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Solana's transaction network: analysis, insights, and comparison

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Abstract

Solana is recognized for its innovative Proof of History consensus mechanism, a cryptographic method that enables validators—participants responsible for verifying transactions—to efficiently record and order events without extensive communication, thus supporting high transaction rates. Despite its high-speed transactions capability, low cost transaction fees and significant market presence, it remains relatively underexplored in academic research. To address this gap, this paper uses graph-based modeling to analyze Solana's transaction network. The analysis reveals several interesting key characteristics, including a high concentration of transactions among central nodes, a prevalence of unidirectional transactions, and a low graph density. Moreover, we observe a significantly higher transaction failure rate (approximately 20% compared to 0.1% on Ethereum) and a substantial proportion of zero-value transfers (around 7.6% versus 0.66% on Ethereum). These findings shed light on underexplored aspects of Solana's ecosystem and provide insights that could influence future blockchain research and applications. The findings are particularly relevant for understanding behavior of blockchains with high transaction rates, and optimizing blockchain scalability and security.

Keywords: Blockchain; Solana; Transaction graph

1 Introduction

Blockchain is a decentralized ledger that records transactions across multiple computers so that the recorded entries cannot be changed. Transactions are grouped into blocks, validated, and then added to the chain in a transparent and immutable manner, ensuring security and trust without needing a central authority. Validators are specialized participants in a blockchain network who verify transactions (the primary method of interacting with the blockchain), maintain consensus, and ensure the integrity and security of the network. Their role is vital in preserving blockchain functionality, security, and decentralization.

The evolution of blockchain-based cryptocurrencies has been marked by remarkable progress in protocol advancement, substantial increases in market capitalization, and widespread acceptance across public and business spheres. Consequently, significant research has been undertaken to explore blockchains' extensive publicly available transaction data, particularly Bitcoin and Ethereum. However, Solana [1], a blockchain with a market capitalization (price per coin × number of coins in circulation) exceeding 108 billion USD as of January 2025, remains underexplored in academic research.

Blockchain networks use consensus mechanisms—rules for reaching agreement on valid transactions—to maintain consistency across their decentralized system. Solana was designed to deliver significantly higher throughput than leading blockchains like Ethereum while maintaining strong security and decentralization. To achieve this, Solana employs an innovative Proof of History (PoH) mechanism, a cryptographic clock that allows validators to verify the timing and order of events without direct communication. This approach offers a more efficient method of processing transactions compared to Bitcoin's Proof of Work (PoW) and Ethereum's Proof of Stake (PoS) mechanisms by integrating the passage of time directly into the blockchain. Also, this mechanism allows Solana to have orders of magnitude lower transaction costs than Ethereum by increasing the throughput of the network.

Despite its unique characteristics and notable market position, Solana has only recently begun to gain attention in the academic world [2, 3]. Specifically, the intricacies of its transaction network are still not well understood.

This research aims to address that gap by applying graph-based modeling to analyze Solana's structure and transaction patterns, and comparing it to Ethereum to highlight Solana's distinct characteristics. The significance of this research lies in Solana's potential to address blockchain scalability challenges, making it important to understand the network's underlying properties and compare it with a more established blockchain such as Ethereum. Through this investigation, by examining and contrasting these differences, we aim to gain insights for future blockchain developments and optimizations. Ethereum and Solana differ in their core design principles, Ethereum prioritizes security, decentralization, and broad applicability across decentralized applications, whereas Solana focuses on maximizing transaction throughput, low latency, and efficiency. However, both Ethereum and Solana share critical practical similarities. Unlike Bitcoin, which primarily acts as a cryptocurrency ledger, both Ethereum and Solana serve as decentralized computers, capable of executing decentralized applications. This commonality in their fundamental functionality makes Ethereum particularly well-suited as a comparative baseline for analyzing Solana. Moreover, Ethereum's mature ecosystem and extensively studied transaction network provide an ideal reference to highlight how Solana's unique architectural choices (most notably its PoH consensus mechanism) impact user behavior and transaction patterns.

Graph-based modeling is a powerful tool that enhances our understanding of transactions and user interactions across multiple domains. Its applications extend from price prediction [4] and address clustering [5–7] to deanonymizing users [8]. Moreover, it has proven effective in detecting malicious activities such as phishing scams and money laundering [9], as well as in identifying anomalies within systems [10, 11]. Graph analysis also reveals the underlying structural properties of networks; many cryptocurrency networks, for example, exhibit small-world structures and adhere to power-law distributions [12]. This approach allows us to identify structural properties, such as power-law distributions, which indicate how information and value flow through the network. Through this comprehensive examination, we aim to enhance our understanding of Solana's network and provide valuable insights.

