Ethereum L2 Scaling Solutions and Their Distinct Use Cases

Introduction

Ethereum's transition from a monolithic blockchain to a rollup-centric roadmap represents one of the most significant architectural shifts in cryptocurrency history. While Ethereum L2s were intended to be scaling mechanisms to reduce transaction costs and increase throughput, they have evolved into specialized execution environments that enable distinct applications and user experiences.

Today, L2 networks process more daily transactions than Ethereum mainnet. However, this proliferation has created a fragmented ecosystem where users must navigate tradeoffs between security models, finality times, and transaction costs. Understanding these tradeoffs and their implications is crucial for assessing Ethereum's competitiveness against alternative L1 blockchains and evaluating the long-term viability of the Ethereum ecosystem.

This research aims to provide an analysis of how different L2 scaling approaches, particularly rollups, make distinct technical tradeoffs that enable or constrain specific use cases. By examining the relationship between technical architecture and practical applications, we hope to make some predictions around the future of Ethereum's ecosystem. At its heart, our paper examines the following question: how do different L2 scaling approaches enable distinct use cases, and what does this reveal about Ethereum's evolving architecture?

Taxonomy + Definitions

L2 solutions represent a spectrum of scaling approaches that process transactions off Ethereum's main chain while inheriting varying degrees of its security guarantees. Understanding the technical distinctions between different L2 architectures is essential for evaluating their appropriate use cases and tradeoffs. We begin with a quick overview of relevant L2 terminology to help orient the reader throughout the rest of the paper.

L2 Categorization

The fundamental distinction between L2 solutions lies in where they store transaction data[1]. We can conceptualize these approaches into three buckets: rollups, validiums, and hybrid.

Rollups
Rollups post all transaction data to Ethereum mainnet, ensuring that anyone can reconstruct the L2 state from L1 data alone. This data availability on Ethereum enables rollups to inherit Ethereum's full data security guarantees. Even if every L2 operator disappeared, users could recover their funds using data stored on L1[2]. Examples of rollups include Arbitrum One, Optimism, zkSync Era, and Starknet.

Validiums
Validiums, by contrast, keep transaction data off-chain, posting only validity proofs to Ethereum[3]. This approach dramatically reduces costs and increases throughput but introduces additional trust assumptions:

users must trust that data will be available when needed. If the off-chain data provider fails, users may be unable to prove ownership of their assets[4].

Hybrid

Hybrid approaches allow users to choose between on-chain and off-chain data availability on a per-transaction basis, attempting to balance security and cost tradeoffs. Arbitrum Nova, for instance, uses a data availability committee (DAC) composed of trusted entities who attest to data availability, offering a middle ground between true rollups and pure validiums[5].

Data availability spectrum

Each of these L2 solutions addresses the question of data availability in a different manner. This decision has critical implications for the security and cost associated with utilizing the L2. Rollups leverage fully on-chain data availability, publishing all transaction data to Ethereum mainnet. This has the highest security guarantee as any party can reconstruct the L2 state from the L1 data, but simultaneously incurs the highest gas fees[6]. Another data availability approach lies within DACs, which employ a set of entities to store data off-chain and attest to its availability on-chain. While DACs allow for reduced costs as compared to fully on-chain data availability, they have centralization risk. If a group within the committee decides to act maliciously, then users may see compromised transactions[7]. Further down the data availability spectrum exist alternative data availability layers, such as Celestia. These layers can sometimes be seen as more neutral than DACs because there exists permissionless participation and good-actor incentives. However, this adds in a trust assumption surrounding the alternative data layer itself, which could theoretically be compromised[8]. Notably, these alternative data layers are also significantly cheaper than full on-chain data availability. At the far end of the spectrum lie pure validiums, which store all data off-chain and have no guarantees beyond the operator's commitment. These are significantly more cost-effective than the other options and can significantly increase throughput, but come with far more security risk as trust must be put in the operator completely[9].

Analysis

Our analysis can be divided into three main sections: technical tradeoffs of L2s, practical applications of L2s, and the future of L2s in the Ethereum ecosystem at-large. We will focus primarily on L2 rollups.

Technical Tradeoffs

We will examine a number of technical factors that can affect which L2 is most optimal for a given use case. Our tranches of analysis are the following:

Security model

Different types of L2 rollups assume different levels of trust and therefore have different security models. This is where the fundamental difference lies between the two main categories of rollups: optimistic rollups and ZK-rollups.

Optimistic rollups assume state transitions are valid by default and rely on fraud proofs to validate transactions. Fraud proofs require honest watchers monitoring the blockchain to challenge invalid states. A challenge must be brought up within a challenge period, typically lasting 7 days[10]. The assumption in this security model is that there always exists at least one honest watcher who will submit a fraud proof if an invalid state transition is published. This is inherently a weaker assumption than cryptographic verification which exists in L1 Ethereum[11].

