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SCALABILITY AND STABILITY OF ETHEREUM LAYER-2 NETWORKS: A COMPARATIVE ANALYSIS OF SCROLL, LINEA, AND BASE ROLLUPS

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Abstract. The article presents an empirical comparison of three contemporary Layer-2 scaling solutions for the Ethereum blockchain: Scroll, Linea, and Base, representing zk-rollup and optimistic rollup architectures. The study aims to evaluate the transaction processing speed and stability of selected Layer-2 networks using real-time data collected from blockchain explorers (Blockscout, Lineascan, Basescan). The dataset comprises 45,000 transactions processed in October 2025 and aggregated at one-second resolution (1 Hz). Statistical analyses include ANOVA, Kruskal–Wallis, Levene, and Brown–Forsythe tests, as well as ADF and KPSS stationarity diagnostics, used to assess differences in throughput and operational stability across the examined networks. The results indicate that the Base network achieves the highest mean throughput ($\approx$ 102 TPS) and the lowest temporal volatility, whereas Linea and Scroll exhibit non-stationary, highly variable transaction dynamics driven by periodic batching. The findings confirm the persistence of the scalability trilemma—where improvements in performance may come at the cost of higher centralization and operational dependency. This research contributes to the quantitative assessment of rollup efficiency and provides a reference point for further empirical studies on blockchain scalability.

1. Introduction

Blockchain technology has become one of the fastest growing innovations of the twenty-first century. The potential applications of a cryptographically secured distributed ledger have been widely discussed in academic literature. Earlier studies examined, among other topics, the use of Ethereum smart contracts in food supply chain management [10], the use of ERC-20 tokens in managing incidents in water distribution networks [2], and the deployment of decentralized trading platforms [18]. In recent years, research has increasingly focused on the economic and technological feasibility of blockchain implementations across different sectors of the economy [21, 22, 13].

Despite its considerable potential, blockchain faces a fundamental scalability challenge. This limitation follows directly from the need to preserve decentralization and security. Performance, decentralization and security are commonly referred to as the "scalability trilemma", a term introduced by Vitalik Buterin [3]. According to this concept, a blockchain system can optimise only two of these three elements at the same time, which forces trade-offs in network architecture.

Traditionally, scalability improvements were introduced through so-called Layer-1 solutions that modified core network parameters such as block size or the consensus mechanism [7]. In recent years, a new class of approaches has emerged. These are Layer-2 protocols, which use off-chain transaction processing to increase throughput while preserving security and compatibility with the base chain. They operate as additional computational layers built on top of existing networks, most often Ethereum, which remains the most popular environment for smart-contract applications [1].

The most important contemporary Layer-2 solutions include Scroll, Linea and Base. These are three rollup networks that differ in their transaction-validation mechanisms and in their level of decentralization. Scroll is an implementation of a zkEVM rollup and uses SNARK-based cryptographic proof (Succinct Non-interactive

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Argument of Knowledge) to verify the correctness of transactions without revealing the underlying data [5]. Linea, developed by ConsenSys, follows a similar zero-knowledge approach but places strong emphasis on full compatibility with the Ethereum Virtual Machine (EVM) and on high processing efficiency [17]. Base relies on Optimistic Rollup technology, which treats transactions as valid unless proven otherwise and uses a fraud-proof mechanism for verification [6].

These solutions address the problem of Ethereum's limited throughput and high gas fees by moving most operations off the main chain. Each of them follows a different trade-off between processing speed, security and decentralization. For example, zk-rollup-based protocols offer stronger cryptographic guarantees and higher efficiency but require more advanced computational infrastructure. Optimistic rollups, in contrast, are easier to implement but have longer finality times due to the challenging period.

The aim of this article is to compare three blockchain-scaling methods: Scroll, Linea and Base, using empirical data from blockchain explorers (Blockscout, Lineascan and Basescan). The analysis examines both the speed and the stability of transaction processing. On this basis, the study assesses the extent to which modern Layer-2 solutions can balance performance, security and decentralization without modifying Ethereum's base layer.

2. Literature overview

The literature highlights that, despite the rapid development of Layer-2 technologies, these solutions are not free from risks. Attacks on rollups and flaws in the implementation of cryptographic proofs can lead to serious security breaches [11]. Growing centralization of sequencer operators in L2 networks also raises questions about whether these systems remain aligned with the original idea of decentralization [15]. Two main research directions can be identified in the existing literature: (1) conceptual studies that classify and analyse rollup architectures, and (2) empirical studies that measure performance, costs and security using real transactional data.