Contributions. This paper presents the first graph-based analysis of the money flow within Solana's transaction network, using Ethereum as a comparative baseline to highlight the unique features of Solana's architecture and its influence on money flow behavior. The key contributions and findings of this study are as follows:

1. *Graph-Based Comparative Analysis.* We conduct a detailed graph-based analysis of Solana's money transfer network, focusing on SOL transfers between November 2023 and March 2024. We compare the findings with those of Ether transfers (transactions that only transfer Ether) during the same period to create money transfer graphs of both chains. Understanding and comparing the money transfer graphs of Solana and Ethereum is essential to understanding how the unique characteristics of Solana differ from Ethereum. This comparative approach reveals Solana's unique structural differences, such as a higher concentration of transactions among a few key nodes, a greater prevalence of unidirectional transactions, and a significantly low graph density. These features, which significantly differ from Ethereum, highlight the distinct structural and transactional differences between the two networks.
2. *High Transaction Failure Rates and Their Implications.* We show that Solana has a significantly higher transaction failure rate of 20.5% compared to Ethereum's negligible 0.09%. Our analysis identifies fundamental causes of these failures, including exceeded slippage tolerance and nonce mismatches, primarily due to Solana's rapid block production enabled by its PoH consensus mechanism. While Solana's PoH enhances scalability, the speed at which transactions are processed also exacerbates the potential for failure, posing a challenge for developers and users. This insight into the network's failure patterns is critical for understanding and mitigating the risks associated with high throughput blockchains.
3. *Analysis of Zero-Value Transfers.* One of the unique characteristics of Solana's transfer network is the high prevalence of zero-value transfers, which account for 7.6% of all successful transfers. In comparison, Ethereum's zero-value transfer rate is much lower (0.66%). Notably, 57% of successful zero-value transfers in Ethereum involve the same source and destination, a common method used to cancel pending transactions by replacing them with a higher gas transaction. Our results show that this practice is rare in Solana, with only 0.5% of successful zero-value transfers having identical source and destination. Moreover, 14% of addresses on Solana committed more than ten zero-value transfers, compared to just 2% in Ethereum. These findings reflect fundamental differences in user behavior and transaction strategies.
4. *Topological and Structural Insights.* Using Ethereum as a benchmark, we calculated key metrics such as degree centrality, graph reciprocity, graph density, and the size of weakly and strongly connected components. Our findings indicate that Solana's transfer network is sparse, with a significant weakly connected component dominating its structure.

Paper Organization. Sect. 2 reviews existing work on Solana and graph analysis of blockchains. Sect. 3 describes the data collection process and graph creation, and outlines the metrics used for analysis. Sect. 4 presents the results of our analysis of Solana's transfer network, using the Ethereum transfer network as a baseline for comparison. Finally, Sect. 5 explains the limitations of our work and suggests future research directions, and Sect. 6 summarizes the study.

2 Related works

Many studies have employed graph-based analysis to investigate key network characteristics in blockchain technology. However, the majority of this research has focused on Bitcoin and Ethereum [13–15]. Additionally, some studies use graph-based analysis to examine the peer-to-peer (P2P) network of nodes rather than focusing solely on unique addresses and transactions. For instance, Cao et al. [16] analyze Monero's P2P network.

In contrast, relatively few studies in the scientific literature have focused on Solana [1]. Among them, some have explored the development of commonly used applications on Solana, such as e-voting systems [17], decentralized email solutions [18], and management platforms [19].

Other studies have examined the reliability and scalability of Solana's blockchain technology. For instance, a recent study by Kniep et al. [2] raises concerns about Solana's reliability due to repeated network outages, which have necessitated centralized manual intervention. Another study by Pierro et al. [3] analyzed the scalability and throughput of the Solana blockchain, concluding that Solana offers significantly higher throughput and lower transaction fees compared to other blockchains with similar features.

Despite these contributions, research on Solana has yet to explore its money transfer dynamics. While studies on money transfer analysis are available for other blockchain networks, Solana remains largely unexamined in this regard. For example, Heimbach et al. [20] conducted a similar investigation on the Ethereum blockchain. Alizadeh et al. [15] focused exclusively on NFT transactions on Ethereum. Guo et al. [21] found that Ethereum's transaction volume, component sizes, and transaction relationships follow a power-law distribution. Additionally, Motamed et al. [13] conducted a comparative study across multiple blockchain networks, analyzing their key characteristics.

The most closely related work to our research is the one by Chen et al. [10], which analyzed the transaction graph between users and contracts in Ethereum, and Abbas et al. [22], which modeled Polkadot's transaction data and explored its properties.

A key distinction of our study is its focus on the Solana blockchain. Our analysis includes a graph-based examination of both Solana and Ethereum transfers, using Ethereum as a baseline for comparison. Additionally, we differentiate between successful and failed transfers in our analysis—an approach that is particularly relevant to Solana due to its notably high failure rate. This distinction offers unique insights into blockchain data analysis.

3 Methodology

Solana transactions are the primary method of interacting with the network. In Solana, each transaction consists of one or more instructions. Each instruction, such as a transfer instruction, represents specific operations to be executed. Solana transactions exhibit two key characteristics: 1) If a transaction includes multiple instructions, they are processed in the exact order they are added to the transaction; 2) a transaction either fully completes with all instructions successfully processed or fails. Notably, none of the instructions are executed if any instruction within the transaction fails. Based on these characteristics, we define *transfer* as follows:

Definition 1 (Transfer) A transfer is an instruction used within a transaction to move SOL, Solana's native cryptocurrency, from one account to another. A transfer is called a *successful transfer* if it is part of a completed transaction. Conversely, if the transfer occurs within a transaction that fails, it is called a *failed transfer*.

