient options, there has been an increasing focus on same-day or even instant PvP solutions that allow for fast and reliable access to liquidity in foreign currency.

Project Rialto's technical experiment has developed a solution that combines PvP with CeBM settlement in a simulated cross-border payment infrastructure by building on previous works conducted by the BIS Innovation Hub. The Rialto PoC successfully integrated simulated interlinked IPS together with a cross-border DLT network for automated FX and settlement in tokenised CeBM. The Rialto PoC simulated a direct transaction between senders and receivers in different jurisdictions and a transaction with a vehicle currency to address cases in which a third currency is needed to facilitate the exchange. The experimental architecture was composed of two main blocks, namely the IPS link to enable cross-jurisdictional clearing of retail transactions via domestic IPS and an interbank XDN that leverages tokenised CeBM and smart contracts for the automatic exchange of currencies among financial institutions involved in the payment chain.

This technical report has also looked at the aspects and key trade-offs that need to be considered to evaluate the viability of the Rialto approach from an economic standpoint vis-à-vis existing arrangements in the retail cross-border market segment. From an economic perspective, the key dimensions that would determine the viability of the Rialto approach in an operational context are its fee structure and overall transaction costs, its performance under different market conditions, the potential impact on transparency and market integrity, and the impact on market liquidity and efficient capital utilisation.

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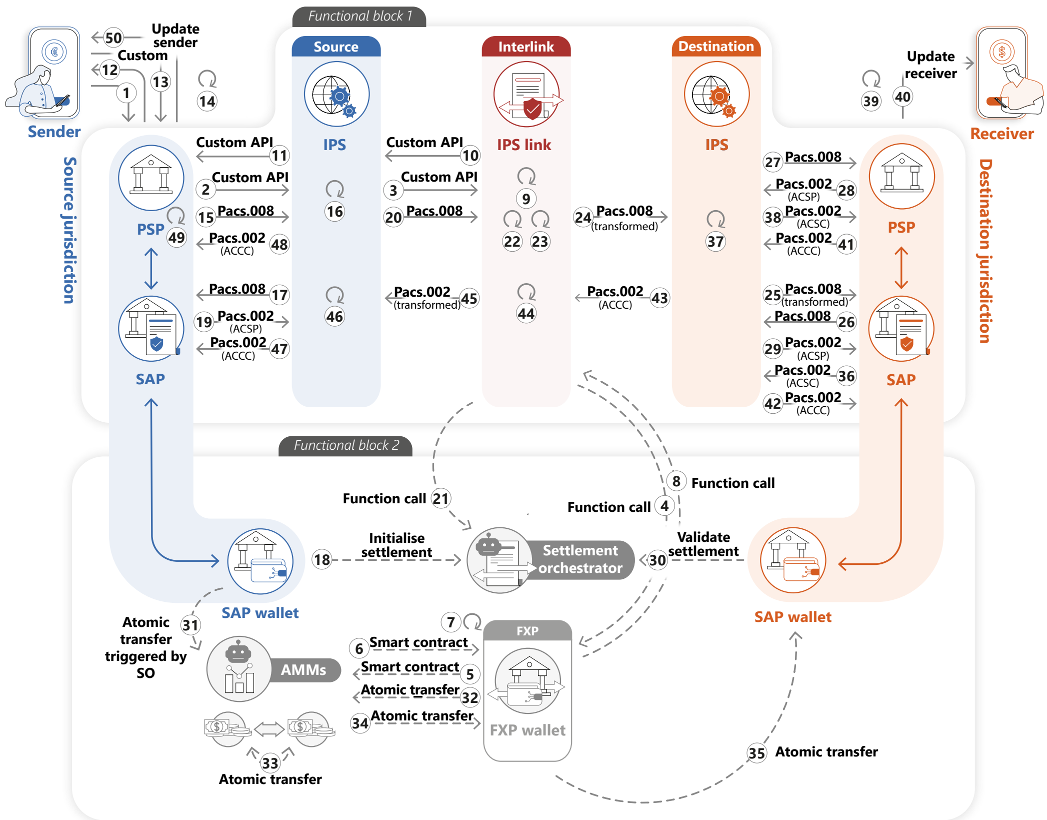
7. Functional annex

This functional annex provides a detailed description of Rialto's main scenario. The main scenario enables a successful direct transaction from EUR to SGD, as depicted in detail in Graph 9. In this scenario, the instructed amount for the payment can be in either EUR or SGD. As this scenario concerns a successful transfer, additional steps for handling errors or significant deviations are omitted from this section.

