An Incentive Mechanism for P2P Network Using Accumulated-Payoff Based Snowdrift Game Model

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Abstract. Cooperation between participators has played a very important role in P2P Network. Whereas, in contradiction to the original design philosophy of P2P file sharing system, it is difficult to guarantee the cooperation of these participators and hard to maintain a high stability of the network due to the selfishness of people without behavior constraints. In this paper, we propose a novel incentive mechanism using Accumulated-Payoff Based Snowdrift Game (APBSG) model to improve frequency of cooperation for P2P network. The performance analysis of this model and simulation results show that APBSG can reduce the sensitivity of cooperation to the selfishness of nodes, which promotes the cooperative behavior in P2P network to a large extent. Meanwhile, we reveal the relationship between the degree distribution and the frequency of cooperation by analyzing APBSG features under small-world and scale-free network. The result suggests that we can adopt different strategies according to degrees of nodes to achieve better stability for P2P network.

Keywords: P2P · Snowdrift game · Incentive mechanism · Scale-free network

1 Introduction

P2P file sharing system has occupied an increasingly important position in Internet applications [1]. However, unlike the traditional HTTP service, each participator is not only a downloader, but also an uploader in P2P network, which requires more cooperation between participators. Nevertheless, each participator is selfish since everyone wants to download more files from others with few contributions. The file sharing system will eventually tend to crash if a high frequency of cooperation can not be well maintained in P2P network. In fact, these selfish "free riders" [2,3] will result in at least two problems:

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- The participators refuse to share their files, and the network resource will be seriously under-utilized.
- The participators download with an unlimited rate, which will lead to the waste of bandwidth and the instability of system.

Hughes et al. [3] found in 2005 that 85 % of Gnutella users are free riders. There are many studies [4] suggest that traditional P2P file sharing systems suffer from free riding due to lacking of an effective incentive mechanism.

Therefore, in order to solve these two problems, an effective mechanism, which can guarantee both the downloading efficiency of participators and the proportion of cooperation behavior should be designed [4]. If each participant not only complies with the rules and restraints downloading rate, but also is willing to share files with others, the P2P system will reach an evolutionary balance. On the contrary, those free riders who do not abide by the rules may get more payoffs in the short term, but then they will be revenged by the system and their payoff would be sharply reduced.

The cooperation mechanism is very complex in such a dynamic system. Since cooperation is ubiquitous all around the real world ranging from biological systems to economic and social systems. Game theory is considered to be an important approach and a powerful framework to solve these problems. In this paper, to emphasize the core issue of cooperation, we consider this mechanism as a snowdrift game [5]. Our goal is to design a simple but effective incentive mechanism to guarantee the cooperation of the participators in the entire network which runs in an efficient and continuous way. An incentive mechanism using Accumulated-Payoff Based Snowdrift Game (APBSG) model is presented, which makes the whole network achieve a high frequency of cooperation and thereby increase the network stability in different conditions. We also analyze the relationship between the frequency of cooperation and degree of nodes, which offers another way to improve the stability of the network.

Similar with other complex networks, P2P network has small-world and scale-free properties. Thus, we conduct our simulation and analysis separately on small-world and scale-free networks instead of on random networks or lattices. Simulation results show that APBSG can reduce the sensitivity of cooperation to the selfishness of nodes, which greatly promotes the cooperative behavior in P2P network.

The rest of the paper is organized as follows. In Sect. 2, we briefly explain the snowdrift game and topological characteristics of P2P network. A cooperation incentive mechanism for P2P network is given in Sect. 3 and simulation results will be presented in Sect. 4. Finally, Sect. 5 gives conclusions and future work.

