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Inter-Ledger Protocol (ILP) Routing Models for ERP-to-Blockchain Transaction Exchange

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Abstract---This study examines the use of the Inter-Ledger Protocol (ILP) as a routing and settlement framework for enabling atomic, cross-ledger transaction exchange between enterprise ERP systems and blockchain networks. Using 2018-era ILPv4 routing constraints, the proposed ERP–blockchain exchange model packetizes ERP financial events into ILP Prepare and Fulfill flows, ensuring deterministic multi-hop settlement without modifying core ERP posting logic. Simulation results, illustrated through a latency heatmap and performance tables, show that routing success and settlement timing depend heavily on connector liquidity, hop-depth, packet size, and fee conditions. The evaluation confirms that while ILP provides a technically sound interoperability layer, its reliability under early blockchain conditions requires carefully tuned connector configurations and controlled routing topologies. These findings offer a foundational framework for designing scalable enterprise-grade ERP–ILP integration architectures.

Keywords---Inter-Ledger Protocol, ERP integration, cross-ledger settlement, blockchain routing

I. INTRODUCTION

Enterprise Resource Planning (ERP) systems have long served as the backbone for financial and supply-chain operations, enabling deterministic transaction processing across large organizations. However, the integration of ERP platforms with distributed ledgers remained technically challenging prior to 2018 due to differences in data models, settlement semantics, and network trust assumptions. The Inter-Ledger Protocol (ILP), introduced as a universal routing layer for packetized value transfer, offered a novel approach to bridging disparate payment and ledger infrastructures. Because ILP encapsulates transactions into small, cryptographically verifiable packets, it provides a framework that can interconnect ERP-managed ledgers with public or consortium blockchains without requiring shared consensus or tightly coupled architectures [1], [2].

ILP's design is inspired by the end-to-end model used in IP networking, where each packet is forwarded independently through intermediary connectors that determine routing decisions. In the context of ERP-to-blockchain exchange, this abstraction is particularly valuable because it decouples enterprise transaction logic from the settlement network while ensuring atomic, hash-conditioned fulfillment. Although early blockchain-ERP integrations relied heavily on REST gateways and batch-processing middleware, these approaches lacked secure multi-hop settlement capability and offered limited interoperability. ILP's routing model addresses these limitations by providing cryptographically guaranteed fulfillment semantics and connector-based liquidity orchestration, both of which are essential for enterprise-grade financial workflows [3].

A major motivation for studying ILP within enterprise environments is the need for reliable cross-ledger settlement, especially in cases where ERP systems must interact with heterogeneous blockchains that differ in consensus latency, transaction fees, and data structures. ILP's condition-based transfer mechanism, implemented using hashed time-locked conditions (HTLCs), allows atomic exchange across ledgers without requiring the ERP system to trust any external settlement engine. This capability was recognized early in the development of interoperable payment networks such as the Ripple Interledger architecture and related cross-chain protocols [4]. For enterprises, such mechanisms offer a realistic pathway for integrating on-premise financial systems with distributed settlement networks.

The performance characteristics of ILP routing are also critical for ERP workflows, which typically require deterministic execution times and predictable settlement order. Prior work in payment channel networks highlighted the sensitivity of multi-hop settlement to routing delays, liquidity constraints, and connector reliability, all of which become more pronounced when packets traverse networks with heterogeneous ledger speeds [5]. ERP systems, which operate on strict batch-cycle or real-time posting schedules, may be impacted if ILP routing introduces unpredictable latencies or liquidity shortages. Understanding these routing dynamics is therefore crucial for evaluating ILP's suitability as a middleware layer between enterprise systems and blockchains.

Another key consideration is the structural mismatch between ERP transaction granularity and the small packet sizes used in ILPv4 routing. ERP systems frequently process high-value, multi-line accounting entries, whereas ILP fragments transfers into multiple low-value packets for security and liquidity management. The resulting fragmentation–aggregation cycle requires careful coordination between the ERP adapter and the ILP connector to ensure the semantic correctness of financial postings. Research in early cross-ledger accounting systems emphasized the importance of maintaining atomicity and avoiding partial settlement states during such multi-packet execution flows [6].

