Quantitative Analysis of the Reward Rate Disparity Among Delegators in a DPoS Blockchain

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***Abstract*—In the blockchain architecture, some selected nodes create blocks. Various consensus protocols, such as Proof of Work (PoW), Proof of Stake (PoS), and Delegated Proof of Stake (DPoS), have been proposed to select nodes. DPoS protocol works similarly to an election, where token holders vote for validator candidates. Elected validators generate blocks and earn block generation rewards. BNB Chain using DPoS has implemented a leveling mechanism to prevent the concentration of votes on a particular validator. However, token holders who have voted do not always act according to economic rationality. This causes disparity in the rewards received by token holders. The electoral process in DPoS causes this disparity; PoS does not have such a disparity. To quantitatively assess the current state of the leveling mechanism, we investigated the reward rate for the top 1,000 addresses based on the number of tokens they had voted on the BNB Chain. As a result, we found that token holders who frequently generated delegate-related transactions earned up to 25% more rewards than those who did not. In addition, we found a greater disparity in reward rates between token holders who have voted and keep a higher reward rate, compared to those who did not.**

***Index Terms*—Blockchain, Delegated Proof of Stake, BNB Chain, reward disparity.**

I. Introduction

Since the debut of Bitcoin in 2008 [1], its core technology, blockchain, has been used as a decentralized digital ledger across various fields such as finance [2], healthcare [3], and IoT [4]. One of the fundamental features of blockchain is the consensus protocol. The consensus protocol plays a role in setting the rules for transaction verification and block creation within the blockchain network. Bitcoin adopted the Proof of Work (PoW) protocol. Since then, various protocols including Proof of Stake (PoS) and Delegated Proof of Stake (DPoS) have been developed [5].

In DPoS, token holders vote for validator candidates through a process similar to an election, selecting a few validators. Validators generate blocks and earn block generation rewards. Subsequently, validators distribute block generation rewards to delegators. In this paper, we use the term *delegator* to represent the token holder who has voted, to distinguish them from token holders.

Compared with PoW, DPoS reduces energy consumption [6], and increases the throughput of transactions [7]. Furthermore, DPoS also increases the transaction throughput compared to PoS [8]. DPoS was proposed in 2014 [9], and since then, many successful blockchain projects such as EOS.IO [10], TRON [11], and BNB Chain [12] have adopted it. Sui [13] and Aptos [14], that were derived from Diem, have also adopted DPoS.

The BNB Chain, one of the successful DPoS blockchains, includes a mechanism to balance the number of votes to prevent the concentration of votes for a few validators. In this paper, we refer to this mechanism as a *leveling mechanism*. The leveling mechanism encourages delegators to vote for validators with fewer votes. This motivates all validators to create blocks with the same probability, and delegators to earn rewards with the same probability. In theory, if all delegators were perfectly economically rational, their reward rate would be the same. However, the behavior of delegators is not always economically rational, and there may be a disparity in rewards among delegators. This difference is caused by an election-like process that is unique to DPoS and not found in PoS.

In this study, we quantitatively analyze the current state of the leveling mechanism, focusing on the disparity in rewards among delegators in the BNB Chain. We show that the group of delegators who frequently generate delegate-related transactions earns more rewards than the group of delegators who do not. In addition, by examining the reward rates of individual delegators, we find that there is a greater disparity in reward rates between delegators who keep a higher reward and who do not.

II. BNB Chain

In this section, we describe the foundational knowledge related to the BNB Chain, which is the subject of our investigation into reward rates.

A. Overview of BNB Chain

As of July 2023, BNB Chain ranks among the world's most popular blockchains, with its native token BNB reaching a market capitalization of approximately 38 billion dollars[1]. The BNB Chain is highly active in Decentralized Finance. Its trading volume on decentralized exchanges is second only to Ethereum[2].

The BNB Chain consists of two main elements. The first is the BNB Beacon Chain (BC), which handles governance. The second is the BNB Smart Chain (BSC), which offers features

[1]https://coinmarketcap.com/ (accessed 2023-09-15)
[2]https://defillama.com/dexs/chains (accessed 2023-09-15)

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like EVM compatibility, a consensus layer, and multi-chain hub capabilities.

B. DPoS in BNB Chain

The selection of validators in BSC is implemented through the DPoS protocol. Token holders of BNB tokens can vote for validator candidates, and based on these votes, validators are chosen to create blocks and earn rewards. Token holders who have voted tokens for validators can receive rewards distributed by validators.

