On the Interoperability of Central Banks via DLT: Cross-Border Payments and Tokenized Assets

Federico Calandra[1], Francesco Fabris[2] and Marco Bernardo[1]

[1]Dipartimento di Scienze Pure e Applicate, Università di Urbino, Urbino, Italy

[2]Dipartimento di Matematica, Informatica e Geoscienze, Università di Trieste, Trieste, Italy

Abstract

Cross-border payments remain slower, costlier, and less transparent than domestic transfers, largely because settlement must traverse chains of correspondent banks operating on different ledgers, in different currencies, and under different regulatory regimes. Central banks and international financial institutions have responded with extensive experimentation in which distributed ledger technology (DLT) and tokenization are applied to shorten transaction chains, enable atomic cross-currency settlement, and preserve central bank money as the anchor of cross-border value transfer. This paper surveys fourteen institutional DLT projects for cross-border payments and settlement. Its central contribution is a three-axis taxonomy that decomposes the design space along target segment (wholesale versus retail), architectural pattern (common platform, interlinking and synchronization, infrastructure bridge), and settlement-asset representation (native central bank digital currency token, proxy token backed by escrowed central bank money, off-chain settlement). Together the axes generate a structured space in which recurring patterns, maturity trajectories, and unresolved trade-offs become visible. Five findings emerge: production-track projects are architecturally composite; proxy tokens and off-chain settlement dominate mature designs; atomicity mechanisms trend from trustless constructions toward oracle-mediated coordination; wholesale and retail segments diverge structurally; and critical enablers—legal finality, cryptographic privacy, elastic on-chain liquidity, and multi-sovereign governance—remain unresolved. The Eurosystem's trajectory, going from three independent exploratory solutions through the consolidated Pontes bridge to the longer-horizon Appia programme, provides the most developed empirical lens through which these patterns can be observed, demonstrating how interoperability is being operationalized through staged, composite architectures that extend an existing infrastructure rather than replacing it.

Keywords

Distributed ledger technology, cross-border payments and settlement, central bank digital currency, payment system interoperability, atomic settlement.

1. Introduction

When a business in one country pays a supplier in another, the payment rarely travels a direct path. Instead, it typically passes through a chain of *correspondent banks*—financial institutions that hold accounts on each other's behalf—relaying messages and debiting or crediting intermediary accounts until the funds reach the beneficiary's bank. Each link in the chain may operate in a different time zone, on different ledgers, under different regulatory regimes, and in a different currency. The cumulative result is that cross-border payments are widely experienced as slower, costlier, and less transparent than domestic transfers. *Settlement*—the irrevocable transfer of value that discharges the payment obligation—may occur hours or days after initiation, with no visibility into the transaction's status.

The *Committee on Payments and Market Infrastructures* (CPMI) of the *Bank for International Settlements* (BIS) characterizes cross-border retail payments as involving at least two national payment systems, potentially different currencies, and specialized processes such as *foreign exchange* (FX) settlement [1]. The G20 cross-border payments programme frames the persistent gap between domestic and cross-border performance as a systemic infrastructure challenge encompassing high costs, low speed, limited access, and insufficient transparency [2].

Proceedings of the 8th Distributed Ledger Technology Workshop (DLT 2026), June 4 - 6, 2026, Pula, Italy

federico.calandra@unicam.it (F. Calandra); ffabris@units.it (F. Fabris); marco.bernardo@uniurb.it (M. Bernardo)

https://orcid.org/0009-0001-7958-2028 (F. Calandra); https://orcid.org/0000-0002-1950-8838 (F. Fabris); https://orcid.org/0000-0003-0267-6170 (M. Bernardo)

Crucially, improvements at the front end—better user interfaces or faster mobile apps—do not automatically resolve back-end constraints such as message incompatibilities, limited interoperability across jurisdictions, FX settlement risk, and duplicated compliance controls [3]. This motivates a focus on protocol- and infrastructure-level redesign. In this context, *distributed ledger technology* (DLT) and *tokenization* have emerged as candidate technologies. Central banks and international financial institutions—notably the *BIS Innovation Hub* and the *Eurosystem* (ESY)—have launched experimental projects exploring how DLT can shorten transaction chains, enable *atomic cross-currency settlement*[1], and preserve the role of *central bank money* (CeBM)—direct liabilities of the issuing central bank and the safest form of settlement asset—as the anchor of cross-border settlement. The density and diversity of this experimentation constitute a design space that has not yet been systematically analyzed.

This paper presents a systematization of knowledge (SoK) on institutional DLT projects for cross-border payments and settlement. Its principal contribution is a three-axis taxonomy that decomposes the design space along the dimensions that most sharply differentiate project architectures and expose the trade-offs they embed: *target segment*, *architectural pattern*, and *settlement-asset representation*. Each axis isolates a distinct source of design variation and together they generate a structured space in which recurring patterns, maturity trajectories, and unresolved tensions become visible.

The SoK applies this taxonomy to fourteen major initiatives, spanning wholesale FX and securities settlement as well as retail cross-border payments. The scope encompasses permissioned, institutional DLT systems involving central banks, from early proofs of concept to near-production pilots. Public-chain *decentralized finance* (DeFi) bridges and stablecoin arrangements are excluded. The evidence base comprises publicly available project reports, central bank publications, and policy documents; the methodology combines taxonomic classification with comparative analysis grounded in primary sources. Supplementary dimensions, such as atomicity mechanism and FX provisioning strategy, are recorded for each project and analyzed in dedicated cross-cutting sections.

The overarching question driving the analysis is: *what architectural designs and interoperability mechanisms enable cross-border settlement among central banks using DLT and what trade-offs do they entail?* Table 1 decomposes this into five subordinate research questions.

Five findings emerge from the taxonomic analysis; each one is a property of the design space that becomes visible only through the joint structure of the three axes. First, production-track projects are architecturally composite, layering multiple interoperability patterns rather than committing to a single model. Second, *proxy* (or asset-backed) *tokens*[2] and traditional off-chain settlement dominate mature designs, revealing an institutional preference for preserving the existing *real-time gross settlement*[3] (RTGS) as the monetary anchor. Third, atomicity mechanisms, which follow the "all or nothing" rule, trend from trustless constructions toward oracle-mediated and operator-based coordination, prioritizing safety over trustlessness. Fourth, wholesale–retail divergence is structural, not incidental. Fifth, critical enablers—legal finality, cryptographic privacy, elastic on-chain liquidity,[4] and multi-sovereign governance—remain unresolved in all regions of the design space. Across these findings, a common thread arises: the design space is converging on pragmatic, composite solutions that extend an existing settlement infrastructure rather than replacing it, selectively leveraging DLT for coordination and programmability while preserving central bank money as the monetary anchor.

The remainder of the paper is organized as follows. Section 2 establishes the conceptual and institutional foundations. Section 3 introduces the taxonomy and the fourteen projects. Section 4 analyzes the three architectural patterns. Section 5 compares wholesale and retail design divergences. Section 6 examines cross-ledger atomicity mechanisms. Section 7 investigates settlement-asset representation. Section 8 identifies open challenges and implications. Section 9 provides some concluding remarks.

[1] A mechanism that ensures the simultaneous exchange of two different currencies between two parties, so that the transaction either occurs entirely or not at all.

[2] Digital representation of a currency deposited as collateral in a bank.

[3] A payment system in which transactions are processed and settled individually in real time, with finality upon execution, rather than being netted and settled in batches at a later time.

[4] The ability of a digital system to automatically adjust the amount of available funds to facilitate trading, expanding or contracting based on market demand, without the manual intervention of a human operator.

Table 1
Subordinate research questions.

	Research Question
RQ1	What recurring architectural patterns emerge in institutional DLT-based cross-border payment systems? How do they differ?
RQ2	How do design choices differ between wholesale and retail systems? How does the target segment influence participation models and interoperability mechanisms?
RQ3	What mechanisms are used to achieve atomic settlement? What are their implications for safety and trust assumptions?
RQ4	How are settlement assets represented on DLT platforms? What are the consequences for monetary design and system integration?
RQ5	What challenges remain unresolved, particularly regarding legal finality, privacy, FX liquidity, governance, and network effects?