3.1 Data gathering

The Solana network's throughput is notably high compared to other blockchains. At the time of writing, Solana has processed over 365 billion transactions.[1] The extended number of transactions on Solana makes a comprehensive computational analysis unfeasible. Therefore, we have made a decision to conduct our analysis on a representative subset of Solana transactions, ensuring the practicality and efficiency of our study.

For this study, we gathered transfer data from slot number 230,000,000 (Nov 14, 2023, at 16:51:29 UTC) until slot number 255,000,000 (Mar 18, 2024, at 20:51:04 UTC). We obtained the data using remote procedure calls (RPC) to the network nodes. We used the `getBlock()` RPC method to gather available blocks in this period and then prune it to have only Solana transfers. For each transfer, we have a source, destination, the transfer's value, log messages, transaction fee, and the transaction's status, which could be true or false. We gathered 270,113,178 transfers for this interval, where 214,567,398 were successful and 55,545,780 failed. During the same interval, we collected all Ether transfers (transactions that only transfer Ether) to establish a baseline for comparison. We utilized the CryptoHouse[2] platform to obtain this data, which included the source, destination, value, and transaction fee for each transfer. We gathered 47,528,706 Ether transfers, where 47,483,596 were successful and 45,110 failed.

3.2 Graph creation

After collecting SOL and Ether transfer data from the specified time range, we constructed two transfer graphs for each blockchain. One graph contained only successful transfers, while the other represented failed transfers. These graphs provide a clear visualization of address interactions in the context of transfers.

In each graph, addresses are represented as nodes, while transfers are depicted as edges. We did not consider the transaction value as the weight of the edges, since our focus is network connectivity, and none of our metrics depend on the edge weight. Consequently, we constructed four graphs: a successful SOL transfer graph, a failed SOL transfer graph, a successful Ether transfer graph, and a failed Ether transfer graph.

To analyze these transfer graphs, we utilized the NetworkX package in Python, a powerful tool specifically designed for working with complex networks. All computations were performed on a high-performance machine equipped with 48 processing cores and 256 gigabytes of RAM.

3.3 Metrics

From the network perspective, we explored several features related to the SOL transfer graph. These calculated features provided valuable insights into different aspects of the network's characteristics and structure.

[1] https://explorer.solana.com/.

[2] https://crypto.clickhouse.com/.

Failed Transfers. To analyze failed transfers, we examined various metrics, such as the frequency of failures, reasons for failure, and associated transaction costs. By evaluating these metrics, we aimed to identify patterns and potential inefficiencies within the network. This analysis provides insights into the system's reliability and performance, helping us understand the underlying causes of transaction failures and informing potential improvements.

Zero-Value Transfers. This metric shows how many zero-value transfers each account committed. It gives us insight into the distribution of zero-value transfers and helps us understand whether a few accounts are responsible for the majority of zero-value transfers.

In-Degree and Out-Degree Distribution. The distribution of incoming and outgoing edges in the SOL and Ether transfer graphs shows the frequency of transfers involving each address. Because each edge corresponds exactly to one transfer. In other words, the degree distribution shows how many separate transfer each address participates in. It provides insights into the connectivity and importance of individual nodes within the graph. Analyzing node degrees helps us understand the overall network structure and the relative significance of each node in our graphs.

Density. Graph density measures the proportion of actual connections in a graph compared to possible connections. It is calculated by dividing the number of edges by the total number of possible edges. The graph density D for a directed graph with m number of edges and n number of nodes is calculated as:

$$D = \frac{m}{n(n-1)}$$

A high density indicates many connections, while a low density suggests only a fraction of possible connections.

Reciprocity. Reciprocity in network analysis measures how often connections in a graph are bidirectional. It quantifies the likelihood that if node X is connected to node Y, node Y is also connected to node X. Formally, reciprocity r is:

$$r = \frac{|\{(u,v) \in E \mid (v,u) \in E\}|}{|\{(u,v) \in E\}|}$$

The reciprocity coefficient can range from 0 to 1. A value of 0 indicates no reciprocity, meaning there are no reciprocal connections in the graph. A value of 1 indicates complete reciprocity, where every edge in the graph has a reciprocal connection.

Strongly and Weakly Connected Components. Strongly connected components (SCCs) and weakly connected components (WCCs) are key graph theory concepts that identify node connectivity in a network. In a directed graph, SCCs are subgraphs where each node can reach every other node, representing tightly interconnected groups. WCCs are subgraphs where nodes are connected through undirected paths. By analyzing the size of SCCs and WCCs, we gain insights into the network's overall connectivity and subgroup patterns.

4 Results

In this section, we present the results of our analysis of Solana's transfer network. We use our analysis of the Ethereum transfer network as a baseline for comparison.

