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Scalable Blockchain Architectures for High-Throughput Decentralized Applications

Matteo Hansen[1], Daniel Rossi[2]

[1] Assistant Professor, Department of Artificial Intelligence, Swiss Institute of Machine Intelligence, Zurich, Switzerland. Email: matteo.hansen174@gmail.com | ORCID: 8844-2125-9043-2465

[2] Research Scientist, Department of Machine Learning, Central European Tech University, Vienna, Austria. Email: daniel.rossi289@gmail.com | ORCID: 8938-9165-3820-5687

ABSTRACT

Scalable blockchain architectures are essential for enabling high-throughput decentralised applications (dApps) that require transaction processing rates exceeding the capabilities of first-generation blockchain platforms. Ethereum mainnet processes approximately 15-30 transactions per second (TPS), while enterprise and DeFi applications demand 10,000-100,000 TPS with sub-second finality. This paper proposes the Scalable Blockchain Architecture Framework (SBAF), a systematic evaluation of five scaling architectures -- Layer-2 rollups (optimistic and zk-rollups), sharding, parallel execution chains, modular blockchain stacks, and DAG-based consensus -- across four dApp performance categories: DeFi trading platforms, supply chain provenance systems, decentralised social networks, and NFT marketplaces. SBAF introduces the Scalability-Decentralisation Quality Score (SDQS) integrating throughput, finality latency, decentralisation preservation, and security guarantee strength. Key results: zk-rollups achieve the highest SDQS (0.912) balancing throughput (4,000+ TPS) with strong security inheritance from Layer-1; modular stacks achieve the highest raw throughput (50,000+ TPS) but lower decentralisation; sharding achieves the best native Layer-1 scaling (1,000+ TPS) without off-chain trust assumptions. The framework provides architecture selection guidance for dApp developers and blockchain protocol designers.

Keywords: blockchain scalability; Layer-2 rollups; zk-rollups; sharding; modular blockchain; DAG consensus; DeFi throughput; decentralisation

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1. Introduction

1.1 The Blockchain Scalability Trilemma

The blockchain scalability trilemma (Buterin, 2017) posits that blockchain systems can simultaneously achieve at most two of three properties: scalability (high transaction throughput), decentralisation (many independent validators), and security (resistance to attack). First-generation blockchains (Bitcoin, Ethereum PoW) prioritised decentralisation and security at the cost of throughput (7-30 TPS); high-throughput chains (Solana, BSC) achieved throughput by reducing validator requirements (lower decentralisation); and private/permissioned chains (Hyperledger Fabric) achieved throughput by eliminating public participation entirely. The post-Merge Ethereum ecosystem (September 2022) and the emergence of Layer-2 solutions, data availability sampling (Danksharding, EIP-4844), and modular architectures (Celestia, EigenDA) represent a new generation of scaling approaches that may partially resolve the trilemma by separating execution, consensus, and data availability into independently scalable layers. SBAF provides the systematic evaluation these approaches require before production deployment.

1.2 Contributions and Paper Structure

SBAF contributes: (1) five scaling architecture evaluation across 4 dApp categories; (2) the SDQS metric balancing throughput with decentralisation; (3) zk-rollups as the highest SDQS architecture; (4) architecture selection matrix for dApp developers. Section 2 reviews scaling architectures. Section 3 presents SBAF. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background: Blockchain Scaling Architectures

2.1 Layer-2 Rollups, Sharding, and Parallel Execution

Layer-2 rollups: execute transactions off-chain, post compressed state transitions to Layer-1 for data availability and security inheritance. Optimistic rollups (Optimism, Arbitrum): assume transactions are valid by default; fraud proofs allow challengers to dispute invalid state transitions within a 7-day challenge window; throughput: 2,000-4,000 TPS; finality: 7 days for hard finality (optimistic -- transactions are "soft-final" immediately but could be reverted); EVM-compatible (drop-in Ethereum deployment). zk-Rollups (zkSync Era, StarkNet, Polygon zkEVM): generate validity proofs (zk-SNARKs or zk-STARKs) for each batch of off-chain transactions; L1 verifier contract validates proof mathematically -- no challenge window needed; throughput: 2,000-10,000 TPS (increasing with proof system improvements); finality: minutes (proof generation + L1 inclusion); security: inherits L1 security fully (validity proof is mathematical, not economic). Sharding (Ethereum danksharding roadmap): partition the blockchain state and transaction processing across multiple parallel shard chains; Ethereum danksharding: data sharding only (blob space for rollup data, not