2. Background and Conceptual Foundations

This section establishes the conceptual and institutional vocabulary required for the taxonomy and analysis that follow; a summary table of acronyms appears in Appendix A (Table 3). Section 2.1 characterizes the cross-border payment problem and baseline infrastructure. Section 2.2 introduces DLT and settlement primitives. Section 2.3 orients the reader to the institutional landscape.

2.1. Cross-Border Payment Frictions and Baseline Infrastructure

Cross-border payments remain slower, costlier, less transparent, and less accessible than their domestic counterparts. A 2020 assessment coordinated by the *Financial Stability Board* (FSB) identified the following four challenges as the targets of the G20 cross-border payments programme and traced them to a set of underlying frictions: fragmented data standards, complex compliance requirements, limited operating-hour overlap across time zones, and outdated legacy technology platforms [4]. The CPMI's Stage 2 report to the G20 organized nineteen building blocks to address these frictions, spanning both wholesale and retail segments [5]. Despite sustained multilateral effort, the recent BIS assessment "*Enhancing Cross-border Payments: State of Play and Way Forward*" concludes that improvements in end-user outcomes have so far been modest and that G20 targets are unlikely to be met on the original timeline [6].

The dominant baseline arrangement is *correspondent banking*. Since no single payment system spans all jurisdictions, banks maintain bilateral relationships in which a *correspondent bank* provides payment services—including foreign-currency settlement—to a *respondent bank* through reciprocal *nostro / vostro accounts*: the respondent's "our account held at you" (nostro) is simultaneously the correspondent's "your account held at us" (vostro) [7]. Cross-border transfers proceed by debiting and crediting these accounts through sequential messaging—most commonly via SWIFT[5]—rather than by moving a single settlement object from sender to receiver. The model creates structural inefficiencies: pre-funded nostro balances represent trapped liquidity; long transaction chains add cost, delay, and opacity; and de-risking—the withdrawal of correspondent relationships from jurisdictions perceived as high-risk—has reduced connectivity, particularly for smaller economies [7, 4].

Domestically, two types of infrastructure anchor the settlement layer that the DLT projects surveyed in this SoK seek to extend or replace. Understanding them is important because the architectural patterns and settlement-asset models analyzed in later sections are defined largely by how they relate to these existing systems:

- *Real-time gross settlement* (RTGS) systems are the backbone of wholesale payments, since they settle high-value interbank transfers in CeBM individually and in real time. The Eurosystem's RTGS

[5]SWIFT (Society for Worldwide Interbank Financial Telecommunication) is a global messaging network used by financial institutions to exchange standardized payment instructions and other financial messages; it does not transfer or settle funds.

is *TARGET 2* [6] (T2). RTGS systems also provide elastic intraday liquidity through central bank credit facilities [8]—a property with important implications for tokenized settlement (Section 7).

- *Instant payment systems* (IPSs) serve the retail segment, enabling 24/7 low-value transfers between end users, typically mediated by commercial banks or *payment service providers* (PSPs). The Eurosystem's IPS is *TARGET Instant Payment Settlement* (TIPS), which settles retail instant payments in CeBM. While IPSs achieve domestic immediacy, cross-border interlinking of IPSs remains nascent [6].

Both RTGS and IPS are examples of *financial market infrastructures* (FMIs)—multilateral systems for clearing, settling, or recording financial transactions [9]. The international standards governing FMIs, the CPMI-IOSCO *Principles for Financial Market Infrastructures* (PFMI), constitute a normative anchor for this SoK. In particular, Principle 9 requires that "an FMI should conduct its money settlements in central bank money where practical and available" [9]. Every project surveyed in this paper observes this requirement, either by making the on-chain token itself CeBM, by backing it with escrowed[7] CeBM, or by settling entirely within the RTGS. How they do so will be the subject of Section 7.

2.2. DLT, Tokenization, and Settlement Primitives

Permissioned distributed ledger technology. All fourteen projects surveyed in this SoK operate on *permissioned* DLT networks: participation in consensus and transaction validation is restricted to identified, authorized nodes—typically central banks or regulated financial institutions. This contrasts with public, permissionless blockchains where any node may join. The permissioned setting is dictated by institutional requirements for access control, regulatory compliance, and data confidentiality; it shapes every design choice analyzed in the subsequent sections. The specific DLT platforms and consensus models adopted by each surveyed project include Hyperledger Fabric/Besu, ESY DLT, Scroll (L2), R3 Corda, Quorum, and Ethereum.

Tokenization. *Tokenization* refers to the representation of financial claims—money, securities, or other assets—as digital tokens on a programmable platform. A token bundles the record of ownership with the rules governing its transfer, enabling automated enforcement of conditions through executable code [10]. A foundational conceptual distinction separates tokens that *constitute* the underlying asset (native issuance, where the token is the claim) from tokens that *represent a right to* an off-chain asset (backed or proxy tokens, where the claim exists in a separate system). This distinction is the basis for the settlement-asset taxonomy that will be developed in Section 3.1.

Settlement primitives: PvP and DvP. Two exchange-of-value primitives recur across the surveyed projects. *Payment versus Payment* (PvP) links two currency transfers so that the final settlement of one is conditional on the final settlement of the other—the standard mechanism for eliminating the principal risk in foreign exchange transactions [9]. *Delivery versus Payment* (DvP) applies the same conditionality between a securities transfer and a cash payment. Both transfer modes represent a functional application of the atomicity principle, ensuring that cross-asset settlement is executed on an "all-or-nothing" basis. PFMI Principle 12 requires that exchange-of-value settlement systems eliminate the principal risk through such a conditionality [9].

Atomicity. *Atomicity* is the guarantee that a multi-leg transaction either completes in its entirety or has no effect: there is no state in which one leg has settled while the other has not. On a single ledger, atomicity can be enforced by the platform's own execution semantics. Across heterogeneous systems, it requires explicit coordination protocols. The surveyed projects employ three principal mechanism families, each embedding different trust assumptions and failure-handling logic: *hash-time-locked*

[6] Trans-European Automated Real-time Gross settlement Express Transfer system.

[7] Escrow refers to a financial arrangement in which a third party temporarily holds and manages funds or assets on behalf of transacting parties, releasing them only when predefined contractual conditions are satisfied.

contracts (HTLCs), *earmark-and-release* via a synchronization operator, and *hash-link contracts* mediated by a trusted oracle. Section 6 will analyze these mechanisms in depth.

Smart contracts. *Smart contracts* are self-executing programs deployed on a DLT platform that enforce predefined rules without discretionary intermediation. In the surveyed projects, they implement conditional transfers, escrow logic, compliance checks, and multi-phase settlement protocols, enabling the programmability that distinguishes DLT-based settlement from message-based RTGS processing.

Settlement finality. *Settlement finality* denotes the irrevocable and unconditional completion of a transfer of value. A critical distinction separates *technical finality*—the point at which a DLT consensus protocol considers a transaction confirmed and irreversible—from *legal finality*—the point at which the transfer is recognized as irrevocable under applicable law [9]. These two moments need not coincide: DLT confirmation does not automatically confer legal finality and the gap between them is a source of regulatory uncertainty for every project in scope (see Sections 7 and 8).

2.3. Institutional Landscape

The corpus analyzed in this SoK comprises fourteen institutional, permissioned DLT projects involving central banks. Its core is defined by the set of all publicly documented BIS Innovation Hub projects relevant to cross-border payments and settlement that leverage DLT. The scope is expanded to include selected Eurosystem initiatives and the Swiss National Bank's Helvetia/SDX pilot. Although these initiatives are domestic rather than cross-border in scope, they are included in this SoK because the interoperability mechanisms they develop—bridge connectors, atomicity protocols, and settlement-asset models for linking DLT platforms with existing RTGS and instant-payment infrastructure—are the building blocks on which cross-border DLT settlement depends. In addition, they document the most advanced institutional pathway currently available from experimentation toward operational deployment, thereby providing valuable evidence on how interoperability architectures evolve beyond the proof-of-concept stage.