Table 1 Top 10 nodes regarding degree centrality of successful SOL transfers

Wallet address	Degree centrality
BswAaS7SVs59zXe45dToq1FKmJr4nMHBHBjBEfibM5b9	0.469
EkZStqj9BSwLS19uLDEsErCW6N1HHzvoGg92Ei3YYBNt	0.234
MeowujaCA1FGaA7hna2ezUXLbrj36qZi4hGx94xNQLo	0.132
AGFCb7sETaMhvKuq6j3iiVmRLh7WtryAJFgnDGt6LTgN	0.111
2n4NKzSjLVqTEgz36DWbhAPupa4WVXoFPYhqPLYC11tU	0.108
q4s8z5dRAt2fKC2tLthBPatakZRXPMx1LfacckSXd4f	0.094
4zdNGgAtFsW1cQgHqkiWyRsxaAgxrSRRynnuunxzjxue	0.094
orc1TYY5L4B4ZWDEMayTqu99ikPM9bQo9fqzoaCPP5Q	0.081
6Q4jQpfMiNpHs3SN4RjAgm7QiZm3YpsNLrSaD4M5p78T	0.072
F5GkEY9zmFLaDtrJZAu8oojgczy2KW1siCtT1GDK8Yru	0.069

4.1 Failed transfers

In the data we analyzed, there were 270,113,178 Solana transfers, of which 55,545,780 failed, resulting in a notable failure rate of 20.53%. In contrast, our evaluation of Ethereum transfers during the same period shows a failure rate of 0.09%. This stark difference prompted us to take a closer look at failed transfers and their underlying causes.

In Sect. 4.3 (Fig. 2), we analyze Solana's transfer network and demonstrate that its transfer graph is highly centralized, with a small number of nodes participating in the majority of transfers. Here, we present the top ten addresses ranked by degree centrality for Solana's transfer graphs in Tables 1 and 2. The degree centrality for a node is calculated as the fraction of nodes it is connected to. Since the graph is a multigraph (two nodes can have multiple edges between them), this value could be greater than one.

We note that three addresses appear in both tables (highlighted). This suggests that they may be key players in the Solana ecosystem. For instance, we identified that one of these addresses, `UefNb6z6yvArqe4cJHTXCqStRsKmWhGxnZzuHbikP5Q`, belongs to Marinade's stake pool.[3] The remaining seven addresses in Table 2 have high centrality in failed transfers but not in successful ones. The failed-to-success ratio, defined as the number of failed transfers an address is involved in (as either the source or destination) divided by the number of its successful transfers, is significantly high. Notably, for four out of the seven addresses, this ratio exceeds 10.

We measured the average block distance between consecutive transfers for the addresses listed in Table 2. The results are presented in Table 3. For instance, the address `7rP7ANYmpAq1tHHXuW7iJdBmHHmishzCXWpvd8dvsLrt` has an average transfer distance of 1.8 blocks, equivalent to about 0.72 ms. This means the address initiates a transfer approximately every about 0.72 ms. Such behavior may be linked to bots and non-organic activity on Solana, an interesting phenomenon that warrants further investigation of its own in future research.

Wasted Fees. Table 4 shows the total fees wasted on failed transfers over our four-month review period. To determine the USD value of these wasted fees, we multiplied the daily wasted SOL fees by the average price of SOL in that day. The results show a considerable sum was lost. For context, we estimated the wasted fees on failed Ethereum transfers during the same period to be about 218,627 USD. Notably, even though Ethereum's

[3] https://marinade.finance.

Table 2 Top 10 nodes regarding degree centrality of failed SOL transfers

Wallet address	Degree centrality	Failed to successful ratio
UefNb6z6yvArqe4cJHTXCqStRsKmWhGxnZzuHbikP5Q	4.641	5.73
BswAaS7SVs59zXe45dToq1FKmJr4nMHBHBjBEfibM5b9	4.425	0.50
MeowujaCA1FGaA7hna2ezUXLbrj36qZi4hGx94xNQLo	1.928	0.77
EkZStqj9BSwLS19uLDEsErCW6N1HHzvoGg92Ei3YYBNt	1.681	0.38
75jTZDE78xpBJokeB2BcimRNY5BZ7U45bWhpgUrTzWZC	1.513	10.56
71WDyyCsZwyEYDV91Qrb212rdg6woCHYQhFnmZUBxiJ6	0.624	1.61
EccxYg7rViwYfn9EMoNu7sUaV82QGyFt6ewiQaH1GYjv	0.484	1.10
32XdShD7WNfbiNsSqKKm2d16gfPKinDzYG4Y4T7Ly4Bb	0.438	11.74
7rP7ANYmpAq1tHHXuW7iJdBmHHmishzCXWpvd8dvsLrt	0.436	11.72
ARWsVR2Jyp3TzbTCaznmBRDcdiprfxYKKE5dRLWC7JAy	0.435	11.76

Table 3 Average block distance between two consecutive transfers to/from addresses reported in Table 2