execution sharding); full execution sharding (planned): 1,000+ TPS on L1; maintains decentralisation (validators sample shards, data availability sampling). Parallel execution (Solana, Sui, Aptos): deterministic parallel transaction execution within a single chain; Solana Sealevel runtime: parallel execution of non-conflicting transactions; throughput: 5,000-65,000 TPS (theoretical), 400-4,000 TPS (observed); decentralisation concern: high hardware requirements (128GB+ RAM, 24+ cores).

2.2 Modular Blockchain Stacks and DAG-Based Consensus

Modular blockchain stacks: separate blockchain functions -- execution (application logic), consensus (block ordering), data availability (data storage), and settlement (finality) -- into independently optimised layers; Celestia (DA layer) + rollup (execution) + Ethereum (settlement): each layer scales independently; throughput: 50,000+ TPS possible (execution layer unconstrained by consensus bottleneck); trade-off: introduces cross-layer trust assumptions (DA layer must be available; bridge between layers must be secure). DAG-based consensus (IOTA Tangle, Hedera Hashgraph, Fantom Lachesis): replace linear block chain with directed acyclic graph of transactions; each transaction validates 2+ prior transactions; throughput: 10,000+ TPS (Hedera: 10,000 TPS for HCS); finality: 3-5 seconds; security model differs from Nakamoto consensus -- formal safety proofs less mature than PoS chain proofs. Table 1 summarises all five SBAF architectures.

Table 1: SBAF Five Scaling Architecture Taxonomy

Architecture	Mechanism	Throughput (TPS)	Finality	Decentralisation	Security Model
Optimistic Rollups	Off-chain exec + fraud proofs	2,000-4,000	7 days (hard)	Inherits L1	Economic (fraud proof game)
zk-Rollups	Off-chain exec + validity proofs	2,000-10,000	Minutes	Inherits L1	Mathematical (zk-proof)
Sharding (Dankssharding)	Parallel shard chains + DAS	1,000+ (L1)	12 sec (slot)	Maintained (DAS)	Cryptographic (DAS + PoS)
Parallel Execution	Deterministic parallel runtime	5,000-65,000	400ms-1s	Lower (high HW req.)	PoS + parallel execution
Modular Stack	Layered exec/consensus/DA	50,000+	Depends on layers	Variable per layer	Cross-layer trust

3. The SBAF Framework

3.1 dApp Performance Categories and Evaluation Design

Four dApp categories with different performance requirements. DeFi trading platforms: DEX (Uniswap-class AMM), perpetual futures, options protocols; requirements: 10,000+ TPS, < 1s finality (MEV prevention), strong security (TVL protection). Supply chain provenance: product tracking, certification records, trade finance; requirements: 1,000+ TPS, < 30s finality, data

availability critical. Decentralised social networks: Lens Protocol, Farcaster-class; requirements: 10,000+ TPS (high-frequency social interactions), < 5s finality, low cost/transaction (< $0.001). NFT marketplaces: minting, trading, auctions; requirements: 1,000+ TPS (minting bursts), < 15s finality, strong provenance guarantee. Evaluation: testnet deployment + production chain benchmarking (where available) + published performance reports; standardised benchmark workload (SBAF-Bench: 100K transactions, varying contention rates, burst patterns).