The BIS Innovation Hub, established in 2019, has a mandate to identify critical technology trends affecting central banking, develop public goods in the technology space, and serve as a focal point for central bank innovation [11]. It operates through centers in multiple jurisdictions and partners with host central banks on proof-of-concept projects. Of the fourteen projects in this SoK, eight originate from or involve the BIS Innovation Hub. The Hub does not describe production systems; its outputs are proofs of concept and prototypes that demonstrate feasibility and highlight design trade-offs [11].

The Eurosystem has pursued a staged trajectory from parallel experimentation through consolidation to architectural vision. Between May and November 2024, the *European Central Bank* (ECB) conducted exploratory work in which 64 participants across nine jurisdictions completed over 50 trials and experiments, settling close to EUR 1.6 billion in CeBM [12]. Three independent interoperability solutions tested as many different mechanisms for connecting market DLT platforms to the TARGET settlement infrastructure. The exploratory results have been consolidated into *Pontes*, a near-term offering targeted for pilot in Q3 2026 that provides a single Eurosystem solution linking market DLT platforms to TARGET services for CeBM settlement [13]. A longer-term initiative, *Appia*, whose roadmap and public consultation were published in March 2026, explores two potential architectural endpoints: a European shared ledger that brings together central bank money, commercial bank money, and other assets on a single platform, along with a network of interoperable platforms; a full blueprint is targeted for 2028 [14, 15]. The ECB frames Pontes and Appia as complementary tracks of a single programme whose objective is to ensure that CeBM remains the settlement anchor as wholesale financial markets tokenize [16]. That these domestic interoperability mechanisms are directly reusable in cross-border settings was demonstrated by Meridian FX, whose synchronization operator achieved atomic cross-border PvP by connecting to all three Eurosystem solutions [17].

Switzerland's Helvetia/SDX pilot occupies a complementary position. Like the Eurosystem's exploratory work, Helvetia is domestic: it settles tokenized bonds in Swiss francs on *SIX Digital Exchange*, a regulated DLT-based market infrastructure [18]. It is included in this SoK for two reasons. First, it is the only live pilot in which a central bank issues a native wholesale CBDC that is legally equivalent to sight deposits; the Swiss National Bank (SNB) extended the pilot to at least mid-2027 and expanded it to include deposits [19] enabled by Switzerland's DLT Act [20]. Second, in 2025 an RTGS-link approach was adopted in which tokenized assets settle on DLT while the cash leg settles in traditional CeBM via the Swiss RTGS [21].

These experimental programmes operate against the backdrop of an ambitious conceptual vision articulated by the BIS. The *unified ledger*, proposed in the *BIS Annual Economic Report 2023*, envisions a new type of FMI that brings together tokenized central bank money, tokenized commercial bank deposits, and tokenized assets on a single programmable platform, enabling atomic settlement and composable transactions [10]. The 2024 *Finternet* paper extends this into a broader vision of "multiple financial ecosystems interconnected with each other—much like the internet" [22], with unified ledgers as the vehicle. The *Annual Economic Report 2025* further elaborates the concept around a "trilogy" of tokenized central bank reserves, commercial bank money, and government bonds [8]. These visions are not yet operational architectures, but they motivate several surveyed projects—Agorá explicitly targets the unified-ledger model [23]—and frame the aspirational end-state against which the design choices documented in this SoK should be read. Appia's shared-ledger track represents the Eurosystem's attempt to chart an institutional path toward a comparable vision within the euro area [15].

3. Taxonomy and Project Landscape

This section introduces the analytical taxonomy that structures the comparative analysis in Sections 4–7. Section 3.1 defines three primary classification axes and their values. Section 3.2 maps the surveyed projects onto these axes. Section 3.3 distills design-space observations that motivate the subsequent deep-dive sections.

3.1. Taxonomy Dimensions

Our taxonomy organizes the projects along three primary axes: *target segment* determines the operational context and participant structure; *architectural pattern* determines the integration topology and governance surface; *settlement-asset representation* determines the monetary relationship between on-chain token and central bank balance sheet. These axes were selected through an iterative analysis of the fourteen project reports on the basis of two criteria: discriminative power—each axis partitions the project set into groups that differ meaningfully in architecture, risk profile, or institutional implication—and analytical independence—each axis captures a source of variation not reducible to the others. A flat feature matrix could record these properties, but the three-axis structure does more: it defines a design space whose regions correlate with distinct trade-off profiles, maturity stages, and institutional strategies—correlations that Section 3.3 identifies as the paper's core empirical findings.

Axis 1: Target segment. A foundational distinction separates *wholesale* and *retail* systems. Wholesale systems settle high-value transfers between financial institutions—central banks, commercial banks, and FMIs—typically in CeBM via RTGS. Retail systems handle high-volume, lower-value transactions involving end users, mediated by PSPs or commercial banks. This boundary is architecturally significant: as Section 5 will demonstrate, it drives divergences in participation models, FX provisioning strategies, privacy and compliance requirements, and scalability targets. It is placed first because it conditions the feasible values on the other two axes: retail systems consistently require interlinking and layered intermediation, constraining their architectural and settlement-asset options in ways wholesale systems are not constrained.

Axis 2: Architectural pattern. Three recurring patterns emerge for achieving cross-border interoperability, ordered by decreasing integration depth:

- *Common platform* (CP). A single, shared multi-jurisdictional ledger on which participants from different jurisdictions transact directly. Cross-border settlement is an on-platform operation.
- *Interlinking / synchronization* (IL). Independent systems—DLT-to-DLT, DLT-to-RTGS, or IPS-to-IPS—are coordinated through cross-system protocols, synchronization operators, or hub-and-spoke connectors. Each system retains operational and governance autonomy.
- *Infrastructure bridge* (IB). A DLT layer acts as a trigger or coordination overlay for existing non-DLT settlement infrastructure (typically RTGS). No on-chain settlement asset is created; the DLT orchestrates but the legacy system settles.

Several projects combine elements of multiple patterns; where a project is composite, we classify it by the dominant cross-border interoperability mechanism and note secondary patterns explicitly. The ordering from CP through IL to IB traces a spectrum of decreasing integration depth and increasing jurisdictional autonomy—a trade-off that will be central to the analysis in Section 4.

Axis 3: Settlement-asset representation. Three models describe how the settlement asset relates to the DLT layer, ordered by decreasing monetary novelty:

- *Native CBDC token* (NT). The on-chain token *is* CeBM—a direct liability of the issuing central bank, legally and economically equivalent to reserves or sight deposits.
- *Proxy token backed by escrowed CeBM* (PT). The token represents a contractual claim on CeBM held in an escrow or segregated account within the RTGS. It is not itself CeBM but is backed one-to-one by escrowed central bank money.
- *Off-chain RTGS settlement* (RS). No on-chain monetary asset exists. The DLT coordinates or triggers settlement, but the actual transfer of value occurs in the RTGS or an existing payment system.

The NT–PT boundary is the taxonomy's most nuanced distinction. The discriminant is *legal characterization*, not technical architecture: in NT the token *constitutes* CeBM, whereas in PT it *represents a claim on* CeBM. This distinction determines whether the DLT platform hosts a new form of central bank money or merely a coordination instrument anchored in the existing RTGS; Section 7 will develop the classification with project-level evidence and analyze its monetary implications. The ordering from NT through PT to RS traces a second spectrum—from monetary novelty to institutional conservatism—that, as the observations below show, correlates strongly with project maturity.

The three axes are analytically separable but empirically correlated: common platforms tend toward on-chain tokens; infrastructure bridges toward off-chain settlement; retail projects consistently employ interlinking. These correlations are not definitional—they are empirical regularities whose identification is one of the taxonomy's contributions. Two supplementary dimensions—the *FX approach* and the *atomicity mechanism*—are recorded in Table 2 and will be analyzed in Sections 5 and 6.

3.2. Project Classification and Selected Profiles

Table 2 classifies the fourteen DLT-based projects surveyed in this SoK along the taxonomy dimensions defined above and records key maturity and institutional data. Dagger symbols (†) mark the three components of the Eurosystem's exploratory work [12]. As noted in Section 2.3, the Eurosystem exploratory solutions, Pontes, and Helvetia/SDX are domestic projects included because the interoperability mechanisms and settlement-asset models they develop are necessary preconditions for cross-border DLT settlement. Prose profiles follow for projects whose composite architecture or distinctive design choices require explanation beyond the tabular classification.

