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Dividend or No Dividend in Delegated Blockchain Governance: A Game Theoretic Analysis

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Abstract. Delegated blockchain governance is the frontier of blockchain design issues that is to improve the scalability of blockchain networks. Delegated proof of stake (DPoS) blockchains such as EOS must select a few super nodes for transaction verification. In particular, the blockchain community has debated recently on whether dividend should be allowed when electing super nodes, which might be considered as unethical or unfair, leading to an open research topic and a new research gap that has theoretical value for both academia and industry. In this paper, we build a theoretical framework to study how dividend affects user decisions and welfare in a DPoS blockchain. Based on game theory, we propose a three-player Hotelling model with two policies to study the behaviors of voters and candidates. We first use a static game analysis to show that the benefits of dividend for voters and for candidates vary with the size of reward and there exists an interval, in which the zero dividend policy would be good for the welfare of both candidates and voters. Then, we use an evolutionary game analysis to examine the process dynamics of super node selection, we find that the campaign strategy of candidates has to do with the size of platform reward given to the candidates by the blockchain platform. Especially in the asymmetric case, we find that higher level of platform reward turns to benefit candidates with large number of votes even more. Our findings are instrumental for designing dividend policies in DPoS blockchains and can stimulate more potential research in blockchain governance.

Keywords: Delegated proof of stake, consensus algorithm, blockchain, Hotelling model, evolutionary game

1. Introduction

Blockchain, the technology that underpins Bitcoin and other virtual currencies, is an open, distributed ledger that can record transactions in an immutable way (Marco 2017). It is believed that the blockchain technology may revolutionize the digital economy because it can create trust between people and reduce transaction cost (Biodun 2015). However, researchers point out that numerous technological challenges have not been solved by existing blockchain technologies(Yli-huumo 2016). According to Swans summary (Swan 2015), technological challenges include throughput, latency, wasted resources (Weber 2017) and so on (Mougayar 2016).

Decentralized nodes in a blockchain need to maintain consistent records that are achieved by consensus algorithms (Lamport et al. 1982). The representative of consensus algorithms are proof of work (PoW), proof of stake (PoS), delegated proof of stake (DPoS) and so on. PoW, the consensus algorithm adopted by the Bitcoin blockchain, has been criticized for its limitations in throughput and latency. Furthermore, hardware competition among miners becomes increasingly fierce and leads to wasteful computation and energy resources (Weber 2017). PoS was developed to solve the problem of wasteful resource consumption by introducing coin age instead of computing power to the block mining process. It was first used in PPCoin blockchain (King and Nadal 2012) and improved by Ethereum blockchain (Buterin and Griffith 2017). Although PoS shortens the time to reach consensus and it is more friendly to new nodes, it has not resolved the fundamental problems. First, PoS is not applicable in most business environments, because its throughput is still far from what is required by businesses. Second, similar to PoW, PoS also cannot avoid "the rich get richer and the poor get poorer" phenomenon, which is harmful for the long-term sustainability of blockchain systems.

Delegated proof of stake (DPoS), which is a consensus algorithm proposed by Daniel Larimer in 2013 (Larimer 2014) is believed to solve most of the technical challenges mentioned above such as throughput, latency, and wasted resources. Furthermore, DPoS significantly improves performance of blockchain systems while retaining a certain degree of decentralization (Gencer et al. 2018, Li and Palanisamy 2020). This feature is very helpful for large-scale applications of blockchain technology. In EOS (Enterprise Operation System), one of the most famous public blockchain systems that utilize the DPoS consensus algorithm, 21 super nodes are selected by voters who hold tokens. A relatively high degree of decentralization is retained in such a system. The super nodes are in charge of block production and community construction and will be rewarded for their effort and service.

As a global platform, the EOS blockchain draws participants from all over the world who hold various viewpoints on super node selection. Some super nodes (mostly from China) suggest that they will share the rewards obtained from platform with voters. For example, Huobi, one of the oldest and largest cryptocurrency exchanges and most powerful candidates in China, has been reported to share rewards with its voters in EOS (Solomon 2018). Some other candidates and voters (mostly from Northern America and Europe) call the maximum dividend strategy as vote buying which is intolerable and should be strictly banned. For example, Kevin Rose, the community manager of EOS New York, thinks that vote trading and reward sharing would damage an organizations independence. This is called another frontier of US-China geopolitical economic warfare by Ethereum founder Vitalik Buterin (Brady 2018). Some voters even claim that they would never vote for any China-based candidates. There are also other users (e.g., users from South Korean) who are neutral about reward sharing. Certainly, according to the EOS interim constitution, Article IV - No Vote Buying: "No Member shall offer nor accept anything of value in exchange for a vote of any type, nor shall any Member unduly influence the vote of another", vote buying is banned. But it has never been ratified by users (Solomon 2018). Furthermore, the EOS platform neither confirmed nor denied the dividend behavior (O'NEAL 2018).

As a main feature of the DPoS consensus algorithm, super node selection is the key component of EOS blockchain governance. Super nodes are responsible for daily operations of a blockchain network and obtain tokens as their rewards. Super nodes have a significant impact on blockchain governance. Therefore, dividend policy that affects the results of super node selection is a critical component of blockchain governance. Specifically, there are two alternative policies: 1) the zero dividend policy that prohibits any form of vote buying; 2) the maximum dividend policy that allows any amount of reward sharing. Users holding different viewpoints on super node selection support for the two opposite policies. Candidates have two strategies: share reward or not. Consequently, we ask the following research questions: What is the difference between two policies? How would the two opposite policies affect voters' and candidates' profits and social welfare? How would candidates behavior evolve when reward sharing is allowed? Building on game theory, we analyze the benefit and welfare of the two voting policies. In the model, candidates compete for as many votes as possible to get elected. All candidates first determine their campaign strategies and then set dividend sizes, finally voters vote according to their utilities.

We find that, allowing dividend is not always bad for voters and good for candidates, which is contrary to our intuition. The platform could set appropriate size of reward in order to lead voters and candidates to follow the rules. In addition, the maximum dividend policy would lessen social welfare, and there exists a particular range of reward that can make the zero dividend policy better for both voter and candidate welfare. Furthermore, we extend the three-player Hotelling model to examine the process of evolution. We find that all the candidates would choose the maximum dividend strategy when the reward size is small enough. When the reward is in a certain range, the two strategies can be used by candidates simultaneously. When the reward size is big enough, if the competing super nodes candidates are in a close game, they will still choose the maximum dividend strategy. Otherwise, high reward only benefits the candidates with more votes.

The rest of the paper will be organized as follows. The related literature is discussed in Section 2. Then, we present the setup for the three-player Hotelling model and equilibrium results in zero and maximum dividend policies in Section 3. In Section 4, we compare the two policies and derive the conditions under which the two policies are good for voter, candidate and social welfare respectively. Dynamic analysis based on evolutionary game and its numerical simulation are presented in Section 5. We conclude this paper with findings and future work in Section 6.

2. Literature Review

Blockchain as a distributed database technology has a wide range of application on cryptocurrencies such as Bitcoin (Nakamoto 2008). Furthermore, blockchain has been adopted in a variety of domains to enable the operation and management of new business processes (Nofer et al. 2017, Staples et al. 2017). Blockchain can be classified into three types: public, private and consortium blockchains. Nodes right of using and maintaining the blockchain network differs among different types. In public blockchains, which are also called permissionless blockchains, any node can join the network freely. Comparatively, in private or consortium blockchains, which are also called permissioned blockchains, nodes need to be authorized (Dinh et al. 2017, Wang 2019). In this paper, we focus on a special public blockchain named EOS.

EOS allows anyone who wants to use the blockchain application to join the blockchain network. Both the data and software are open source. Although a blockchain is "owned by no-one", it is not "governed by no-one" (Howell et al. 2019). Because of self-organizing, the capabilities of blockchain and heterogeneous objectives would lead to new patterns of organizing and to the pursuit of new objectives (Andersen and Bogusz 2019). As a blockchain-based organization, the EOS community can be seen as a "decentralized autonomous organization" (DAO) (Weill 2004, Beck et al. 2018) which needs new IT governance (Brown and Grant 2005). IT governance has three key dimensions: decision rights, accountability and incentives (Weill 2004). Decision right consists of decision management right and decision control right (Fama and Jensen 1983). According to the DPoS consensus utilized in EOS blockchain, selected super nodes are granted part of decision right by ceding from token holders. Then the token holders have the decision control right and super nodes hold the decision management right. This paper adds insights on the allocation of decision right of IT governance.