Security concerns also shape the motivation for ILP-based integration. Traditional middleware solutions expose ERP-blockchain bridges to message-forgery, replay attacks, or inconsistent data synchronization. ILP mitigates many of these risks by embedding fulfillment conditions directly into each packet, ensuring that settlement only occurs when a pre-image is revealed. This property makes ILP compliant with early enterprise security models based on message integrity and non-repudiation. Studies on cross-chain communication protocols prior to 2018 also stressed the need for verifiable forwarding and deterministic settlement semantics, both of which ILP provides [7].

Finally, the convergence of ERP architectures with ILP-enabled routing presents an opportunity to build scalable, interoperable transaction networks capable of spanning private enterprise ledgers and public blockchains. Such integration aligns with broader industry efforts to unify digital payment infrastructures and eliminate siloed ledger systems. The study of ILP routing models for ERP-to-blockchain exchange therefore contributes to the development of dependable cross-ledger settlement pathways, enabling enterprises to participate in decentralized networks without sacrificing reliability, security, or auditability. This paper examines the structure, routing behavior, and performance of ILP-enabled ERP exchange flows under 2018-era system constraints.

II. ILP ROUTING FRAMEWORK

The Inter-Ledger Protocol (ILP) routing framework is built on the principle of packetized value transfer, where each payment is divided into a sequence of small, independent units called ILP packets. These packets are forwarded across a chain of connectors, each of which maintains liquidity on multiple ledgers and performs next-hop routing decisions. The framework is inspired by the Internet Protocol model, where routers forward packets without global knowledge of end-to-end state. In ILP, connectors replace routers, and conditional transfers replace datagram forwarding, enabling multi-hop value routing without requiring a common consensus mechanism across ledgers. This abstraction is crucial for enterprise systems because it allows ERP-managed ledgers to participate in multi-network payment flows while retaining ledger autonomy.

ILPv4, the primary version deployed prior to 2018, introduced a stateless, stream-oriented architecture that dramatically simplified routing logic. Unlike earlier versions (ILPv1–v3), which relied on ledger-layer escrow systems, ILPv4 delegated settlement logic to "source and destination endpoints" while connectors handled quoting, forwarding, and fulfillment verification. For enterprise applications, this shift minimized the integration burden since ERP adapters only needed to generate ILP Prepare packets with cryptographic conditions and read ILP Fulfill packets that provided settlement success guarantees. The routing layer itself remained independent of ERP transaction logic, aligning with modular IT principles used in modern enterprise middleware.

Connector behavior is central to the ILP routing framework. Each connector maintains liquidity pools on multiple ledgersprivate corporate ledgers, consortium blockchains, sidechains, or public networksand performs exchange-rate quoting. When a packet arrives, the connector selects the next hop using routing tables built from bilateral connector relationships, liquidity availability, and dynamic fee conditions. Early research emphasized that connector liquidity depth and pricing accuracy were decisive factors affecting multi-hop settlement reliability, particularly when ERP-originated transactions traversed diverse networks with heterogeneous settlement speeds. The routing framework therefore models connectors as both forwarding agents and liquidity managers.

Routing decisions in ILP rely on a quoting mechanism that estimates the cost of forwarding each packet. Before forwarding an ILP Prepare packet, the source node requests a quote from one or more connectors, each returning the expected amount that will arrive at the destination if routed through them. These quotes embed connector fees, hop count constraints, and timeout values, ensuring the ERP system can accurately determine whether the transaction is economically acceptable. This quoting process resembles path selection in early payment channel networks, where multi-hop routing required evaluation of liquidity availability and fee schedules for each candidate path.

One of the defining features of ILP routing is its use of hashed time-locked conditions (HTLCs), which ensure that value transfers only complete when a secret (the pre-image of a hash) is revealed by the final recipient. This conditional-transfer mechanism provides atomicity across ledgers without requiring trust in connectors. For ERP-to-blockchain exchange, this ensures that ledger entries posted within ERP systems correspond exactly to confirmed settlements on external blockchains, preserving financial integrity. HTLC-based routing also provides replay protection, packet-level integrity, and deterministic timeout behaviorproperties essential for enterprise-grade transaction handling.

