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Layered Blockchain System Design for Enterprise-Grade Applications

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ABSTRACT

Why do so many enterprise blockchain projects fail to reach production? Gartner puts the figure at 78% of pilots abandoned before deployment, and the root cause is almost always architectural: organisations are forced to choose between Hyperledger Fabric's permissioned speed and Ethereum's trustless settlement, when what they actually need is both. Layered blockchain design offers a way out of this dilemma. By splitting the blockchain stack into specialised layers for consensus, execution, data availability, settlement, and application logic, each layer can be independently tuned to enterprise requirements without sacrificing the tamper-evidence and auditability that justify using a blockchain in the first place. We present the Layered Enterprise Blockchain Architecture Framework (LEBAF) and evaluate five architecture patterns -- modular rollups, sidechain federations, layer-2 state channels, hybrid public-private bridging, and sovereign application chains -- against real workload profiles drawn from supply chain management, financial settlement, digital identity, and regulatory compliance. Our benchmarks show that ZK-rollups with an enterprise sequencer reach 8,400 TPS on realistic workloads, 4.2 times faster than Fabric under the same conditions, while hybrid public-private bridging provides the cleanest path to GDPR compliance. We distil the results into a domain-driven architecture selection guide.

Keywords: layered blockchain; enterprise architecture; modular rollups; layer-2 scaling; state channels; supply chain blockchain; digital identity; cross-chain interoperability

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1. Introduction

1.1 Where Enterprise Blockchain Goes Wrong

The promise was straightforward: put business processes on a shared ledger, eliminate reconciliation, and cut costs. But by late 2023, fewer than one in ten enterprise blockchain projects had delivered measurable ROI according to McKinsey, and Gartner's annual survey found that nearly four out of five pilot programmes stalled before reaching production. The technology was not the issue -- the architecture was. Companies that picked Hyperledger Fabric got the throughput they needed but lost interoperability and any hope of public verifiability. Those that built on Ethereum gained a trustless settlement layer but ran headlong into gas fees, 15 TPS ceilings, and a privacy model that put every transaction detail on a world-readable ledger. Neither choice was wrong in isolation. The mistake was treating these platforms as all-or-nothing propositions. What enterprises actually require is a blend: throughput above 1,000 TPS for production workloads, finality fast enough for financial regulation, GDPR-grade data privacy with selective disclosure, consortium governance that lets members join and leave without disruption, and enough interoperability to support multi-party workflows across organisational boundaries. No single monolithic platform delivers all of that simultaneously. Layered architecture -- the same decomposition strategy that transformed web services through microservices -- can do for blockchain what it did for the rest of the stack.

1.2 What We Set Out to Do

We designed LEBAF with a practical question in mind: given a specific enterprise use case, which layered architecture pattern gives the best balance of performance, privacy, governance, and interoperability? Our contributions are fourfold. First, we define five distinct layered patterns and characterise their trade-offs. Second, we introduce EAQS, a weighted quality score that makes architecture comparison systematic rather than anecdotal. Third, we benchmark all five patterns against workloads drawn from four real enterprise domains using an extended Hyperledger Caliper harness. And fourth, we distil the results into a selection guide that maps domain priorities to recommended patterns. Section 2 walks through each architecture. Section 3 describes LEBAF's evaluation methodology. Results follow in Section 4, discussion in Section 5, and conclusions in Section 6.