Blockchain makes it possible for strangers to transact with one another on the Internet by using a combination of consensus algorithm, cryptography and P2P network. The consensus algorithm has been considered as the bottleneck of blockchain system performance (Bonneau et al. 2015). According to the classification in (Bonneau et al. 2015), there are four types of consensus algorithms: 1) classical consensus, such as Practical Byzantine Fault Tolerance (PBFT) (Castro and Liskov 1999), 2) proof-of-work (PoW) (Dwork and Naor 1993, Gervais et al. 2016), 3) proof-of-X (PoX), including proof-of-stake (Bentov et al. 2016, David et al. 2018), Proof-of-Capacity and Proof-of-Elapsed-Time (Park 2018), 4) hybrid consensus including single committee (Decker et al. 2016, Cachin 2016) and multiple committees (Syta 2017, Danezis and Meiklejohn 2015). Delegated Proof of Stake (DPoS) belongs to hybrid consensus algorithms. It is believed that DPoS can solve most of the technological challenges, such as throughput, latency and wasted resources. So far, DPoS has been used in several major blockchains such as Steem, Tron and EOS (Jeong 2020). This paper contributes to the consensus mechanism literature by proposing a game theoretical model to analyze decisions of participants in the DPoS consensus process.

Under the rules of DPoS consensus, token holders have to vote for candidates. Naturally, conflict among different organizations would emerge (Rosemann and Brocke 2015). Conflict is expressed both on policy design and strategy selection. A decentralized blockchain can be used for cross-culture and cross-organizational cooperation (Lin 2014). Huntington (2000) argued that future wars would be fought not between countries, but between cultures. This paper contributes to the cooperation mechanism design in DPoS blockchains. Vitalik the co-founder and inventor of Ethereum claims that DPoS results in rule by plutocracy (Pierson 2017). However, Daniel the co-founder of EOS thinks that PoW and PoS will result in ruling by plutocracy as we can see the hard forks of Bitcoin happened in 2017, while DPoS would create competition which is the foundation of true decentralization. The findings from the game theoretical analysis in this paper contributes to the research of voter and candidate welfare in DPoS blockchain systems.

3. The Base Model and Static Analysis

3.1 Model Setup

In this section, we use the improved Hotelling setup (Hotelling 1990) to study behaviors of voters and candidates in a DPoS blockchain. The standard Hotelling model consists of two players while our improved model (hereafter called the three-player Hotelling model) consists three players (i.e. three groups of candidates). We classify candidates into three competing groups in our model and regard candidates from the same group as a whole. We use c to indicate the group of candidates who favors reward sharing, a to indicate the group of candidates who oppose reward sharing, and k to indicate the group of candidates who are neutral about reward sharing. The three groups of candidates compete for votes to win the super node selection. As the representatives of two absolutely different views on reward sharing, candidates c and a are situated on the points 0 and 1 respectively. We assume the k group of candidates locate on the point l between 0.5 and 1, which means that the mainstream viewpoint of the whole community is close to the candidates in group a.

In this paper, zero and maximum dividend policies are antipodal. EOS is a global public

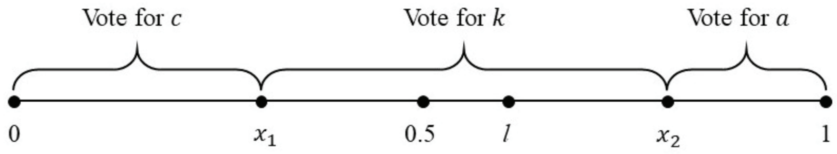


Figure 1 Three-Player Hotelling Line

blockchain system. When number of users is large enough, distribution of users will tend to uniform very closely. Therefore, without loss of generality, we assume that the continuous voters are uniformly distributed from 0 to 1 on a line segment of length 1 as shown in Figure 1. Number of voters at any point of the line segment is the same. Voter utility for each group of candidates is the value a voter derives from the candidate group net the disutility from the mismatch between the candidate group and the voter. The mismatch is measured by the psychological distance which is equal to the distance between the candidates and voters locations on the line (Adner et al. 2019).

3.2 Zero Dividend Policy

For group $i \in \{c, k, a\}$, we denote that the utility obtained by a voter is u_i. Under the zero dividend policy, any form of vote buying is banned. Therefore, the utilities for voters locating at $x_1 \in (0, l)$ and $x_2 \in (l, 1)$ derived from different candidates is the difference between voters preference and mismatch cost. They can be formulated as

$$\begin{cases} u_c = \sigma - \tau x_1^2 \\ u_{k1} = \sigma - \tau\,(l - x_1)^2 \\ u_a = \sigma - \tau\,(1 - x_2)^2 \\ u_{k2} = \sigma - \tau\,(x_2 - l)^2 \end{cases}$$

u_c denotes the utility that a voter in $(0, l)$ obtains from voting for candidates in group c, u_{k1} and u_{k2} denote the utilities that voters in $(0, l)$ and $(l, 1)$ obtain from voting for candidates in group k respectively, u_a denotes the utility that a voter in $(l, 1)$ obtains from voting for candidates in group a. σ is the utility derived from the right candidate that complies with the voter's preference completely. τ denotes the unit mismatch cost. In other word, it measures the unit difference between candidates and voters viewpoint preference. Opposite to the preference of financial wealth, τ means the preference of a voters subjective or abstract value, which can be affected by many factors. For example, pressure of public opinion and moral may increase τ. The expression of vote buying morally denies the maximum dividend policy. If this expression dominates public opinions, voter preference would be affected. It can increase the importance of subjective value and decrease the importance of reward sharing to voters. Candidate reputation may also affect τ. Because famous people or famous companies (e.g., founders) in the blockchain industry have more influence which can affect voter preference in super node selection. Similarly, trust in the project may affect τ. For voters who hold low level of trust in the blockchain system, they tend to prefer more reward sharing rather than candidate reputation.

Voters vote for the candidates that offers the most utility. By letting $u_c = u_{k1}$ and $u_a = u_{k2}$, we can get the indifferent voters' locations as $x_1^* = \frac{1}{2}l$, $x_2^* = \frac{1}{2}(1 + l)$. Voters locating from 0 to x_1^* choose to vote for c group of candidates, from x_1^* to x_2^* choose to vote for k group of candidates, and from x_2^* to 1 would choose to vote for a group of candidates.

Let I denote the reward that the elected super nodes would obtain and D_i denote the number of voters who vote for candidates i. The more votes the group of candidates get, the more reward the group of candidates will obtain. Therefore, the groups profit function is the product of I and D_i as follows:

$$\pi_i = ID_i$$

When x_1^* and x_2^* are substituted into the above equation, we can get different profits for different candidate groups as

$$\pi_c^* = \frac{1}{2}Il, \pi_k^* = \frac{1}{2}I, \pi_a^* = \frac{1}{2}I(1-l)$$

Based on the above results, we observe that the profit of candidates in group c increases as the distance between candidates in groups c and k increases. Note that the profit that candidates in group k would get is always $0.5I$, which is irrelevant to their location l.

3.3 Maximum Dividend Policy

Under the maximum dividend policy, any amount of reward sharing is allowed. We assume the reward that candidates from groups c, k and a would share is P_c, P_k and P_a respectively. Then the reward sharing will be factored into the process of voters decision making. Then the utilities for voters are

$$\begin{cases} u_c = \sigma - \tau x_1^2 + P_c \\ u_{k1} = \sigma - \tau\left(l - x_1\right)^2 + P_k \\ u_a = \sigma - \tau\left(1 - x_2\right)^2 + P_a \\ u_{k2} = \sigma - \tau\left(x_2 - l\right)^2 + P_k \end{cases}$$

We can derive the indifferent voters locations by letting $u_c = u_{k1}$ and $u_a = u_{k2}$, as

$$\begin{cases} \tilde{x_1} = \frac{1}{2}\left(l - \frac{P_k - P_c}{\tau l}\right) \\ \tilde{x_2} = \frac{1}{2}\left(1 + l - \frac{P_a - P_k}{\tau(1-l)}\right) \end{cases}$$

In addition, the profit functions of the candidates in different groups can be formulated as

$$\begin{cases} \pi_c = (I - P_c)\tilde{x_1} \\ \pi_k = (I - P_k)\left(\tilde{x_2} - \tilde{x_1}\right) \\ \pi_a = (I - P_a)\left(1 - \tilde{x_2}\right) \end{cases}$$

By solving the first order conditions for the three profit-maximizing groups of candidates, we can derive the equilibrium reward sharing, profits, and indifferent consumer, as summarized by the following lemma. All proofs of lemmas and propositions hereinafter are included in the appendix section.

