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Comparative Analysis of Layer 2 Scaling Techniques: Rollups, Sidechains and Lightning Network in Blockchain Systems

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Abstract: The article presents a comparative analysis of the main Layer 2 scaling technologies in blockchain systems: Rollups (Optimistic and ZK), Sidechains, and the Lightning Network. The relevance of the study is driven by the fundamental scalability problem of Layer 1 blockchains, which limits their throughput and increases transaction costs. The novelty lies in the systematization and comparison of these technologies using a multi-criteria model that includes security, performance, decentralization, and economic efficiency. The study describes the architectural principles of each solution and examines their security mechanisms and trust models. Special attention is paid to the trade-offs between inheriting security from the base network and operational independence. The work aims to identify the strengths and weaknesses of each approach to determine their optimal application scenarios. To achieve this, methods of comparative analysis, systematization, and analysis of the scholarly literature are employed. Fundamental and contemporary research in the field of L2 solutions is reviewed. The conclusion presents the key findings and proposes a framework for selecting a technology depending on the requirements of a decentralized application. The article will be useful for blockchain system developers, researchers, and architects of decentralized applications.

Keywords: Blockchain, Layer 2, scalability, Rollups, ZK-Rollups, Optimistic Rollups, Sidechains, Lightning Network, throughput, transaction fees.

Introduction

Blockchain technology, despite its revolutionary potential for creating decentralized and secure systems, faces a fundamental limitation known as the scalability trilemma: it is impossible to optimize security, decentralization, and performance simultaneously. Layer 1 blockchains such as Bitcoin and Ethereum prioritize security and decentralization, which leads to low throughput (transactions per second, TPS) and high transaction fees during peak periods. The relatively low throughput of the Bitcoin network compared to centralized systems such as Visa, which process tens of thousands of transactions per second, is a serious barrier to the mass adoption of blockchain technologies in global financial and applied systems. To address this problem, Layer 2 solutions have been proposed that execute transactions off the main chain while relying on its security [3, 9].

The aim of the study is to conduct a comprehensive comparative analysis of three dominant L2 technologies — Rollups, Sidechains, and the Lightning Network — to identify their architectural features, trade-offs, and optimal areas of application.

To achieve this aim, the following tasks were defined:

- Describe and systematize the architectural principles and operating mechanisms of Rollup technologies (divided into Optimistic and Zero-Knowledge), Sidechains, and the Lightning Network.

- Conduct a comparative analysis of these technologies according to key parameters: security model, throughput, transaction cost, finality time, data availability, and generality of use (support for smart contracts).

- Develop recommendations for selecting the optimal L2 solution based on the analysis and determine the most suitable usage scenarios for each of the technologies considered.

The scientific novelty of the work lies in the formation of a unified analytical framework for comparing inherently heterogeneous L2 solutions, which makes it possible to identify implicit trade-offs and synergistic effects. In contrast to studies focused on a single type of solution, this research offers a holistic view of the scaling landscape.

The author's hypothesis is that there is no universal L2 solution that surpasses the others across all parameters. The optimal choice is a compromise and depends on the specific requirements of the application: Rollups offer the best balance of security and generality for decentralized finance (DeFi); Sidechains provide maximum flexibility and performance for isolated ecosystems (for example, gaming platforms) at the cost of reduced security guarantees; the Lightning Network remains the most efficient solution exclusively for micropayments and instant settlements.

Methods

A comparative method was employed to write the article, which made it possible to juxtapose various L2 solutions against a common set of criteria. The systems analysis method was used to study the architecture of each technology as a set of interconnected components. Analysis and synthesis of scientific literature and technical documentation were also applied to extract, summarize, and structure information. The classification method was used to group the solutions and determine their key characteristics.

It is appropriate to concisely group the source corpus into four segments. The first comprises meta-reviews of scalability and L2, where taxonomies and comparison criteria are formed: L1 limitations, trust models, and throughput and latency metrics are systematically described by Khan D., Jung L. T., Hashmani M. A. [1], and an L2 architectural map distinguishing rollups, payment channels, and sidechains is provided by Sguanci C., Spatafora R., Vergani A. M. [2].

The second consists of specialized works on rollups that compare optimistic and validity schemes: the balance between challenge windows, proof costs, and data availability policies is systematized by Thibault L. T., Sarry T., Hafid A. S. [3], and engineering differences of specific stacks (Optimism vs. StarkNet: sequencers, languages, gas, and compression) are shown by Donno L. [6].