Wallet Address	Average block distance between two transfers
UefNb6z6yvArqe4cJHTXCqStRsKmWhGxnZzuHbikP5Q	2.51
BswAaS7SVs59zXe45dToq1FKmJr4nMHBHBjBEfibM5b9	33.53
MeowujaCA1FGaA7hna2ezUXLbrj36qZi4hGx94xNQLo	4.79
EkZStqj9BSwLS19uLDEsErCW6N1HHzvoGg92Ei3YYBNt	0.48
75jTZDE78xpBJokeB2BcimRNY5BZ7U45bWhpgUrTzWZC	33.61
71WDyyCsZwyEYDV91Qrb212rdg6woCHYQhFnmZUBxiJ6	33.35
EccxYg7rViwYfn9EMoNu7sUaV82QGyFt6ewiQaH1GYjv	27.71
32XdShD7WNfbiNsSqKKm2d16gfPKinDzYG4Y4T7Ly4Bb	6.71
7rP7ANYmpAq1tHHXuW7iJdBmHHmishzCXWpvd8dvsLrt	1.80
ARWsVR2Jyp3TzbTCaznmBRDcdiprfxYKKE5dRLWC7JAy	35.01

Table 4 Fee of Solana Failed Transactions

Wasted fees (SOL)	Wasted fees (USD)
20,039	$2,180,069

transaction fees were more than two orders of magnitude higher than Solana,[4] the total fees wasted on failed Solana transfers were an order of magnitude greater than those on Ethereum.

Failure Factors. We analyzed the log messages of failed transactions and identified the following major factors contributing to failure along with their associated fees:

- *Slippage Tolerance Exceeded.* This error occurs when the price of the token changes beyond the allowed slippage tolerance between the time a trade is submitted and confirmed. Slippage tolerance is set to protect users from unexpected price changes; if exceeded, the transaction is canceled to avoid unfavorable trades.
- *Insufficient Funds.* This occurs when the user's account does not have enough tokens or SOL to cover the transaction, including any fees. Both Solana and DeFi platforms require sufficient balance to complete transfers, token swaps, or other operations.
- *Current Nonce Mismatch.* This error occurs when the expected transaction nonce (a counter used to ensure transaction order) differs from the current one. Nonce

[4]Considering the average ETH and SOL prices, the average transaction fee during the examination period was $0.004 for Solana (0.00004 SOL) and $0.50 for Ethereum (0.0002 ETH).

Table 5 Top Five Reasons of Solana Transaction Failure

Reason	Portion (percentage)
Slippage Tolerance Exceeded	51%
Insufficient Funds	11%
Current Nonce Mismatch	8%
AMM Account Owner Mismatch	4%
Account Not Initialized	3%
Other	23%

mismatches typically result from another transaction being processed out of order, leading to failure.

- *AMM Account Owner Mismatch.* This error occurs when an Automated Market Maker (AMM) program tries to access an account owned by a different program. On Solana, each account is owned by a specific program. If the wrong program interacts with the account, the transaction will fail.
- *Account Not Initialized.* This error happens when a program attempts to use an account that has been created but not properly initialized. On Solana, accounts must be initialized before they can store data or interact with other programs; otherwise, the program cannot operate on the account.

Table 5 lists the top five factors contributing to transaction failures, along with their relative percentages. As shown in Table 5, these five factors account for 77% of all failures. Notably, two of the factors (i.e., *Current Nonce Mismatch* and *Slippage Tolerance Exceeded*) can be attributed to Solana's fast block production, a result of its PoH consensus mechanism.

In the case of *Current Nonce Mismatch*, transactions must be processed sequentially. If they are submitted out of order or too quickly, the nonce–which ensures correct transaction sequencing–may not match, leading to transaction failure. For *Slippage Tolerance Exceeded*, PoH combined with rapid block production can cause significant price fluctuations during trading. If the token price shifts beyond the allowed slippage tolerance within the time it takes to produce a block, the transaction will fail to protect users from executing trades at unfavorable prices.

The remaining three reasons are typically caused by issues on the user's end, such as improper setup, insufficient resources, or incorrect usage, rather than the Solana's blockchain protocol or PoH itself.

4.2 Zero-value transfers

Our collected data on Solana contains 214,567,398 successful transfers, where 16,460,982 (approximately 7.6%) are zero-value transfers. On the other hand, our data on Ethereum contains 0.66% of zero transfers.[5] This motivated us to take a closer look at zero-value transfers of Solana and compare it to Ethereum as our baseline.

In Ethereum, over 57% of successful zero-value Ether transfers–180,833 out of 317,246—originate from and are sent to the same address. This practice, known as self-transfers, is commonly used to cancel pending transactions. To do so, a user issues a new transaction with the same nonce but a higher gas fee, sending it to their own address. This ensures the

[5] The number of zero-value transfers was reported to be 0.06% of transfers in the Polkadot blockchain [22].