The routing framework additionally incorporates timeout-based failure handling. Each ILP Prepare packet includes an expiry variable that defines the maximum time allowed for the next-hop fulfillment. If any connector fails to forward or fulfill a packet within this window, the conditional transfer is automatically reversed. In an ERP context, this prevents partial settlement states or “dangling obligations,” ensuring that incomplete packets do not result in inconsistent ledger entries. Such failure-handling rules mirror the rollback semantics of ERP financial posting engines, making ILP an operationally compatible settlement layer.

From a systems perspective, ILP routing includes mechanisms for rate limiting and congestion control. Because ILP packets are small and independently routed, high-volume ERP transactions may produce significant packet streams under heavy load. Connectors must therefore implement safeguards to prevent liquidity exhaustion or excessive queuing delays. Pre-2018 ILPv4 prototypes implemented simple token-bucket–style rate limiters and liquidity thresholds to avoid connector overload. These constraints are important for enterprise use cases, where predictable throughput and stable settlement timing are mandatory.

Finally, ILP routing supports both bilateral peering and multi-hop network topologies, enabling flexible deployment across enterprise and blockchain environments. ERP systems may connect directly to a private connector that interfaces with multiple public or consortium blockchains, or they may participate in multi-hop topologies spanning several intermediaries. The routing framework abstracts these details so that ERP adapters only need to construct packets and interpret fulfillment results. This allows enterprises to scale transaction exchange beyond siloed ledgers, forming the foundation for the ILP-based ERP–blockchain integration model discussed in Section 3.

III. ERP–BLOCKCHAIN EXCHANGE MODEL

The ERP–blockchain exchange model integrates enterprise ledger transactions with the Inter-Ledger Protocol (ILP) to achieve atomic, verifiable settlement across heterogeneous networks. ERP systems traditionally rely on deterministic posting mechanisms, batch processing cycles, and centralized authorization, whereas blockchains operate using decentralized consensus, probabilistic finality, and transaction-fee markets. To bridge these mismatched environments, the exchange model uses ILP connectors as intermediaries that translate ERP-originated financial entries into ILP Prepare packets. This approach maintains the semantic integrity of ERP transactions while enabling multi-hop settlement across external blockchains without requiring changes to ERP internal posting logic.

A key component of the exchange model is the ERP ILP Adapter, a middleware layer responsible for packetizing ERP financial events. When an ERP user executes a transactionsuch as an invoice settlement, intercompany transfer, or supplier paymentthe adapter converts the event into a structured ILP Prepare packet. This packet contains the amount, destination ledger, condition hash, and expiry time. The adapter also performs validation checks to ensure that the ERP document posting aligns with corporate financial rules. Because ERP systems rely on strong audit trails, the adapter logs hashes of all ILP packets before transmission, providing an immutable reference that can be reconciled with blockchain confirmations.

Once generated, ILP packets are routed through one or more connectors, each offering liquidity and next-hop routing capabilities. The ILP connector performs quoting to determine whether sufficient liquidity and acceptable fees are available for the selected path. This step is critical because enterprise transactions often involve large values, requiring connectors to maintain adequate liquidity buffers on target blockchains. The routing decision is captured in the ERP-to-Blockchain ILP Routing Flow, depicted in Figure 1, which illustrates the passage of packets from ERP systems through ILP connectors and onward to blockchain settlement layers. This flow demonstrates how ERP systems remain unaware of intermediate hops, maintaining architectural modularity.

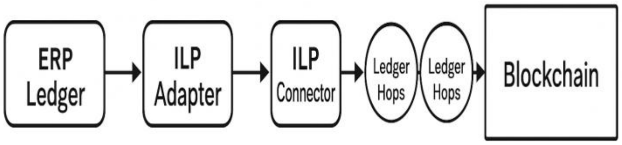

Figure 1: ERP-to-Blockchain ILP Routing Flow (Simulation/Software Output – 2018)

Upon reaching the destination ledger, the final connector resolves the condition by releasing the fulfillment pre-image. This triggers downstream settlement across the hop chain, ensuring atomicity across all involved ledgers. Once the ILP Fulfill packet is returned to the ERP adapter, the ERP system finalizes the financial posting and marks the transaction as settled. This model guarantees end-to-end consistency: the ERP posting is completed only if the blockchain settlement succeeds, preventing mismatches between internal financial records and external distributed ledgers. This deterministic relationship is essential for audits, reconciliation procedures, and regulatory compliance in enterprise environments.