Conceptual approaches and comparative frameworks.

In "A Rollup Comparison Framework", Gorzny and Derka [9] propose a four-dimensional framework for evaluating rollup solutions. Their framework includes familiarity, finality time, modularity and maturity. The authors compare several optimistic and zero-knowledge rollup projects based on their technical documentation and public project descriptions. Although the study is conceptual rather than empirical, it emphasises the role of transaction finality time as both a measure of user experience and an indicator of system efficiency. This methodological perspective aligns with throughput and stability measurements (TPS and variability) that form the basis of the empirical analysis presented in this article.

The study by Roşca, Butnaru and Simion [19] provides an overview of security issues in the context of Layer-2 solutions. It covers risks related to sequencers, delays in data publication (data availability) and potential attack vectors targeting bridge layers. The authors discuss protective mechanisms used in leading protocols such as Arbitrum, Optimism and zkSync. Similar to earlier conceptual studies, this work focuses on theoretical and analytical considerations and does not include original empirical data.

Zyskind et al. [23] propose an innovative FHE-rollup model that combines fully homomorphic encryption (FHE) with rollup architecture to enhance user privacy. This contribution is primarily design-oriented and introduces a new class of rollups (confidential smart contracts). It does not address performance or throughput.

Empirical studies and quantitative analyses of rollups.

In the past two years, several studies have attempted to conduct quantitative analyses of Ethereum rollups using real-world data. The most comprehensive example is Park et al. [14]. Their study examines the effects of EIP-4844 (proto-danksharding) on Ethereum's consensus security, the fee-market structure and transaction dynamics across rollup networks. The analysis covers hundreds of thousands of blocks before and after the upgrade and applies stationarity tests (ADF) and VAR models to study temporal relationships between L1 activity and L2 load.

Chaliasos et al. [4] conduct a quantitative study of attacks on pricing and settlement mechanisms in rollups, focusing on the prover-killer attack and data-availability saturation. The authors estimate these attacks' effects on transaction finality delays and processing costs, showing that confirmation times may increase several dozen-fold under extreme conditions. Although the study concentrates on security and economics, it includes an empirical component based on simulations and L2 network data, which contributes to the broader understanding of rollup processing dynamics.

Another empirical study, by Gogola et al. [8], investigates arbitrage in automated market makers (AMMs) operating within zkSync Era. Using historical L2 ledger data, the authors analyse the persistence of price discrepancies and the speed of convergence, offering an empirical description of liquidity behaviour in zk-rollup environments.

Taken together, these studies show that, although interest in empirical rollup research has grown, most existing analyses focus on specific aspects such as security, economic efficiency or protocol changes. To the best of the author's knowledge, no previous work has conducted a systematic measurement of throughput (TPS) from transaction registers at one-second resolution or performed statistical comparisons of performance (ANOVA, Kruskal–Wallis, Levene/Brown–Forsythe) across different rollup networks.

Implications for the research method.

Against this background, the study presented in this article extends empirical approaches by analysing the microstructure of throughput in rollup networks. Using one-second (1 Hz) time series and statistical tests makes it possible to examine not only average processing speed but also stability and variability. This provides an important complement to earlier research. The findings of Park et al. [14], which highlight the role of stationarity tests in interpreting transaction dynamics, together with the evaluation framework proposed by Gorzny and Derka [9], which emphasises finality and stability metrics, support the methodological choices adopted in the present study.

3. Materials and Methods

The empirical data used in this study were obtained directly from the public API interfaces of Blockscout for three rollup networks: Base, Linea and Scroll. A custom Python script was used to retrieve the data in parallel from multiple Layer-2 networks, with full control over request limits and precise recording of processing times. The script relied on the following libraries:

- `requests` – for HTTP communication with Blockscout API endpoints,
- `pandas` – for structuring and saving data in `.csv` format,
- `datetime` and `timezone` – for normalising transaction timestamps to the UTC ISO 8601 format,
- `web3` – as an alternative RPC fallback for networks that do not return data through the API, such as Linea.

Each network was queried through a separate dedicated endpoint:

Base: `https://base.blockscout.com/api/v2/transactions`,

Linea: `https://linea.blockscout.com/api/v2/transactions`,

Scroll: `https://scroll.blockscout.com/api/v2/transactions`.

The script iteratively downloaded successive pages of JSON results while controlling the number of requests per second ($rps = 8.0$) and the transaction limit ($max\_tx = 15{,}000$). For each transaction object, the script extracted and normalised the key fields: `hash`, `block_number`, `from`, `to`, `value`, `fee`, `input_len`, `success`, and the timestamp expressed in UNIX epoch seconds.