Detailed sequence flow for the main scenario with direct transaction – Graph 9



Let us assume that a European Union-based sender needs to make a payment to a Singapore-based receiver. The process involves the following 50 steps, organised into four high-level conceptual segments.

Segment 1: Quote retrieval (functional blocks 1 and 2)

- Step 1: The sender commits a quote request to the S-PSP.
- Step 2: The S-PSP sends the quote request to the S-IPS.
- Step 3: The S-IPS forwards the quote request to the IPS link.
- Step 4: The IPS link forwards the quote request to the FXP.
- Step 5: The FXP forwards the quote request to the AMM.

- Step 6: The AMM responds to the FXP with the amount of EUR needed to obtain the required SGD for the transaction.
- Step 7: The FXP adds a margin to the quote provided by the AMM.
- Step 8: The FXP sends the quote for this transaction including its margin, back to the IPS link.
- Step 9: The IPS link calculates the service fees, namely the IPS link platform fee (in EUR, the source currency) and the destination PSP fee (in SGD, the destination currency). This was according to Nexus specifications.
- Step 10: The IPS link sends subsequent information includes the quotes, service fees and interbank settlement amounts at the source and destination legs in the quote provision (or response) and sends it back to the S-IPS.
- Step 11: The S-IPS forwards received information to the S-PSP.
- Step 12: The S-PSP offers the sender the FX conditions, including quote and fees.

Segment 2: Cross-border settlement preparation (functional blocks 1 and 2)

- Step 13: The sender accepts the FX conditions and thus instructs Rialto payment initiation.
- Step 14: The S-PSP blocks the sender's funds on its balance sheet.
- Step 15: The S-PSP orders the Rialto end-to-end payment instruction via a specific pacs.008 message to the S-IPS.
- Step 16: The S-IPS blocks the S-PSP's funds on the central bank balance sheet.
- Step 17: The S-IPS forwards the pacs.008 message to the S-SAP.
- Step 18: The S-SAP makes a function call to the SO – this creates a record for this transaction indexed with the UETR of the payment. This acts as confirmation of the commitment of funds at the S-SAP end.
- Step 19: The S-SAP confirms payment instruction via a pacs.002 (AcceptedSettlementInProcess - ACSP) message to the S-IPS.
- Step 20: The S-IPS forwards the pacs.008 message to the IPS link.
- Step 21: The IPS link fetches the settlement data from the SO.
- Step 22: The IPS link validates the quote in the incoming pacs.008 instruction (with the one that was communicated earlier in the quote response using the quote ID).
- Step 23: The IPS link transforms the pacs.008 message for the payment instruction to be processed in the destination leg of the payment.
- Step 24: The IPS link forwards the transformed pacs.008 message to the D-IPS.

- Step 25: The D-IPS forwards the transformed pacs.008 message to the D-SAP.
- Step 26: The D-SAP, upon confirmation on its willingness to process this payment, instructs a mirror pacs.008 message to the D-IPS.
- Step 27: The D-IPS forwards the pacs.008 message that it received from the D-SAP to the D-PSP.
- Step 28: The D-PSP confirms the payment via a pacs.002 message (ACSP) to the D-IPS.
- Step 29: The D-IPS forwards the pacs.002 confirmation (ACSP) to the D-SAP.

Segment 3: On-chain settlement (functional blocks 1 and 2)

- Step 30: On receiving the confirmation status of the payment via the pacs.002 from D-IPS, the D-SAP triggers a function call to the SO that in turn initiates a series of atomic transfer actions (steps 31 to 35, as detailed below).
- Step 31: The SO triggers a transfer of EUR-CeBM tokens from the S-SAP's wallet to the FXP's wallet.
- Step 32: The SO triggers a movement of EUR-CeBM tokens from the FXP's wallet to the AMM smart contract.
- Step 33: The AMM smart contract exchanges EUR-CeBM tokens to SGD-CeBM tokens.
- Step 34: The AMM smart contract transfers SGD-CeBM tokens to the FXP's wallet.
- Step 35: The SO triggers a transfer of SGD-CeBM tokens from the FXP's wallet to the D-SAP's wallet.