Token holders can vote any amount of tokens for any number of validator candidates. Votes are counted daily at UTC 0:00. Based on the count, the top 21 validator candidates become the Cabinet, while those ranked 22nd to 29th become the Candidates. Note that here, Candidates are a specific group mentioned in BEP-131, not the same as general validator candidates [15]. For each epoch, members of the Cabinet are more likely, while Candidates are less likely, to be selected as one of the 21 validators. This results in higher rewards for the Cabinet and lower rewards for the Candidates.

Blocks are generated every three seconds, and validators receive BNB tokens as rewards, which are sourced from the transaction fees contained within those blocks. Each validator sets its commission rate for reward distribution, and the net block generation rewards after commission are distributed to delegators on a daily basis. The reward for delegator i on day d voting for validator v is calculated using the following equation:

$$R_{i,d} = (R_{v,d} \times (1 - C_{v,d})) \times \left(\frac{V_{i,d}}{V_{v,d}}\right) \tag{1}$$

where $R_{v,d}$ is the block generation rewards for validator v on day d, $C_{v,d}$ is the commission rate of validator v on day d, $V_{i,d}$ is the amount of tokens voted by delegator i for validator v on day d, and $V_{v,d}$ is the total amount of tokens voted by any delegators for validator v on day d.

In the BNB Chain, there exists a leveling mechanism. This ensures that validators within the Cabinet have an equal chance to earn block generation rewards, no matter how many votes they have. Similarly, validators among the Candidates also have an equal chance to earn block generation rewards within their group. However, the chances of earning rewards are not the same for validators in the Cabinet and those in the Candidates. In other words, the value of $R_{v,d}$ remains constant either within the Cabinet or among the Candidates. This mechanism activates an economic incentive to vote for validators with fewer votes within the same Cabinet or among the Candidates. This is because, with $R_{v,d}$ being constant and assuming equal commission rates $C_{v,d}$, delegators can get higher rewards $R_{i,d}$ by voting for validators with fewer voted tokens $V_{v,d}$. This leveling mechanism aims to prevent vote concentration on a few validators and to stop a few from controlling elections due to large token holdings. Under this mechanism, assuming that delegators make rational economic decisions, the rewards received by delegators should statistically be the same regardless of which validator is chosen for voting.

However, it is unclear how much delegators actually behave rationally. Even if the vote counts among validators temporarily approach similar levels, various factors can still create disparity in the vote counts between validators. These include changes in the election process and new votes from recent token holders. Therefore, the presence of delegators who switch their vote in response to imbalances in the number of votes validators receive relative to the block generation rewards they obtain, is essential. These delegators keep their own rewards higher and help bring the vote counts among validators closer to similar levels.

III. Related Work

Since the development of DPoS, numerous studies have been conducted on attacks specific to DPoS blockchains. Hasanova et al. [16] have studied specific vulnerabilities in DPoS blockchains. They point out risks such as exploiting low voter turnout by large token holders and the threat of block producers colluding.

Against this backdrop, Liu et al. [17] investigated EOS.IO, one of the DPoS blockchains. They revealed that voting power is concentrated among a few voters and that there is suspicion of collusion between several validators.

Additionally, Wang et al. [18] proposed a method to reduce these risks by using clustering algorithms to categorize voting nodes. Based on these results, they provide more rewards to nodes that actively participate in voting. This approach deliberately creates a reward disparity to encourage node participation in voting.

However, in the BNB Chain, vulnerabilities can arise not only from the rate of voting participation but also from the imbalance of vote counts. Additionally, reward disparity can also lead to further centralization of BNB tokens. Therefore, the leveling mechanism for the number of votes is crucial. To the best of our knowledge, this is the first work to quantitatively investigate the current state of the leveling mechanism. We quantitatively analyze the disparity in rewards in the BNB Chain.

IV. Data

To analyze the disparity in rewards, we prepared data on voted balance and rewards for each delegator. We collected delegate-related transactions from BNB Beacon Chain Explorer[3]. Delegate-related transactions refer to the following three types:

- **Delegate Smart Chain Validator**
  Voting BNB tokens to validator candidates.
- **Redelegate Smart Chain Validator**
  Changing the vote of BNB tokens from one validator candidate to another.
- **Undelegate Smart Chain Validator**
  Removing the vote of BNB tokens that are currently voted.