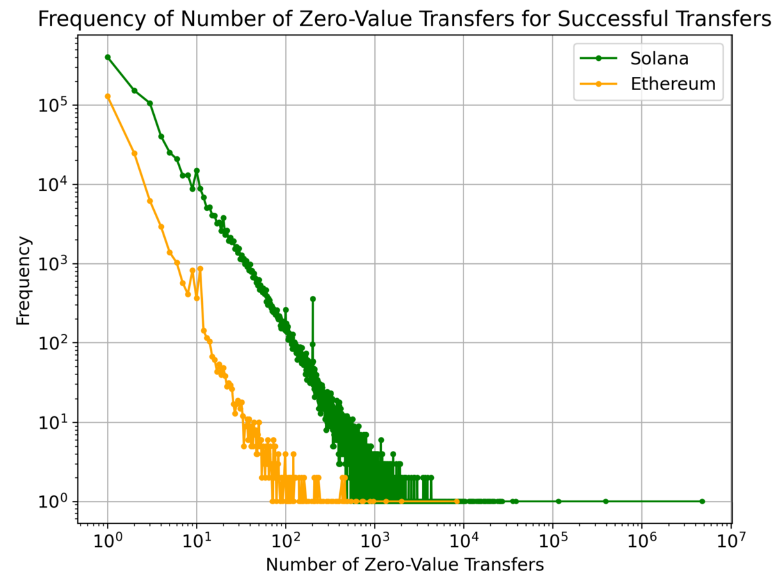

Figure 1 *Frequency of successful zero-value transfers*. The *x*-axis represents the number of successful zero-value transfers, while the *y*-axis denotes the number of addresses that executed the corresponding *x* zero-value transfers

new transaction is processed first, which effectively cancels the original one. Zero-value transfers are particularly suitable for this purpose, as they do not require checking the sender's current balance, which simplifies execution.

In contrast, this behavior is not well-justified in Solana, as its significantly lower fees and faster block times reduce the need for such cancellation tactics. Our data support this, as only a small percentage of zero-value transfers (0.5%) in Solana involve the same source and destination. This discrepancy highlights a fundamental difference in user behavior and transaction mechanics between the two blockchains, and demonstrate how Solana's unique architecture not only impacts network performance but also shapes distinct user interactions.

Fig. 1 shows the frequency of zero-value transfer per address in the successful transfer graph. More specifically, (x, y) on this plot means there is y number of addresses commit x number of zero-value transfers. The mean of the number of zero-value transfers per address in Solana is 18.09 (1.86 in Ethereum), and the median is 2 (1 in Ethereum). This indicates that most users only committed a few zero-value transfers.

By comparing the two plots of Fig. 1, we can observe certain similarities in pattern of zero-value transfers in Solana and Ethereum. In particular, in both blockchains, the number of accounts that commit a few zero-value transfers is more frequent, and the number of accounts that commit more zero-value transfers is less frequent. However, compared to Ethereum, Solana's mean and median have a meaningful difference, meaning Ethereum is closer to having a symmetrical distribution regarding zero-value transfers per address.

The address that committed the most zero-value transfers in Solana contributed 4,784,106 transfers, while this number for Ethereum is 8385, which suggests a meaningful gap. Also, in Solana, 909,502 unique addresses committed zero-value transfers (170,413 in Ethereum), whereas 783,247 addresses made ten zero-value transfers or less (168,245 in Ethereum). In other words, in Solana, 14% of addresses committed more than ten zero-value transfers. In contrast, only 2% of addresses in Ethereum performed more than ten zero-value transfers. This difference further emphasizes the differences in user behavior between the two blockchains.

The address responsible for the highest number of zero-value transfers in Solana is

orc1TYY5L4B4ZWDEMayTqu99ikPM9bQo9fqzoaCPP5Q,

which executed 4,784,107 zero-value transfers, accounting for 29% of all such transfers in the studied period. We identified that this address belongs to the Helium project.

By examining the code of this project,[6] we discovered that the function *resize_to_fit* in the *lazy_distributor* subproject—an instruction for resizing an account—triggers a transfer instruction. Additionally, *resize_to_fit* is invoked every time the *SetCurrentRewardsV0* instruction is executed. This leads to a zero-value transfer if the difference between the new minimum balance and the account balance is zero.

The zero-value transfers generated in this case appears to be an unintended side effect of the `resize_to_fit` function, rather than a necessary action. It happens because the program blindly calls the transfer function, even when no additional SOL is required. While this does leave an on-chain footprint that can be useful for debugging, auditing, and tracking execution, it is not inherently needed and could be avoided by adding a simple if statement to check if the transfer amount is greater than zero before executing the instruction.

4.3 Transfer graph analysis

In this section, we present the results of our analysis of the transfer graphs in Solana and Ethereum. Tables 6 and 7 summarize the number of nodes, edges, and zero-value transfers within these graphs.

Degree Distributions. Fig. 2 shows the distribution of the in-degree and out-degree for both successful and failed transfers in Solana and Ethereum, in log-log scale. For both distributions, the power-law model ($y \sim x^{-\alpha}$) provides an appropriate fit. Compared to a pure power law, the tail of the distribution shows an excess of extreme values.

In both networks, highly influential nodes play a dominant role, consistent with a power-law distribution. However, the power law is more pronounced in Solana, with a higher

Table 6 Successful transfer graph statistics

Chain	Nodes	Edges	Zero transfers (% of edges)
Solana	58,766,579	214,567,398	16,460,982 (7.6%)
Ethereum	18,632,456	47,483,596	317,246 (0.66%)

Table 7 Failed transfer graph statistics

Chain	Nodes	Edges	Zero transfers (% of edges)
Solana	3,149,191	55,545,780	776,072 (1.3%)
Ethereum	31,596	45,110	2735 (6.06%)

[6]https://github.com/helium/helium-program-library/.