Segment 4: Subsequent settlements and notifications (functional block 1)

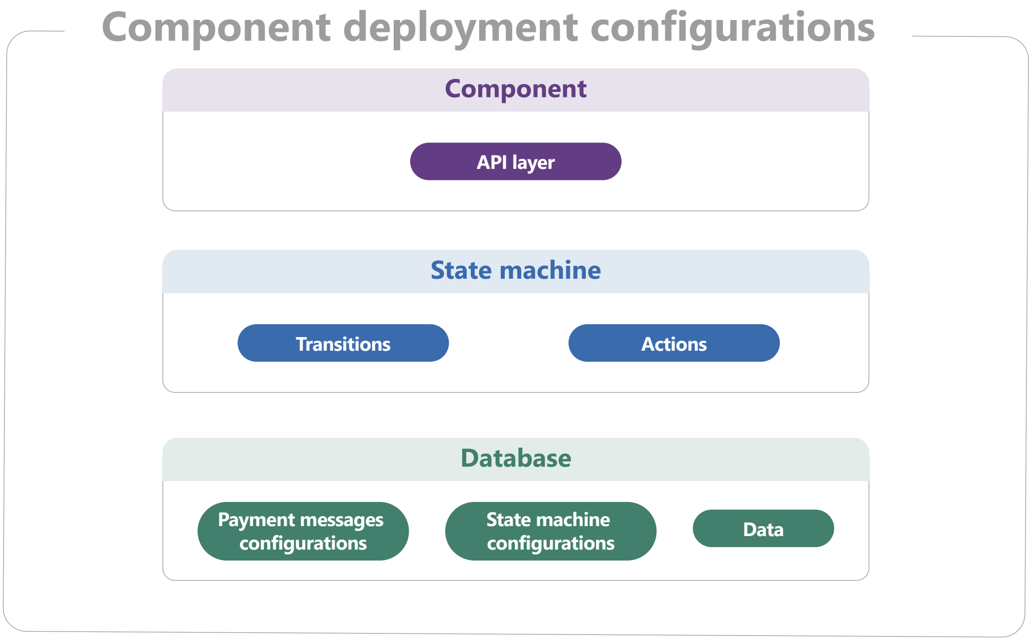
- Step 36: The D-SAP confirms the arrival of the funds on its wallet via a pacs.002 message (ACSC) to the D-IPS.
- Step 37: The D-IPS settles the destination instant payment by debiting the D-SAP and crediting the D-PSP account at the central bank.
- Step 38: The D-IPS forwards the pacs.002 confirmation (ACSC) to the D-PSP.
- Step 39: The D-PSP credits the receiver's bank account.
- Step 40: The D-PSP notifies the receiver on the successful transaction.
- Step 41: The D-PSP confirms the crediting of the receiver via the pacs.002 message (ACCC) to the D-IPS.
- Step 42: The D-IPS forwards the pacs.002 confirmation (ACCC) to the D-SAP.

- Step 43: The D-IPS forwards the pacs.002 confirmation (ACCC) to the IPS link.
- Step 44: The IPS link transforms the pacs.002 message so that the source participants can consume it.
- Step 45: The IPS link forwards the transformed pacs.002 confirmation (ACCC) to the S-IPS.
- Step 46: The S-IPS settles the source instant payment by debiting the prior blocked amount of the S-PSP and crediting the S-SAP account at the central bank.
- Step 47: The S-IPS forwards the transformed pacs.002 confirmation (ACCC) to the S-SAP.
- Step 48: The S-IPS forwards the transformed pacs.002 confirmation (ACCC) to the S-PSP.
- Step 49: The S-PSP debits the prior blocked amount of the sender's account on its balance sheet.
- Step 50: The S-PSP notifies the sender on the successful transaction.