Eurosystem interoperability trajectory. The Eurosystem's exploratory work [12] tested three solutions that span the bridge pattern's internal design space: the *Trigger Solution* (Deutsche Bundesbank, IB / RS), a pure bridge translating on-chain events into T2 RTGS instructions with no on-chain monetary

Table 2
Design-space classification and institutional context of the DLT-based projects surveyed in this SoK. **Segment**: W = wholesale, R = retail. **Architecture**: CP = common platform, IL = interlinking/synchronization, IB = infrastructure bridge. **Settlement**: NT = native CBDC token, PT = proxy token backed by escrowed CeBM, RS = off-chain RTGS settlement, TBD = to be determined. **Atomicity**: PL = platform-level, HTLC = hash-time-locked contract, HL = oracle-mediated Hash-Link (no timelock), EaR = earmark-and-release. **FX**: OTC = bilateral / pre-agreed, SO-orch. = SO-orchestrated PvP, AMM = automated market maker, FXP mktpl. = FX-provider marketplace, — = not applicable (DvP or single currency). **Maturity:** PoC = proof of concept, MVP = minimum viable product; reflects the status reported in the most recent project documentation available at the time of writing. **Institution**: BdF = Banque de France, BdI = Banca d'Italia, BNM = Bank Negara Malaysia, BoE = Bank of England, BoT = Bank of Thailand, CBUAE = Central Bank of the UAE, DBB = Deutsche Bundesbank, ECB = European Central Bank, HKMA = Hong Kong Monetary Authority, IIF = Institute of International Finance, IL/NO/SE CBs = Central banks of Israel, Norway, and Sweden, MAS = Monetary Authority of Singapore, PBC = People's Bank of China, RBA = Reserve Bank of Australia, SARB = South African Reserve Bank, SIX/SDX = SIX Group / SIX Digital Exchange, SNB = Swiss National Bank.

Project	Seg.	Arch.	Settl.	Atomicity	FX	Maturity	Institution
Trigger Sol.[†]	W	IB	RS	HTLC	—	Concluded (2024)	DBB
DL3S[†]	W	IL	PT	HTLC	—	Concluded (2024)	BdF
TIPS Hash-Link[†]	W	IL	PT	HL	—	Concluded (2024)	BdI
Pontes	W	IB + IL	PT + RS	PL + HL	—	Pilot (exp. Q3 2026)	Eurosystem
Appia	W	CP / IL	TBD	TBD	TBD	Consultation (2026)	Eurosystem
Rialto[a]	R	IL	PT	PL	AMM + FXP[b]	PoC (2025)	BIS, BdF, BdI, BNM, MAS
Meridian FX	W	IL	RS	EaR	SO-orch.[b]	PoC (2025)	BIS, BoE, BdF, BdI, DBB, ECB
Helvetia/SDX[c]	W	CP + IB	NT + RS	PL	—	Live pilot (ext. 2027)	SNB, SIX/SDX
mBridge[d]	W	CP	PT	PL	OTC	MVP (2024)	HKMA, CBUAE, BoT, PBC, BIS
Agorá	W	CP	PT	PL	Planned[b]	Prototype (2025)	BIS, IIF, 7 CBs
Dunbar	W	CP	NT	PL	OTC	Concluded (2022)	BIS, RBA, BNM, MAS, SARB
Jura	W	CP	PT	PL	OTC	Concluded (2021)	BdF, SNB, BIS
Mariana	W	CP	NT	PL	AMM	Concluded (2023)	BIS, BdF, MAS, SNB
Icebreaker	R	IL	NT	HTLC	FXP mktpl.[b]	Concluded (2023)	BIS, IL/NO/SE CBs

[†] Eurosystem exploratory work component [12]. [a] Technical atomicity within ZK-rollup (EVM); functional atomicity (compensating refund) across the IPS–DLT boundary. [b] Vehicle-currency routing demonstrated or planned. [c] Since 2025, the SNB also explores an RTGS-link approach (IB, RS) alongside the integrated wholesale CBDC model (CP, NT) [21].
[d] BIS Innovation Hub withdrew in late 2024.

asset; *DL3S* (Banque de France, IL / PT), issuing escrow-backed cash tokens with HTLC-based cross-ledger atomicity on Hyperledger Fabric; and *TIPS Hash-Link* (Banca d'Italia, IL / PT), an oracle-mediated protocol linking market DLTs to a TIPS-based cash settlement platform via a DLT-agnostic API gateway. *Pontes* [13] consolidates these into a near-term composite offering—combining a T2 trigger backend, an Eurosystem DLT for cash-token issuance, and cross-ledger coordination via the Hash-Link protocol—with both token (PT) and direct RTGS (RS) settlement tracks; a pilot is expected in Q3 2026. *Appia* [14, 15] explores longer-term paths—a European shared ledger (CP) or interconnected platforms (IL)—with a blueprint targeted for 2028.

Rialto [24]. It targets retail cross-border payments through a two-block architecture: *Block 1* interlinks domestic IPSs via ISO 20022 messaging[8]; *Block 2* is a DLT settlement network (Scroll ZK rollup[9]) where

[8]ISO 20022 messaging refers to a global standard for electronic data interchange between financial institutions, defining a common platform for the development of structured financial messages (e.g., payments, securities, trade services) using a shared data dictionary and XML-based syntax to improve interoperability and automation.
[9]A zero-knowledge (ZK) rollup executes transactions off the main chain and posts a succinct cryptographic proof of their validity back to a base layer, achieving scalability while inheriting the base layer's security guarantees.

FX conversion occurs via an on-chain *automated market maker* (AMM)[10]. FX Providers absorb slippage[11] risk by intermediating between the pool and PSPs, which access the system through settlement access providers without DLT connectivity.

Meridian FX [17]. It prototypes a *synchronization operator* (SO) that orchestrates atomic PvP FX settlement across heterogeneous systems—RTGS and DLT—without holding accounts or assuming credit risk. Settlement occurs off-chain (RS) via earmark-and-release, extending to vehicle-currency PvP across three currencies. Its direct connection to all three Eurosystem solutions demonstrates cross-border reusability of the domestic mechanisms described above.

Helvetia/SDX [18]. It is a live pilot in which the SNB issues wholesale CBDC—legally equivalent to sight deposits [19]—on SIX Digital Exchange for DvP settlement of tokenized bonds (CP, NT).

Remaining projects. The remaining six projects are classified in Table 2. Among common platforms, *mBridge* [25] reached MVP status with a custom *Byzantine fault-tolerant* (BFT) blockchain supporting multi-CBDC PvP; *Agorá* [23] targets unified-ledger integration of tokenized CeBM and commercial bank deposits; *Dunbar* [26] and *Jura* [27] explored multi-CBDC platform prototypes (concluded 2021–2022); and *Mariana* [28] tested AMM-based wholesale CBDC (wCBDC) exchange (concluded 2023). In the interlinking category, *Icebreaker* [29] explored retail CBDC interlinking via hub-and-spoke with HTLC-based PvP and vehicle-currency routing (concluded 2023).

3.3. Design-Space Observations

The taxonomic classification yields four observations. Each one is an empirical regularity visible in the three-axis design space and identifies a cross-axis correlation or a structural constraint that motivates a dedicated analytical section.

Observation 1: Composite, interlinking-first architectures dominate production-track projects. Among mature projects, only mBridge employs a pure common-platform architecture. The Eurosystem's trajectory—from three independent exploratory solutions through the consolidated Pontes to the visionary Appia—reveals a staged progression that starts with interoperability and reserves full integration for the long term. Meridian FX and Rialto similarly favor interlinking. More broadly, the two projects closest to production—Pontes and Helvetia/SDX—and the most architecturally complex PoC (Rialto) all combine elements from multiple architectural categories; pure single-pattern designs characterize earlier experiments. This will be developed in Section 4.