Lemma 1 *When candidates are allowed to share reward with voters, the equilibrium reward sharing are*

$$\begin{cases} P_c = I - \frac{1}{2}\tau l \\ P_k = I - \tau l(1-l) \\ P_a = I - \frac{1}{2}\tau(1-l) \end{cases}$$

the indifferent consumers are at $\tilde{x_1} = \frac{1}{4}$, $\tilde{x_2} = \frac{3}{4}$, *and the equilibrium profits are*

$$\begin{cases} \tilde{\pi}_c = \frac{1}{8}\tau l \\ \tilde{\pi}_k = \frac{1}{2}\tau l(1-l) \\ \tilde{\pi}_a = \frac{1}{8}\tau(1-l) \end{cases}$$

As we can see, when l increases, the profit of candidates c would also increase, but profits of candidates k and a would decline. No matter for self-interest or alliance interest, candidates k have to approach to be neutral. Secondly, $\pi_i, i \in \{c, k, a\}$, are positively correlated with τ, instead of I. This demonstrates that, in this case, profits of candidates increase as the preference of voters increases. Consequently, the candidates tend to lobby the voters in order to change their viewpoint preference.

4. Policy Comparison

In this section, we would compare the equilibriums in two policies and get the conditions under which the candidates will support for one policy. We define the candidate welfare as the sum of all candidates profits, the voter welfare as the sum of all voters utilities and the social welfare as the sum of candidate welfare and voter welfare. Therefore, by comparing candidate welfare and voter welfare in two opposite policies, we can get the following propositions. Hereinafter we use r to substitute $\frac{I}{\tau}$ which means the relative reward value to mismatch cost. In the rest of this paper, we find that the relative reward r is very significant to all the results we obtain.

As mentioned in Sections 3.2 and 3.3, candidate equilibrium profits increase as I increases under the zero dividend policy or τ increases under the maximum dividend policy. This is because the zero dividend policy makes candidates hold platform reward all to themselves while the maximum dividend policy intensifies competition among candidates which makes them sensitive to voters viewpoint preference. Therefore, when the relative reward r is high enough, the zero dividend policy is better for candidates, and when the relative reward r is below a certain threshold, the maximum dividend policy is better for candidates. In other words, the relative reward r determines which policy is better for candidates, as formalized in the following proposition.

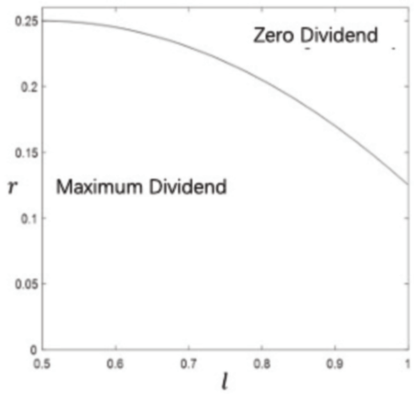


Figure 2 Optimal Policy for Candidates

Proposition 1 *(Candidate Welfare) As shown in Figure 2, the optimal policy for candidates as a whole is*
1) zero dividend policy, if $r > \frac{1+4l-4l^2}{8}$;
2) maximum dividend policy, if $r < \frac{1+4l-4l^2}{8}$.

In contrast, when the relative reward r is high enough, voters benefit more from the maximum dividend policy than the loss of mismatch cost. Thus, we have the following proposition.

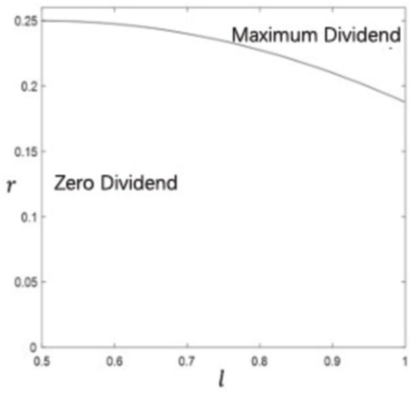


Figure 3 Optimal Policy for Voters

Proposition 2 *(Voter Welfare) As shown in Figure 3, the optimal policy for voters as a whole is*
1) zero dividend policy, if $r < \frac{(1+2l)(3-2l)}{16}$;
2) maximum dividend policy, if $r > \frac{(1+2l)(3-2l)}{16}$.

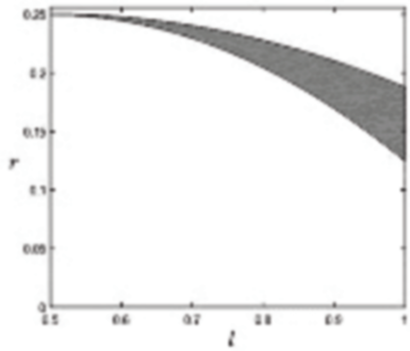


Figure 4 Comparative Analysis

According to Propositions 1 and 2, we find that neither policy is always good or bad, which is contrary to popular believes. By comparing the above propositions, we can see that there exists an interval, in which the zero dividend policy would be good for both the voters and candidates. This is because it is high enough for candidates to give up competition and small enough for voters to give up benefit from dividend. The dark region in Figure 4 represents the superiority interval of zero dividend policy.

Proposition 3 *As shown in Figure 4, zero dividend policy could be the best choice for both the voters and candidates only when* $\frac{1+4l-4l^2}{8} < r < \frac{(1+2l)(3-2l)}{16}$.

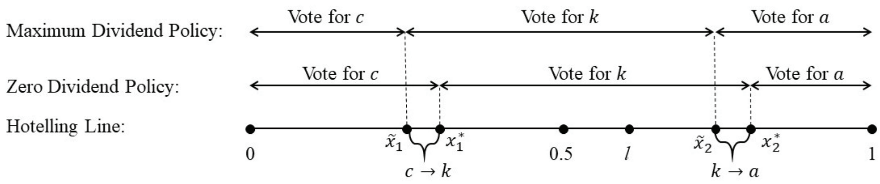


Figure 5 Changes in Voting for Each Group of Candidates

Figure 5 indicates how voters choose candidates under the two opposite policies: those on $[\tilde{x}_1, x_1^*]$ choose the c group of candidates under zero dividend policy, but switch to the k group of candidates under maximum dividend policy; and those on $[\tilde{x}_2, x_2^*]$ choose the k group of candidates under the zero dividend policy, but switch to the a group of candidates under maximum dividend policy. Hence, social welfare is lower under the maximum dividend policy compared to the zero dividend policy because of inefficient voter switching. However, the interval of switching voters tends to be 0 as l tends to be 0.5, which indicates that the loss of social welfare tends to be 0.

Proposition 4 *(Social Welfare)*
1) Compared to the zero dividend policy, the maximum dividend policy would lessen the social welfare;
2) The gap of social welfare between two policies approaches to disappearing as l tends to be 0.5.

As demonstrated in proposition 4, maximum dividend policy indeed would lessen the social welfare.

5. Dynamic Analysis

In order to deepen our understanding of this game, we set up two extensions, symmetric and asymmetric evolutionary models. The evolutionary game is used in the dynamic analysis for two reasons. First, its assumption of bounded rationality suits the reality better (Simon 1997). Second, the dividend policy is regarded as an endogenous choice that candidates can make freely and this is more in line with the actual situation.

In the symmetric evolutionary model, there is no difference between the two players. As the payoff matrix shows in Table 1, the two players obtain the same payoff when they choose the same strategy, and their payoffs are symmetric when they choose different strategies. In Section 5.1, we show the symmetric game which is a simplified case, but it is suitable to delineate the competition in a single group or between two groups of players with the same viewpoints. The asymmetric model includes two different players because two players case can represent the principles inside well enough, and avoid the problem that three or more players case can hardly be solved mathematically. As shown in Table 2, the two players payoffs are not symmetric in any case. The asymmetric evolutionary model will be used to characterize the competition between two different groups of players in Section 5.2, as is found in the EOS blockchain system. Furthermore, analyzing these extensions also establishes the robustness of our results on strategy choices and welfare comparison.

5.1 Symmetric Evolutionary Game Analysis

First, we consider the symmetric case, in which two groups of candidates (A and B) compete for votes to win the super node selection. The other assumptions are the same as the base model. Compared to the zero dividend strategy, the maximum dividend strategy can help candidates win more votes under the same condition. We can obtain the results in the following proposition.

Proposition 5 *In the symmetric game,*
1) when groups A and B both choose the zero dividend strategy, the indifferent consumer is at

Table 1 Payoff Matrix of Symmetric Game

A \ B	maximum dividend	zero dividend
maximum dividend	$0.5\tau, 0.5\tau$	$\frac{(I+\tau)^2}{8\tau}, \frac{I(3\tau-I)}{4\tau}$
zero dividend	$\frac{I(3\tau-I)}{4\tau}, \frac{(I+\tau)^2}{8\tau}$	$0.5I, 0.5I$

$x^* = 0.5$, and the equilibrium profits are $\pi_A = \pi_B = 0.5I$;
2) when groups A and B both choose the maximum dividend strategy, the indifferent consumer is at $x^* = 0.5$, the equilibrium bonus sharing are $P_A = P_B = I - \tau$, and the equilibrium profits are $\pi_A = \pi_B = 0.5\tau$;
3) when group A choose the maximum dividend strategy and group B choose the zero dividend strategy, the indifferent consumer is at $x^* = \frac{I+\tau}{4\tau}$, the equilibrium bonus sharing is $P_A = \frac{I-\tau}{2}$, and the equilibrium profits are $\pi_A = \frac{(I+\tau)^2}{8\tau}$ and $\pi_B = \frac{I(3\tau-I)}{4\tau}$, and vice versa.