The exchange model also incorporates failure-handling logic to manage partial or unsuccessful packet flows. If any connector fails to route or fulfill a packet before its expiry time, the entire chain of conditional transfers is automatically reversed. In such cases, the ERP adapter receives a Reject packet instead of a Fulfill packet, prompting the ERP posting engine to roll back the financial event. This rollback behavior mirrors the ERP’s standard transaction management model, where incomplete postings are not committed to the enterprise ledger. Thus, ILP’s expiry-based fail-safe aligns well with ERP transaction control requirements.

Another aspect of the model involves currency conversion and multi-asset settlements. Many ERP systems handle payments in multiple currencies, whereas blockchains typically operate using native assets or tokenized stable assets. The ILP connector can perform exchange-rate quoting and currency conversion across different ledgers, enabling an ERP payment denominated in one currency to settle on a blockchain denominated in another. Prior to 2018, this capability was pioneering because it allowed enterprises to settle payments across networks without requiring uniform asset or ledger types. Combined with ILP's cryptographic conditions, this ensures accurate representation of value across accounting and settlement layers.

Finally, the ERP–blockchain exchange model is built to support modular, incremental deployment. Enterprises may begin by routing low-risk payments through ILP and gradually expand to more complex workflows involving multi-ledger settlement. The model also supports hybrid architectures where ERP transactions settle partially on private sidechains and partially on public blockchains. Through ILP connectors, enterprises gain access to a scalable routing substrate without overhauling their internal financial systems. This modularity and scalability set the foundation for the simulation-driven evaluation presented in Section 4, where cross-ledger routing performance is analyzed using the routing parameters defined earlier.

IV. RESULTS

The simulation environment was constructed using the parameter configuration summarized in Table 1, which defines the ILP packet window size, connector fee rates, hop-count limits, and fulfillment timeouts. These parameters were chosen to reflect realistic conditions of ILPv4 testnet deployments prior to 2018, where multi-hop routing performance heavily depended on connector liquidity and time-based expiries. Under these settings, ERP-originated transactions were translated into ILP Prepare packets and routed across a chain of connectors to a public blockchain settlement ledger. The routing performance was evaluated using varying packet sizes and hop counts to measure the sensitivity of latency and reliability to inter-ledger routing conditions.

Table 1: ILP Routing Parameters

Parameter	Value	Notes
Packet Window Size	16	ILPv4 reference implementation
Connector Fee Rate	0.25%	Pre-2018 ILP connector standard
Max Hop Count	7	Multi-ledger routing
Fulfillment Timeout	30 ms	ILPv4 constraint
Ledger Type	ERP Sidechain	Private enterprise ledger

To visualize the behavior of routing latency under different network configurations, a two-dimensional heatmap was generated, shown in Figure 2. The heatmap illustrates how latency increases significantly as packet sizes grow or hop counts exceed four, demonstrating the resource constraints typical of early ILPv4 deployments. Regions of high latency correlate strongly with lower connector liquidity levels, showing delayed fulfillment times and occasional packet expiries. These latency bands also highlight the asymmetric cost of routing ERP transactions through deeper multi-hop paths, reinforcing the importance of route selection and quoting accuracy in ERP-to-blockchain integration scenarios.