Observation 2: The retail design space is underexplored. Only two projects—Rialto and Icebreaker—target retail cross-border payments. Retail designs consistently require layered intermediation, automated FX with vehicle-currency routing, and federated compliance—features absent from wholesale projects. The small sample limits generalizability but confirms that Axis 1 is not merely a labeling convenience: the wholesale–retail boundary propagates into qualitatively different feasible regions on Axes 2 and 3. This will be developed in Section 5.

Observation 3: Atomicity mechanisms vary within architectural categories. Common platforms do not converge on a single atomicity model: mBridge uses three-phase smart-contract PvP, Jura dual-notary signing, Mariana AMM-based settlement, and Agorá unified-ledger composability. Interlinking architectures display comparable diversity (HTLC, hash-link with oracle, earmark-and-release). No single mechanism has emerged as dominant, but a maturity-correlated trajectory is discernible:

[10] It algorithmically prices and executes asset swaps using pre-funded liquidity pools rather than a traditional order book.
[11] Slippage refers to the difference between the expected price of a trade and the actual executed price, typically caused by market volatility or insufficient liquidity during the transaction.

production-proximate designs favor oracle-mediated or operator-based coordination over trustless primitives. This will be developed in Section 6.

Observation 4: The proxy-token consensus. Proxy tokens (PT) and off-chain RTGS settlement (RS) dominate recent and production-track projects. Native CBDC tokens (NT) appear only in earlier experiments (Dunbar 2022, Mariana 2023, Icebreaker 2023) and in the singular case of Helvetia/SDX—a domestic, single-jurisdiction pilot on a regulated FMI. Axis 3 thus reveals an unambiguous maturity trajectory: the design space is migrating away from monetary novelty and toward preserving the RTGS as the canonical settlement layer. The institutional logic—reducing legal, governance, and operational exposure—will be analyzed in Section 7.

4. Architectural Patterns

This section addresses **RQ1** (architectural patterns in DLT-based cross-border payments) by analyzing the recurring architectural patterns that emerge in institutional DLT-based cross-border payment and settlement systems. Three structural archetypes—*common platforms*, *synchronization and interlinking models*, and *interoperability bridges*—are examined in turn, followed by a comparative synthesis.

Common platforms. The common-platform pattern consolidates cross-border settlement onto a single shared ledger on which multiple central banks issue, transfer, and redeem digital currencies [25]. Five wholesale projects instantiate this pattern (Table 2); Appia's shared-ledger track explores it at the European level. The chief advantage is *coordination depth*: because all transaction legs execute in a single environment, atomicity, FX settlement, and compliance checks can be embedded in on-platform smart contracts, minimizing the protocol surface spanning institutional boundaries. Helvetia/SDX illustrates this most concretely—wholesale CBDC and tokenized bonds co-reside on a regulated FMI, making DvP an atomic on-platform operation [18]. The corresponding cost is *governance complexity*. Dunbar identified three unresolved questions: which entities may transact, how regulatory differences are respected across borders, and what governance arrangements give countries sufficient comfort to share critical national infrastructure [26]. Even domestically, the SNB has flagged fragmentation risk from issuing CBDC on multiple platforms [19]. Privacy is limited to data compartmentalization—pseudonymous addresses ensure counterparty-only visibility without cryptographic guarantees [25]—and *path dependence* is structural: commitment to a shared ledger's consensus protocol, smart-contract language, and governance rulebook create high migration costs, making regional fragmentation into multiple platforms a likely outcome [26].

Synchronization and interlinking. The synchronization pattern preserves the independence of domestic payment systems while introducing a neutral coordination layer—the SO—that orchestrates atomic settlement across heterogeneous ledgers. The SO holds no accounts, assumes no credit risk, and requires no common ledger or consensus protocol among participants [17]. Atomicity is achieved through distributed earmark-and-release: funds are conditionally reserved on each leg and released simultaneously upon satisfaction of all preconditions; failure on any leg triggers full abort. The mechanism is agnostic to both asset type and ledger technology [17], as demonstrated by Meridian FX's coordination across all three Eurosystem bridge solutions. Rialto extends interlinking logic to the retail segment, positioning the DLT component beneath existing payment rails so that PSPs participate without DLT connectivity [24]. The principal trade-off is *liveness dependence*: all participating systems must respond within coordinated time windows, with the SO being a trust-critical single coordination point whose availability and correctness are necessary for settlement.

Bridges and protocol-level connectors. The bridge pattern provides protocol-level connectors—APIs, smart contracts, or hash-based linking mechanisms—that enable market DLT platforms to trigger settlement in existing payment systems without joining a shared platform or routing through a central orchestrator. The Eurosystem's trajectory from exploratory work through Pontes is the most developed instantiation. The 2024 exploratory work [12] tested three designs that span the bridge pattern's internal design space: from shallow coupling (Trigger Solution: DLT-to-RTGS translation, no on-chain asset) through token-mediated interlinking (DL3S: escrow-backed cash tokens with HTLC atomicity) to oracle-mediated synchronization (TIPS Hash-Link: API gateway with trusted-oracle release, eliminating the inadvertent-option and timeout failures of standard HTLCs). Pontes [13] consolidates these into a "bring-your-own-market-DLT" offering in which the Eurosystem provides the cash-settlement rail while market operators retain full control of their asset platforms. Helvetia has converged from the opposite direction, adding an RTGS-link bridge alongside its integrated common-platform model [21]. The bridge pattern's core advantage is *minimal coupling*: TIPS Hash-Link requires no new development for additional DLTs and imposes no wallet requirement [12]. The trade-off is shallow, point-to-point interoperability: complex multi-leg transactions require layering multiple bridge interactions, each with its own timeout and failure-handling logic.

The three patterns occupy distinct positions on an *integration–interoperability spectrum*. Common platforms maximize coordination depth—atomicity, programmability, and policy enforcement are native—but demand the highest governance investment and expose participants to lock-in. Synchronization models preserve domestic independence and offer technology neutrality, at the cost of liveness constraints and SO dependence. Bridges impose minimal requirements and deploy incrementally, but provide only shallow interoperability. These patterns are not mutually exclusive. Pontes combines bridge connectors with platform elements [13]; Rialto layers IPS interlinking over a DLT settlement network [24]; Meridian FX connected its SO to three distinct Eurosystem solutions [17]; Helvetia simultaneously operates both an integrated and a bridge-based model [21]. The practical architecture of cross-border DLT settlement is converging not on a single pattern but on *composable stacks* that layer patterns to balance integration depth against jurisdictional flexibility.

5. Wholesale vs. Retail: Segment-Driven Design Divergence

This section addresses **RQ2** (design choices for wholesale and retail systems) by examining how the target segment—wholesale or retail—shapes architectural choices, settlement mechanisms, and system design. Of the fourteen projects in scope, twelve target wholesale use cases; only Rialto [24] and Icebreaker [29] address the retail segment. The small retail sample limits generalizability but makes the structural divergences analytically significant: they arise from fundamentally different operational requirements, not incidental design variation.

Participation models and intermediation. Wholesale systems admit a narrow, institutionally homogeneous participant set—central banks operate validating nodes, commercial banks connect as transacting participants—and require no intermediation layer [25, 13]. Retail systems must bridge the gap between end users and institutional settlement infrastructure through multi-tier intermediation. Rialto introduces at least six functional layers—PSPs, domestic IPSs, an IPS Link, settlement access providers, a settlement orchestrator, and FX providers [24]; Icebreaker is structurally simpler but still requires dedicated FXPs with wallets in multiple jurisdictions [29]. The common design principle is *infrastructure shielding*: retail architectures systematically insulate end users and PSPs from cross-border settlement complexity.

FX provisioning. FX provisioning is the dimension along which the two segments diverge most sharply. Wholesale projects overwhelmingly rely on pre-agreed or bilaterally negotiated rates settled off-platform [25, 27, 26, 17]—the standard assumption that counterparties maintain trading relationships and that FX markets provide pre-trade price formation. Retail systems cannot rely on this assumption and instead embed automated price discovery: Icebreaker operates a marketplace in which FXPs submit competing rates to a hub that selects the best quote [29]; Rialto interposes FXPs between an on-chain

AMM (Uniswap v3) and the payment flow, with the FXP absorbing slippage risk [24]. Both retail projects support *vehicle-currency routing* for low-liquidity corridors [24, 29]. Vehicle-currency support appears in wholesale designs—Meridian FX demonstrated atomic bridge-currency PvP [17]; Agorá targets it [23]—but in retail projects it is a core routing primitive rather than an extension.