[3]https://explorer.bnbchain.org/ (accessed 2023-09-15)

Delegate-related transactions contain a variety of information. To analyze the voted balance, only the timestamp, delegator_address, validator_address, and delegation_amount of Delegate Smart Chain Validator and Undelegate Smart Chain Validator transactions are used. This is because the voted balance does not change by Redelegate Smart Chain Validator transaction.

We collected delegate-related transactions between August 16, 2020 and May 31, 2023. As a result, we obtained a total of 709,133 transactions. Based on these transactions, we calculated the voted balances for each delegator.

The voted balance $V_{i,d}$ for delegator i on day d is calculated as follows:

$$V_{i,d} = A_{\text{delegate},i,d} - A_{\text{undelegate},i,d}$$

where $A_{\text{delegate},i,d}$ is the total amount from the Delegate Smart Chain Validator transactions generated by delegator i before day d, and $A_{\text{undelegate},i,d}$ is the total amount from the Undelegate Smart Chain Validator transactions generated by delegator i before day d. If tokens are voted for multiple validator candidates, the sum of all such votes is considered.

Next, to calculate rewards, we collect data on delegate-reward transactions. To determine the target delegators for data collection, we calculated the voted balance for each delegator as of May 31, 2023, based on the delegate-related transactions. From these calculations, we identified the top 1,000 delegators in terms of their voted balances as of May 31, 2023. We then collected delegate-reward transactions for these top 1,000 delegators. As a result, we collected 1,616,939 delegate-reward transactions.

$R_{i,m}$, the total reward for delegator i in month m, is calculated as the total amount of rewards contained in the delegate-reward transactions generated in month m.

V. Analysis

We investigated the disparity in rewards between delegators on the BNB Chain. Delegators who receive larger rewards relative to their voted balances are likely employing strategies to keep a higher reward rate. We then hypothesized that such delegators would need to change their voting destination frequently. Therefore, we examined the relationship between the number of delegate-related transactions and the rewards received by the delegators.

To evaluate the rewards relative to the voted balance, we calculated the reward rate for each delegator. First, we identified delegators and subsequently calculated their monthly reward rates.

We identified delegators who maintained a voted balance in each month from January 2022 to May 2023, among the top 1,000 delegators based on their voted balances as of May 31, 2023. Subsequently, we calculated the reward rate for these delegators based on their consistent votes.

The reward rate $r_{i,m}$ for delegator i in month m is calculated using the following equation:

$$r_{i,m} = \frac{R_{i,m}}{V_{i,m}} \times \left(\frac{365}{N_m}\right) \times 100 \tag{2}$$

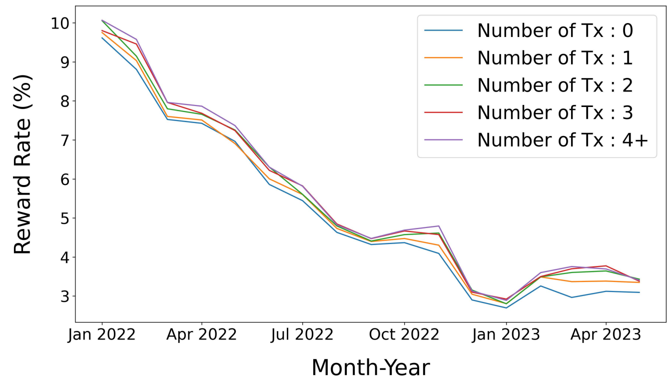

Fig. 1: Average reward rate of delegators grouped by monthly delegate-related transaction frequency from January 2022 to May 2023. This shows that delegators with zero delegate-related transactions had a lower average reward rate than those with one or more delegate-related transactions for all periods, except for May 2022.

TABLE I: Average reward rates of delegators from January 2022 to May 2023, grouped by monthly delegate-related transaction frequency.