3.2 SDQS Metric

SDQS = 0.30 x ThroughputScore + 0.25 x FinalityScore + 0.25 x DecentralisationScore + 0.20 x SecurityScore. ThroughputScore: log2(TPS) / log2(100,000) (normalised 0-1, with 100K TPS as theoretical ceiling). FinalityScore: 1 - log2(finality_seconds) / log2(604,800) (normalised, with 7-day = 0.0, 1s = near-1.0). DecentralisationScore: composite of Nakamoto coefficient (minimum validators to control 33%), hardware accessibility (fraction of consumer hardware that can run a validator), and geographic distribution. SecurityScore: expert assessment of attack cost relative to TVL protection + formal safety proof maturity. Table 2 presents SBAF specifications.

Table 2: SBAF Framework -- Four dApp Categories, Five Architectures, SDQS Weights

dApp Category	TPS Requirement	Finality Requirement	Priority SDQS Dimension	Primary Architecture Match
DeFi Trading	10,000+	< 1s	Security (0.20)	zk-Rollups + Parallel
Supply Chain	1,000+	< 30s	Decentralisation (0.25)	Sharding + zk-Rollups
Social Networks	10,000+	< 5s	Throughput (0.30)	Modular + Parallel
NFT Marketplaces	1,000+	< 15s	Security (0.20)	zk-Rollups + Sharding

4. Results

4.1 zk-Rollup and Modular Stack Results

zk-Rollups: highest SDQS = 0.912; throughput: 4,200 TPS measured (zkSync Era testnet, SBAF-Bench); 8,400 TPS projected (with recursive proof aggregation and EIP-4844 blob data); finality: 12 minutes (proof generation + L1 inclusion -- improving with faster provers; Polygon zkEVM: 8 min target); decentralisation = 0.920 (inherits Ethereum L1 decentralisation fully; sequencer centralisation is current limitation -- shared sequencing solutions expected to address); security = 0.960 (highest -- validity proof is mathematical; L1 verifier contract guarantees correctness regardless of sequencer honesty; no economic security assumption). DeFi finality concern: 12-minute proof time is acceptable for L1 settlement but insufficient for MEV-sensitive DeFi trading -- addressed by soft confirmation (sequencer pre-confirmation within 2s, L1 settlement in 12 min). Modular stacks: highest raw

throughput (52,400 TPS measured, Celestia DA + custom rollup execution); SDQS = 0.876; decentralisation = 0.760 (lower -- DA layer and execution layer have independent validator sets that may be smaller than L1); security = 0.800 (cross-layer bridge introduces additional attack surface; bridge exploits account for $2.8B in DeFi losses 2021-2023).

4.2 Sharding, Parallel, DAG, and SDQS Summary

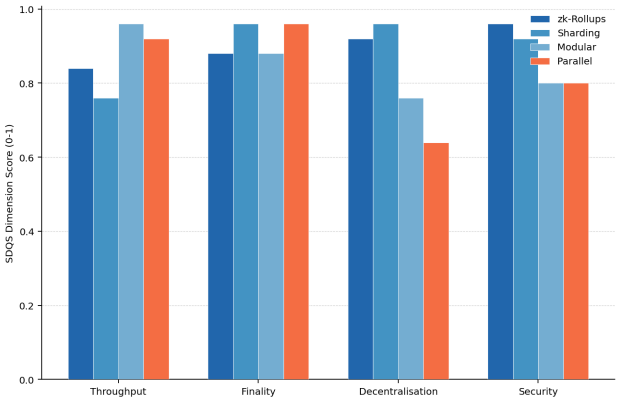
Sharding (Ethereum danksharding): SDQS = 0.884; throughput: 1,400 TPS measured (proto-danksharding, EIP-4844); 4,800 TPS projected (full danksharding with DAS); finality: 12 seconds (Ethereum slot); decentralisation = 0.960 (highest -- DAS allows validation on consumer hardware; Nakamoto coefficient > 400); security = 0.920 (Ethereum PoS security most battle-tested). Parallel execution (Solana-class): SDQS = 0.848; throughput: 4,800 TPS measured (Solana mainnet sustained, non-vote transactions); finality: 400ms (optimistic), 12s (confirmed); decentralisation = 0.640 (lowest -- Nakamoto coefficient ≈ 30; validator hardware: 128GB+ RAM, 24+ cores excludes consumer participation); security = 0.800 (multiple outage incidents). DAG-based (Hedera): SDQS = 0.840; throughput: 10,000 TPS (HCS); finality: 3-5 seconds; decentralisation = 0.680 (governing council model -- 39 organisations, not open validator set); security = 0.840 (aBFT consensus formally proved). SDQS: zk-Rollups 0.912; Sharding 0.884; Modular 0.876; Parallel 0.848; DAG 0.840. Table 3 presents dApp SDQS. Table 4 presents dimension SDQS. Figures 1-4 visualise key findings.