Scalability and compliance. Wholesale systems prioritize settlement finality over raw throughput; sustained volumes are modest, e.g., Pontes targets 10 transactions per second (TPS) on average [13]. Retail systems must match domestic IPS latency—near-instant, 24/7/365—but sustained throughput benchmarks at retail scale remain unreported across all surveyed projects, limiting production-readiness assessment. Compliance follows a parallel divergence: wholesale systems enforce it through institutional onboarding of known, regulated counterparties [25], whereas retail systems adopt a *federated compliance model*, delegating anti-money-laundering (AML) and combating-the-financing-of-terrorism (CFT) screening to PSPs or domestic wallet providers within each jurisdiction [24, 29]. Whether federated models can satisfy travel-rule obligations without centralized data repositories remains open (see Section 8).

The wholesale–retail boundary propagates through every layer of system design. These divergences are structural and unlikely to be resolved by a single converged architecture.

6. Atomicity and Cross-Ledger Settlement Mechanisms

This section addresses **RQ3** (mechanisms for atomic settlements) by analyzing the mechanisms through which the surveyed projects achieve atomic settlement. Three mechanism families are distinguished by trust model, failure-handling logic, and the degree of coupling they impose between participating systems.

Platform-level and hybrid mechanisms. When all transaction legs execute on a single shared ledger, atomicity can be enforced by the platform's own execution semantics. The surveyed common-platform projects instantiate this in several ways: mBridge implements a three-phase smart-contract PvP protocol (*initiate*, *commit*, *execute*) that separates compliance authorization from settlement execution [25]; Jura relies on Corda's[12] dual-notary signing, distributing trust across two jurisdictional notary nodes [27]; Mariana collapses FX conversion and settlement into a single atomic AMM transaction [28]. Other common-platform projects achieve atomicity through conditional transfers (Dunbar [26]), co-located DvP on a regulated FMI (Helvetia/SDX [18]), or unified-ledger composability (Agorá [23]). On-platform mechanisms offer the strongest atomicity guarantee—inheriting the all-or-nothing semantics of the underlying execution engine—but their scope is limited to transactions whose legs reside on the same ledger. When transaction legs span heterogeneous execution environments, pure on-platform atomicity is insufficient. Rialto's two-block architecture illustrates the challenge: within its ZK-rollup (Block 2), FX swaps execute atomically via *Ethereum virtual machine* (EVM) transaction semantics; across the IPS–DLT boundary, however, the IPS lacks smart-contract capabilities [24]. Rialto therefore implements *functional atomicity*: if the on-chain leg fails, a catch-block mechanism triggers a compensating refund in the IPS layer [24]. This is a weaker guarantee—a transient window exists in which one leg may have completed while compensation is pending—but is argued to be operationally acceptable for retail amounts. Pontes is similarly composite: intra-platform settlement on the ESY DLT benefits from on-platform atomicity, while cross-platform DvP relies on the Hash-Link protocol [13].

Distributed earmark-and-release. Meridian FX introduces an atomicity model designed for heterogeneous, multi-system environments. Its SO orchestrates PvP settlement across independent payment systems—RTGS and DLT alike—without holding accounts or assuming credit risk [17]. The protocol

[12] Corda is a DLT platform developed by R3, designed for financial institutions, where transactions are shared only among relevant parties and validated through consensus without relying on a global broadcast or native cryptocurrency.

proceeds in stages: (i) each participating system *earmarks* (conditionally reserves) the relevant funds; (ii) once all earmarks are confirmed, the SO issues simultaneous *release* instructions; (iii) if any earmark fails or times out, the SO aborts the entire transaction. Settlement occurs off-chain in the respective domestic infrastructures. The key advantage is *technology neutrality*: the mechanism imposes no requirements on connected systems beyond the ability to conditionally hold and release funds [17]. The Meridian FX prototype demonstrated this by coordinating atomic PvP across pairings with all three Eurosystem bridge solutions [17]. The principal vulnerability is *liveness dependence*: all systems must respond within coordinated time windows, with the SO itself being a single coordination point whose availability and correctness are necessary for settlement.

Hash-link and HTLC-based protocols. Hash-based cryptographic linking is the most widely deployed cross-ledger atomicity technique in the surveyed corpus, but a critical distinction separates two variants: *standard HTLCs* (with timelocks) and the *Hash-Link Contract* (HLC, without timelocks), as developed by the Banca d'Italia.

Standard HTLCs. DL3S [12] and Icebreaker [29] use HTLCs to coordinate DvP or PvP across independent ledgers. Party A locks funds on Ledger 1 under a hash $h = H(s)$ with a timelock t_1; Party B locks corresponding funds on Ledger 2 under the same hash with a shorter timelock $t_2 < t_1$. Revealing the secret s releases both legs; expiry triggers automatic refunds. The Trigger Solution similarly uses HTLCs to coordinate DLT-originated transactions with T2 RTGS settlement [12]. The well-known limitation is the *inadvertent option problem*: between locking and reveal, the party holding the secret possesses a free option—it can choose to execute or let the lock expire depending on market movements. In wholesale FX settlement, this creates an asymmetric risk that is unacceptable for CeBM.

Hash-Link Contract (HLC). The TIPS Hash-Link solution modifies the HTLC construction by removing the timelock and introducing a *trusted oracle* (the API Gateway) that controls release of the cryptographic pre-image [12]. The asset is locked on the market DLT until cash payment on the TIPS-based platform is confirmed; only then does the Gateway release the pre-image. Crucially, liquidity is *not* locked during the process [12]. This eliminates the inadvertent option problem and timeout-induced DvP failure risk, at the cost of a trusted intermediary as a new trust assumption. Pontes adopts the Hash-Link protocol as its primary cross-ledger atomicity mechanism via the Extended Interoperability Interface [13].

On-platform mechanisms provide the strongest guarantees but the narrowest scope. Earmark-and-release offers technology neutrality at the cost of SO liveness dependence. Standard HTLCs provide trustless cross-ledger atomicity, but the inadvertent option problem makes them unsuitable for CeBM settlement—explaining their absence from production-proximate designs. The Hash-Link variant trades trustlessness for safety, a pragmatic compromise standardized via Pontes; hybrid mechanisms substitute compensating logic where true atomicity is unachievable.

No single atomicity mechanism dominates the design space. The choice is shaped by the architectural pattern, the nature of the connected systems, and the institutional tolerance for trust assumptions. The institutional DLT community prioritizes *safety*—the elimination of partial settlement—over *trustlessness*, accepting curated intermediaries where they eliminate failure modes incompatible with CeBM.

7. Settlement Asset Representation and Monetary Design

This section addresses **RQ4** (settlement asset representation on DLT platforms) by examining how the surveyed projects represent settlement assets on DLT platforms and the consequences for monetary architecture, counterparty risk, and system integration. The three models differ not in *whether* they anchor to CeBM, but in *where* that anchor is instantiated and what consequences follow.

Native CBDC tokens. In the NT model the on-chain token *constitutes* central bank money—a direct liability legally equivalent to reserves or sight deposits. Helvetia/SDX is the most advanced instance:

the SNB characterizes its wholesale CBDC as an alternative representation of sight deposits [18] and Swiss law recognizes DLT-ledger entries as conferring legal ownership, enabling settlement finality directly on the platform. Dunbar, Mariana, and Icebreaker similarly issue tokens as direct central bank liabilities [26, 28, 29]. The NT model offers the strongest settlement finality guarantee *in principle*—on-chain transfer is final without requiring a separate RTGS confirmation—yet the *International Monetary Fund* (IMF) observes that the legislative landscape for CBDC remains nascent worldwide [30].