Date	Tx : 0	Tx : 1	Tx : 2	Tx : 3	Tx : 4+
2022-01	9.61	9.75	10.06	9.80	10.07
2022-02	8.81	9.03	9.15	9.46	9.58
2022-03	7.53	7.60	7.80	7.96	7.96
2022-04	7.43	7.51	7.66	7.68	7.86
2022-05	6.96	6.91	7.25	7.24	7.37
2022-06	5.86	6.00	6.30	6.22	6.30
2022-07	5.44	5.60	5.61	5.82	5.81
2022-08	4.63	4.73	4.79	4.85	4.82
2022-09	4.32	4.40	4.41	4.47	4.48
2022-10	4.37	4.47	4.57	4.67	4.69
2022-11	4.09	4.30	4.61	4.57	4.79
2022-12	2.90	3.05	3.15	3.10	3.13
2023-01	2.69	2.80	2.80	2.92	2.89
2023-02	3.26	3.49	3.49	3.50	3.60
2023-03	2.96	3.37	3.60	3.70	3.75
2023-04	3.12	3.38	3.64	3.77	3.69
2023-05	3.09	3.35	3.43	3.38	3.40

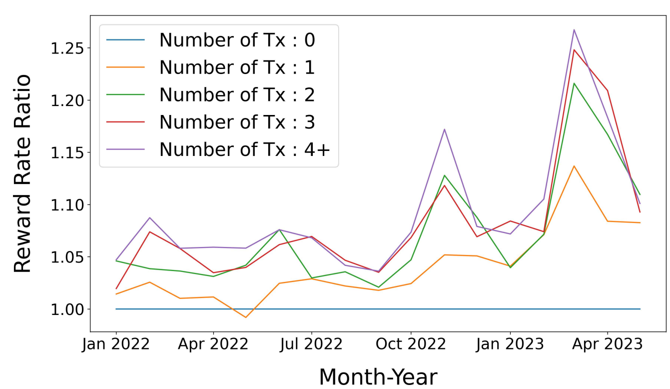

Fig. 2: Average reward rate ratios of delegators grouped by monthly delegate-related transaction frequency from January 2022 to May 2023. This shows that the average reward rate for delegators with four or more delegate-related transactions was up to approximately 25% higher than that for delegators with zero transactions.

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where $R_{i,m}$ is the total rewards earned by delegator i in month m, calculated from the delegation_amount in the delegate-reward transactions. $V_{i,m}$ is the sum of the daily voted balances $V_{i,d}$ for each day of month m for delegator i. N_m is the number of days in month m. The reward rate $r_{i,m}$ is calculated under the assumption that both the rewards and voted balance for delegator i would continue for a year, thus the formula includes a multiplication by $\frac{365}{N_m}$.

To analyze the relationship between the number of delegate-related transactions generated and the average reward rate of delegators, we categorized delegators into five groups based on their transaction frequency: 0, 1, 2, 3, and 4 or more times. We then calculated the average reward rate for each group.

Fig. 1 shows the average reward rate of delegators grouped by the number of generated transactions. See Table 1 for detailed values. Fig. 1 shows that delegators with zero delegate-related transactions had a lower average reward rate than those with one or more delegate-related transactions for all periods, except for May 2022. This suggests that delegators who frequently generate delegate-related transactions tend to get their rewards effectively.

Fig. 1 also shows that the decline in the average reward rate throughout 2022. This results from the decrease in the overall transaction volume and fees on the BNB Chain, as well as the stability in the total number of tokens voted. Transaction fees on the BNB Chain are shown in Fig. 3. The total number of BNB tokens voted is shown in Fig. 4. This has made it less clear how reward rates differ among different transaction frequency groups.

To clarify the differences in monthly delegate-related transaction frequencies, we calculated the ratio between the reward rate for other transaction frequencies (r_{other}) to the reward rate for the group with zero transactions (r_0). The ratio ρ is calculated using the following equation:

$$\rho = \frac{r_{\text{other}}}{r_0}. \tag{3}$$

The results are shown in Fig. 2. We observed that the average reward rate for delegators with four or more delegate-related transactions was up to approximately 25% higher than that for delegators with zero transactions. This result is shown in March 2023, the number of votes for different validators varied significantly. Further analysis of Fig. 2 suggests that the reward disparity between frequent and infrequent delegators was widening over time. If this trend continues, it could increase the risk of attacks.

From Figs. 1 and 2, it is clear that there exists a difference in average reward rates between delegators who generated delegate-related transactions frequently and those who did not. However, not all delegators in the group with frequent delegate-related transactions are employing a strategy to keep a higher reward rate. Therefore, an analysis of individual delegators' reward rates is needed to understand the disparity in rewards between those employing a strategy and those who do not.