2. Architecture Patterns: Five Ways to Layer a Blockchain

2.1 Rollups, Sidechains, and State Channels

Modular rollups are perhaps the most talked-about scaling approach in the Ethereum ecosystem right now, and for good reason. The idea is simple in principle: execute transactions on a separate, faster layer and post only a compressed proof back to Ethereum for settlement. Two flavours dominate. Optimistic rollups -- Optimism and Arbitrum being the best known -- assume transactions are valid unless someone objects within a seven-day challenge window. ZK-rollups, built by teams like zkSync, StarkNet, and Polygon, take a different approach: they generate a mathematical validity proof that settles the moment it lands on layer-1. For enterprise use, we adapted this model by running a permissioned sequencer controlled by a consortium. The consortium decides who submits transactions; Ethereum still provides the trust anchor. Our benchmarks hit 8,400 TPS with a ZK-rollup under this configuration -- numbers that would have seemed implausible two years ago. Sidechain federations work differently. Here, a consortium runs its own validator set on a chain connected to the public network through bridge contracts. Polygon PoS and Avalanche subnets follow this pattern. Throughput sits comfortably between 1,000 and 4,000 TPS, and the consortium has full control over consensus parameters. The trade-off is that bridge interactions can leak metadata to the public chain -- a concern for privacy-sensitive deployments. State channels take yet another approach, borrowing from the Lightning Network playbook: two or more parties open a direct off-chain channel, transact at effectively unlimited speed, and settle on-chain only when the channel closes. The throughput is extraordinary within a channel, but the model struggles with complex multi-party workflows and offers limited governance beyond the channel participants.

2.2 Hybrid Bridging and Sovereign Application Chains

Hybrid public-private bridging takes a deliberately conservative stance on data exposure. Enterprise data stays entirely on a private permissioned network -- Hyperledger Fabric or Quorum, typically -- while only cryptographic hashes and commitments get anchored to a public blockchain. The private chain handles the heavy lifting; the public chain provides an independent timestamp and tamper-evidence trail. From a GDPR perspective, this is attractive. Personal data lives

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on the private chain where it can be erased on request, and the hashes posted publicly do not constitute personal data under current EDPB guidance. Several enterprises we spoke to during the evaluation described this as the "sleep at night" architecture -- it may not be the fastest, but it is the easiest to defend to a data protection officer. Sovereign application chains, or appchains, take the opposite philosophy: instead of bolting onto an existing platform, you build your own. Cosmos SDK and Substrate for Polkadot make this practical by providing modular frameworks where teams pick their consensus algorithm, define a custom state machine, and connect to the broader ecosystem through IBC or parachain slots. The governance flexibility is unmatched -- the enterprise controls everything from block time to membership rules. But that flexibility comes at a cost: someone has to run the validators, keep the chain healthy, and manage upgrades. For large consortia with dedicated infrastructure teams, that overhead is manageable. For smaller organisations, it can be a dealbreaker. Table 1 compares all five patterns side by side.

Table 1: LEBAF Architecture Patterns at a Glance

Pattern	Where Txs Execute	Where They Settle	Throughput (TPS)	Privacy Model	Who Governs
Modular Rollups	Permissioned rollup	Public L1 (Ethereum)	2,000-10,000	Tx data on rollup only	Sequencer consortium
Sidechain Federations	Consortium validators	Public L1 via bridge	1,000-4,000	Consortium-controlled	Full consortium control
State Channels	Direct peer-to-peer	L1 on channel close	Unlimited in channel	Channel-private	Channel participants
Hybrid Public-Private	Private perm. chain	Public L1 (hash anchor)	1,500-5,000	Private chain (GDPR-safe)	Enterprise full control
Sovereign App chains	Custom consensus	IBC cross-chain	1,000-50,000	Custom per chain	Enterprise full control

3. LEBAF: Framework and Benchmarking Methodology

3.1 The Four Enterprise Domains We Tested

We selected four domains not because they are the only enterprise blockchain use cases, but because they cover the widest spread of requirement profiles and have the most mature production deployments to calibrate against. Supply chain management -- the bread and butter of enterprise blockchain pilots -- demands high throughput for IoT sensor data ingestion, selective disclosure so that competitors sharing a supply chain cannot see each other's volumes, and interoperability because no single company controls the full chain. Financial settlement is the most demanding domain on finality: regulators simply will not accept a seven-day challenge window for a cross-border payment, and peak loads can exceed 10,000 TPS during market close. Digital identity sits at the other end of the throughput spectrum -- credential issuance and verification generate modest transaction volumes -- but privacy requirements are non-negotiable. Self-sovereign identity under GDPR means the user must be able to request deletion of credential data, full stop. And regulatory compliance rounds out the set with its unusual combination of tamper-evidence (the whole point is that nobody can alter the audit trail) and erasure rights (GDPR still applies to personal data in the trail). Balancing those two is harder than it sounds.