Then, we can obtain the payoff matrix of symmetric game as shown in Table 1. According to the payoff matrix, we can obtain results about ESS (evolutionary stable strategy) by the means of replicator dynamics as follows:

Proposition 6 *In the symmetric game, the ESS is*
1) $\theta^* = 1$, when $r < 1$ or $r > 2$;
2) $\theta^* = \frac{r-1}{3-r}$, when $1 < r < 2$.

θ denotes the participation of choosing the maximum dividend strategy. This proposition demonstrates that, in symmetric case, the campaign strategy of candidates is only related to the size of relative reward in the long term. To be specific, when platform reward is large or small enough, all the candidates would choose maximum dividend strategy. When platform reward is in a particular range, the mixed strategy would be chosen by candidates. That is to say that candidates would not choose maximum dividend strategy for certain, even its not banned. This also explains and further validates the result in Proposition 1 that both the zero dividend policy and the maximum dividend policy could be better for candidates under certain conditions.

In addition, this symmetric evolutionary game can be understood in two ways. First, it can be used to describe the situation that two opposite organizations of similar sizes. Second, A and B can be seen as any two single persons. Then proposition 6 represents the evolutionary results of maximum dividend strategy in a single organization.

5.2 Asymmetric Evolutionary Game Analysis

In practice, the two rival organizations are always unequal. For example, the power of candidates who favors reward sharing is not equal to the power of candidates who oppose reward sharing. Subsequently, we make an asymmetric analysis about the evolutionary process that are suitable for wider range of applications. In this section, we denote A as the group of candidates c, and B as the group of candidates k and a.

The conditions that all the candidates choose the zero/maximum dividend strategy have been discussed in section 2. Then the conditions that only one side chooses maximum dividend strategy need to be addressed. Firstly, we discuss the case that group A choose the maximum dividend strategy while group B choose the zero dividend strategy. In this game, only candidates c choose maximum dividend strategy. And their optimal strategy is to maximize profit rather than to strive for all the voters. Consequently, all the candidates arrive at the equilibrium when candidates c obtain optimal profit. We assume that the farthermost

Table 2 Payoff Matrix of Asymmetric Game

A \ B	maximum dividend	zero dividend
maximum dividend	$\frac{1}{8}\tau l,\ \frac{1}{8}\tau(1-l)(1+4l)$	$\frac{(I+\tau l^2)^2}{8\tau l}, -\frac{I^2}{4\tau l}+\frac{I(4-l)}{4}$; $r < 2l + l^2$ $\frac{(1+l)(I-\tau l)}{2}, \frac{I(1-l))}{2}$; $2l + l^2 < r < 1 + 2l$ $\frac{(I+\tau)^2}{8\tau}, \frac{I(3\tau-I)}{4\tau}$; $1 + 2l < r < 3$ $I-\tau, 0$; $r > 3$
zero dividend	$\frac{I(3\tau l-I(2+l))}{2\tau l(4-l)}, \frac{(1-l)[(2I+\tau l(3-l))^2+l(I+\tau(2-l))^2]}{2\tau l(4-l)^2}$	$\frac{1}{2}Il, 1-\frac{1}{2}Il$

voter who votes for candidates c when profit maximization strategy is occupied locates at $\hat{x}$. Then we can obtain the subsequent lemma.

Lemma 2 *When candidates c choose maximum dividend strategy and candidates k and a choose zero dividend strategy,*

1) If $r < 2l + l^2$, the indifferent voters are at $\hat{x}_1 = \frac{I+\tau l^2}{4\tau l}$, $\hat{x}_2 = \frac{1+l}{2}$, and the equilibrium profits are

$$\begin{cases} \hat{\pi}_{c1} = \frac{(I+\tau l^2)^2}{8\tau l} \\ \hat{\pi}_{k1} = -\frac{I^2}{4\tau l} + \frac{I(2+l)}{4} \\ \hat{\pi}_{a1} = \frac{I(1-l)}{2} \end{cases}$$

2) If $2l + l^2 < r < 1 + 2l$, the indifferent voter is at $\hat{x} = \frac{1+l}{2}$, and the equilibrium profits are

$$\begin{cases} \hat{\pi}_{c2} = \frac{(1+l)(I-\tau l)}{2} \\ \hat{\pi}_{k2} = 0 \\ \hat{\pi}_{a2} = \frac{I(1-l)}{2} \end{cases}$$

3) If $1 + 2l < r < 3$, the indifferent voter is at $\hat{x} = \frac{I+\tau}{4\tau}$, and the equilibrium profits are

$$\begin{cases} \hat{\pi}_{c3} = \frac{(I+\tau)^2}{8\tau} \\ \hat{\pi}_{k3} = 0 \\ \hat{\pi}_{a3} = \frac{I(3\tau-I)}{4\tau} \end{cases}$$

4) If $r > 3$, the indifferent consumer is at $\hat{x} = 1$, and the equilibrium profits are

$$\begin{cases} \hat{\pi}_{c4} = I - \tau \\ \hat{\pi}_{k4} = 0 \\ \hat{\pi}_{a4} = 0 \end{cases}$$

This lemma demonstrates that, when relative reward r is very small, candidates c would not choose to compete for all the votes. When relative reward increases, candidates c would choose to compete for more votes.

Secondly, we discuss the case that group B chooses the maximum dividend strategy while group A chooses the zero dividend strategy. In this case, the game transforms into a model that includes a pair of players candidates k and a competing under maximum dividend policy, and the player candidates c under zero dividend policy out of participation in contest. We could derive the equilibrium reward sharing, profits, and indifferent consumers, as summarized by the following lemma.

Lemma 3 *When candidates k and a choose maximum dividend strategy and candidates c choose zero dividend strategy, the equilibrium reward sharing are*

$$\begin{cases} P_k = \frac{I(2+l)+\tau l(1-l)(l-3)}{4-l} \\ P_a = \frac{3I+\tau(1-l)(l-2)}{4-l} \end{cases}$$

the indifferent voters are at

$$\begin{cases} x'_1 = \frac{3\tau l-I(2+l)}{2\tau l(4-l)} \\ x'_2 = \frac{\tau(6-l)-I}{2\tau(4-l)} \end{cases}$$

and the equilibrium profits are

$$\begin{cases} \pi'_c = \frac{I(3\tau l-I(2+l))}{2\tau l(4-l)} \\ \pi'_k = \frac{(1-l)(2I+\tau l(3-l))^2}{2\tau l(4-l)^2} \\ \pi'_a = \frac{(1-l)(I+\tau(2-l))^2}{2\tau(4-l)^2} \end{cases}$$

According to section 3, lemma 2 and 3, we can obtain the payoff matrix of asymmetric game which is showed in Table 2.

Table 3 ESS in the Asymmetric Game

$0.5 < l < 0.6375$		$0.6375 < l < 1$	
r	ESS	r	ESS
$(0, \frac{l}{2})$	$(1,1)$	$(0, \frac{l}{2})$	$(1,1)$
$(\frac{l}{2}, l^2)$	$(0,1)$ or $(1,0)$	$(\frac{l}{2}, \frac{l(4-l)}{2(l+2)})$	$(0,1)$ or $(1,0)$
(l^2, ∞)	$(1,0)$	$(\frac{l(4-l)}{2(l+2)}, \infty)$	$(1,0)$

We assume that participation of choosing maximum dividend strategy in population A is μ, zero dividend strategy is $1-\mu$. And in population B, participation of choosing maximum dividend strategy is δ, zero dividend strategy is $1-\delta$. Thus, by the means of replicator dynamics, we could get the following proposition.

Proposition 7 *In the asymmetric game, when* $0.5 < l < 0.6375$, *ESS is*
1) $(\mu,\delta) = (1,1)$, *if* $0 < r < \frac{l}{2}$;
2) $(\mu,\delta) = (0,1)$ *or* $(1,0)$, *if* $\frac{l}{2} < r < l^2$;
3) $(\mu,\delta) = (1,0)$, *if* $r > l^2$;
when $0.6375 < l < 1$, *ESS is*
1) $(\mu,\delta) = (1,1)$, *if* $0 < r < \frac{l}{2}$;
2) $(\mu,\delta) = (0,1)$ *or* $(1,0)$, *if* $\frac{l}{2} < r < \frac{l(4-l)}{2(l+2)}$;
3) $(\mu,\delta) = (1,0)$, *if* $r > \frac{l(4-l)}{2(l+2)}$.