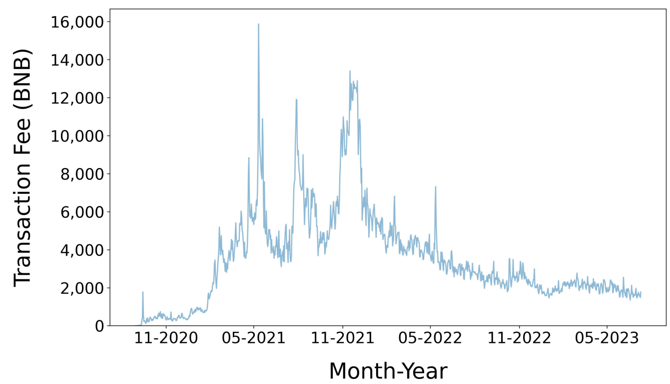


Fig. 3: Total amount of BNB tokens paid as transaction fees on each day for the BNB Smart Chain network. The transaction fees have been decreasing throughout 2022. Data sourced from BscScan[4].

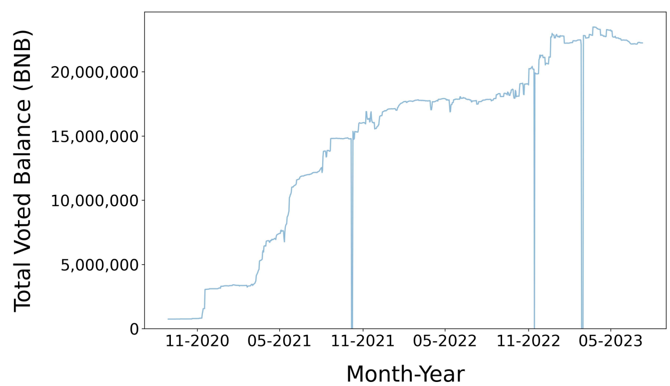
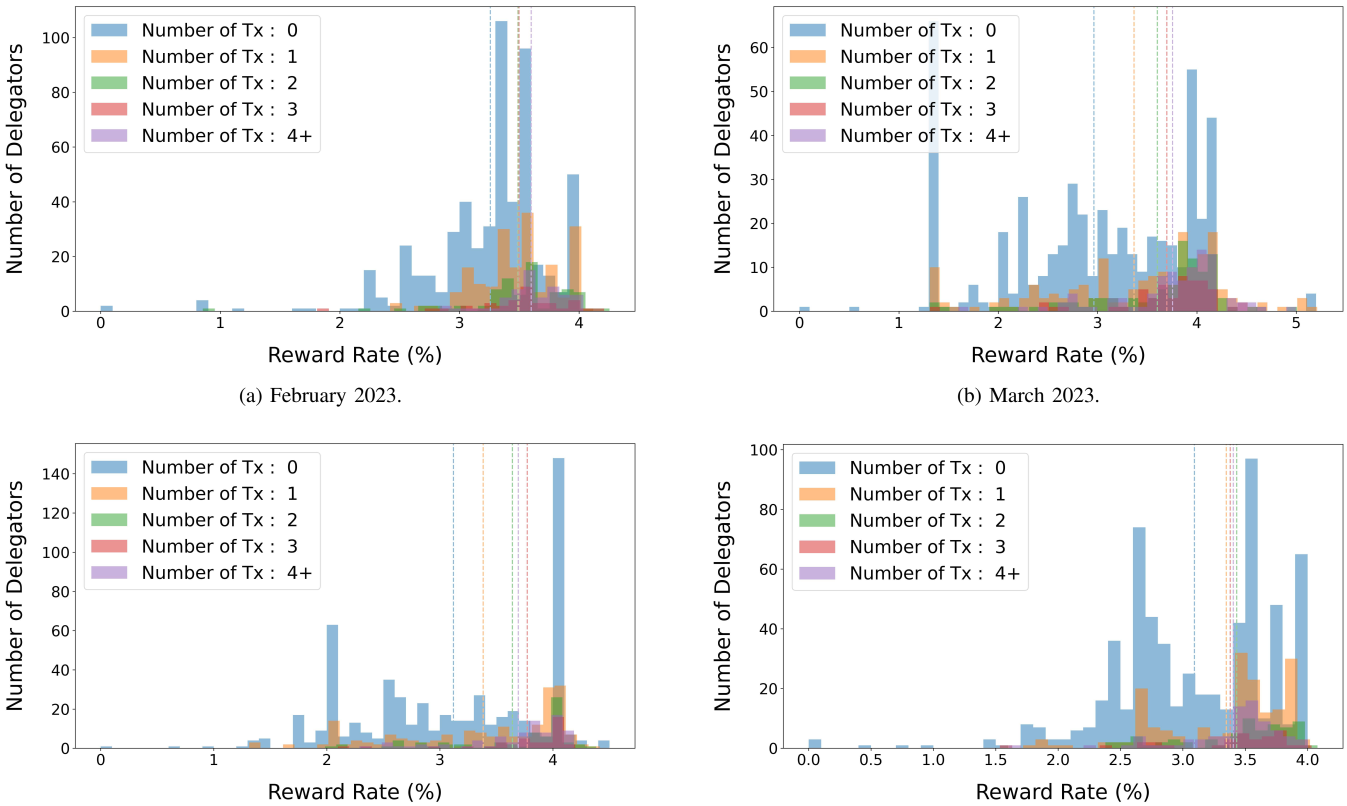