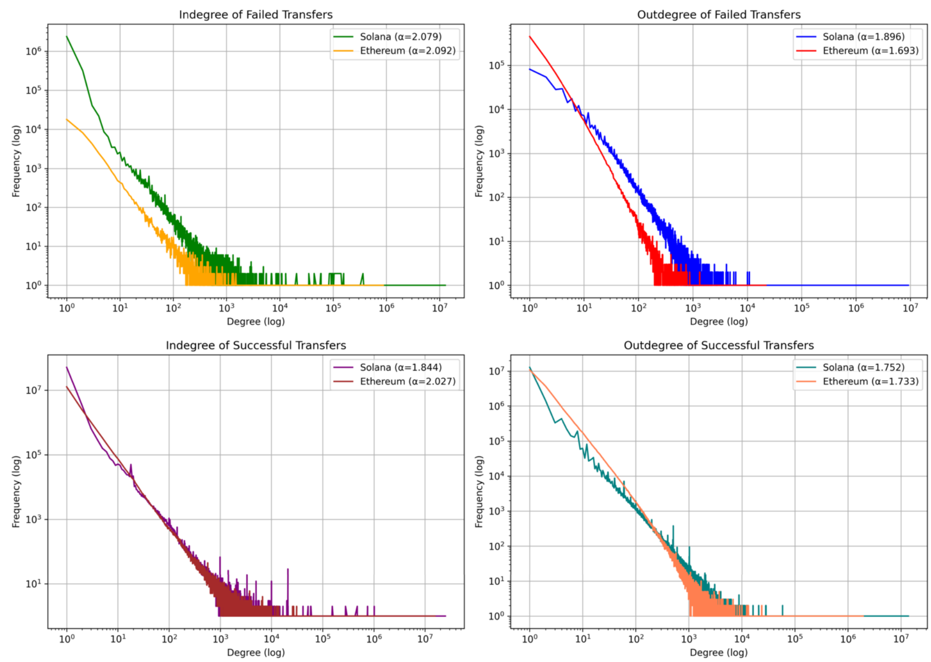

Figure 2 Degree distribution in the SOL and ETH transfer graphs

Table 8 Density for transfer graphs

Chain	Failed transfer graph	Successful transfer graph
Solana	0.000005600	0.000000062
Ethereum	0.000045187	0.000000136

Table 9 Size of the giant graph connected components in the successful transfer graphs

Chain	SCC (% of graph)	WCC (% of graph)
Solana	13,568,960 (23%)	48,188,499 (82%)
Ethereum	6,070,521 (32%)	16,988,061 (91%)

proportion of nodes having a degree of one. This suggests that Solana has more addresses that perform a single transfer and then leave their address inactive compared to Ethereum.

Graph Density. Table 8 shows the density of the failed and successful Solana transfer graphs. In both cases, the density is close to zero indicating a very low number of edges compared to the maximum possible.

The density of the Solana network is significantly lower than that of Ethereum, primarily due to its larger network size, as density generally decreases when the network size increases. To further illustrate this point, we calculated the average out-degree (the average number of transfers per address), which is 3.6 for Solana and 2.5 for Ethereum, indicating comparable address activity levels in both networks.

Connected Components. Fig. 3 illustrates the frequency distribution of the sizes of SCCs and WCCs for both successful and failed Solana transfer graphs, with Ethereum included for comparison. These plots reveal that the graphs contain a giant component, where many smaller nodes are connected to this central subgraph. In this giant component, nodes are

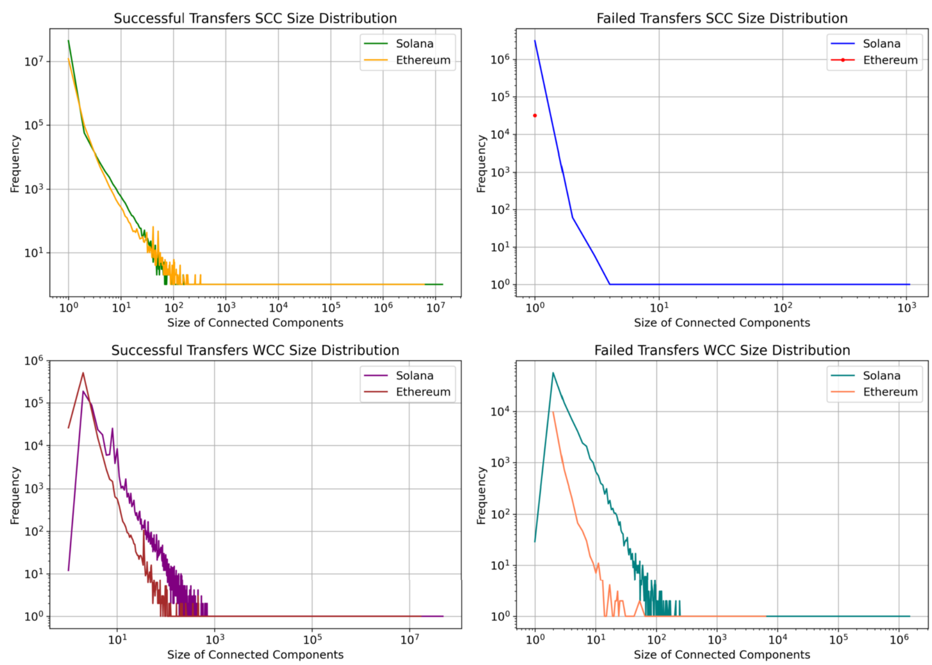

Figure 3 Frequency distribution of the sizes of SCCs and WCCs

highly interconnected, transferring SOL, while many other nodes exist in isolated components of size one, meaning they do not interact with the giant subgraph and only transact within their small group. Table 9 shows the size of the largest subgraph and its portion of the whole graph in the successful transfer graphs. This indicates that both chains contain a set of nodes that transact with other nodes, which form a giant subgraph. This set of nodes can be interpreted as the nodes that play a significant role in the market, such as exchanges.