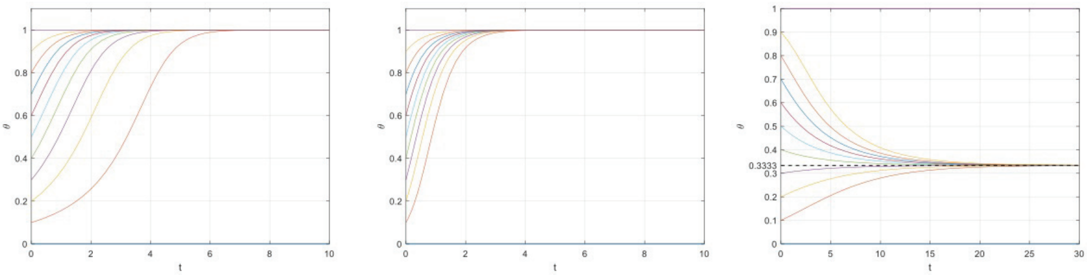
The results in proposition 7 can be summarized as Table 3. Counterintuitively, this proposition reveals several insights. When the relative reward is small, both of population A and B would choose the maximum dividend strategy. When the relative reward is in a certain range, only one of them would choose the maximum dividend strategy according to different initial states. When the relative reward is high enough, only population A choose maximum dividend strategy while population B gives up the maximum dividend strategy completely.

5.3 Numerical Simulation

In order to intuitively analyze the dynamic evolutionary process of generalized dividend behavior in super node selection, we simulate the effect of relative reward r on ESS in symmetric and asymmetric games as shown in Figure 6 and 7 respectively.

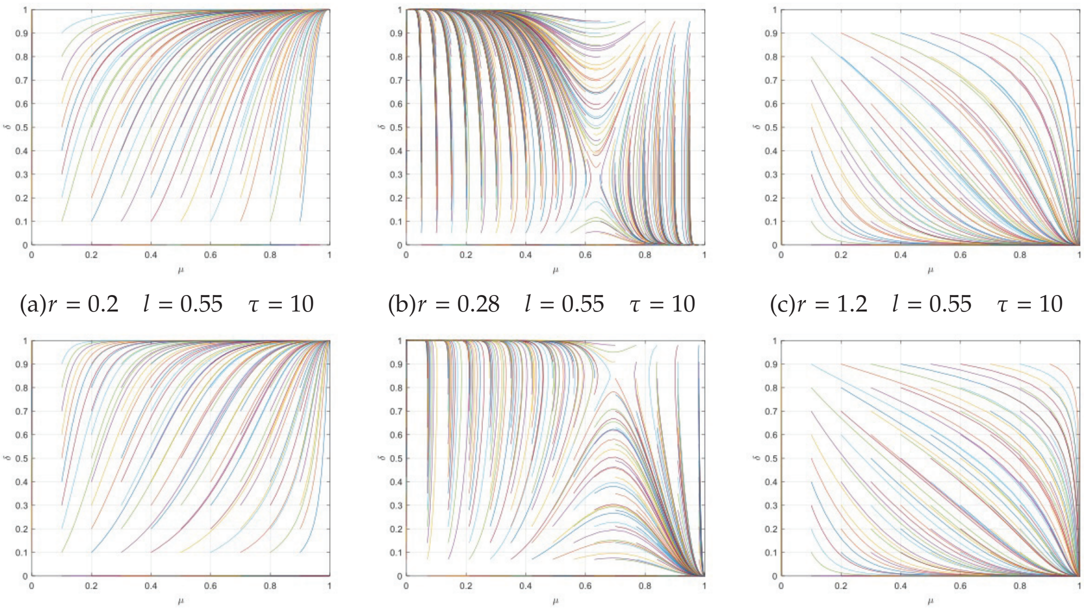
In Figure 6, the abscissa axis denotes time t and the ordinate axis denotes the participation of choosing maximum dividend strategy θ. We show the dynamic process of the dividend behavior with different initial states in the symmetric case. The parameter τ which is irrelevant to ESS is chosen as 10 hereinafter. Figures 6(a) and 6(b) show that when $r < 1$ or $r > 2$, θ tends to be 1 as time goes on. This demonstrates that for a relatively low or high level of reward, all the candidates would choose the maximum dividend strategy eventually, no matter how many candidates choose maximum dividend strategy initially. In Figure 6(c), we assume that $r = 1.5$ which belongs to the range $(1,2)$. Then θ tends to be $\frac{r-1}{3-r} = \frac{1}{3}$ as time goes on. This demonstrates that when the level of reward is in a particular range, only part of candidates would choose the maximum dividend strategy eventually, no matter how many candidates choose maximum dividend strategy initially. The results shown in Figure 6 are in line with proposition 6.

In Figure 7, a series of numerical simulations are performed to verify the results in Proposition 7. The abscissa axis and the ordinate axis denote μ and δ, the participation of choosing maximum dividend strategy in population A and B respectively. When $l = 0.55 \in (0.5, 0.6375)$, Figure 7(a) shows that ESS is $(1,1)$ with $r = 0.2 \in (0, \frac{l}{2})$, Figure 7(b) shows that ESS is $(0,1)$ or $(1,0)$ with $r = 0.28 \in (\frac{l}{2}, l^2)$, and Figure 7(c) shows that ESS is $(1,0)$ with $r = 1.2 \in (l^2, \infty)$. When $l = 0.75 \in (0.6375, 1)$, Figure 7(d) shows that ESS is $(1,1)$ with $r = 0.3 \in (0, \frac{l}{2})$, Figure



(a)$r = 0.5 \quad \tau = 10$ (b)$r = 2.5 \quad \tau = 10$ (c)$r = 1.5 \quad \tau = 10$

Figure 6 Evolutionary Process of Symmetric Game



(a)$r = 0.2 \quad l = 0.55 \quad \tau = 10$ (b)$r = 0.28 \quad l = 0.55 \quad \tau = 10$ (c)$r = 1.2 \quad l = 0.55 \quad \tau = 10$

(d)$r = 0.3 \quad l = 0.75 \quad \tau = 10$ (e)$r = 0.42 \quad l = 0.75 \quad \tau = 10$ (f)$r = 1.5 \quad l = 0.75 \quad \tau = 10$

Figure 7 Evolutionary Process of Symmetric Game

7(e) shows that ESS is $(0, 1)$ or $(1, 0)$ with $r = 0.42 \in (\frac{l}{2}, \frac{l(4-l)}{2(l+2)})$ and Figure 7(f) shows that ESS is $(1, 0)$ with $r = 1.5 \in (\frac{l(4-l)}{2(l+2)}, \infty)$. The simulation results in Figure 7 demonstrate that no matter the location of middle force is close to center or edge, there exist three final states. No matter how many candidates choose the maximum dividend strategy initially, for a low level of reward, all the candidates would choose the maximum dividend strategy eventually, but for a relatively high level of reward, the group of candidates with more votes give up the maximum dividend strategy completely and all the other candidates choose the maximum dividend strategy. When the level of reward is in a particular range, different initial states would result in different choices of campaign strategies.

6. Conclusions and Future Research

In this paper, we develop a three-player Hotelling model with two policies to study how voting policies in DPoS blockchains affect voter decisions, candidate strategies and their welfare. Our analytical results present several novel insights on blockchain governance and campaign strategy in DPoS blockchains. First, we derive the conditions to guarantee the existence of the positive equilibriums in different cases such as zero dividend and maximum dividend cases. Second, if the zero dividend policy is adopted, the profit of candidates who are neutral about reward sharing is constant. However, if the maximum dividend policy is adopted, the neutral candidates profit decreases as their viewpoint close to extreme. Third, many voters regard offering dividend in DPoS as an immoral practice, but the maximum dividend policy is proven to be beneficial for voters when relative reward r is larger than a specific threshold. To the opposite, candidates tend to support the maximum dividend policy. However, candidate profit under the maximum dividend policy is lower than that under the zero dividend policy when r is big enough. The maximum dividend policy actually transfers the profit from candidates to voters. Fourth, only when r is in a particular range, the zero dividend policy is a better choice for both the voters and candidates. No matter which policy the community chooses to implement, it should manage to guide the ratio of platform reward and mismatch cost instead of simply forbidding the other policy. Therefore, the community managers who oppose the maximum dividend policy should increase the reward that super nodes would obtain in order to make the maximum dividend policy less attractive for candidates. And certainly, the reward should not be too high to hurt the voter welfare. Fifth, our dynamic analysis of evolutionary game shows when relative reward r is big or small enough, the maximum dividend strategy would be the dominant strategy in the symmetric game. When the reward is in a certain range, both the maximum and zero dividend strategies would coexist. However, in the asymmetric game, we show that the strong organization with more votes in the super node competition would not choose the maximum dividend strategy. High reward would protect the benefit of the candidates with more votes and consolidate its strong position while low reward would intensify competition among candidates. We also perform a series of numerical simulations to verify the above results.