Fig. 4: Total number of BNB tokens voted across the BNB Chain. The voted balance has been largely stable throughout 2022. Data sourced from BscScan[4].

We used the latest data to investigate the difference in reward rates among individual delegators. Specifically, we used data from February 2023 to May 2023. The delegators investigated in Fig. 5 is the same as those in Figs. 1 and 2, meaning they maintained a voted balance in the month. We then calculated the reward rates for each delegator and classified them based on the frequency of delegate-related transactions. Fig. 5 shows the number of delegators by reward rate, with data from February 2023 to May 2023, respectively. The dotted lines in Fig. 5 indicate the average reward rate for each frequency of delegate-related transactions, consistent with the values reported from February to May 2023 in Fig. 1.

Fig. 5 shows that the delegators' reward rates are widely distributed regardless of the frequency of delegate-related transactions. This indicates that the majority do not necessarily employ a strategy to keep a higher reward rate, even within the group of delegators with frequent delegate-related transactions.

[4]https://bscscan.com/charts (accessed 2023-07-15)



(a) February 2023.

(b) March 2023.

(c) April 2023.

(d) May 2023.

Fig. 5: Number of delegators by reward rate, grouped by different counts of monthly delegate-related transactions. The dotted lines indicate the average reward rate for each frequency of delegate-related transactions. These figures show that the delegators' reward rates are widely distributed regardless of the frequency of delegate-related transactions.

Fig. 5 also shows that delegators who generate a lower number of transactions can get higher rewards. In fact, in April 2023, the delegator who got the highest reward rate did not generate delegate-related transactions. In other months, the difference in the highest reward rate between the group with zero delegate-related transactions and other groups was less than 0.15%. This suggests that generating delegate-related transactions and optimizing the votes does not necessarily lead delegators to a higher reward rate than those who do not. In other words, not changing the votes can sometimes reduce the reward rate. This is because delegators need to change their vote to maintain their reward rate only when there is an imbalance in the number of votes received by validators relative to the block generation rewards. Such imbalances occur when there is a significant influx of votes or when there are changes in the status of validator candidates, such as cabinet, candidate and another. However, these opportunities are infrequent. Consequently, most delegators do not need to change their vote frequently to achieve a higher reward rate.

Furthermore, the highest reward rate achieved by a delegator in a month was at most 5.1–5.2% in Fig. 5b and at least 4.0–4.1% in Fig. 5d. The lowest reward rate in Fig. 5 was between 0.0–0.1%. This implies that delegators employing a strategy to keep a higher reward rate likely earned rewards around these highest percentages, whereas those not doing so had a minimum reward rate of 0.0–0.1%. From these findings, it is clear that there is a significant disparity in reward rates. While Fig. 2 showed an average reward rate difference of up to approximately 25% between groups segmented by delegate-related transactions as of March 2023. Therefore, the data from Fig. 5 suggests that reward rate disparity is even larger at the individual level.

Note that while this paper uses data from February 2023 to May 2023 as examples, significant disparities in reward rates were observed among delegators in other months from January 2022 to March 2023.

