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Procedia Computer Science 9 (2012) 1345 – 1353

Procedia Computer Science

International Conference on Computational Science, ICCS 2012

Free-riding Analysis Via Dynamic Game with Incomplete Information*

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Abstract

P2P networks are distributed, acentric and self-organized systems. Due to the incomplete information of network environment, the uncertainty of trust relationship among peers and the selfishness of the peers in P2P networks, which give rise to many free-riders that seriously impact the stability and scalability of P2P networks. In this paper, by analyzing the incomplete information of network environment, the uncertainty of trust relationship among nodes, the phenomenon of the free-riding is studied based on game theory. The IIDGTrust (Incomplete Information Dynamic Game Trust)mechanism is presented through the case “Supplying the Public Resources”. Updating the trust relationship among the nodes according to the Bayesian law, which make nodes choose better strategies in time. The experimental results demonstrate that the IIDGTrust mechanism can effectively reduce the proportion of the free-riders in the P2P networks and maintain the stability of networks better.

Keyword: *Free-riding, Incomplete Information Dynamic Game, Bayesian law, Perfect Bayesian-Nash Equilibrium;*

1. Introduction

In recent years, with the successful application of Gnutella, KaZaA, Napster etc., the application of the P2P systems has made progress rapidly. However with the development of the P2P systems, the problems of robustness, safety, scalability and etc. of the networks are also becoming more and more important. Since literature[1] found the free-riding phenomenon in P2P systems, the phenomenon have been studied by some researchers. A measurement result [1-2] of Gnutella system shows that peers who provide no files account for proximately 70% in 2000, and that top 1% of the peers provide approximately 37% of the total responses queried. But in 2005, the number of free-riders increased to proximately 85% in Gnutella. In 2006, a measurement of e-Donkey file sharing network in literature [3] found that there were about 80% free-riders. The existence of so many free-riders, severely affect the stability of the whole system. Besides [4-5] found that the problems of collusion, false reports, zero-cost identities, traitors, whitewashing etc. in the system have brought lots of hidden troubles to the robustness and safety of the P2P networks. Paper[6] analyzed the game among the strangers with

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doi:10.1016/j.procs.2012.04.148

the case 'eBay auction website' and illustrated the necessity of Trust mechanism with experimental data. In the absence of incentive mechanism, a study of[7] also shows that users' enthusiasm of providing evaluation information is not very high. Therefore, in order to ensure the stability and the safety of the networks, it is necessary to establish a sustainable mechanism to promote the stable running of the P2P network.

The research achievements of trust mechanisms and models are summarized by literature [8-10] in different periods. At present, the research of trust mechanisms can be mainly classified into three aspects: trust mechanisms based on fuzzy theory, trust mechanisms based on probability, and trust mechanisms based on game theory. During the interaction in the networks, peers' behaviours are mainly involved, and peers make decisions and weight the payoff depending on how much they trust the opponents. Thus, comparing with trusts based on fuzzy theory and probability, trust mechanism based on game theory seems more applicable.

There already have some researches on the trust mechanism based on game theory. Feldman M elaborates the free-riding problem and the serious consequences caused by the problem in paper [11] and points out some reasons of free-riding caused and provides some methods of solving the problem. In [12] Golle P analysis free-riding problem based on the game theory, presents the incentive mechanism based on the micro-payment, and proves the effectiveness of the mechanism restraining free-riding problem in network. In order to solve the free-riding problem, literature [13] established an incentive compatibility mechanism based on the mechanism design theory, which essentially is asymmetrical information game theory. However literatures mentioned above studied trust mechanisms on the basis of the static game or complete information dynamic game theory. Obviously, the uncertainty of the trust and the incompleteness of the information are not considered in these literatures. In the condition of incomplete information, paper [14] analyzes the process of implementing the cooperative equilibrium based on repeated game on the platform of taobao. But the dynamic of trust is not considered in the analyzing process.

Combining the incompleteness of information and the uncertainty of trust among peers in networks, this paper provides a new method of studying free-riding phenomenon based on the incomplete information dynamic game theory. Namely, under the circumstance of incomplete information, according to the different types and its distributions of the opponents, peers establish the initial trust. During interactions, in order to choose a responding strategy, peers update trust value using Bayesian law on the basis of the actions observed from the opponent peers. In order to better study the phenomenon of free-riding in P2P networks, this paper models 'Supplying the Public Resource' from viewpoint of game theory. According the payoff matrix of the game playing among the peers, concrete analysis process of the trust mechanism IIDGRust is presented. The algorithm of interactions among peers is also described. At last, some simulation results are shown.