2 Related Work

2.1 Snowdrift Game

Snowdrift Game describes the situation that involves two drivers both want to go home, but they are trapped on opposite sides of a snowdrift. Each of them can make the choice of staying in the car (defect-D) or shoveling the snow (cooperation-C) to clear a path. If they both shovel the snow from the opposite sides which means they both choose cooperation strategy, both of them can obtain the payoff R by driving home and sharing the labor cost of shoveling snow. If one of them choose to stay in the car and the other shovels snow, the cooperator gets a payoff S and the defector yields the highest payoff T. However if both stay in the car, they cannot go home and obtain the minimum payoff P. Thus, we have $T > R > S > P$, and the payoff of the defect and cooperation behaviors can be formulated in a payoff matrix as following:

$$\begin{array}{cc} & \begin{array}{cc} C & D \end{array} \\ \begin{array}{c} C \\ D \end{array} & \begin{pmatrix} R & S \\ T & P \end{pmatrix} \end{array} \tag{1}$$

[6,7] shows that snowdrift game is an evolutionary game and both sides will eventually converge to the evolutionary strategy. Meanwhile, game theory has been widely utilized in modeling various networks in [8,16].

2.2 Topological Characteristic of P2P Network

Many recent works have shown that a lot of complex networks have the same or similar features in the real world. Actually, the P2P network is one type of complex networks and has the same features [17–20]. The most typical features are that they all have a small average path length, a large clustering coefficient and a long tail on degree distribution. This makes the P2P network differ a lot from the lattice or random graph. Two of the most famous models for simulation are the Small-World network proposed by Watts and Strogatz [19] in 1998 and Scale-free network which is proposed in 1999 by Barabási and Albert [20].

Figure 1 shows a small-world network and a scale-free network, which both have 50 nodes. Figure 1(a) shows a small-world network with an average degree of 10 which derives from the nearest-neighbor-coupled network. In this network, every edge is cut the connection in a probability of p with its neighbors and reconnected up to another node. When $p = 0$, the network is a regular nearest-neighbor-coupled network, and the increase of p makes the existence of "short-cut" in the network, which brings a sharp reduce of average path length. But the clustering coefficient remains very large due to the fact that most edges are still connected to the neighbor nodes. When $p = 1$, the network becomes a random network.

A different strategy is taken for scale-free network with an average degree of 13 which is shown in Fig. 1(b). It derives from a full-connected network with m_0 nodes, then adds one node at each step, from which m edges ($m \leq m_0$) are added to the existent nodes in a probability of $p_i = \frac{k_i}{\sum_{j=1}^{N} k_j}$. [20] shows that degrees of nodes in network generated in such a mechanism meets the power-law distribution.

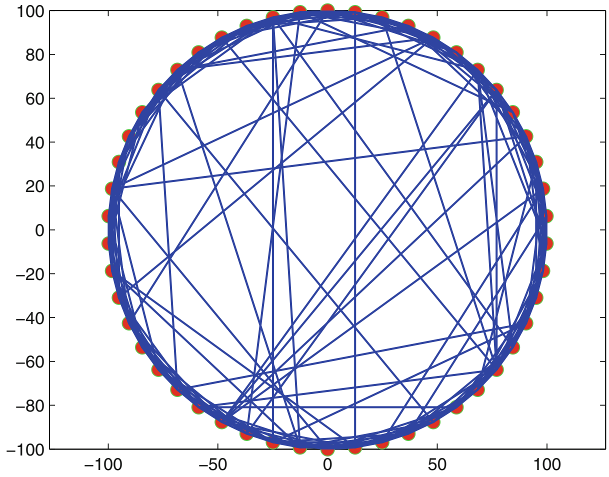

Fig. 1. Small-world network and Scale-free network.

3 Cooperation Incentive Mechanism

3.1 Assumption

Assume that the topology of realistic P2P network is in accordance with the small-world and scale-free networks mentioned above. In this paper, we conduct our simulation based on this assumption. Before modeling, we need to make some assumptions relating to P2P network:

- In this model, each node represents a participant in P2P network, and the edge between two nodes means there is a relationship of uploading and downloading between them. To simplify the model, we consider the topology of network is static, which means that all the nodes will not withdraw from the network and no new node will be added in, and also the connection between nodes will not be changed.
- Each node needs to choose the cooperation or defect strategy to game with its neighbor nodes for every round and gets a certain payoff which is the summary of payoffs when gaming with every neighbor nodes.
- Each node will choose the strategy to get a maximum payoff for next round.