There exist several limitations in this study. Firstly, we made a few assumptions to simplify the analysis. First, we study only the situation in which voters are uniformly distributed from zero dividend to maximum dividend. Future work could find out how other kinds of voter distribution, such as normal distribution, would affect the conditions in our results. Secondly, due to a lack of real-world data, we could not conduct an empirical analysis in this paper. Future work can include an empirical component to validate the theoretical results in this paper once empirical data becomes available. Finally, while we have discussed the separation of decision rights and the influence of decision control right (voting policy making), the resolution of conflicts about decision-making in blockchains should be studied in future research.

Appendix A Proofs

Proof of lemma 1. The profit functions can be formulated as

$$\begin{cases}\pi_c = (I - P_c)\tilde{x_1} \\ \pi_k = (I - P_k)(\tilde{x_2} - \tilde{x_1}) \\ \pi_a = (I - P_a)(1 - \tilde{x_2})\end{cases}$$

and transformed into

$$\begin{cases}\pi_c = \frac{1}{2}(I - P_c)(l - \frac{P_k - P_c}{\tau l}) \\ \pi_k = \frac{1}{2}(I - P_k)(1 - \frac{P_a - P_k}{\tau(1-l)} + \frac{P_k - P_c}{\tau l}) \\ \pi_a = \frac{1}{2}(I - P_a)(1 - l + \frac{P_a - P_k}{\tau(1-l)})\end{cases}$$

Using the first order conditions, $\frac{\partial \pi_c}{\partial P_c} = 0$, $\frac{\partial \pi_k}{\partial P_k} = 0$ and $\frac{\partial \pi_a}{\partial P_a} = 0$, we have

$$\begin{cases}-l + \frac{P_k}{\tau l} - \frac{2P_c}{\tau l} + \frac{I}{\tau l} = 0 \\ -1 + \frac{P_a}{\tau(1-l)} - \frac{2P_k}{\tau(1-l)} - \frac{2P_k}{\tau l} + \frac{P_c}{\tau l} + \frac{I}{\tau(1-l)} + \frac{I}{\tau l} = 0 \\ -1 + l - \frac{2P_a}{\tau(1-l)} + \frac{P_k}{\tau(1-l)} + \frac{I}{\tau(1-l)} = 0\end{cases}$$

It is obvious that the second order conditions are negative in each case. Solving the three equations above yields the equilibrium bonus sharing of P_c, P_k and P_a in the lemma. Accordingly, we could derive the equilibrium $\widetilde{x}_1$, $\widetilde{x}_2$, $\widetilde{\pi}_c$, $\widetilde{\pi}_k$ and $\widetilde{\pi}_a$ using the equilibrium bonus sharing. ■

Proof of proposition 1. We assume Π and $\widetilde{\Pi}$ are sum of profits all the candidates would get under zero dividend policy and maximum dividend policy respectively, formulated as

$$\Pi = \pi_c^* + \pi_k^* + \pi_a^* = I$$

$$\widetilde{\Pi} = \widetilde{\pi}_c + \widetilde{\pi}_k + \widetilde{\pi}_a = \frac{1}{8}\tau(1 + 4l - 4l^2)$$

By letting $\Pi = \widetilde{\Pi}$, we can obtain $\frac{\tau}{I} = \frac{8}{(1+4l-4l^2)}$. Then the results in the proposition can be obtained. ■

Proof of proposition 2. We assume U and $\widetilde{U}$ are sum of utilities derived from all the candidates under zero dividend policy and maximum dividend policy respectively, formulated as

$$\begin{aligned} U =& u_c + u_{k1} + u_a + u_{k2} \\ =& \int_0^{x_1} \left(\sigma - \tau x^2\right) dx \\ &+ \int_{x_1}^{l} \left(\sigma - \tau\left(l - x\right)^2\right) dx \\ &+ \int_{l}^{x_2} \left(\sigma - \tau\left(x - l\right)^2\right) dx \\ &+ \int_{x_2}^{l} \left(\sigma - \tau\left(1 - x\right)^2\right) dx \\ =& \sigma - \frac{\tau}{12}(3l^2 - 3l + 1) \end{aligned}$$

$$\begin{aligned} \widetilde{U} =& \widetilde{u}_c + \widetilde{u}_{k1} + \widetilde{u}_a + \widetilde{u}_{k2} \\ =& \int_0^{\widetilde{x}_1} \left(\sigma - \tau x^2 + P_c\right) dx \\ &+ \int_{\widetilde{x}_1}^{l} \left(\sigma - \tau\left(l - x\right)^2 + P_k\right) dx \\ &+ \int_{l}^{\widetilde{x}_2} \left(\sigma - \tau\left(x - l\right)^2 + P_k\right) dx \\ &+ \int_{\widetilde{x}_2}^{l} \left(\sigma - \tau\left(1 - x\right)^2 + P_a\right) dx \\ =& I + \sigma - \frac{13\tau}{48} \end{aligned}$$

By letting $U = \widetilde{U}$, we can obtain $\frac{I}{\tau} = \frac{(1+2l)(3-2l)}{16}$. Then the results in the proposition can be obtained. ■

Proof of proposition 3. When $0.5 < l < 1$, we have $\left(3 + 4l - 4l^2\right) - \left(2 + 8l - 8l^2\right) = 1 - 4l + 4l^2 = \left(1 - 2l\right)^2 > 0$. Then $\frac{(1+2l)(3-2l)}{16} > \frac{(2+8l-8l^2)}{16} = \frac{(1+4l-4l^2)}{8}$. Proposition gets proved. ■

Proof of proposition 4. Social welfare under zero dividend and maximum dividend policy are denoted by W and $\widetilde{W}$ respectively, and formulated as

$$W = \Pi + U = I + r - \frac{\tau}{12}(3l^2 - 3l + 1)$$

$$\widetilde{W} = \widetilde{\Pi} + \widetilde{U} = I + r - \frac{\tau}{2}(l^2 - l + \frac{7}{24})$$

Then we get,

$$\widetilde{W} - W = -\frac{\tau}{16}(2l - 1)^2 < 0$$

So, this proposition gets proved. ■

Proof of proposition 5.

1) The utility functions can be formulated as

$$\begin{cases} u_A = \sigma - \tau x^2 \\ u_B = \sigma - \tau\left(1 - x\right)^2 \end{cases}$$

By letting $u_A = u_B$, we can get the indifferent consumers location is at $x^* = 0.5$. Then we have equilibrium profits as $\pi_A = \pi_B = 0.5I$.

2) The utility functions can be formulated as

$$\begin{cases} u_A = \sigma - \tau x^2 + P_A \\ u_B = \sigma - \tau\left(1 - x\right)^2 + P_B \end{cases}$$

By letting $u_A = u_B$, we can get the indifferent consumers location is at $x^* = \frac{1}{2}(\frac{P_A - P_B}{\tau} + 1)$. Then we have equilibrium profits as

$$\begin{cases} \pi_A = \frac{1}{2}\left(I - P_A\right)\left(\frac{P_A - P_B}{\tau} + 1\right) \\ \pi_B = \frac{1}{2}\left(I - P_B\right)\left(\frac{P_B - P_A}{\tau} + 1\right) \end{cases}$$

Using the first order conditions, $\frac{\partial \pi_A}{\partial P_A} = 0$ and $\frac{\partial \pi_B}{\partial P_B} = 0$, we have $P_A = P_B = I - \tau$. Then we obtain $x^* = 0.5$, $\pi_A = \pi_B = 0.5\tau$.

3) The utility functions can be formulated as

$$\begin{cases} u_A = \sigma - \tau x^2 + P_A \\ u_B = \sigma - \tau(1-x)^2 \end{cases}$$

By letting $u_A = u_B$, we can get the indifferent consumers location is at $x^* = \frac{1}{2}(\frac{P_A}{\tau} + 1)$. Then we have equilibrium profits as

$$\begin{cases} \pi_A = (I - P_A)x = \frac{1}{2}(I - P_A)\left(\frac{P_A}{\tau} + 1\right) \\ \pi_B = I(1-x) = \frac{1}{2}I\left(1 - \frac{P_A}{\tau}\right) \end{cases}$$

Using the first order conditions, $\frac{\partial \pi_A}{\partial P_A} = 0$, we have $P_A = \frac{1}{2}(I - \tau)$. Then we obtain $x^* = \frac{1}{4}(\frac{I}{\tau} + 1)$, $\pi_A = \frac{(I+\tau)^2}{8\tau}$ and $\pi_B = \frac{I(3\tau - I)}{4\tau}$, and vice versa. ■