Proxy tokens backed by escrowed CeBM. The PT model interposes a contractual layer: the token represents a claim on funds held in a segregated RTGS account, preserving the RTGS as the canonical monetary layer. mBridge tokens embody a right to claim a central bank liability guaranteed by immobilized reserves [25]; Pontes cash tokens are contractual claims subject to mandatory end-of-day redemption [13]; Jura wCBDCs carry no independent legal force [27]. DL3S, Rialto, and Agorá follow the same structural logic. Legal complexity is reduced but three costs arise. First, one-to-one backing imposes *prefunding*: escrowed funds bear no interest and do not count toward reserve requirements [12]; the FSB warns that at scale this could raise financial stability risks [31]. Second, full backing forecloses the *elastic intraday credit* that underpins RTGS systems—the BIS emphasizes that without such an on-demand liquidity the system could not operate smoothly [8]—imposing a cash-in-advance constraint incompatible with sound money design at scale [8]. Third, the holder bears operational and legal risks absent from NT: the claim must be enforceable and redemption functional under stress.

Off-chain RTGS settlement. The RS model eliminates the on-chain monetary asset entirely. Meridian FX settles off-chain via earmark-and-release, lowering liquidity costs by removing the need for extended prefunding [17]; the Trigger Solution translates DLT events into conventional T2 instructions [12]. No new monetary instrument is required and finality is inherited from the RTGS, but programmability is sacrificed: the settlement asset cannot participate in smart-contract logic and the IMF notes that cross-ledger transactions can at best achieve "weak" atomicity [32].

Implications for monetary design. The three models trace a spectrum from monetary novelty to institutional conservatism. Native CBDC tokens create a new form of CeBM with the strongest finality guarantee but the heaviest governance and legal burden. Proxy tokens PT preserves the RTGS while enabling DLT-based programmability, at the cost of prefunding, contractual risk, and forgone elasticity. Off-chain RTGS settlement RS imposes no monetary innovation but sacrifices on-chain composability. The empirical trajectory is unambiguous: production-track projects converge on PT and RS, while NT remains confined to early experiments and the singular Helvetia pilot. A residual tension persists: PT and RS designs bind the DLT layer to RTGS operating hours, yet very few RTGS systems currently provide near-24/7 service [33]; the ECB's T2 closes for 48 hours each weekend [34]; the Bank of England acknowledges that longer RTGS operating hours could be an important enabler for synchronization and PvP settlement [35]. For projects targeting instant cross-border settlement, this dependency is a binding constraint that NT designs can, in principle, eliminate.

8. Discussion and Open Challenges

This section reflects on the implications of the preceding analysis and identifies the challenges that remain unresolved across the design space (**RQ5**).

Settlement finality on DLT lacks a uniform statutory basis. Native-token deployments offer the strongest guarantee in principle, yet outside jurisdictions with bespoke legislation—such as Switzerland's DLT Act [18]—on-chain transfers carry no assured legal force [30]. Proxy-token and off-chain designs inherit finality from the RTGS but bind the DLT layer to legacy operating hours [33, 34]; the Eurosystem's statement that DL3S is not a "system" under the Settlement Finality Directive [12] illustrates the regulatory gap. The Appia roadmap accordingly identifies legal and regulatory harmonization as a building block, acknowledging that technology alone cannot resolve the jurisdictional fragmentation underlying cross-border settlement [16, 15]. No surveyed project provides cryptographic privacy guarantees: wholesale systems rely on pseudonymous addressing [25], retail systems delegate screening to PSPs [24, 29], and whether federated compliance models can satisfy travel-rule obligations without centralized data repositories remains open.

On the monetary side, proxy-token designs impose a cash-in-advance constraint that eliminates the elastic intraday credit central banks routinely supply through RTGS facilities [8]; at scale, full prefunding could fragment liquidity and raise financial stability concerns [31]. Helvetia mitigates this by aligning RTGS and SDX operating hours [19], but the approach depends on domestic coordination and does not generalize where RTGS schedules diverge [33, 34]. AMM-based FX provisioning, as prototyped by Mariana and Rialto, has not been stress-tested under volatile conditions at production volumes. These liquidity and operating-hour constraints are structural limits on how far PT and RS designs can advance toward 24/7 cross-border settlement without changes to underlying RTGS infrastructure [35].

Governance remains the least developed dimension. Dunbar's unanswered question—what arrangements could give countries sufficient comfort to share critical national infrastructure [26]—has grown more salient as projects approach production. Interlinking models reduce governance scope but shift the problem to the SO or bridge provider; no surveyed project has published a comprehensive governance framework for cross-border production use. Appia frames the issue as a choice between a single European shared ledger and multiple interconnected networks [15, 16]—a decision that could shape both the Eurosystem's architecture and the broader international design space. Regional experiments with limited interoperability risk replicating the fragmentation DLT seeks to overcome; the ECB's framing of these initiatives as safeguarding CeBM against private stablecoins [16] underscores that interoperability design is also a contest between central bank money and private stablecoins over which settlement asset anchors tokenized markets.

For infrastructure designers, the evidence favors modular architectures that extend existing RTGS and IPS infrastructure with DLT coordination layers. For policymakers, three priorities stand out: harmonizing legal frameworks for settlement finality, extending RTGS operating hours toward near-24/7 availability [35], and developing governance models for multi-jurisdictional coordination that balance efficiency with sovereignty. This SoK is subject to three limitations: the evidence base excludes proprietary design details; most projects remain at proof-of-concept stage with claims unvalidated under production conditions; and the retail design space is represented by only two projects.

9. Conclusion

This paper has systematized fourteen institutional DLT-based projects for cross-border payments and settlement. Its central contribution is a three-axis taxonomy—target segment, architectural pattern, and settlement-asset representation—that decomposes the design space along its most consequential dimensions and makes it visible the trade-off structures that shape institutional choices.

The taxonomy shows that surveyed projects cluster into a small number of recurring configurations. Production-track initiatives are architecturally composite, layering bridge connectors, synchronization protocols, and platform elements to balance integration depth against jurisdictional autonomy. Proxy tokens and off-chain settlement dominate mature designs, tracing an unambiguous trajectory away from native CBDC issuance and toward preserving the RTGS as the canonical monetary layer. Atomicity mechanisms evolve in tandem, shifting from trustless hash-time-locked constructions toward oracle-mediated and operator-based coordination that prioritizes safety over trustlessness. The wholesale–retail boundary propagates through every design layer, making a single converged architecture unlikely. Critical enablers—legal finality, cryptographic privacy, elastic on-chain liquidity, and multi-sovereign governance—remain unresolved across the design space.

The Eurosystem's trajectory provides the most developed empirical lens through which these patterns can be observed. It shows how interoperability is being operationalized through staged, composite architectures that (i) extend an existing settlement infrastructure rather than replacing it and (ii) preserve central bank money as the settlement anchor while using DLT for coordination and programmability.

References

[1] Committee on Payments and Market Infrastructures, Cross-border retail payments, CPMI Report, Bank for International Settlements, Basel, Switzerland, 2018.

[2] Financial Stability Board, G20 Roadmap for Enhancing Cross-border Payments: Consolidated Progress Report for 2025, Progress Report, Financial Stability Board, Basel, Switzerland, 2025.

[3] Bank for International Settlements, Blueprint for the future monetary system: improving the old, enabling the new, Annual Economic Report 2023, Chapter III, Bank for International Settlements, Basel, Switzerland, 2023.

[4] Financial Stability Board, Enhancing Cross-border Payments: Stage 1 Report to the G20, Technical Report, FSB, 2020. URL: https://www.fsb.org/uploads/P090420-1.pdf.

[5] Committee on Payments and Market Infrastructures, Enhancing Cross-border Payments: Building Blocks of a Global Roadmap, Technical Report CPMI Papers, No. 193, BIS, 2020. URL: https://www.bis.org/cpmi/publ/d193.pdf.

[6] Bank for International Settlements, Enhancing Cross-border Payments: State of Play and Way Forward, Technical Report BIS Bulletin, No. 119, BIS, 2025. URL: https://www.bis.org/publ/bisbull119.pdf.

[7] Committee on Payments and Market Infrastructures, Correspondent Banking, Technical Report CPMI Papers, No. 147, BIS, 2016. URL: https://www.bis.org/cpmi/publ/d147.pdf.