This game strategy is configurable, i.e., the system can be pre-configured to control the downloading and uploading for each node. In fact, specific client software is necessary when downloading, and the strategy will be setup inside the software.

3.2 Accumulated-Payoff Based Snowdrift Game

Consider a P2P network of N nodes, for each pair of nodes with connection, normal utilization by downloading brings users a payoff b, meanwhile they must pay an extra cost c by sharing files and observing the bandwidth limitations. Whereas, the two sides in the game share the cost c if they both comply with this agreement by cooperation. Thus, each user needs to pay $c/2$ and get a total payoff $b - c/2$. If one of them chooses not to share its files while the other do, the cooperator takes the total cost c, and the defector yields the highest payoff b. Whereas if both are not willing to share their files they cannot get anything from the other side and obtain the minimum payoff 0. So we can obtain the following payoff matrix:

$$\begin{array}{c} \\ C \\ D \end{array}\begin{array}{c} \begin{matrix} C & D \end{matrix} \\ \begin{pmatrix} b - c/2 & b - c \\ b & 0 \end{pmatrix} \end{array} \tag{2}$$

It is obvious that the user's payoff is a non-negative number in any case. Thus the payoff matrix meets the snowdrift game model mentioned previously since $b > b - c/2 > b - c > 0$. Without loss of generality, we normalize the payoff matrix by defining $b - c/2 = 1$ and $r = c/2$, where r for the payoff ratio. The normalized payoff matrix is as follows:

$$\begin{array}{c} \\ C \\ D \end{array}\begin{array}{c} \begin{matrix} C & D \end{matrix} \\ \begin{pmatrix} 1 & 1 - r \\ 1 + r & 0 \end{pmatrix} \end{array} \tag{3}$$

The effects of each node's accumulated payoff have not received enough attention in the study of snowdrift game on complex networks in previous works. Since individuals always make decisions based on the payoffs they got in the past time, we decide to construct a model based on accumulated payoff.

Here defines two variables $\pi_C(i)$ and $\pi_D(i)$ to indicate the accumulated payoff from the initial state to current round of node i for cooperation and defect strategy respectively. Strategy in kth round is determined by $\pi_C(i)$ and $\pi_D(i)$. Also, $P_C(i)$ and $P_D(i)$ is defined as follows:

$$P_C(i) = \frac{\pi_C(i)}{\pi_C(i) + \pi_D(i)} \tag{4}$$

$$P_D(i) = \frac{\pi_D(i)}{\pi_C(i) + \pi_D(i)} \tag{5}$$

Obviously, $P_C(i) + P_D(i) = 1$, so we define $P_C(i)$ as the probability of choosing the strategy of cooperation in the kth round, also $P_D(i)$ for defect. Without loss of generality, we initialize both $\pi_C(i)$ and $\pi_D(i)$ to 1 before the start of the game.

In our model, the strategy of choosing cooperation or defect for the next round is not determined by the strategy or payoff in a specific round, but by

Algorithm 1. Accumulated-Payoff Based Snowdrift Game

```
Input r, N
Initialize the initial strategies of all nodes s[1...N]
Initialize π_C(i) = π_D(i) = 1
for k = 1 to the number of round do
  for node i = 1 to N do
    Update π_C(i) and π_D(i)
    Calculate P_C(i) and P_D(i) using Eqs. (4) and (5)
    Generate a random number R ranging from 0 to 1
    if R > P_C(i) then
      s(i) = Defect
    else
      s(i) = Cooperation
    end if
  end for
end for
```

the proportion of the accumulated payoff of all previous game rounds. Hence, we call this model as Accumulated-Payoff Based Snowdrift Game (APBSG).