Moreover, in May 2023, the top 29 validator candidates maintained their positions as top candidates, and no other candidates managed to break into the top 29 rankings. Therefore, we created Fig. 6, which indicates the number of validators by the reward rates they would offer if continuously voted throughout May 2023. Fig. 6 shows that no validator candidates offered a reward rate between 0.0–1.3%. Consequently, among the delegators with zero delegate-related transactions, as indicated in Fig. 5d, those who received a reward rate between 0.0–1.3% were likely to have continuously voted for

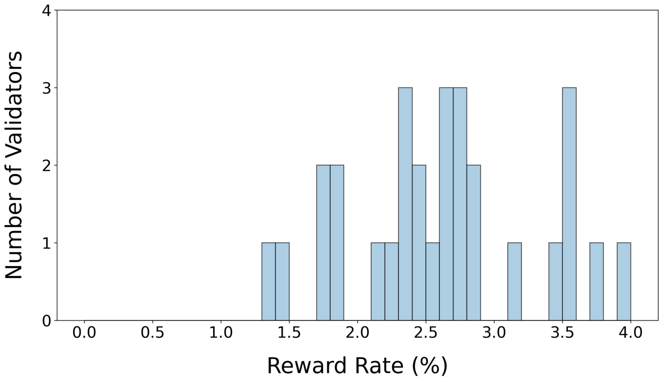


Fig. 6: Number of validators by the reward rate they would offer if continuously voted throughout May 2023. This shows that no validator candidates offered a reward rate between 0.0–1.3%.

validator candidates who distributed no rewards in May 2023.

Additionally, a significant portion of delegators had no delegate-related transactions: 59% in February 2023, 54% in March 2023, 59% in April 2023, and 64% in May 2023, according to Fig. 5. Considering that our study focuses on the top 1,000 delegator addresses by voted balance, these individuals are likely to have a stronger motivation to keep a higher reward rate than addresses with fewer voted tokens. For this reason, the fact that a majority of delegators had zero delegate-related transactions is surprising.

We discuss the influence of reward rate disparity. In the short term, an imbalance in the number of votes for validator candidates and the disparity in reward rate can increase the risk of centralizing control over the election process in the hands of a few token holders with large numbers of tokens. In the long term, the reward rate disparity can lead to the centralization of BNB tokens. In PoS, token centralization remains a concern although staking rewards are distributed almost uniformly [19]. Therefore, more intense token centralization can occur in the BNB Chain, where significant disparities in reward rate among delegators exist.

VI. Conclusion

BNB Chain using DPoS has implemented a leveling mechanism to balance the number of votes to prevent the concentration of votes for a few validators. Theoretically, if all delegators behave perfectly economically rational, their reward rate would be the same. However, in practice, the behavior of delegators is not always economically rational, and there is a reward rate disparity among delegators. This study quantitatively investigated the disparity in rewards in the BNB Chain.

We focused on the number of delegate-related transactions generated as an indicator for evaluating the economic rationality of delegators. We compared monthly average reward rates of the delegators by counting delegate-related transactions from January 2022 to May 2023. The results showed that delegators who generated four or more delegate-related transactions earned up to 25% more rewards than those who generated no transactions on a monthly average. In other words, we found a 25% difference in reward rates between delegators who were considered to be acting in an economically rational manner, and those who were not. To further examine the differences in reward rates for individual delegators, we calculated the number of delegators by reward rate from February to May 2023. The data showed a wide distribution of delegator reward rates. Across all months, the minimum reward rate was consistently between 0.0–0.1%, while the maximum reward rate varied each month, generally around 5.0%. This result indicates that even though the number of delegate-related transactions is the same, there is a large disparity in reward rates among delegators. This suggests that some delegators have a strategy to keep a higher reward rate and others do not.

An imbalance in the number of votes for validator candidates and the disparity in reward rates can increase the risk of centralizing control over the election process in the hands of a few token holders with large numbers of tokens in the short term. In the long term, this reward rate disparity can lead to further centralization of BNB tokens.

We evaluate the impact of the disparity in reward rate on the blockchain network. Firstly, disparity in reward rate and the number of votes can lead to variations in the difficulty of becoming part of the same Cabinet or Candidates. This increases the risk of large token holders controlling the elections. Secondly, tokens may concentrate in delegators who keep higher rewards. This concentration benefits the blockchain network by increasing the voting power of delegators who contribute to the election. However, this concentration also reduces the distribution of token balances, which reflects the decentralization of DPoS blockchains [20].

Our study offers the first quantitative analysis of reward rate disparity, and we anticipate that these findings will contribute to the design and improvement of DPoS.

In future work, we plan to compare the current number of votes with the theoretical optimal number of votes. The optimal number of votes could be determined based on a validator's current ranking and commission rate. This will provide direct insight into the current state of the leveling mechanism.

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