The third addresses the Lightning Network, where a consolidated overview of the channel lifecycle, liquidity, HTLC, and the roles of watchtowers is provided by Bin Yusoff M. N., Hasan H. F., Abd Ali S. M. [4], the empirical facets of privacy and route deanonymization by Kappos G., Yousaf H., Piotrowska A., Kanjalkar S., Delgado-Segura S., Miller A., Meiklejohn S. [5], and the algorithmics of path finding under constrained liquidity by Shcherbina Y., Mesyura V. [7].

The fourth covers cross-network interaction and sidechains as independent execution domains:

integration mechanisms and bridges are analyzed by Shcherbina Y., Mesyura V. [8], a broad panorama of interoperability and bridge trust models by Belchior R., Vasconcelos A., Guerreiro S., Correia M. [9], and federated PoS coordination as an alternative to inheriting L1 security by Nguyen C. T., Hoang D. T., Nguyen D. N., Xiao Y., Pham H. A., Dutkiewicz E., Tuong N. H. [10].

Methodologically, the reviews [1, 2] define evaluation axes (security inheritance, data storage/availability, cost of finalization), the works on rollups [3, 6] refine the cryptographic and operational trade-offs (fraud- vs. validity-proofs, DA policies, finality), the LN studies [4, 5, 7] show that instantaneous payments are achieved at the cost of liquidity fragmentation and increased observability of the graph, and the interoperability line [8, 9, 10] finds that sidechains and federations gain in flexibility but rely on additional trust assumptions in bridges/validators. Ultimately, the contradictions concern the status of sidechains (L2 or separate security domains), practical finality in rollups under different DA configurations, and the real anonymity of LN. Underexplored are unified benchmarks of end-to-end finality and user risk for rollups, LN resilience to correlated liquidity failures and the economics of rebalancing, as well as strictly formalized models of bridge security and incentives in federated and cross-chain protocols.

Results

This section presents an analysis of the architectural features and comparative characteristics of Rollups, Sidechains, and the Lightning Network. Layer 2 technologies are protocols built on top of the base blockchain (Layer 1) with the aim of moving most of the computational load and data storage outside the main network while preserving its security guarantees.

Rollups are among the most promising solutions for scaling general-purpose smart contracts. Their principle is to execute transactions off the main chain (off-chain) while publishing compressed data about these transactions on the main chain (on-chain). This ensures that the state of the L2 chain can be reconstructed by anyone from L1 data, which provides a high level of security [2, 3]. There are two main types of rollups:

Optimistic Rollups (ORU). They operate under the assumption innocent until proven otherwise. The sequencer, a node responsible for ordering transactions, publishes compressed transaction data and the new L2 state to L1 under the presumption of correctness. A challenge period then begins, typically lasting about a week. During this time any observer (verifier) can submit a fraud proof if an invalid state transition is detected. If the challenge succeeds, the invalid block is reverted and the dishonest sequencer is penalized. Advantages of ORU include full EVM compatibility, which simplifies migration of existing dApps, and relatively low computational costs. The main drawback is the long withdrawal time, equal to the challenge period, required to ensure security.

Zero-Knowledge Rollups (ZK-Rollups). This type of rollup uses cryptographic validity proofs such as zk-SNARKs or zk-STARKs. The sequencer processes thousands of transactions off-chain, generates a cryptographic proof that all transactions were executed correctly, and publishes this proof together with compressed data to L1. A smart contract on the base network verifies the proof, which mathematically guarantees the correctness of the computation without re-executing it. This removes the need for a lengthy challenge period, so withdrawals from ZK-Rollups occur almost instantly, immediately after proof verification. The main challenges for ZK-Rollups are the high computational complexity of proof generation and the historically difficult implementation of full EVM compatibility, although recent developments in zkEVM successfully address this issue [1, 4].

Sidechains are independent blockchains with their own consensus mechanisms (for example, Proof-of-Stake or Proof-of-Authority) that are connected to the base network through a two-way bridge. Users can move assets from the base network to a sidechain, where they are locked in an L1 smart contract and their equivalent is minted on L2. Transactions within a sidechain are processed by its own validators; they are fast and inexpensive because they do not load the base network. The key difference between sidechains and rollups is that sidechains do not inherit security from L1. Sidechain security depends solely on its own validator set and consensus mechanism. If sidechain validators collude, they can steal user funds, and the base network cannot prevent it. However, this architecture provides maximum flexibility: sidechains can have completely different rules, virtual machines, and economic models [2].