The algorithm is summarized by the following pseudo code:

For example, before the kth round begins, if a node i has $\pi_C(i) = 60$ and $\pi_D(i) = 40$, it will choose cooperation strategy in a probability of 0.6 and defect strategy of 0.4. To achieve this effect, we generate a random number R ranging from 0 to 1. The node will choose defect strategy if R is greater than 0.6, otherwise choose cooperation. Another benefit for this algorithm is that it is easy to promote the generation of cooperation behavior, i.e., cooperation is probably to emerge in a network where all the participators take defect as their initial strategy because of the principle that strategy for each round is not absolute, but in a certain probability. With the game advancing, more and more nodes will tend to an evolutionary equilibrium to choose the strategy in a certain probability to maximize their payoffs.

4 Simulation

As mentioned above, our goal is to guarantee the downloading efficiency and the stability of the P2P network. This mainly relies on the frequency of cooperation, which is the proportion of nodes taking cooperation strategy while the system gets an evolutionary balance in the network. We define f_c as the frequency of cooperation. It can be easily seen that f_c ranges from 0 to 1. When $f_c = 0$, there's no nodes choosing cooperation strategy, while $f_c = 1$ means that all the nodes have chosen cooperation strategy in the network.

In our simulation, the performance metric is f_c, and we observe how f_c changes as a function of different parameters both in the small-world network and scale-free network.

4.1 APBSG on Small World Network

Firstly, we investigate APBSG on small-world network. Simulation is carried out for a population of $N = 2500$ nodes. Figure 2 shows the results where f_c as a function of parameter r.

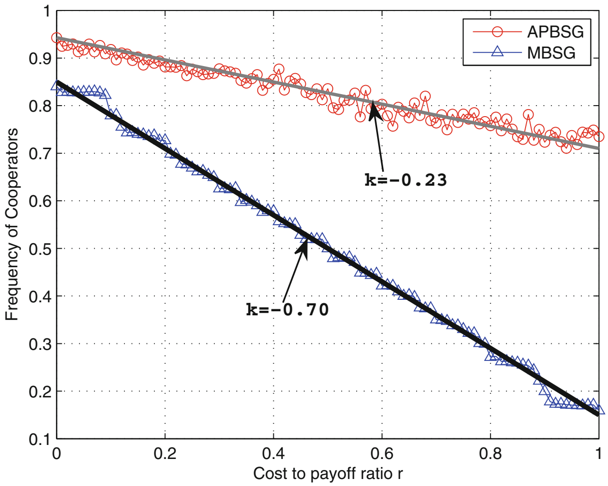

Fig. 2. f_c as a function of r in small-world network with average degree of 200. The network size is 2500. f_c for each simulation is obtained by averaging from time step $t = 1000$ to 5000 where the system has reached a steady state.

As a comparison, the result of Memory-Based Snowdrift Game (MBSG) [21] is also shown. It can be seen from Fig. 2 that f_c linearly decreases while the payoff ratio r increases both in APBSG and MBSG, i.e., the greater the r is, the more payoff a user will obtain from others while taking defect strategy, which inhibits the cooperation in the network. In particular, when $r = 1$, for a node i, no matter which strategy it takes, it gains nothing as long as it's neighbors take defect strategy. In this case, the frequency of cooperation drops to below 0.2 under MBSG. It is a very bad situation where more than 80 % of the participators do not offer uploading service or over-occupied downloading bandwidth in a P2P network, the network has in fact degenerated to the traditional HTTP service. Those nodes taking cooperation strategy can be considered as the servers and the other users download files from these servers.

Although f_c also declines in APBSG, the decrease speed is very slow. f_c still remains at up to 0.7 when $r = 1$.