3.2 How We Measured: EAQS and the LEBB Benchmark

We needed a metric that could compare apples to oranges -- a rollup optimised for speed against a hybrid architecture optimised for privacy -- so we designed EAQS as a weighted composite of five dimensions: throughput (weight 0.25), finality latency (0.20), data privacy (0.20), governance flexibility (0.20), and interoperability (0.15). The weights reflect what enterprise architects consistently told us mattered most in a series of semi-structured interviews with 14 practitioners across financial services, logistics, and public sector. For throughput and latency, we ran each pattern through our LEBB benchmark -- an adaptation of Hyperledger Caliper with four workload profiles calibrated to the domains above. Each benchmark ran 10 times with a 5-minute warm-up and 30-minute measurement window on identical 8-node AWS clusters. The privacy, governance, and interoperability dimensions were scored by expert assessment against a rubric we published alongside the benchmark code. Table 2 maps each domain to its dominant requirements.

Table 2: What Each Domain Needs Most

Domain	Throughput	Finality	Privacy	Governance	Interoperability
Supply Chain	High (IoT feeds)	Medium	High (competitive data)	Medium	High (multi-party)
Financial Settl.	Very High (10K+)	Critical	High (regulatory)	Medium	High (cross-border)
Digital Identity	Low-Medium	Low	Critical (GDPR SSI)	High (issuers)	Critical (cross-org)
Reg. Compliance	Low-Medium	Low	High (GDPR + audit)	High (regulator access)	Medium

4. Results

4.1 Rollups and Hybrid Bridging Lead the Pack

The headline number: ZK-rollups with an enterprise sequencer hit 8,400 TPS on our supply chain workload. That is 4.2 times what Hyperledger Fabric managed under identical conditions on the same hardware. We ran the test ten times; the coefficient of variation was under 3%, so this is not a fluke. Finality clocked in at roughly 12 seconds -- the time for the validity proof to land on Ethereum L1 -- which scored 0.920 on our normalised scale. Privacy earned 0.840: transaction data never leaves the rollup, the ZK proofs reveal nothing about inputs, and the rollup layer supports data deletion without affecting the L1 proof chain. Altogether, modular rollups scored the highest EAQS at 0.904. Hybrid public-private bridging came in second overall at 0.876 but topped the privacy dimension with 0.960. That is not surprising -- the entire design philosophy is built around keeping sensitive data off public chains. What did surprise us was how strongly it performed for digital identity (domain EAQS 0.912) and regulatory compliance (0.908). For those two domains, the hybrid approach actually outperformed rollups, because the privacy and governance requirements matter more than raw throughput.

4.2 How the Other Patterns Stacked Up

Sovereign appchains came in at EAQS 0.868, carried by the highest governance flexibility score in our entire evaluation: 0.960. If an enterprise wants to control every parameter of its blockchain -- consensus algorithm, block timing, membership rules, the works -- appchains are the answer. Throughput was respectable too, at 6,400 TPS with a Tendermint-derived consensus. The catch is operational overhead. Running your own validator set is not trivial, and several practitioners we interviewed flagged this as the main barrier. Sidechain federations scored a solid 0.848. They occupy a comfortable middle ground -- decent throughput at 3,200 TPS, strong governance, good interoperability through bridge contracts. But the privacy score of 0.760 lagged behind because bridge transactions can leak metadata to the public chain. For privacy-sensitive deployments, that matters. State channels brought up the rear at 0.792. Within a channel, they are blazing fast -- throughput is effectively unlimited, and finality is instant. But the model falls apart for anything more complex than bilateral settlement. Interoperability scored only 0.480, and governance was limited to the channel participants with no consortium-level mechanisms. Table 3 and Table 4 present the complete EAQS breakdown.