A built-in function, `parse_timestamp_any()`, handled all common timestamp formats encountered in blockchain data: ISO 8601 strings, epoch seconds, epoch milliseconds and alternative timestamp fields such as `block_timestamp`, `inserted_at` and `created_at`. Each batch of data (by default 1,000 transactions) was appended to the corresponding CSV files. For the Linea network, an additional RPC fallback (`rpc.linea.build`) based on the `web3` library was used to retrieve data directly from full blocks via the `eth_getBlock` method.

The data were collected on 26 October 2025 during active network hours and included 15,000 consecutive transactions for each of the analyzed networks: Base, Linea and Scroll. Each record corresponds to a single transaction confirmed by the respective rollup sequencer, enabling a detailed reconstruction of second-by-second processing dynamics.

Data processing and analysis.

The collected data were then analysed quantitatively using a second custom script. This script loaded the CSV files, converted timestamps to UTC `datetime` format and aggregated transactions into one-second intervals.

Based on the resulting time series, the following elements were computed:

- descriptive statistics (mean, median, standard deviation, coefficient of variation, selected percentiles),
- box plots illustrating throughput variability,
- comparative tests:
  - ANOVA and Kruskal–Wallis, used to assess differences in mean and median TPS across networks,
  - Levene and Brown–Forsythe tests, used to compare stability (equality of variances) between groups,
- stationarity tests:
  - ADF (Augmented Dickey–Fuller), used to detect random-walk behaviour,
  - KPSS (Kwiatkowski–Phillips–Schmidt–Shin), used to confirm or reject the assumption of stationarity.

All analytical steps were carried out in Python 3.11 using the `scipy`, `statsmodels` and `matplotlib` libraries. The results of statistical tests and descriptive statistics were saved in `.csv` and `.json` formats. This workflow enabled an objective, second-level measurement of throughput in rollup networks and allowed for empirical verification of their stability and variability over time.

4. Main results

The comparative analysis revealed significant differences in the dynamics and stability of transaction processing across the examined Ethereum rollup networks. A summary of the TPS analysis is presented in Table 1.

General characteristics and TPS distribution.

Table 1. Summary of general throughput statistics (TPS) for the analysed L2 networks

L2 network	Mean TPS	Median TPS	SD	CV	Max TPS
Base	102.04	128.0	107.12	1.05	344.0
Linea	1.26	0.0	2.17	1.72	41.0
Scroll	0.87	1.0	1.78	2.04	52.0

Based on the one-second time series, Base shows the highest average TPS value (102.04) and a relatively low coefficient of variation ($CV = 1.05$), which indicates high processing stability. Linea demonstrates much lower throughput (1.26 TPS) combined with considerably higher short-term variability ($CV = 1.72$) and frequent periods with no transactions (median = 0.0). Scroll records the lowest TPS values (0.87) and displays many intervals with no transactions (median = 1.0).

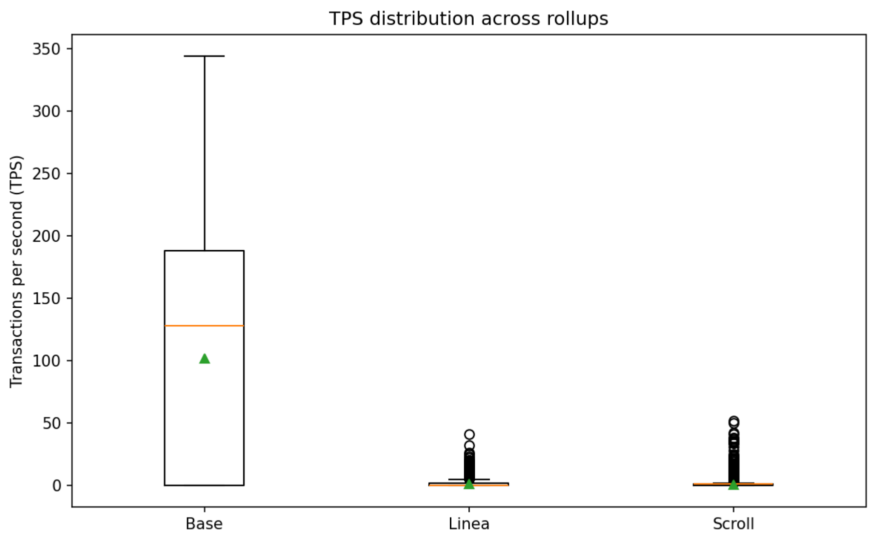

Figure 1. Distribution of instantaneous throughput (TPS) for the analysed L2 networks.