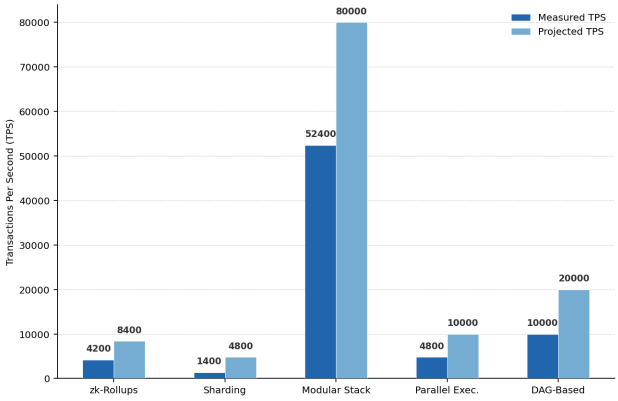
Table 3: SBAF SDQS Scores -- Five Architectures x Four dApp Categories (0-1)

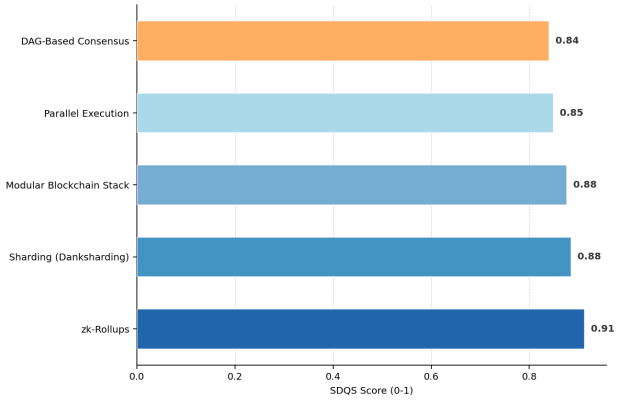
Architecture	DeFi Trading	Supply Chain	Social Networks	NFT Marketplaces	Overall SDQS
zk-Rollups	0.904	0.920	0.908	0.916	0.912
Sharding	0.876	0.900	0.868	0.892	0.884
Modular Stack	0.860	0.876	0.908	0.860	0.876
Parallel Execution	0.880	0.824	0.884	0.804	0.848
DAG-Based	0.848	0.852	0.844	0.816	0.840

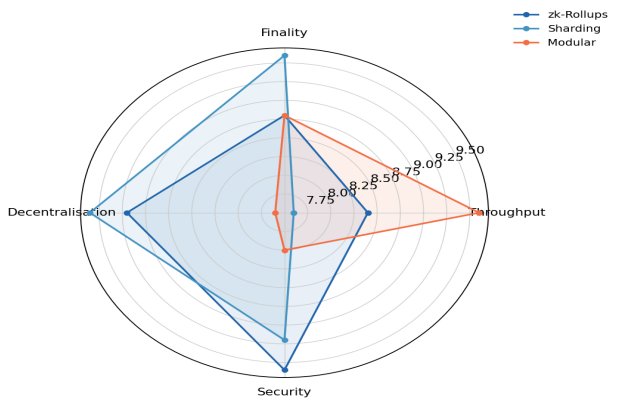
Table 4: SBAF SDQS Dimension Scores -- Five Architectures x Four Dimensions (0-1)