8. Technical annex

8.1. Functional block 1

Architecture of a back-end component – Graph 10



The technical architecture shared among all the different components of functional block 1 (ie PSP, SAP, IPS, IPS link) is illustrated in Graph 10. The microservices architecture was selected to represent the different institutions in real-life payments flow through a separate service. At the microservices layer, each component, representing participants, was deployed as a separate state machine with a dedicated database schema. At a high level:

- The API layer exposes endpoints for interaction with the services of other components within the broader microservices architecture. This layer serves as the gateway for receiving requests, validating them and triggering the internal workflow via a state machine.

- At the core of each microservice, a state machine was implemented to maintain the flow of each transaction through predefined states. Each state transition may include associated actions, executing business logic. The structure of the state machine was configurable, with definitions of states, events, transitions, actions and guards stored in the database.

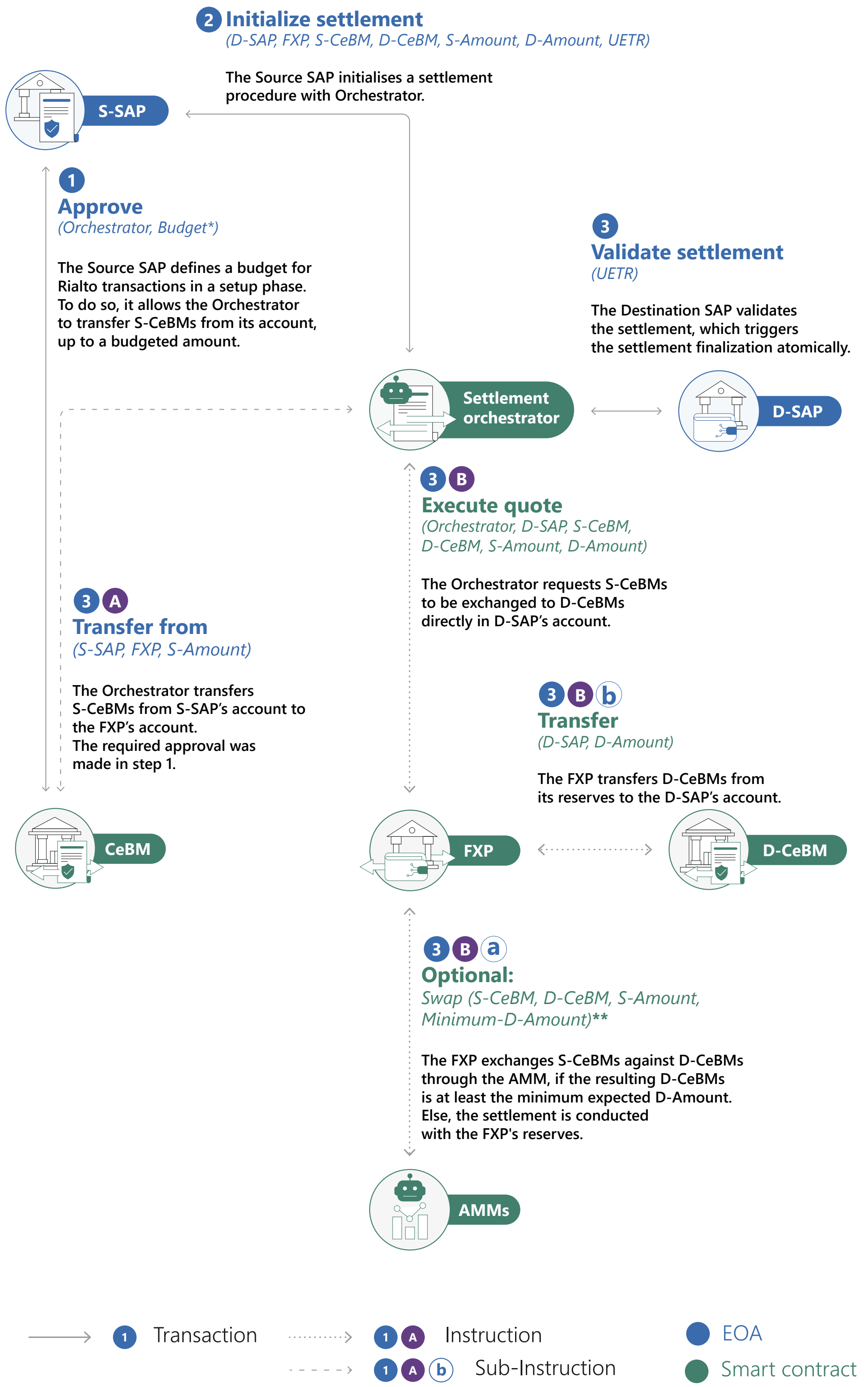
- Each microservice also contains a dedicated database schema responsible for storing three primary types of data, payment message configurations (eg structure, validation rules), state machine configurations (eg workflow definitions) and runtime data (eg transaction payloads, user data, logs).