Notably, in Ethereum, all SCCs of failed transfers are of size one, unlike in Solana. This indicates that, in Ethereum, no SCCs contain paths between all their nodes, suggesting a lack of strong interactions in failed transfers. In contrast, Solana shows some degree of strong interaction among nodes, even in failed transfers.

Another key finding is the higher frequency of small-size WCCs in Ethereum's successful transfer graph compared to Solana, although Solana has a greater overall number of transfers. However, the opposite is true for SCCs, where Solana displays a higher frequency of small strongly connected components. This suggests that Solana addresses are less isolated and more likely to have unidirectional connections to major hubs, while Ethereum's addresses tend to form smaller, isolated clusters.

Reciprocity Coefficients. Table 10 presents the reciprocity coefficient for both the failed and successful Solana transfer graphs. For the failed Solana transfer graph, the reciprocity coefficient is close to 0, indicating that failed transfers are rarely bidirectional. In other words, if one address attempts to transfer funds to another and the transaction fails, the likelihood of a failed transfer occurring in the reverse direction is nearly zero. This behavior is similar to Ethereum, where failed transfers also exhibit little to no reciprocity.

In contrast, the reciprocity coefficient for the successful Solana transfer graph is 0.13622, indicating a low but notable level of mutual transferring. This means that roughly 13%

Table 10 Reciprocity coefficient for transfer graphs

Chain	Failed transfer graph	Successful transfer graph
Solana	0.01019	0.13622
Ethereum	0.0	0.07305

of the edges in the successful transfer graph are reciprocal, while the remaining 87% are unidirectional. Compared to Ethereum, Solana has a higher proportion of mutual connections in successful transfers, suggesting that Solana users are more likely to engage in bidirectional transactions.

5 Limitations

This research presents a detailed graph-based analysis of Solana's transaction network, highlighting unique structural and behavioral characteristics. However, our study has several limitations that offer opportunities for future research. Firstly, our analysis was deliberately limited to SOL transfers. We did not explore the broader scope of program executions or interactions involving decentralized applications (dApps) deployed on Solana. Future research could benefit from analyzing program instructions, and the NFT ecosystem. Furthermore, due to the enormous volume of transactions processed by the Solana network, our analysis was performed over a specific interval rather than the entire transaction history of the blockchain. While our selected timeframe is representative and robust, analyzing the entire historical transaction dataset could potentially discover long-term behavioral trends and structural changes in user interactions. Finally, extending the comparative analysis to include additional blockchains—particularly those that offer similar functionalities to Solana, such as DeFi—may provide further insight into how different design choices influence blockchain performance and application scope.

6 Conclusion

In this paper, we conducted a detailed graph-based analysis of Solana's transaction network. We used Ethereum as a benchmark for comparison to understand and highlight Solana's unique characteristics that enable it to have considerably high throughput compared to other blockchains.

We observed a notable centralization in Solana's transfer network, where a small number of hub addresses handled the majority of transfers. This centralization, coupled with a low reciprocity coefficient, indicates that most interactions on Solana are unidirectional and short-lived. These traits contrast with Ethereum, which showed a more distributed and interconnected network structure.

Moreover, our analysis revealed that Solana experiences a higher incidence of transaction failures compared to Ethereum, with 20.53% of transactions failing due to issues such as exceeded slippage tolerance and nonce mismatches, likely caused by its rapid block production. Solana also shows a greater prevalence of zero-value transfers, which suggests transient address usage and differentiates it from Ethereum's more consistent transaction patterns.

The implications of these findings are important for the design and optimization of blockchain systems, particularly concerning scalability, reliability, and security. Particularly, the fast block production in Solana, while beneficial for throughput, poses challenges in transaction reliability. These insights offer valuable guidance for future enhancements in blockchain infrastructure development.

This research sets the stage for further investigations into the transaction networks of emerging blockchains. Future work could focus on developing strategies to minimize transaction failures in high-throughput systems like Solana, improve their decentralization, and track the evolution of network behaviors as blockchain ecosystems continue to expand.

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Author contributions
All authors participated in the study's design and writing the final manuscript. MK supervised the project at all steps and provided essential feedback for the investigation. SA collected the data and analyzed graphs and other features. Additionally, all authors helped in interpreting the results and writing the manuscript.

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Data availability
All codes and datasets are available in the: https://figshare.com/articles/dataset/Solana_transfer_data_and_results_/29090909?file=54612803

Materials availability
All codes and datasets are available in this link.

Declarations

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