[8] Bank for International Settlements, The next-generation monetary and financial system, in: BIS Annual Economic Report 2025, 2025. URL: https://www.bis.org/publ/arpdf/ar2025e3.htm.

[9] CPSS, IOSCO, Principles for Financial Market Infrastructures, Technical Report, Bank for International Settlements and International Organization of Securities Commissions, 2012. URL: https://www.bis.org/cpmi/publ/d101a.pdf, cPSS Publications No. 101.

[10] Bank for International Settlements, Blueprint for the Future Monetary System: Improving the Old, Enabling the New, Technical Report, BIS, 2023. URL: https://www.bis.org/publ/arpdf/ar2023e3.htm.

[11] Bank for International Settlements, About the BIS innovation hub, https://www.bis.org/about/bisih/about.htm, 2024. Accessed 2025.

[12] European Central Bank, Bridging innovation and stability: the Eurosystem's exploratory work on new technologies for wholesale central bank money settlement, Report, European Central Bank, Frankfurt am Main, Germany, 2025.

[13] European Central Bank, Pontes Pilot: Business Description Document (BDD), Pilot Project Report, European Central Bank, Frankfurt am Main, Germany, 2025.

[14] European Central Bank, Appia, https://www.ecb.europa.eu/paym/dlt/appia/html/index.it.html, 2025. Accessed: 2026-03-06.

[15] European Central Bank, Appia – paving the way for a future-ready, integrated financial ecosystem leveraging tokenisation and DLT, Consultation paper, 2026. URL: https://www.ecb.europa.eu/press/payments-news/ecb.pubconpm202603.en.html, accessed: 2026-04-09.

[16] P. Cipollone, Building the rails for Europe's tokenised financial markets, Speech at the House of the Euro, Brussels, 23 March, 2026. URL: https://www.ecb.europa.eu/press/key/date/2026/html/ecb.sp260323~a88f20c049.en.html, accessed: 2026-04-09.

[17] Bank for International Settlements, Project Meridian FX: Exploring synchronised settlement in FX, BIS Innovation Hub Project Report, Bank for International Settlements, Basel, Switzerland, 2025.

[18] Bank for International Settlements, Project Helvetia: A Multi-phase Investigation on the Settlement of Tokenised Assets in Central Bank Money, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2023.

[19] T. Jordan, Project Helvetia III – The Swiss National Bank's pilot for wholesale CBDC, Speech at the BIS Innovation Summit, Basel, 6 May, 2024. URL: https://www.bis.org/review/r240506e.htm, accessed: 2026-04-09.

[20] Swiss Confederation, Bundesgesetz zur anpassung des bundesrechts an entwicklungen der technik verteilter elektronischer register, Official Federal Law (AS 2021 33), 2020. URL: https://www.fedlex.admin.ch/eli/cc/2021/33/de, adopted 25 September 2020, entered into force 1 February 2021.

[21] Swiss National Bank, Swiss national bank extends and expands Project Helvetia, Press release, 30 June, 2025. URL: https://www.snb.ch/en/publications/communication/press-releases/2025/pre_20250630, accessed: 2026-04-09.

[22] A. Carstens, N. Nilekani, Finternet: The Financial System for the Future, Technical Report BIS Working Papers, No. 1178, BIS, 2024. URL: https://www.bis.org/publ/work1178.pdf.

[23] Bank for International Settlements, Project Agorá: Exploring Tokenisation of Cross-border Payments, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2025.

[24] Bank for International Settlements, Project Rialto – Technical report: Improving instant cross-border payments using central bank money settlement, BIS Innovation Hub Technical Report, Bank for International Settlements, Basel, Switzerland, 2025.

[25] Bank for International Settlements, Project mBridge: Connecting Economies through CBDC, Report, Bank for International Settlements, Basel, Switzerland, 2022.

[26] Bank for International Settlements, Project Dunbar: International Settlements Using Multi-CBDCs, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2021.

[27] Bank for International Settlements, Project Jura: Cross-border Settlement Using Wholesale CBDC, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2021.

[28] Bank for International Settlements, Project Mariana: BIS and Central Banks of France, Singapore and Switzerland Successfully Test Cross-border Wholesale CBDCs, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2023.

[29] Bank for International Settlements, Project Icebreaker: Breaking New Paths in Cross-border Retail CBDC Payments, BIS Innovation Hub Report, Bank for International Settlements, Basel, Switzerland, 2023.

[30] International Monetary Fund, Central Bank Digital Currency: Further Navigating Challenges and Opportunities, Technical Report, International Monetary Fund, 2025. URL: https://www.imf.org/-/media/files/publications/pp/2025/english/ppea2025041.pdf, iMF Policy Paper No. 2025/041.

[31] Financial Stability Board, The Financial Stability Implications of Tokenisation, Technical Report, Financial Stability Board, 2024. URL: https://www.fsb.org/uploads/P221024-2.pdf.

[32] International Monetary Fund, Central Bank Exploration of Tokenized Reserves, Technical Report, International Monetary Fund, 2025. URL: https://www.imf.org/-/media/files/publications/ftn063/2025/english/ftnea2025011.pdf, fintech Note No. 2025/011.

[33] CPMI, Extending and Aligning Payment System Operating Hours for Cross-Border Payments, Technical Report, Bank for International Settlements, 2022. URL: https://www.bis.org/cpmi/publ/d203.htm, cPMI Papers No. 203.

[34] Ledger Insights, ECB consults on extending RTGS hours—could help DLT payments, digital euro, 2025. URL: https://www.ledgerinsights.com/ecb-consults-on-extending-rtgs-hours-could-help-dlt-payments-digital-euro/, accessed 2025-07-01.

[35] Bank of England, Exploring Longer Operating Hours for RTGS, Technical Report, Bank of England, 2024. URL: https://www.bankofengland.co.uk/paper/2024/dp/exploring-longer-operating-hours-for-rtgs, discussion Paper.

A. Acronyms

Table 3
Acronyms used in the paper.

Acronym / Term	Full Form	Definition / Explanation
AMM	Automated Market Maker	Mechanism that algorithmically prices and executes asset swaps using pre-funded liquidity pools rather than a traditional order book.
BIS	Bank for International Settlements	International financial institution that supports central banks and fosters monetary and financial stability.
CBDC	Central Bank Digital Currency	Digital form of sovereign money issued by a central bank.
CeBM	Central Bank Money	Liability of a central bank (e.g., reserves or cash) used as the safest settlement asset in financial market infrastructures.
DvP	Delivery versus Payment	Settlement mechanism linking the transfer of a financial asset to the corresponding payment so that delivery occurs only if payment takes place.
ESY	Eurosystem	Institutional framework composed of the European Central Bank and the national central banks of the euro area.
FX	Foreign Exchange	Process of converting one currency into another, typically involving exchange-rate determination and settlement mechanisms such as PvP.
HTLC	Hash Time-Locked Contract	Conditional transfer mechanism that executes only if a cryptographic preimage is revealed within a specified time window; otherwise the funds can be refunded to the sender.
IPS	Instant Payment System	Payment infrastructure that enables near real-time clearing and settlement of retail payments, typically operating 24/7.
ISO 20022	International financial messaging standard	Global standard for structured financial messaging defining a common data model and syntax to improve interoperability across payment systems.
PSP	Payment Service Provider	Regulated entity that offers payment services to end users, such as banks or licensed payment institutions.
PvP	Payment versus Payment	Settlement mechanism linking two payment legs—typically in different currencies—so that both settle simultaneously, eliminating principal risk in foreign exchange transactions.
RTGS	Real-Time Gross Settlement	Central bank infrastructure used to settle high-value interbank payments individually, in real time, and on a gross basis (without netting). Each payment is final and irrevocable once processed, reducing settlement and credit risk.
SAP	Settlement Access Provider	Intermediary that provides institutions (e.g., PSPs) with access to a settlement infrastructure when they do not connect to it directly.
SO	Synchronization Operator	Entity or mechanism that coordinates atomic settlement across independent systems by orchestrating conditional reservation and release of funds without holding accounts.
T2	TARGET2	Eurosystem's real-time gross settlement system used for large-value euro payments in central bank money.