The increase of r leads to a high payoff when choosing the defect strategy, thus the value of r represents the degree of a rational selfish individual. A rational individual's selfishness is to maximize its payoff as far as possible, and a unilateral defect always brings a greater payoff. Therefore, we defined $\theta(r)$ as the sensitivity of the frequency of cooperation $f_C(r)$ to nodes' selfishness when payoff ratio is r:

$$\theta(r) = \left| \lim_{\Delta x \to 0} \frac{f_C(r + \Delta r) - f_C(r)}{\Delta r} \right| \quad (6)$$

The simulation result is an approximately straight line for both APBSG and MBSG in Fig. 2, thus $\theta(r)$ equals the absolute value of the slope of fitting curve when r ranges from 0 to 1. We can calculate that slope of fitting line in APBSG is -0.23, and -0.7 for MBSG, so we can see that $\theta_{APBSG}(r) = 0.23$ and $\theta_{MBSG}(r) = 0.7$ in these simulation conditions. Thus it can be concluded that the sensitivity for frequency of cooperation to individuals' selfishness in APBSG is only about 1/3 of that in MBSG and P2P network using APBSG is better in stability than in MBSG when the condition changes. Due to the fact that a strong punishment will be taken when the one node chooses defect behavior, although one can get a temporarily high payoff in one round, it will immediately change its strategy from defect to cooperation to gain a maximum payoff.

Figure 3 shows how frequency f_c of cooperation changes with different degrees in small-world network which has an average degree of 200 when $r = 0.2$. When the degree ranges from 180 to 200, i.e., those nodes having middle degrees are typical "strategy swingers" who will choose a cooperation strategy in one round and maybe defect for next round. Although they have a high average percentage of cooperation, they almost never choose one strategy continuously to the end. In contrast, those nodes that have smaller or larger degrees tend to be "pure cooperators". They will always adhere to the cooperative behavior no matter what strategy their neighbors take.

According to this, if the node distribution of P2P network is similar to small-world network, we can appropriately reduce the degree of nodes that have intermediate degree by controlling its connection to others using client software to promote a more emergence of cooperative strategies, which will go a long way towards improving the stability of P2P network.

4.2 APBSG on Scale-Free Network

Going beyond small-world, we also investigate the APBSG on scale-free network. Figure 4 shows the simulation results on the Barabási-Albert network.

Result in Fig. 4 shows that similar to the results in the small-world network, the frequency of cooperation linearly decreases when payoff ratio r increases in scale-free network. However, there're still about 80 % nodes choose cooperation strategy while in small-world it's about 70 % when $r = 1$, and the sensitivity $\theta(r)$ of the frequency of cooperation is 0.15, which is lower than that in small-world network. This indicates that scale-free network is more likely to promote emergence of cooperation than small-world network because of the wider range of degree distribution in scale-free network.

Figure 5 shows how the frequency of cooperation changes with the different degrees in scale-free network when $r = 0.2$. It can be easily seen that only the nodes with larger degrees tend to be "pure cooperators", while most of the other nodes tend to be "strategy swingers", which is very different from that in small-world. Thus we can increase the heterogeneity of nodes for P2P network to improve the frequency of cooperation and guarantee the stability of the network.

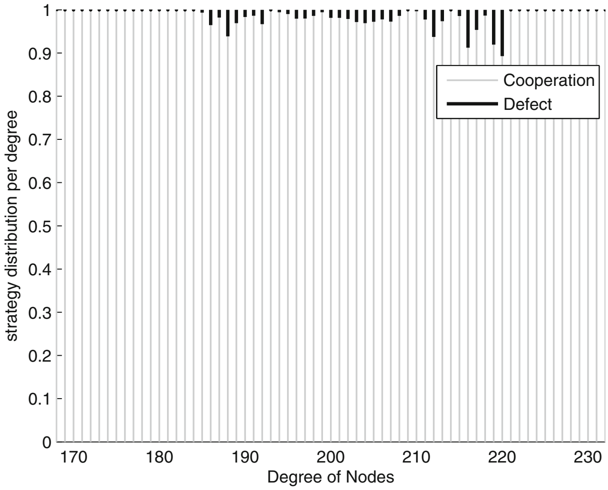

Fig. 3. Distributions of strategies in small-world network. Cooperators and defectors are denoted by gray bars and black bars respectively. Each bar adds up to a total fraction of 1 per degree, the gray and black fractions being directly proportional to relative percentage of respective strategy for each degree. Those nodes which have middle degrees will choose the cooperation strategy in one round and maybe defect for next round. In contrast, those having smaller or larger degrees tend to adhere to the cooperative behavior no matter what strategy their neighbors take.