Proof of proposition 6. As shown in table 1, participation of choosing maximum dividend strategy in population A is θ, zero dividend policy is $1-\theta$. Thus, by the means of replicator dynamics, we could get,

$$\begin{cases} U_1 = 0.5\tau\theta + (1-\theta)\frac{(I+\tau)^2}{8\tau} \\ U_2 = \theta\frac{I(3\tau - I)}{4\tau} + 0.5I(1-\theta) \\ \overline{U} = \theta U_1 + (1-\theta)U_2 \end{cases}$$

where $U_i, i \in 1, 2$, denotes the fitness of the ith strategy depending on the state of the population A and $\bar{U}$ is called the mean fitness. Therefore, the replicator equation is

$$\begin{aligned} F(\theta) = \frac{d\theta}{dt} &= \theta(U_1 - \overline{U}) \\ &= \theta(1-\theta)[\theta\frac{(I-\tau)(I-3\tau)}{8\tau} + \frac{(I-\tau)^2}{8\tau}] \end{aligned}$$

When $F(\theta) = 0$, we could obtain equilibrium $\theta_1^* = 0$, $\theta_2^* = 1$, $\theta_3^* = \frac{r-1}{3-r}$. In the light of the dynamic replication phase diagram showed in Figure 8, when $r < 1$ or $r > 2$, we can get $F\prime(0) > 0$, $F\prime(1) < 0$, so $\theta^* = 1$ is ESS. When $1 < r < 2$, we can get $F\prime(0) > 0$, $F\prime(1) > 0$, $F\prime(\frac{r-1}{3-r}) < 0$, then $\theta^* = \frac{r-1}{3-r}$ is ESS. ■

Proof of lemma 2. Here we have two kinds of situations as demonstrated below.

1)If $x < \frac{1}{2}(1 + l)$, which means that voters who vote for candidates k at first are not all taken away by candidates c. Then equilibrium could be formulated as

$$\sigma + P_c - \tau x^2 = \sigma - \tau(x - l)^2$$

Then we could get $P_c = 2\tau l x - \tau l^2$, and candidates cs profit function is

$$\pi_c = (I - P_c)x = -2\tau l x^2 + (I + \tau l^2)x$$

Easy to find out that

(i) $\pi_c(x)$ arrives at maximization $\hat{\pi}_{c1}(\frac{I+\tau l^2}{4\tau l}) = \frac{(I+\tau l^2)^2}{8\tau l}$, when $\frac{I}{\tau} < 2l + l^2$;

(ii) $\pi_c(x)$ arrives at maximization $\hat{\pi}_{c2}(\frac{1+l}{2}) = \frac{(1+l)(I-\tau l)}{2}$, when $\frac{I}{\tau} > 2l + l^2$.

2) If $x > \frac{1}{2}(1 + l)$, which means that voters who vote for candidates k at first change to vote for candidates c now. The equilibrium could be formulated as

$$\sigma + P_c - \tau x^2 = \sigma - \tau(1 - x)^2$$

Then we could get $P_c = 2\tau x - \tau$, and candidates cs profit function is

$$\pi_c = (I - P_c)x = -2\tau x^2 + (I + \tau)x$$

Easy to find out that

(i) $\pi_c(x)$ arrives at maximization $\hat{\pi}_{c2}(\frac{1+l}{2}) = \frac{(1+l)(I-\tau l)}{2}$, when $l < \frac{I}{\tau} < 1 + 2l$;

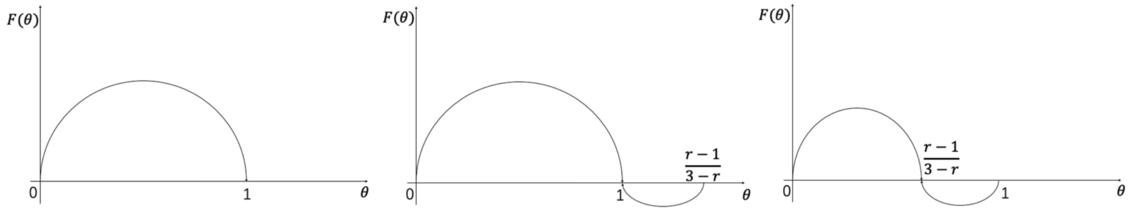
(ii) $\pi_c(x)$ arrives at maximization $\hat{\pi}_{c3}(\frac{I+\tau}{4\tau}) = \frac{(I+\tau)^2}{8\tau}$, when $1 + 2l < \frac{I}{\tau} < 3$;

(iii) $\pi_c(x)$ arrives at maximization $\hat{\pi}_{c4}(1) = I - \tau$, when $\frac{I}{\tau} > 3$.

In summary, by comparing above situations we could obtain the results of lemma. ■

Proof of lemma 3. The utilities for voters are

$$\begin{cases} u_c = \sigma - \tau x_1^2 + P_c \\ u_{k1} = \sigma - \tau(l - x_1)^2 + P_k \\ u_a = \sigma - \tau(1 - x_2)^2 + P_a \\ u_{k2} = \sigma - \tau(x_2 - l)^2 + P_k \end{cases}$$



$r < 1$ or $r > 3$ $\quad 2 < r < 3$ $\quad 1 < r < 2$

Figure 8 Phase Diagram

We can derive the indifferent voters locations by letting $u_c = u_{k1}$ and $u_a = u_{k2}$, as $x'_1 = \frac{1}{2}(l - \frac{P_k}{\tau l})$, $x'_2 = \frac{1}{2}(1 + l - \frac{P_a - P_k}{\tau(1-l)})$. In addition, the profit functions under maximum dividend policy can be formulated as

$$\begin{cases} \pi_c = I x'_1 \\ \pi_k = (I - P_k)(x'_2 - x'_1) \\ \pi_a = (I - P_a)(1 - x'_2) \end{cases}$$

By putting into x'_1 and x'_2, we can transform the profit functions into

$$\begin{cases} \pi_c = \frac{1}{2} I (l - \frac{P_k}{\tau l}) \\ \pi_k = \frac{1}{2}(I - P_k)(1 - \frac{P_a - P_k}{\tau(1-l)} + \frac{P_k}{\tau l}) \\ \pi_a = \frac{1}{2}(I - P_a)(1 - l + \frac{P_a - P_k}{\tau(1-l)}) \end{cases}$$

Using the first order conditions $\frac{\partial \pi_k}{\partial P_k} = 0$ and $\frac{\partial \pi_a}{\partial P_a} = 0$, we have

$$\begin{cases} -1 - \frac{2P_k}{\tau(1-l)} - \frac{2P_k}{\tau l} + \frac{P_a}{\tau(1-l)} + \frac{I}{\tau(1-l)} + \frac{I}{\tau l} = 0 \\ -1 + l - \frac{2P_a}{\tau(1-l)} + \frac{P_k}{\tau(1-l)} + \frac{I}{\tau(1-l)} = 0 \end{cases}$$

It is obvious that the second order conditions are negative in each case. Solving the equations above yields the equilibrium bonus sharing of P_k and P_a in the lemma. Accordingly, we could derive the equilibrium x'_1, x'_2, π'_c, π'_k and π'_a using the equilibrium bonus sharing. ■

Proof of proposition 7. According to the assumptions, we could get the fitness functions and replicator equation for population A, formulated as

$$\begin{cases} U_{A1} = \delta \widetilde{\pi}_c + (1 - \delta)\hat{\pi}_c \\ U_{A2} = \delta \pi'_c + (1 - \delta)\pi^*_c \\ \overline{U}_A = \mu U_{A1} + (1 - \mu) U_{A2} \end{cases}$$

$$\begin{aligned} F(\mu) = \frac{d\mu}{dt} &= \mu \left(U_{A1} - \overline{U}_A \right) = \mu (1 - \mu)(U_{A1} - U_{A2}) \\ &= \mu (1 - \mu) \left[\delta (\widetilde{\pi}_c - \pi'_c + \pi^*_c - \hat{\pi}_c) - (\pi^*_c - \hat{\pi}_c) \right] \end{aligned}$$

$$\begin{aligned} b &= \widetilde{\pi}_c - \pi'_c \\ &= \frac{\tau}{8l(4-l)} (4(2+l) r^2 - 12rl + l^2 (4 - l)) \end{aligned}$$

$$a = \pi^*_c - \hat{\pi}_c$$
$$= \begin{cases} -\frac{\tau}{8l}(r - l^2)^2, & r < 2l + l^2 \\ \frac{\tau}{2}(-r + l^2 + l), & 2l + l^2 < r < 1 + 2l \\ -\frac{\tau}{8}(r^2 + 2r(1 - 2l) + 1), & 1 + 2l < r < 3 \\ \frac{\tau}{2}(r(l-2) + 2), & r > 3 \end{cases}$$

$$a + b = \widetilde{\pi}_c - \pi'_c + \pi^*_c - \hat{\pi}_c$$
$$= \begin{cases} \frac{\tau}{8l(4-l)}[r^2(5l + 4) - 2rl(l^2 - 4l + 6) + l^2(4 - l)(1 - l^2)], \\ r < 2l + l^2 \\ \frac{\tau}{8l(4-l)}\left[4r^2(l+2) - 4rl(7 - l) + l^2(4 - l)(5 + 4l)\right], \\ 2l + l^2 < r < 1 + 2l \\ \frac{\tau}{8l(4-l)}\left[r^2(l^2 + 8) - 2rl(2l^2 - 9l + 10) + (4 - l)(l^2 - l)\right], \\ 1 + 2l < r < 3 \\ \frac{\tau}{8l(4-l)}[4r^2(l+2) - 4rl(l^2 - 6l + 11) + (4 - l)(l^2 + 8l)], \\ r > 3 \end{cases}$$