The box plot in Figure 1 reveals asymmetric TPS distributions for all networks, with clear right-skewness. This indicates the presence of short, intensive activity peaks. The computed coefficients of variation confirm that Scroll and Linea are less stable than Base.

TABLE 2. Effective TPS (TPS_{active}) – throughput during active network periods

L2 network	Mean TPS	Median TPS	SD	CV	Max TPS	Active time
Base	202.70	188.0	47.61	0.235	344.0	50.34%
Linea	3.02	2.0	2.44	0.810	41.0	41.79%
Scroll	1.71	1.0	2.19	1.278	52.0	50.95%

Examining only the active seconds did not provide a clear answer regarding TPS differences between the networks, because these values depend not only on the number of processed transactions but also on the architecture and maturity of each rollup (Table 2). The lower share of active seconds in Linea (41.79%) and the large gap between mean and maximum TPS (3.02 vs. 41.0) indicate that transactions are batched and published periodically in large groups. This produces intervals of apparent inactivity. The pattern is typical of zk-rollups, where processing a batch requires generating and verifying a cryptographic proof (zk-proof).

It should also be noted that both Linea and Scroll are still in the adoption and testing phase. Some nodes operate experimentally, and the overall transaction volume is sometimes constrained by whitelisting mechanisms or anti-spam protections. As a result, the lower average TPS in these networks does not reflect reduced activity, but rather the naturally smaller user base and operational properties of early-stage zk-rollup infrastructure.

Importantly, despite the very low average throughput in Linea and Scroll, both networks recorded maximum TPS values exceeding the peak capacity of native Ethereum (approximately 25 TPS). This confirms that all three rollup technologies objectively improve processing performance and enable substantial throughput expansion within the Ethereum ecosystem.

Comparison of means and variances.

Table 3 presents the statistical test results used to assess differences in the level and stability of transactional throughput (TPS) across the three analysed rollup networks: Base, Linea and Scroll.

TABLE 3. Results of comparative tests (ANOVA, Kruskal–Wallis, Levene, Brown–Forsythe)

Test	Statistic	p-value	Conclusion
ANOVA	$F = 12212.34$	$p < 0.001$	H_0 rejected; TPS differ significantly
Kruskal–Wallis	$H = 38.96$	$p < 0.001$	TPS distributions differ significantly
Levene (mean)	$W = 91200.37$	$p < 0.001$	variances are not homogeneous
Brown–Forsythe	$W = 58228.93$	$p < 0.001$	differences in stability confirmed

The high F statistic in the ANOVA test ($F = 12212.34$, $p < 0.001$) clearly indicates significant differences in average TPS levels across the groups, confirming that the networks do not deliver comparable throughput. The Kruskal–Wallis test ($H = 38.96$, $p < 0.001$), which is the non-parametric counterpart to ANOVA, reaches the same conclusion for the medians of the distributions. This shows that the differences in processing efficiency persist regardless of the assumption of normally distributed data.

The results of the Levene test ($W = 91200.37$, $p < 0.001$) and the Brown–Forsythe test ($W = 58228.93$, $p < 0.001$) demonstrate that the variances across the networks are not homogeneous, meaning that their processing stability differs significantly. Scroll exhibits the highest instability; Linea shows moderate variability and Base is the most stable in terms of short-term TPS fluctuations.

Stationarity of the TPS time series.

The results of the ADF and KPSS tests (Table 4) show that only the Base network exhibits behaviour close to stationarity, while Linea and Scroll display non-stationary structures (p-value < 0.01 in the KPSS test). This indicates the presence of trend-like and periodic fluctuations in transaction intensity in both networks, which is likely caused by sequencer batching and varying user demand.

Table 4. Results of ADF and KPSS stationarity tests for TPS time series

Network	ADF p-value	KPSS p-value	Conclusion
Base	0.055	0.10	close to stationarity
Linea	4.54×10^{-20}	0.01	non-stationary
Scroll	1.87×10^{-20}	0.01	non-stationary

In the ADF (Augmented Dickey–Fuller) test, the null hypothesis assumes that the time series contains a unit root, meaning that it is non-stationary. In contrast, the KPSS (Kwiatkowski–Phillips–Schmidt–Shin) test takes stationarity as its null hypothesis. The obtained results—KPSS $p < 0.01$ for Linea and Scroll—lead to the rejection of stationarity and confirm the unstable nature of their throughput over time. For Base, the p-values of ADF ≈ 0.055 and KPSS $= 0.10$ do not provide grounds to reject the null hypotheses, which means that TPS in this network can be considered stationary or close to stationary.