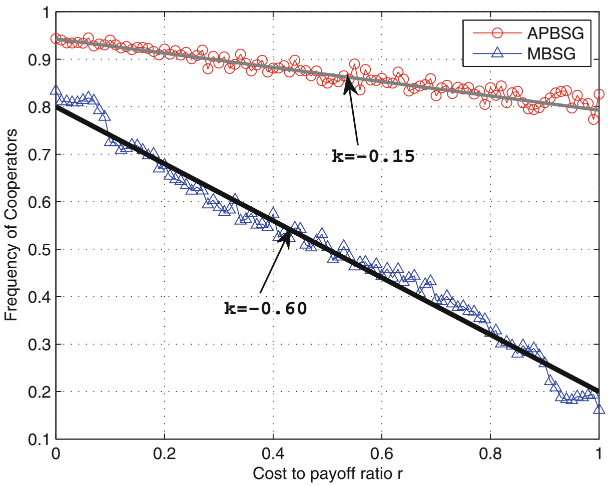

Fig. 4. f_C as a function of r in scale-free network whose size is 2500. f_C for each simulation is obtained by averaging from time step $t = 1000$ to 5000 where the system has reached a steady state.

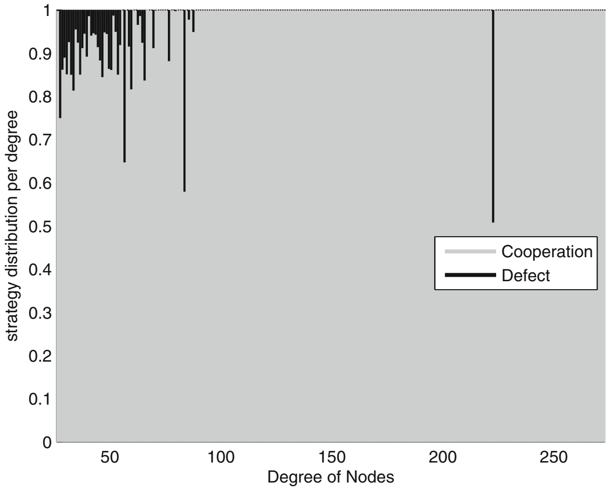

Fig. 5. Distributions of strategies in scale-free network. Cooperators and defectors are denoted by gray bars and black bars respectively. Each bar adds up to a total fraction of 1 per degree, the gray and black fractions being directly proportional to relative percentage of respective strategy for each degree. Those nodes which have smaller degrees will choose the cooperation strategy in one round and maybe defect for next round. In contrast, those having larger degrees tend to adhere to the cooperative behavior no matter what strategy their neighbors take.

5 Conclusion

In this paper, we have investigated the cooperative behavior in the P2P file sharing system and found that it's essentially a snowdrift game. A novel incentive mechanism called Accumulated-Payoff Based Snowdrift Game is adapted to guarantee a high proportion of cooperation and maintain a continuing stability of the P2P network. The results show that APBSG can reduce the sensitivity of cooperation to the selfishness of nodes, which greatly promotes the cooperative behavior in P2P network. Meanwhile, the results also give a relationship of frequency of cooperation and the degrees of nodes. Nodes with larger or smaller degrees promote the emergence of cooperative behavior in small-world network, while in scale-free networks, the larger degree nodes tend to be pure cooperators.

In current work, the topology of network is static, and this assumption is true for some cases. In future work, we will investigate the incentive mechanism in the situation when nodes can withdraw from or add dynamically in to the P2P network.

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