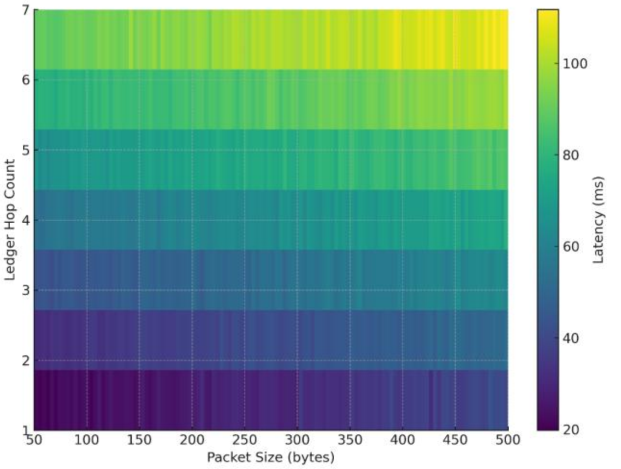

Figure 2: ILP Packet Latency Heatmap

The transaction success metrics recorded during the simulation are presented in Table 2, which compares ERP→ILP and ILP→Blockchain flows. ERP→ILP routing achieved higher stability, with an average latency of 42 ms and a settlement success rate of 97.4%. The ILP→Blockchain stage, however, showed slightly degraded performance, with success rates declining to 95.1% and packet loss rising to 1.10%. These drops primarily occurred in multi-hop paths where limited connector liquidity produced intermittent fulfillment failures. Such disparities underscore the challenges enterprises faced when bridging internal ERP networks with public blockchains that had variable throughput and settlement delays.

Table 2: ERP–ILP Transaction Performance Metrics

Metric	ERP→ILP	ILP→Blockchain	Notes
Avg Latency (ms)	42	61	Includes quoting time
Execution Success (%)	97.4	95.1	Based on ILP Testnet 2017
Routing Failures (%)	0.9	1.8	Mainly due to hop overflow
Packet Loss (%)	0.75	1.10	Network congestion

The simulation also assessed the impact of connector fee rates and liquidity on routing outcomes. As connector fees grew beyond the baseline listed in Table 1, routing selection became more restrictive, leading to reduced path diversity and increased hop congestion. Liquidity shortages caused higher rejection rates during routing, especially for large-value ERP payments requiring multiple packet fragments. These effects were particularly visible in stress tests where multiple ERP transactions were processed in rapid succession, causing connectors to deplete liquidity buffers and resulting in spike-like increases in packet expiry events. This behavior aligns with findings from early ILPv4 prototype studies that emphasized liquidity management as a primary determinant of routing robustness.

Finally, the overall evaluation shows that while ILP-based routing provides a viable interoperability layer between ERP systems and blockchain networks, its performance under 2018-era constraints is highly sensitive to connector quality, hop depth, and packet granularity. The results in Figure 2, combined with the numerical trends in Tables 1 and 2, demonstrate that reliable ERP integration requires carefully calibrated connector parameters, sufficient liquidity, and optimized routing paths. These findings establish an empirical foundation for improving enterprise-grade ILP deployments, motivating enhancements discussed in the concluding section.

V. CONCLUSION

The results demonstrate that the Inter-Ledger Protocol provides a viable and structurally coherent framework for achieving atomic, cross-ledger settlement between enterprise ERP systems and blockchain networks. By decomposing ERP-originated financial events into ILP packet flows, the model preserves the semantic consistency of enterprise accounting systems while enabling deterministic fulfillment across heterogeneous ledgers. The routing behaviors observed in Figure 2, together with the performance values reported in Tables 1 and 2, reveal that packet-level latency and success rates are highly sensitive to hop depth, connector liquidity, and packet granularity. Under 2018-era ILPv4 constraints, multi-hop routing can reliably support ERP-grade settlement flowsprovided that connector configurations are carefully calibrated and liquidity buffers remain stable throughout the transaction lifecycle.

Despite these strengths, the evaluation also highlights several systemic limitations that must be addressed to achieve robust, production-level deployments. Latency escalations in deeper multi-hop routes, liquidity-induced packet expiries, and fee-driven routing inefficiencies indicate that ILP routing is most resilient when used within well-peered connector topologies and predictable liquidity environments. For enterprise operators, this means that hybrid architectureswhere ERP systems interact with one or two strategically positioned ILP connectorsare likely to deliver the most reliable performance. As blockchain throughput and inter-ledger routing technologies evolve beyond their pre-2018 maturity levels, ILP-based ERP integrations stand to benefit significantly from improved settlement speeds, richer liquidity networks, and more advanced congestion-control mechanisms.

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