2. A Model of the 'Supplying the Public Resource'

In economics, game theory is a theory of studying strategy selection and payoff equilibrium during interactions among the peers. For purposes of analysis of free-riding phenomenon in networks, we formulate the free-riding behavior as the game $G=<N,a_i(\theta_i),(\Theta_i),(p_i),(u_i)>$. N denotes the set of peers in the networks. The behaviors strategies set dependent on type is denoted by $a_i(\theta_i)$. The type of i is $\theta_i \in \Theta_i$, and θ_i is private information. In the condition of peer $i's$ type θ_i, the prior probability is $p_i = p_i(\theta_{-i} | \theta_i)$, which peer i thinks other n-1 peers's types is $\theta_{-i} = (\theta_1,\cdots,\theta_{i-1},\theta_{i+1},\cdots,\theta_n)$ .The posterior probability is $p_i(\theta_{-i} | a_{-i})$ that peer i thought the other n-1 peers' type is θ_{-i} after observing their action $a_{-i}=(a_1,\cdots,a_{i-1},a_{i+1},\cdots a_n)$. $u_i(a_i,a_{-i},\theta_i)$ is the payoff function of peer i. According to the game G, some assumptions are set as follows:

- In the interaction, peers just have two strategies: provide or not provide, so there are just provider and free-rider in the analysis.
- All peers hope the network can be long-term stable performance.
- The functions of the peers are full symmetry, and the resources provided are available.
- During the interaction, it is random matching to play game among the peers, who decide whether to provide the

resources at same time.

- In order to better analyze the process, we take every stage game as the imperfect information static game. The payoff matrix of peers is shown in table 1.

Table 1 payoff matrix of peers

		Peer j	
		Provide	Not-provide
Peer i	Provide	$1-c_i, 1-c_j$	$1-c_i, 1$
	Not-provide	$1, 1-c_j$	$0, 0$

If peer i does not provide the resources, then he will gain 1 units payoff. If provide c_i units resources, then he will get $1-c_i$ units of payoff. If both peer i and peer j do not provide resource, then both of them will get nothing. The c units of resources provided are private information of peers. c_i and c_j are also the types of the peer i and j respectively, and they are independent and identical distribution. All the peers know that the units of resources provided by opponents obey a strict increasing and continuous function F on the $[0, c]$ (c>1).

In P2P networks, the pure strategies of player i denoted by $a_i(c_i)$ are the mapping $[0,\bar{c}] \to \{0,1\}$. Let $a_i(c_i)=0$ denotes the player i does provide nothing, $a_i(c_i)=1$ denotes the player i does provide resources. Consider the table 1, the utility function of the player i can be written as follows:

$$u_i\left(a_i, a_j, c_i\right) = \begin{cases} 0, & a_i = 0, a_j = 0 \\ 1, & a_i = 0, a_j = 1, j \neq i \\ 1-c_i & a_i = 1, a_j = 1 \end{cases}, \text{ then } u_i\left(a_i, a_j, c_i\right) = \max(a_i, a_j) - c_i a_i .$$

3. The IIDGTrust Mechanism

3.1. One-stage game

Consider the game mentioned above and the related definition of the equilibrium [15], the Bayesian-Nash equilibrium of the peers can be denoted by a strategy profile $\left(a_i^*(c_i), a_j^*(c_j)\right)$. So, we have the inequalities: $\mathrm{E}_{c_j} u_i(a_i, a_j^*(c_j), c_i) \le \mathrm{E}_{c_j} u_i(a_i^*(c_i), a_j^*(c_j), c_i)$ and $\mathrm{E}_{c_i} u_j(a_i^*(c_i), a_j, c_j) \le \mathrm{E}_{c_i} u_j(a_i^*(c_i), a_j^*(c_j), c_j)$. E is the expected value.