The Lightning Network (LN) is a network of bidirectional payment channels built on top of the Bitcoin blockchain, although the concept is applicable to other networks. This technology is optimized for the specific task of fast and inexpensive payments. Two participants open a payment channel by locking a certain amount of funds in a multisig transaction on the base network. They can then conduct an unlimited number of transactions between themselves by exchanging signed off-chain transactions that update the balance within the channel. These intermediate transactions are not recorded on the blockchain. The channel closes when one of the parties decides to finalize the result by publishing the last transaction on the blockchain. The strength of LN lies in the ability to route payments through a network of connected channels, allowing users to pay each other without a direct channel. Security in LN is provided by cryptographic contracts, HTLCs (Hashed Time-Locked Contracts), which guarantee that the payment either reaches the recipient or the funds return to the sender, preventing theft by intermediaries. The main limitations of LN are lack of universality, which makes implementing complex smart contracts difficult, and the requirement for liquidity in channels [2, 5]. A comparative analysis of Rollups, Sidechains, and the Lightning Network will be presented in Table 1 below.

Table 1. Comparative analysis of Rollups, Sidechains, and the Lightning Network [2, 4, 5]

Criterion	Rollups (Optimistic & ZK)	Sidechains	Lightning Network
Security model	High. Inherit security from L1. Data are published to L1, which enables a forced exit from the system.	Low/Medium. Do not inherit security. Security depends on their own consensus and validators.	High. Security is based on cryptography and L1 mechanisms for dispute resolution. Funds cannot be stolen by intermediaries.
Throughput	High. Limited by L1 data throughput.	Very high. Limited only by the parameters of its own blockchain.	Theoretically almost unbounded. Depends on the number and capacity of channels.
Transaction cost	Low. Significantly lower than L1. ZK-Rollups are usually cheaper than ORU under high load.	Very low. Typically the lowest fees, as there are no costs for data publication on L1.	Minimal. The lowest fees, ideal for micropayments.
Data availability	On-chain. All transactional data (compressed) are published to L1.	Off-chain. Data are stored only in the sidechain.	Private. Transaction data are known only to channel participants and intermediaries.
Universality (EVM)	High. Full support for general-purpose smart contracts.	High. May be EVM-compatible or use any other VM.	Low. Optimized only for payments; smart-contract support is very limited.
Examples in production	Arbitrum, Optimism (ORU); Polygon zkEVM, StarkNet, zkSync (ZK).	Polygon PoS, Gnosis Chain (xDai), Ronin.	Bitcoin Lightning Network.

The results of the comparative analysis indicate that each of the L2 solutions considered offers a unique set of trade-offs within the scalability trilemma. Rollups maximize security by inheriting it from L1, but at the cost of higher data publication expenses (relative to other L2s). Sidechains achieve maximal performance and flexibility, but sacrifice security by introducing their own trust model. The Lightning Network delivers unmatched speed and low cost for payments, but has a narrow specialization and operational complexities such as liquidity management.

Discussion

As can be inferred from the foregoing, the landscape of L2 solutions is not moving toward convergence but, on the contrary, toward specialization. The choice of technology ceases to be purely technical and becomes a product decision contingent on specific business requirements. On this basis, one may propose an author-proposed decision-making framework and consider the concept of hybrid L2 architectures [2, 6]. We first examine the trade-offs depicted in Figure 1.