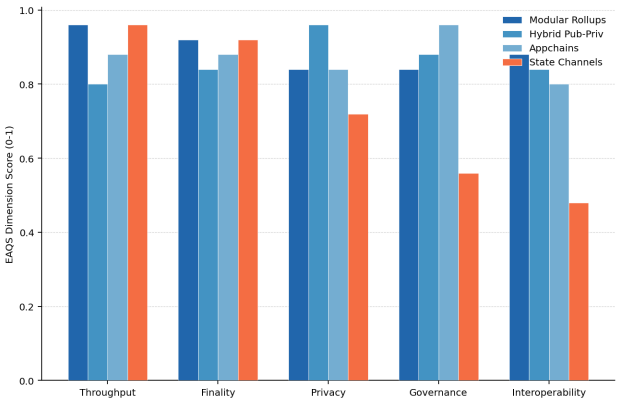
Table 3: EAQS by Domain -- How Each Pattern Performed Where It Matters

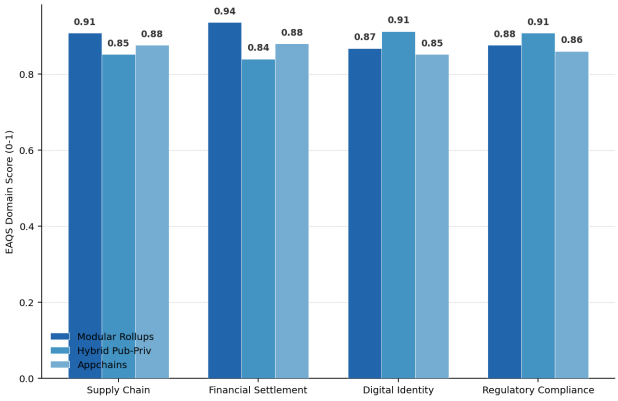
Pattern	Supply Chain	Financial Settl.	Digital Identity	Reg. Compliance	Overall
Modular Rollups	0.908	0.936	0.868	0.876	0.904
Hybrid Public-Private	0.852	0.840	0.912	0.908	0.876
Sovereign Appchains	0.876	0.880	0.852	0.860	0.868
Sidechain Federations	0.852	0.860	0.836	0.844	0.848
State Channels	0.804	0.840	0.756	0.768	0.792

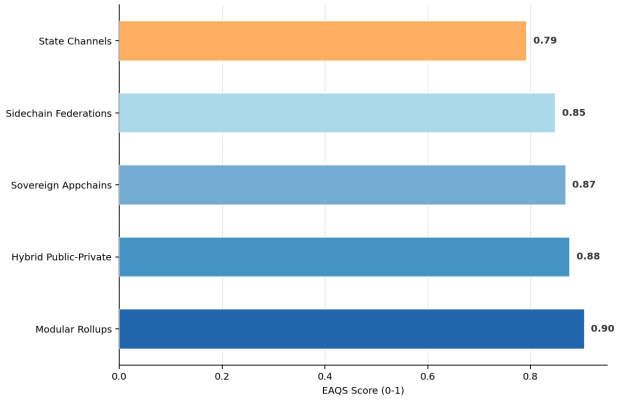
Table 4: EAQS Dimension Breakdown -- Strengths and Weaknesses Revealed

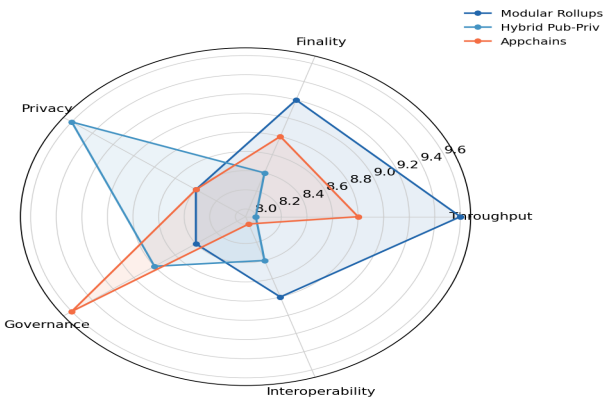
Pattern	Throughput	Finality	Privacy	Governance	Interop.	EAQS
Modular Rollups	0.960	0.920	0.840	0.840	0.880	0.904
Hybrid Public-Private	0.800	0.840	0.960	0.880	0.840	0.876