In P2P networks, in the condition of equilibrium, the probability of anyone player j providing the resource is denoted by $p_j \triangleq P_r(a_j^*(c_j)=1)$. So the following formula holds.

$$\begin{aligned} &\mathrm{E}_{c_j} u_i(a_i, a_j^*(c_j), c_i) = \mathrm{E}_{c_j}\left[\max(a_i, a_j^*(c_j)) - c_i a_i\right] \\ &= p_j\left[\max(a_i(c_i), 1) - c_i a_i\right] + \left(1-p_j\right)\left[\max(a_i(c_i), 0) - c_i a_i\right] \\ &= p_j + (1-p_j)\max(a_i(c_i), 0) - c_i a_i \end{aligned}$$

The formula above implies: a). If player i provides resources, then $a_i(c_i)=1$, the formula result is $1-c_i$.
b). If player i provides nothing, then $a_i(c_i)=0$, the formula result is p_j.

So, if the inequality $1-c_i > p_j$ holds, it implies player i will get more payoffs when he provides resources. We have the following expression (0) in view of maximizing the expected payoff of player i. Similarly, expression (1) holds to player j .

$$a_i^*(c_i)=1,\quad c_i \le 1-p_j$$
$$a_i^*(c_i)=0,\quad c_i > 1-p_j \tag{0}$$

$$a_j^*(c_j)=1,\quad c_j \le 1-p_i$$
$$a_j^*(c_j)=0,\quad c_j > 1-p_i \tag{1}$$

The expressions (0) above implies that player i has a critical point c_i^* about whether or not to provide resources c_i . The c_i obeys the strict continuous distribution which is an increasing function. So, player i will provide the resources c_i if and only if the inequality $0 \le c_i \le c_i^*$ holds.

When $c_i \in [0, c_i^*]$, $p_i \triangleq P_r(a_i^*(c_i)=1) = P_r(0 \le c_i \le c_i^*) = F\left(c_i^*\right)$, then $c_i^* = 1-p_i = 1-F(c_i^*)$. So, c_i^* satisfy the formula $c_i^* = 1-F(1-F(c_i^*))$. The equation $c = 1-F(1-F(c))$ will have a unique solution c^* . Then the formula (2) must hold.

$$c_i^* = c_j^* = c^* = 1-F(c^*) \tag{2}$$

In conclusion, when the unique value c^* exists, the only Bayesian-Nash equilibrium must be exists. So, when the type of the player i $c_i \le c^*$, player i provides resources, otherwise nothing.

3.2. The utilities of the two-stage game

The interactions among peers can be seen as the process of repeated games. We assume that the probabilities of two kinds of peers encountered by a player i are equal to the proportion of that type of peers in networks. In order to analyze the process of the dynamic game, two-stage game of the interaction among players is analyzed and each stage game can be considered as imperfect information static game. To get the total utilities of a player i in two-stage game, some parameters are set as follows.

Let p_i denotes the probability of player i providing resources in the first stage of a game. Probability of player i deciding to provide the resources in the second stage game is denoted by p_i^{xy} . x and y denote the strategies of players i , j respectively about whether or not to provide resources in the first stage game. $x = 0$ denotes player i provides nothing and $x = 1$ denotes player i does provide resources. We denote the discount factor of the expected payoff of the two stages game by δ ($0<\delta<1$), which can be considered as players' patience to the succeeding stages game. The smaller the value, the payoff of the current stage will be valued more seriously; otherwise, more attention will be shifted to succeeding stages game. The concrete parameters value will depend on the environment of the networks.

According the parameters mentioned above, the total expected utilities of the players i in a two stages game can be obtained and denoted by

$$U_i = \sum_{l=1}^{2} \delta^{l-1} u_i(l)$$

$u_i(l)$ is the expected utilities of the players i in the l^{th} stage game. If players i provide nothing in the first stage game, that is $a_i(c_i)=0$,then according to table 1, the concrete total expected utilities of players i in the two stages game can be obtained with formula (3).

$$\begin{aligned} U_i &= [p_j + 0(1-p_j)] + \delta[(1-c_i)(p_i^{00}+p_i^{01}) + (p_j^{00}+p_j^{01})] \\ &= p_j + \delta[(1-c_i)(p_i^{00}+p_i^{01}) + (p_j^{00}+p_j^{01})] \end{aligned} \tag{3}$$