8.2. Functional block 2

For the PoC, the smart contracts were developed and compiled for the Ethereum Virtual Machine (EVM). Ethereum was selected as it is a widely used open source and robust technology in finance applications. In particular, the Ethereum-based Scroll protocol was chosen for its transaction speed and low gas fees, as well as easily available open source code for smart contracts, efficiency and the convenience of the execution of currency exchange in a decentralised fashion via Uniswap v3.

Different protocols for automatic FX were evaluated. Uniswap v3 offered the right mix of concentrated liquidity, market-driven flexibility and minimal governance costs (Ottina et al (2023)). In this setup (see Graph 11), the PoC uses several smart contracts, including FXP, SO, source currency CeBM, vehicle currency CeBM and destination currency CeBM. For the sake of simplicity, the FXP was a single smart contract, able to return a quote and later execute it. This design allows for quick iterations without the need to have a full liquidity stack implemented as a fixed percentage spread was used. The IPS link retrieves quotes directly from the FXP via a read-only function (without an on-chain transaction). In the background, the FXP smart contract requests quotes from the relevant AMMs, adds the spread and returns the net price to the IPS link.

Interaction between the PoC's smart contracts – Graph 11



*Corresponds to the periodic budget allocated to Rialto operations by the Source SAP

**AMM Sub-instructions have been simplified and are not shown in this diagram

The step-by-step interactions of smart contracts are as follows.

Request for quote

- Step 1: The IPS link submits a quote request to the FXP for the target FX pair in a specific currency.
- Step 2: The FXP queries the current on-chain rate for that trade size.
- Step 3: The FXP adds its predefined spread the retrieved rate and returns the final quote to the IPS link.

Payment execution

- Step 1: The S-SAP sets an amount that the SO was authorised to use for the currency exchange.
- Step 2: The S-SAP calls the SO to initialise the on-chain settlement.
- Step 3: The D-SAP validates this on-chain settlement via the SO.
  - The SO consumes its authorised amount to move the specified source destination CeBM from the S-SAP to the FXP.
  - The SO instructs the FXP smart contract to complete the FX leg under the agreed settlement terms.
  - The FXP executes the swap through the AMM or its own reserves.
- Step 4: The FXP transfers the resulting destination currency CeBM from its balance to the D-SAP account.

As the implementation supports retail instant payments, on-chain transactions are minimised. There are only two on-chain transactions per settlement (one from each SAP), so the throughput was not significantly impacted even on moderate-latency networks. Finally, for each currency, tokenised CeBM was represented in the form of a smart contract that defines the list of potential holders and manages the token lifecycle. For simplicity, an Ethereum-native token standard has been chosen (ERC20).

8.3. Integration between the functional blocks

The Rialto implementation comprises two heterogeneous functional blocks – one reflecting traditional payment systems, the other DLT-based CeBM settlement. These blocks can operate asynchronously, supporting distinct functionalities for their respective participants in the Rialto payment flow. Their technological differences require specific conditions to ensure successful interaction.

- The smart contracts' addresses and the functions for the smart contracts' executions should be known. Each SAP should have an address for its own unique wallet. SAP wallets need to be whitelisted on the XDN so that they can use the smart contracts. SAP wallets should have enough Ether balance on the Scroll network (for the PoC, testnet Ether) to call the functions for initiating and validating settlement. If just retrieving information from the XDN, there was no need for a balance. The S-SAP was responsible for initiating a settlement and approving the transfer. Without approval, the D-SAP will not be able to validate a settlement.