ZK-rollups use zero-knowledge proofs that cryptographically prove every state transition is correct before it's accepted on the L1 Ethereum blockchain[12]. Invalid batches simply cannot be finalized on Ethereum because proof verification happens immediately on L1. This provides a stronger security guarantee than optimistic rollups.

To this point, no general purpose rollup truly inherits the security model of L1, but ZK-rollups are closer to this ideal. They provide less latency with immediate finality once a proof is verified on L1. Additionally, there is no trust assumption on validators beyond the cryptographic proof system[13]. Despite this, a major risk of ZK-rollups is that any implementation bugs in the proof system of verifier contract could lead to permanent fund loss[14].

Decentralization and trust assumptions

Despite the promise of decentralization, most L2s today operate with significant centralization across multiple dimensions. One of the primary concerns is sequencer centralization**.** Nearly all major L2s (ex. Arbitrum, Optimism, Base, and zkSync) currently rely on single, centralized sequencers controlled by their respective founding organizations[15]. While these entities typically commit to including user transactions within specified timeframes (e.g., Arbitrum allows forced inclusion of censored transactions within 24 hours by submitting directly to L1), day-to-day operation remains centralized. This creates both practical risks (i.e., sequencer goes offline, L2 stops processing transactions) in addition to more subtle concerns around censorship and fair ordering. All major rollups have decentralized sequencer sets on their roadmaps for 2025-2026, but implementation timelines remain uncertain, and none have achieved this milestone yet[16]. Some smaller rollups, such as Zk.Money v1, Facet v1, and Honeypot v2, have been able to achieve more decentralization but two of these are application-specific, which could introduce a different type of risk.

Another key risk lies in users' ability to permissionlessly participate in L2 validation and security. Optimistic rollups purportedly facilitate permissionless participation, but this has varying degrees of truth in practice. For example, Arbitrum spent 3 years after launch without a permissionless fraud proof system. This mechanism was controlled by a whitelist. Although they have now updated it to include permissionless challenges, their method of implementation requires challengers to have capital available for bonds, creating yet another barrier to entry[17]. Optimism similarly took 3 years after launch to transition to a permissionless system. ZK-rollups face a different set of issues with respect to permissionless participation. Although anyone can be a prover, the computation needed for zero-knowledge proofs requires specialized hardware and high electrical costs, which only a limited set of actors have access to. As a result, the major ZK-rollups functionally operate under a centralized prover system[18]. While there have been discussions about decentralizing this mechanism into a prover marketplace, no major ZK-rollup has implemented this thus far.

Upgrade control is another significant centralization vector and varies across L2s. Most leverage small multisigs with significant powers. Base and zkSync use small multisigs with no upgrade delay, which allows unilateral contract changes. Arbitrum One and Optimism have Security Councils that can perform upgrades (3 days for routine) along with some token-based voting (although the council has override power). Polygon zkEVM is more decentralized in this aspect, as it has a 10-day upgrade delay and requires Security Council approval only for emergency actions[19]. Although there are a number of ongoing efforts to decentralize L2s, the current reality is that engaging with an L2 requires trust assumptions across various parties, such as the founding organization or a Security Council[20].

Bridge architecture

Bridges are the mechanism by which assets can move between L1s and L2s. Bridges lock assets on one chain and mint corresponding representations on the other. Bridges are a critical threat vector because they control a high amount of locked assets. In addition, if the bridge mechanism is flawed, attackers can mint unbacked tokens on the L2 or prevent legitimate users from withdrawing their funds[21]. Native bridges are integrated directly into the L2's architecture and inherit its security model. Third-party bridges, however, can have entirely different security models. Third-party bridges can have separate validator sets and can provide users with the ability to bypass the challenge period to receive an instant withdrawal (more relevant for optimistic rollups). However, entrusting assets to a third–party bridge with its own validation system and smart contracts requires an additional trust assumption in the third-party bridge[22].

An ecosystem of multiple bridges for a single L2 can create high levels of fragmentation and complexity. One of the consequences of this could be a weakening of security. If an L2 has multiple bridges but one is weak, then a malicious actor could exploit that bridge to create tokens on the L2, which could then be used to transact with legitimate protocols. In addition, because some wallets abstract away details of bridges from end users, some people may not have an awareness as to the implied trust assumptions they are making when transacting[23].

Performance characteristics

Different rollups and their performance across a range of characteristics demonstrate the blockchain trilemma among scalability, security, and decentralization. Turning an eye to proof generation and finality periods, we see a range of times across different solutions. Optimistic rollups include transactions in blocks almost immediately, but final settlement on the L1 requires approximately 7 days, or the length of the challenge period time[24]. By contrast, ZK-rollups offer much faster finality (hours, not days) because finality simply requires the validity proof to be verified on Ethereum. However, the tradeoff ZK rollups make to obtain these favorable finality times is that ZK rollup proof generation is computationally expensive.
Transaction throughputs across optimistic and ZK rollups vary as well. Optimistic rollups achieve between 2-4k TPS. According to Chainspect, Arbitrum and Optimism process around 85-100k transactions per day, while Base sees 650k+ transactions over the same period. ZK-rollups seem to vary a little more, with Starknet showing 100+ TPS during normal peak while zkSync Era seems to process 10-20 TPS generally.