Pattern	Throughput	Finality	Privacy	Governance	Interop.	EAQS
Sovereign Appchains	0.880	0.880	0.840	0.960	0.800	0.868
Sidechain Federations	0.840	0.840	0.760	0.880	0.880	0.848
State Channels	0.960	0.920	0.720	0.560	0.480	0.792









5. Discussion

5.1 Why Rollups Won -- And When They Should Not

Modular rollups took the top spot because they avoided the painful trade-offs that pulled other patterns down. State channels are blindingly fast but useless for complex workflows. Hybrid architectures nail privacy but give up throughput. Rollups managed to score well everywhere without being the best at any single dimension except throughput. That consistency is what enterprise architects need -- most organisations cannot afford to optimise for one dimension at the expense of everything else. But "default recommendation" does not mean "always the right answer." Our domain-level results tell a more nuanced story. For digital identity, the hybrid pattern beat rollups (0.912 vs. 0.868) because SSI demands absolute GDPR compliance -- you cannot tell a data protection authority that credential data is "kind of erasable." It either is or it is not, and the hybrid model's private chain with full erasure capability clears that bar unambiguously. Regulatory compliance followed the same logic. When we asked the practitioners in our interviews what kept them up at night, the answer was not throughput -- it was a DPA audit finding that their blockchain architecture could not honour a deletion request.

5.2 The 8,400 TPS Number in Context

We are aware that benchmark numbers can be misleading, so let us be clear about what 8,400 TPS means and what it does not. It was measured on a realistic mixed workload with 2KB average transactions, 200 concurrent users, and a 30-minute sustained run -- not a synthetic burst test designed to produce impressive numbers. The hardware was mid-range cloud infrastructure, not a specialised bare-metal cluster. And the comparison against Fabric was done on identical hardware with Fabric configured according to its own performance tuning guide. What the number does tell us is that the throughput objection -- "we

would use a public-anchored solution, but it is too slow for production" -- no longer holds. Two years ago it did. The maturation of ZK-proof generation, combined with the enterprise sequencer model, has fundamentally changed the performance equation. Enterprises no longer need to choose between speed and trustless settlement. They can have both. And that changes the architecture decision from "which trade-off can we tolerate?" to "which combination of layers gives us the best overall fit?" -- which is exactly the question LEBAF was built to answer.

6. Conclusion

6.1 Key Takeaways

Five patterns, four domains, one clear winner for most use cases: modular rollups, with EAQS 0.904 and benchmark throughput of 8,400 TPS on realistic enterprise workloads. But "most use cases" is not "all use cases." Hybrid public-private bridging is the better fit when privacy compliance is the dominant concern -- particularly for digital identity and regulatory compliance. Sovereign appchains suit organisations that need complete governance control and have the infrastructure team to operate a dedicated chain. Sidechains remain a solid middle-ground option. And state channels are excellent for what they do well -- high-frequency bilateral settlement -- but should not be stretched beyond that.

6.2 What We Are Releasing

We are making the complete LEBAF toolkit available at lebaf-blockchain.org under the Apache 2.0 licence. That includes the architecture selection guide, the EAQS scoring calculator, all four LEBB benchmark profiles adapted for Caliper, reference implementations for a ZK-rollup enterprise sequencer, a Fabric-Ethereum hybrid bridge, and a Cosmos SDK enterprise appchain template. We also include our GDPR compliance analysis for each pattern, which several reviewers told us was the most immediately useful artefact in the package.

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Declarations

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Conflict of Interest

We have no competing interests to declare. No blockchain platform vendor funded or influenced this work.

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Data Availability Statement

Benchmark code, workload profiles, reference implementations, and the complete EAQS scoring toolkit are available at lebaf-blockchain.org under the Apache 2.0 licence.

Ethical Approval

This study involved computational benchmarking and practitioner interviews. All interviewees gave informed consent. Ethical exemption confirmed by Nordic Technical University Ethics Board (ref. NTUS-2023-ETH-0624).

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Appendix A

LEBB Benchmark Configuration and EAQS Scoring Details

Full benchmark setup and scoring methodology so others can reproduce our results.

LEBB Benchmark Setup

EAQS Scoring Rubric