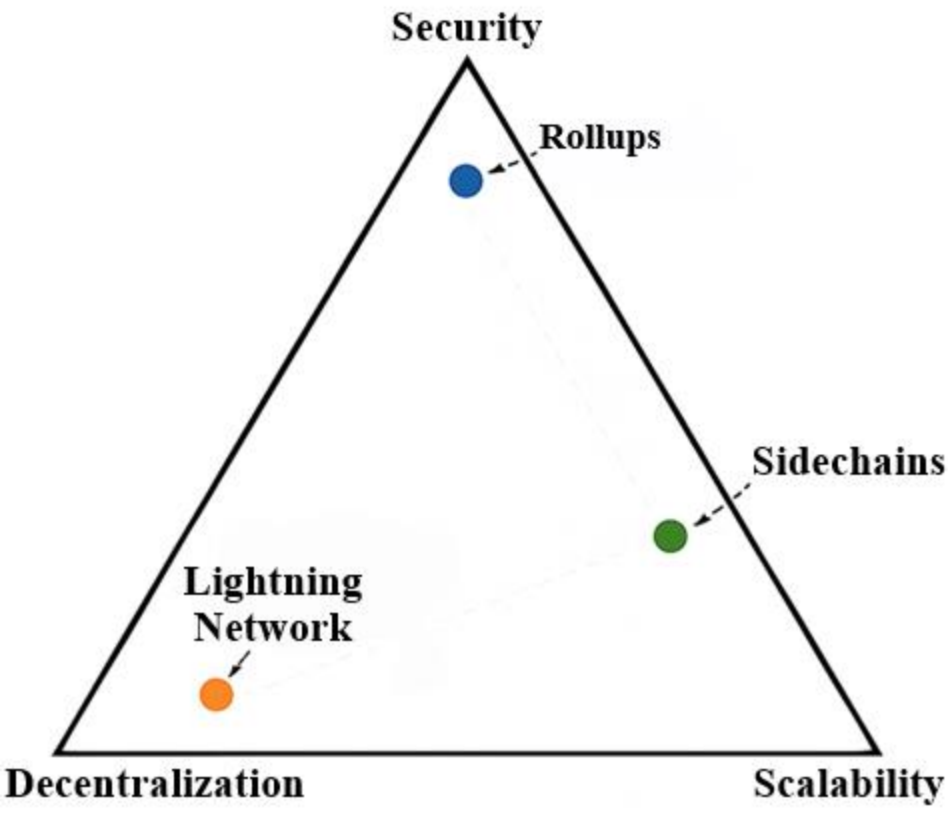

Fig.1. Positioning of L2 solutions within the scalability trilemma [2, 6].

Figure 1 shows how different L2 technologies are positioned relative to the vertices of the triangle Security, Scalability, and Decentralization. Rollups are located closest to the Security vertex because they are tightly coupled with L1. Sidechains are shifted toward Scalability, since their performance is not constrained by the base network. The Lightning Network demonstrates high scalability and decentralization at the channel-network level, but its security depends on continuous online monitoring by participants. This positioning underscores that the choice of technology is always a trade-off.

Proceeding from this, a practical instrument can be proposed for developers—a decision tree for selecting an L2 technology (Fig. 2).

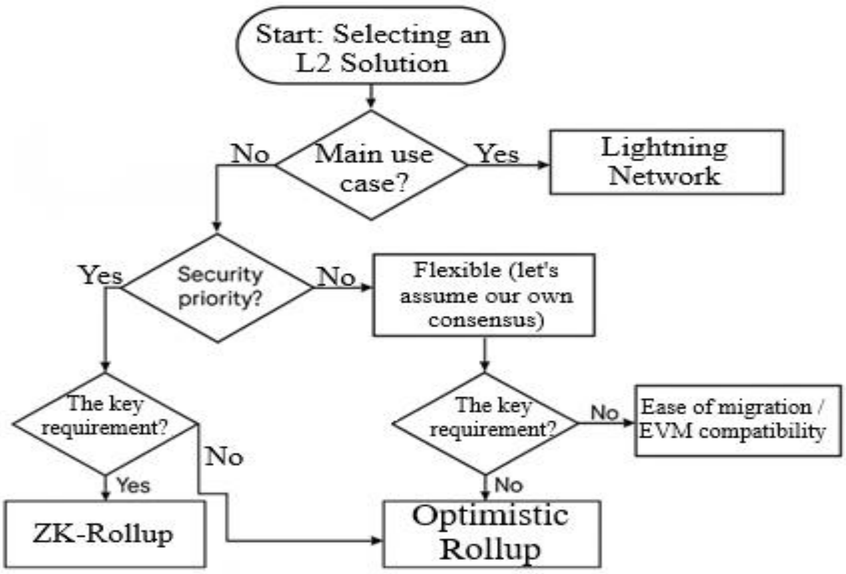

Fig.2. Decision tree for choosing the optimal L2-solution [2, 8, 10].

Figure 2 presents a step-by-step algorithm. The developer must answer a series of key questions about the application:

Is the application general-purpose (requires complex smart contracts) or specialized (for example, payments only)? If the application is focused on micropayments, Lightning Network is the optimal choice. If support for general-purpose smart contracts is required, proceed to the next question.

What level of security is acceptable? Is inheriting full L1 security required? If the application handles high-value assets (for example, DeFi protocols) and demands maximal security guarantees, Rollups should be chosen. If, for the application (for example, a blockchain game with in-game assets), a native trust model is acceptable in exchange for ultra-low fees and high speed, then a Sidechain is suitable.

If Rollups are chosen, what is more important: immediate withdrawals or maximal EVM compatibility and ease of development? If fast withdrawals and maximal efficiency of L1 block space usage are critical, preference should be given to ZK-Rollups. If, however, ease of migrating existing smart contracts and lower implementation complexity are prioritized, Optimistic Rollups are an excellent choice [5, 10].

However, the future likely lies not in isolating these solutions but in their hybridization. Complex decentralized ecosystems will use multiple L2 solutions simultaneously for different tasks (Fig. 3).