5. Conclusions

The results show that Base achieves the highest efficiency and processing stability, reflected in its highest average TPS and the lowest temporal variability. Linea and Scroll display much stronger fluctuations in short-term load, which reflects the behaviour of zk-rollups, where transactions are batched and published periodically as cryptographic proofs (zk-proofs). The lack of stationarity observed in both networks suggests that their throughput depends on short-term operational conditions. It is influenced by sequencer availability, batch publication cycles and the degree of sequencer congestion.

From a research perspective, this confirms that rollup comparisons require an assessment not only of average TPS but also of temporal stability and trend variability, which are essential for evaluating their practical usefulness in scaling the Ethereum network. The results obtained for Base (an optimistic rollup) indicate more predictable and stable performance parameters. zk-rollup solutions (Linea and Scroll), despite their higher instability, demonstrate potentially higher peak throughput during periods of intensive batching, which makes them attractive for high-throughput applications with short finality requirements.

Comparing these results with previous studies supports the literature's observation of a trade-off between performance, security and decentralisation, often referred to as the blockchain trilemma [3]. As noted by Lokhava et al. [12], attempts to increase network performance through off-chain processing or delegated validation tend to reduce validator independence. Similarly, Schmid and Shestakov [20] argue that rollup-based architectures may introduce new forms of sequencer centralisation, raising concerns about their alignment with the principles of openness and distribution that underpin blockchain systems.

Petryk and Li [16] add that governance mechanisms in L2 projects, despite improving operational efficiency, often generate new risk vectors. These include security risks (such as possible manipulation of batches) and social risks linked to the concentration of decision-making in the hands of operators. The findings of this study are consistent with these observations: although rollups increase throughput without altering Ethereum's base layer, they simultaneously introduce new centralisation points and potential security gaps, which call for further research on their resilience and transparency.

In summary, the empirical results confirm the literature's claim that modern Layer-2 solutions only partially overcome the constraints of the scalability trilemma. Rollups improve throughput and reduce gas costs, but at the expense of increased reliance on sequencer operators and potentially reduced decentralisation. Future research should focus on long-term analyses of L2 network stability under varying load conditions, as well as on evaluating how architectural developments such as shared sequencers or enshrined rollups affect the balance between security, decentralisation and performance.

6. Limitations and future research

It should be emphasised that the results presented in this study are based on a relatively small data sample: 15,000 transactions for each of the analysed networks. This limitation stems from the technical constraints of the API interfaces and the selected observation window. The dataset represents only a fragment of network activity and may not fully capture daily or weekly variability. This is particularly relevant for Linea and Scroll, which remain in the early stages of adoption and infrastructure development, with some nodes still operating in test mode. As a result, transaction volume and network behaviour may change considerably in the coming months. Repeating the study once these projects reach greater stability and a larger user base would make it possible to determine whether the observed differences in throughput and stability are persistent characteristics or temporary effects of the deployment phase.

In this study, comparative tests were conducted for three groups (Base, Linea, Scroll) at the aggregate level (ANOVA, Kruskal–Wallis, Levene, Brown–Forsythe). This approach allowed for the identification of overall differences between the networks as classes of solutions but did not specify which individual pairs differ significantly. Future stages of the research will include an expanded dataset and the use of post-hoc procedures (such as Tukey's test or Dunn's test with Bonferroni correction), which will allow for a more precise examination of pairwise relationships between the networks.

Future research will also extend the analysis to a broader range of Layer-2 solutions. In particular, the study will include Arbitrum One and Optimism, which are high-volume examples of optimistic rollups, as well as zkSync Era, Starknet and Polygon zkEVM, representing the family of zk-rollups based on different cryptographic proof systems (SNARK, STARK). Later stages will examine hybrid solutions such as Mantle, Blast and Metis, which belong to the category of modular rollups and combine features of optimistic and zk architectures in terms of scalability and L1 data-publication costs.

Repeating the study once Linea and Scroll achieve higher adoption will enable a more representative dataset and a more accurate assessment of zk-rollup performance under real operational load. This will make it possible not only to compare their throughput with optimistic rollup solutions but also to evaluate, on an empirical basis, the future direction of the Ethereum ecosystem in the context of long-term scalability.

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