- ISO 20022 payment messages are specified to also include DLT-related fields (eg wallet addresses).

- The IPS link receives the FX quote's amount from the FXP and calculates the rate and fees for the sender to initiate a payment in the functional block 1.

- The S-SAP initialises the settlement, and the D-SAP validates the settlement to trigger the transfer of CeBM from source to destination in the functional block 2.

Conclusively, the integration between the two functional blocks happens at three points: each SAP at each end (source and destination) reading and writing on the XDN and the IPS link, in between, only reading the XDN (but as a central checkpoint in block 1).

8.4. Technical decisions related to functional block 2

Different EVM-based protocols on different layers were considered before deciding on the PoC's smart contract deployment on the Scroll Sepolia Testnet.

The criteria for this choice included the following:

- Public testnet: The project team focused on implementing the core functionality of Rialto by leveraging an existing underlying network and associated tools (eg faucet ETH, block explorer and monitoring). So for the PoC there was no need to create or maintain a private chain.

- Layer-2 environment: This environment offers short block times while inheriting Ethereum's security through rollup posting, providing a stronger security model than a sidechain.

- Zero-knowledge (ZK) rollup: validity proofs offer near-instant, deterministic finality, eliminating the long challenge periods associated with optimistic rollups.

- PUSH0 opcode support: the Uniswap v3 redeployment scripts required the new PUSH0 opcode (EIP-3855). During the Rialto development, Scroll Sepolia was the only ZK-rollup testnet that had already implemented it.

- A tick-based constant product AMM (Uniswap v3): This was chosen for the experiment because it combines the capital-efficiency benefits of a dynamic concentrated liquidity AMM (tight pricing bands and dynamic fees) without the need for an administrator to predetermine the shape of the curve. Dynamic concentrated liquidity AMM administrator-set parameters work well for tightly correlated tri-token pools, but each new asset mix demands fresh volatility analysis and manual tuning.

- A constant product AMM was ruled out because its linear curve spreads liquidity too thin and weight-based pools are optimised for asymmetrical reserves rather than the micro-spread behaviour block 2 wanted to study. By letting market-makers themselves allocate liquidity to the price ranges they deem optimal, the AMM in Rialto decentralises concentration decisions and lets the market, not an operator, reveal the true distribution. Fee tier overlays (eg EUR–SGD at 0.05 %, 0.3 %, 1 %) provide a clean way to model different spreads when needed (something that can be layered in later without touching core smart contracts).

• Payment vs payment achievement: the flow secures payment-versus-payment through a blend of technical and functional atomicity. Technically, the process was split into only two on-chain transactions. The first – `initializeSettlement` – just records metadata, so it either commits wholly or reverts. The second begins when the destination SAP invokes `validateSettlement`. Inside the latter, the function instantly calls the internal `finalizeSettlement`, which pulls the source CeBM from the source SAP and, still synchronously, executes the FX swap via the FX provider's `executeQuote`, finally crediting the destination SAP.

  - Because every nested call shares a single EVM context, any error (whitelist breach, allowance failure etc) causes an all-or-nothing revert, satisfying technical atomicity. On top of that, the smart contracts add functional atomicity: if the swap fails after the source tokens have been pulled, the SO catch-block triggers "`returnTokens`" to refund the entire source amount, flags the settlement as cancelled and emits "`SettlementFinalizationFailed`" followed by "`SettlementCanceled`" events.

  - A third clean outcome exists as well: if the D-SAP does not validate before the 15-minute deadline, "`validateSettlement`" auto-cancels on timeout, emits "`SettlementCanceled`" and no funds have moved. Thus, the system guarantees that observers will see one of the following: (i) both money-leg transfer events and "`SettlementFinalized`"; (ii) a refund path ending in "`SettlementCanceled`"; or (iii) a pre-swap timeout/manual cancelation ending in "`SettlementCanceled`" with zero token movement. No party can ever be left half paid.

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