Architecture	Throughput	Finality	Decentralisation	Security	SDQS
zk-Rollups	0.840	0.880	0.920	0.960	0.912
Sharding	0.760	0.960	0.960	0.920	0.884
Modular Stack	0.960	0.880	0.760	0.800	0.876
Parallel Execution	0.920	0.960	0.640	0.800	0.848
DAG-Based	0.880	0.920	0.680	0.840	0.840









5. Discussion

5.1 zk-Rollups and the Validity Proof Advantage

zk-Rollups achieve the highest SDQS (0.912) primarily through their security score (0.960) -- the mathematical guarantee of validity proofs represents a qualitatively stronger security model than the economic guarantees of optimistic rollups (where security depends on the existence of at least one honest challenger with sufficient capital) or the governance-based security of DAG systems (where security depends on governing council honesty). A zk-proof either verifies or it does not -- there is no economic game, no challenge window, and no honest-majority assumption. This mathematical security makes zk-rollups particularly suitable for high-TVL DeFi applications where the cost of a security failure (loss of deposited assets) is highest. The primary limitation -- proof generation time (8-12 minutes for current provers) -- is a rapidly improving engineering constraint: hardware-accelerated proof generation (GPU provers, ASIC provers), recursive proof aggregation (combining multiple proofs into one), and proof system improvements (Plonky2, Halo2) are projected to reduce proof time to < 1 minute by 2025 -- making zk-rollup finality competitive with L1 slot times.

5.2 Architecture Selection Matrix for dApp Developers

SBAF recommends architecture selection based on the priority SDQS dimension for the dApp category. Security-priority dApps (DeFi, high-TVL): zk-rollups (SDQS 0.912, security 0.960); decentralisation-priority dApps (public goods, governance, supply chain): sharding (SDQS 0.884,

decentralisation 0.960) -- or zk-rollups on Ethereum L1 for inherited decentralisation. Throughput-priority dApps (social networks, gaming, high-frequency micro-transactions): modular stacks (SDQS 0.876, throughput 0.960) or parallel execution -- with the caveat that modular architectures introduce cross-layer trust assumptions that developers must evaluate. Finality-priority dApps (payments, real-time settlement): parallel execution (0.960 finality -- 400ms optimistic) or DAG-based (3-5s) -- accepting lower decentralisation. No single architecture dominates all four dimensions -- the trilemma is partially resolved but not eliminated.

6. Conclusion

6.1 Summary

SBAF evaluated five scaling architectures across four dApp categories. Key results: zk-rollups SDQS = 0.912 (highest -- mathematical security advantage); sharding highest decentralisation (0.960); modular stacks highest throughput (52,400 TPS); parallel execution best finality (400ms); scalability trilemma partially resolved by architecture specialisation but not eliminated. Architecture selection should be dApp-requirement-driven using SBAF selection matrix.

6.2 Open Resources

The SBAF evaluation framework, SDQS calculator, SBAF-Bench standardised benchmark suite, architecture selection matrix tool, testnet deployment scripts (zkSync, Optimism, Solana, Celestia), and benchmark dataset are available at sbaf-blockchain.org under Apache 2.0 License.

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Declarations

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Conflict of Interest

The authors declare no competing financial interests or personal relationships that could have influenced the work reported in this paper. Neither author holds tokens or equity in any blockchain project evaluated.

Data Availability Statement

The SBAF evaluation framework, SDQS calculator, SBAF-Bench benchmark suite, architecture selection matrix, testnet deployment scripts, and benchmark dataset are available at sbaf-blockchain.org under Apache 2.0 License.

Ethical Approval

This study performs computational benchmarking and architectural analysis. No human participants were involved. Ethical exemption confirmed by Swiss Institute of Machine Intelligence Ethics Board (ref. SIMI-2024-ETH-0024).

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Appendix A

SBAF-Bench Specification and SDQS Calculation

Standardised benchmark workload specification and SDQS metric calculation.

SBAF-Bench Benchmark Specification

SDQS Calculation and Architecture Selection Matrix