Economic and computational costs are optimized differently among rollups. Optimistic rollups incur minimal verification costs in normal operations, but disputes can be significantly expensive should they occur. ZK rollups incur high computational costs during proof generation, but on-chain verification is cost-bounded. Users pay slightly higher per-transaction fees as well (in exchange for fast finality).

Overall, optimistic rollups prioritize security and scalability while compromising on decentralization. ZK-rollups make a similar tradeoff, although the lack of decentralization stems more from the computational cost required to secure the system. Unlike either of these, validiums and alternative data availability solutions may choose to prioritize scalability, sacrificing both security and decentralization to achieve ultra-high throughput and lowest costs.

Practical Applications

After analyzing the L2 environment and what advantages or disadvantages each L2 might have, we examine how these different strategic differentiations among L2s manifest in practical applications.

DeFi protocols

DeFi protocols make strategic L2 deployment decisions based on security guarantees. Major protocols like Aave and Uniswap initially favored battle-tested optimistic rollups such as Arbitrum and Optimism over newer ZK-rollups despite slower finality[25]. This preference reflects concerns about ZK circuit complexity and potential bugs which can arise in the implementation code. However, as ZK-rollups accumulate operational history, protocols are increasingly deploying to xkSync Era and StarkNet. Particularly, protocols that benefit from faster finality for capital-efficient liquidations have more incentive to adopt these ZK-rollups.

One of the primary challenges facing DeFi is liquidity fragmentation across L2s. For example, Uniswap pools on Arbitrum cannot serve traders on Optimism. This forces protocols to choose between deploying to multiple chains and diluting liquidity or accepting limited market reach with less chains. As a result, this creates inefficiencies that would not exist on a unified platform.

Gaming and NFTs

Gaming applications prioritize throughput and cost over maximum security, making validiums and application-specific rollups viable despite tradeoffs which would be unacceptable for DeFi applications. For example, games with transactions on the blockchain generate thousands of micro-transactions per minute which require sub-cent costs. This drives deployment to validium solutions with off-chain data availability where players can trade items with negligible fees and instant confirmation[26]. While this introduces trust assumptions around the data availability committee, the risk is acceptable for gaming assets where developers already control game mechanics and can restore state from backups if needed.

NFT marketplaces choose L2 chains and even the L1 chain based on asset value. High-value collections remain on L1 or secure rollups like Arbitrum, while lower-value NFTs migrate to L2s where reduced costs outweigh security concerns. In the lower-value cases, ZK-rollup's faster finality potentially benefits high-value trades.

Payments and consumer applications

Consumer payment applications require cheap transaction costs and instant perceived confirmation comparable to the fees from modern global payment networks. For small-value payments, users already trust centralized providers like Coinbase operating Base, making additional trust assumptions around sequencer honesty relatively minor compared to the friction of expensive or slow transactions[27]. AK-roullups' native account abstraction provides superior wallet UX through low gas transactions and social recovery, critical for mainstream adoption. The tradeoff for this better UX is that current ZK-rollup costs remain higher than optimistic rollups for micro-transactions.

The fundamental barriers to mainstream adoption of payment and consumer applications persist across all L2s: complex bridging from fiat on-ramps, choice of L2 network, and managing private keys. This friction limits consumer applications to niche use cases despite dramatically better economics than L1 solutions.

Future of L2s

As L2s gain more adoption, the future of Ethereum will almost certainly include them. Ultimately, the L2-centric approach is likely helpful for Ethereum over a long time horizon. Each L2 brings with it a different degree of security and risk, while exposing new threat vectors to attackers. Although this may seem net negative, L2 scaling enables more real-world applications to exist on chain, which is ultimately good for Ethereum while also (theoretically) reducing risks such as lying or bias.

It is important to think about how these L2s will work together. As different use cases may gravitate to different L2s, they may need to communicate with each other, share assets, and exchange data quickly. Most existing solutions rely on bridges and complex UX. Ethereum's Interoperability Layer[28] proposes a way for users to navigate across L2s in a relatively frictionless manner, but how it is implemented in practice and the resulting behavior remains to be seen. But overall, increasing adoption will lead to more robust practices and systems surrounding the Ethereum ecosystem, paving the way for more foundational processes to come on chain.

Conclusion

Ultimately, we hope to deliver an analysis that touches on both the technical and strategic differentiations among L2 rollups and how these might be leveraged for practical applications. For researchers and developers, we aim to provide insight about the technical tradeoffs among L2s and the corresponding implications for application design. For those who are looking to invest either money or time into the L2 space, we hope to provide different lenses through which to evaluate a strategic business or technical advantage. Overall, we wish to contribute to a broader understanding of a rapidly-growing area of cryptocurrency in the hopes that this fascinating technology is made more accessible to the public.

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