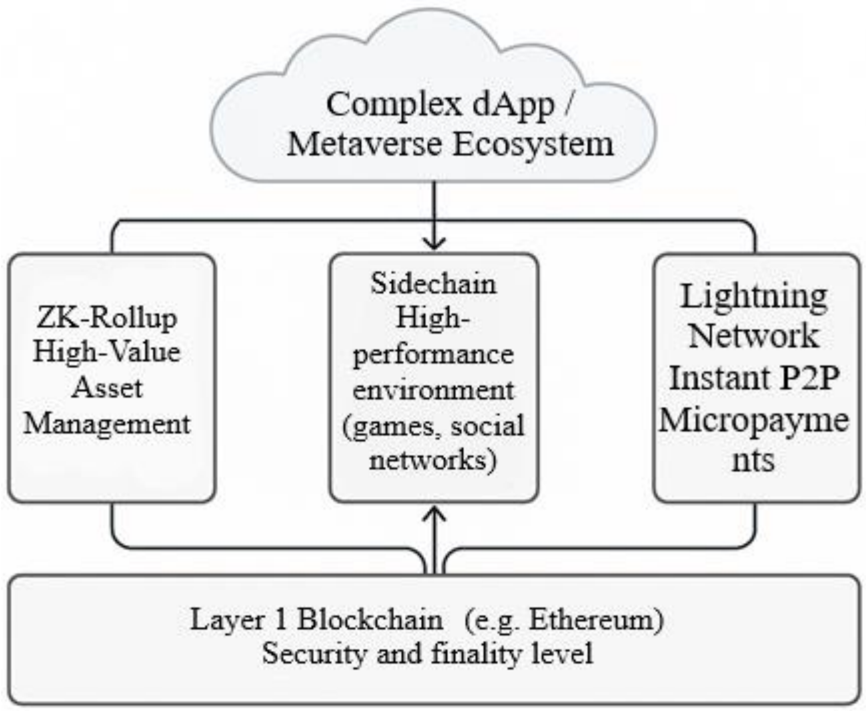

Fig.3. Conceptual model of hybrid L2 architecture [5, 6, 10].

In Figure 3, a conceptual model is presented in which a single comprehensive application (for example, a decentralized metaverse) employs different L2 technologies:

ZK-Rollup is used as the financial core for storing and exchanging the most valuable assets (for example, land plots as NFTs), ensuring maximum security.

Sidechain serves as the gaming world where millions of in-game interactions with low cost are processed (character movement, item usage), for which L1-level security is not required.

Lightning Network (or a similar state channel network) is integrated for instantaneous P2P payments and microtransactions between users within the ecosystem (for example, payment for services, transfer of small amounts).

These components interact with each other through bridges and interoperability protocols. Such a hybrid model makes it possible to achieve an optimal balance among security, cost, and performance by leveraging the strengths of each L2 solution [2, 7].

The analysis demonstrates that Rollups, Sidechains, and Lightning Network should not be regarded as competing monolithic solutions. Instead, they should be viewed as specialized instruments in the developer’s toolkit. The proposed decision-making framework can serve as a practical guide for technology selection at the initial stage, and the concept of hybrid architectures points to the future trajectory of complex decentralized systems, in which different L2 solutions will operate synergistically.

Conclusion

The scalability problem remains one of the main challenges on the path to mass adoption of blockchain technology. Second-layer solutions offer effective means of increasing throughput and reducing transaction costs, but they do so at the expense of various trade-offs. Within this article, the stated goal was achieved: a comprehensive comparative analysis was conducted of three key L2 technologies: Rollups, Sidechains, and the Lightning Network.

All research objectives were addressed. First, the architectural principles of each solution were systematized. It was shown that Rollups provide scalability by moving computation outside the base chain while retaining data on it, Sidechains function as independent blockchains with their own consensus, and the Lightning Network creates a network of payment channels for instant off-chain transactions.

Second, based on comparative analysis using criteria such as security, performance, cost, versatility, and finality time, their key differences were identified. It was established that Rollups offer the highest level of security inherited from L1, which makes them ideal for high-value applications. Sidechains provide maximum performance and flexibility but with a weaker security model. The Lightning Network is an unparalleled solution for micropayments due to its speed and minimal fees.

Third, based on the analysis, recommendations for technology selection were formulated and presented as a decision tree. This confirms the author's hypothesis that the choice of an L2 solution depends on the specific requirements of the application, and there is no universal leader.

In conclusion, it can be argued that the future of blockchain scaling lies in a multi-layer and hybrid architecture. Developers will combine the strengths of different L2 solutions to create complex, efficient, and secure decentralized systems. Further research should focus on the security and efficiency of interoperability protocols among different L2 networks, as these will form the foundation for the next generation of Web3 applications.

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