1) $r < 2l + l^2$

$$r_1 = \frac{l^3 - 4l^2 + 6l - l\sqrt{-4l^4 + 8l^3 + 49l^2 - 64l + 20}}{5l + 4}$$

$$r_2 = \frac{l^3 - 4l^2 + 6l + l\sqrt{-4l^4 + 8l^3 + 49l^2 - 64l + 20}}{5l + 4}$$

$$x_1 = l/2, x_2 = \frac{l(4 - l)}{2(l + 2)}$$

$$a < 0, a + b \begin{cases} < 0, & r \in (r_1, r_2) \\ > 0, & r \in (0, r_1) \cup (r_2, 2l + l^2) \end{cases}$$

$$\frac{a}{a + b} \begin{cases} > 1 & r \in (r_1, l/2) \cup (\frac{l(4-l)}{2(l+2)}, r_2) \\ \in (0, 1), & r \in (l/2, \frac{l(4-l)}{2(l+2)}) \\ < 0, & r \in (0, r_1) \cup (r_2, 2l + l^2) \end{cases}$$

2) $2l + l^2 < r < 1 + 2l$

$$a < 0, a + b > 0, \frac{a}{a + b} < 0$$

3) $1 + 2l < r < 3$

$$a < 0, a + b > 0, \frac{a}{a+b} < 0$$

4) $r > 3$

$$a < 0, a + b > 0, \frac{a}{a+b} < 0$$

Then we could get the fitness functions and replicator equation for population B, formulated as

$$\begin{cases} U_{B1} = \mu(\widetilde{\pi}_k + \widetilde{\pi}_a) + (1-\mu)(\pi'_k + \pi'_a) \\ U_{B2} = \mu(\hat{\pi}_k + \hat{\pi}_a) + (1-\mu)(\pi^*_k + \pi^*_a) \\ \overline{U}_B = \delta U_{B1} + (1-\delta) U_{B2} \end{cases}$$

$$\begin{aligned} F(\delta) = \frac{d\delta}{dt} &= \delta\left(U_{B1} - \overline{U}_B\right) \\ &= \delta(1-\delta)\left[\left(\widetilde{\pi}_k + \widetilde{\pi}_a - \pi'_k - \pi'_a + \pi^*_k + \pi^*_a - \hat{\pi}_k - \hat{\pi}_a\right)\mu \right. \\ &\quad \left. - \left(\pi^*_k + \pi^*_a - \hat{\pi}_k - \hat{\pi}_a\right)\right] \end{aligned}$$

$$\begin{aligned} d &= \widetilde{\pi}_k + \widetilde{\pi}_a - \pi'_k - \pi'_a \\ &= \frac{\tau(1-l)}{8l(4-l)^2}\left(-4(4+l)r^2 - 8rl(8-3l) - 11l^3 + 36l^2\right) \end{aligned}$$

$$\begin{aligned} c &= \pi^*_k + \pi^*_a - \hat{\pi}_k - \hat{\pi}_a \\ &= \begin{cases} \frac{\tau}{4l}\left(r^2 - rl^2\right), & r < 2l + l^2 \\ \frac{\tau}{2} r, & 2l + l^2 < r < 1 + 2l \\ \frac{\tau}{4}\left(r^2 + (1-2l)r\right), & 1 + 2l < r < 3 \\ \frac{\tau}{2} r(2-l), & r > 3 \end{cases} \end{aligned}$$

$$\begin{aligned} &c + d \\ &= \widetilde{\pi}_k + \widetilde{\pi}_a - \pi'_k - \pi'_a + \pi^*_k + \pi^*_a - \hat{\pi}_k - \hat{\pi}_a \\ &= \begin{cases} \frac{\tau}{8l(4-l)^2}\left[2r^2\left(3l^2 - 2l + 8\right) - 2rl\left(l^3 + 4l^2 - 28l + 32\right) + 11l^4 - 47l^3 + 36l^2\right], \\ r < 2l + l^2 \\ \frac{\tau}{8l(4-l)^2}\left[4r^2\left(l^2 + 3l - 4\right) - 4rl^2(5l - 14) + 11l^4 - 47l^3 + 36l^2\right], \\ 2l + l^2 < r < 1 + 2l \\ \frac{\tau}{8l(4-l)^2}\left[2r^2\left(l^3 - 6l^2 + 22l - 8\right) - 2rl\left(2l^3 - 5l^2 - 4l + 16\right) + 11l^4 - 47l^3 + 36l^2\right], \\ 1 + 2l < r < 3 \\ \frac{\tau}{8l(4-l)^2}\left[4r^2\left(l^2 + 3l - 4\right) - 4rl\left(l^3 - 4l^2 + 10l - 16\right) + 11l^4 - 47l^3 + 36l^2\right], \\ r > 3 \end{cases} \end{aligned}$$

1) $r < 2l + l^2$

$$r_3 = \frac{l^4 + 4l^3 - 28l^2 + 32l + (l^2 - 4l)\sqrt{l^4 + 16l^3 + 6l^2 - 42l + 28}}{2(3l^2 - 2l + 8)}$$

$$r_4 = \frac{l^4 + 4l^3 - 28l^2 + 32l - (l^2 - 4l)\sqrt{l^4 + 16l^3 + 6l^2 - 42l + 28}}{2(3l^2 - 2l + 8)}$$

$$c \begin{cases} < 0, & r \in \left(0, l^2\right) \\ > 0, & r \in \left(l^2, 2l + l^2\right) \end{cases}$$

$$c + d \begin{cases} < 0, & r \in (r_3, r_4) \\ > 0, & r \in (0, r_3) \cup \left(r_4, 2l + l^2\right) \end{cases}$$

$$\frac{c}{c+d} \begin{cases} < 0, & r \in (0, r_3) \cup (l^2, r_4) \\ \in (0,1), & r \in (l/2, l^2) \\ > 1, & r \in (r_3, l/2) \cup (r_4, 2l + l^2) \end{cases}$$

2) $2l + l^2 < r < 1 + 2l$

$$r_5 = \frac{5l^3 - 14l^2 + (l^2 - 4l)\sqrt{14l^2 - 14l + 9}}{2(l^2 + 3l - 4)}, c > 0$$

when $l < 0.5761$,

$$c + d \begin{cases} < 0, & r \in (r_5, 1 + 2l) \\ > 0, & r \in (2l + l^2, r_5) \end{cases}$$

$$\frac{c}{c+d} \begin{cases} < 0, & r \in (r_5, 1 + 2l) \\ > 1, & r \in (2l + l^2, r_5) \end{cases}$$

when $l > 0.5761$, $c + d > 0$, $\frac{c}{c+d} > 1$

3) $1 + 2l < r < 3$

$$r_6 = \frac{2l^4 - 5l^3 - 4l^2 + 16l + (4l - l^2)\sqrt{4l^4 - 10l^3 + 91l^2 - 128l + 52}}{2(l^3 - 6l^2 + 22l - 8)},$$

$$c > 0$$

when $l > 0.5761$, $c + d > 0$, $\frac{c}{c+d} > 1$;
when $l < 0.5236$, $c + d < 0$, $\frac{c}{c+d} < 0$;
when $0.5236 < l < 0.5761$,

$$c + d \begin{cases} < 0, & r \in (1 + 2l, r_6) \\ > 0, & r \in (r_6, 3) \end{cases}$$

$$\frac{c}{c+d} \begin{cases} < 0, & r \in (1 + 2l, r_6) \\ > 1, & r \in (r_6, 3) \end{cases}$$

4) $r > 3$

$$r_7 = \frac{l^4 - 4l^3 + 10l^2 - 16l + (l^2 - 4l)\sqrt{l^4 + 9l^2 - 26l + 25}}{2(l^2 + 3l - 4)},$$

$$c > 0$$

when $l < 0.5236$, $c + d < 0$, $\frac{c}{c+d} < 0$;
when $l > 0.5236$,

$$c + d \begin{cases} < 0, & r \in (r_7, \infty) \\ > 0, & r \in (3, r_7) \end{cases}$$

$$\frac{c}{c+d} \begin{cases} < 0, & r \in (r_7, \infty) \\ > 1, & r \in (3, r_7) \end{cases}$$

Above all in summary, we could get the results demonstrated in Table 3. Proposition has been proved. ■

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