If player i provides resources in the first stage game, that is $a_i(c_i)=1$. The concrete total expected utilities of the players i in the two stages game can be obtained with formula (4).

$$U_i=(1-c_i)+\delta[(1-c_i)(p_i^{10}+p_i^{11})+(p_j^{10}+p_j^{11})] \tag{4}$$

Therefore, the necessary and sufficient condition of player i deciding to provide resources satisfies the inequality (3) ≤ (4), i.e.

$$c_i[1+\delta(p_i^{10}+p_i^{11}-p_i^{00}-p_i^{01})]\le[1+\delta(p_i^{10}+p_i^{11}-p_i^{00}-p_i^{01})]-[p_j+\delta(p_j^{00}+p_j^{01}-p_j^{10}-p_j^{11})].$$

So there exists a value $\overline{c_i}$. Player i decides to provide resource in the first stage game, if and only if $c_i\le\overline{c_i}$ holds.The following section 3.3, the utility of a second stage game will be analyzed through the trust changing based on the Bayesian law among the peers in networks.

3.3. The dynamic change of trust among the peers

According to the definition of the Bayesian-Nash equilibrium which is a fixed point, the optimal strategy of the current stage game can be chosen if given the prior probability of the trust of the players. The posterior probability of players' trust can also be obtained by computing the Bayesian law on the basis of the equilibrium strategies and the opponent's actions observed.

Considering the equilibrium of the one-stage game and formula (2) mentioned above, we know that there exists $c^{'}$ which make the refine Bayesian-Nash equilibrium satisfies $c_i^{'}=c_j^{'}=c^{'}$. By combining the analysis of the first stage game in section 3.1, the equilibrium of the second stage game is discussed by dividing it into three cases on the basis of analyzing the strategies choice and the dynamic change of peers' trust.

Case 1: Both player i and j do provide nothing in the first stage game. That is $a_i(c_i)=0,\ a_j(c_j)=0, i\ne j$ .In such case, by observing the history of player j , player i knows the strategies of player j in the last stage and will obtain a new trust value by updating the prior trust (prior probability) of player j through the Bayesian law. The new trust value (posterior probability) can be denoted by a conditional probability

$$P_r(c_i\mid a_i(c_i)=0,a_j(c_j)=0)=\begin{cases}0, & c_i<c^{'}\\ \dfrac{F(c_i)-F(c^{'})}{1-F(c^{'})}, & c_i\ge c^{'}\end{cases} \tag{5}$$

As the second stage game also is a one-stage game. Based on the analysis of one-stage game mentioned above, there must exist $c^*\in[c^{'},\underline{c}]$. Hence, player i will provide resources in the second stage game if and only if $c^{'}\le c_i\le c^*$ hold. Where c^* satisfies the formula holds.

$$c^*=1-F(c^*)=1-\frac{F(c^*)-F(c^{'})}{1-F(c^{'})}\text{, that is } c^*=\frac{1-F(c^*)}{1-F(c^{'})} \tag{6}$$

Because $c^{'}<c^*<1$, when the type of player i is $c^{'}$, he provides nothing in the first stage game. Player i will provide resources in the second stage because of the inequality $c_i=c^{'}\ge c^{'}$. So the payoff of player i in the second stage game is $1-c^{'}$.

Case 2: Both player i , j decide to provide resources in the first stage. That is $a_i(c_i)=1,\ a_j(c_j)=1, i\ne j$. For case 2, the new conditional probability can be denoted by

$$P_r(c_i\mid a_i(c_i)=1,a_j(c_j)=1)=\begin{cases}0, & c_i>c^{'}\\ \dfrac{F(c_i)}{F(c^{'})}, & c_i\le c^{'}\end{cases}.$$

Then, there must exists c^{**} , and player i will provide resources in the second stage if and only if $0 < c_i < c^{**} \le c^{'}$ holds. According to the formula (2), we know c^{**} satisfies the equality

$$c^{**} = \frac{F(c^{'}) - F(c^{**})}{F(c^{'})} \tag{7}$$

So when $0 < c^{**} \le c^{'}$, the utility of player i in the second stage is $F(c^{**}) / F(c^{'})$. Then, the player whose type is $c^{'}$ provide nothing.

Case 3: Player i provides resources, and Player j ($\neq i$) provides nothing in the first stage game. That is $a_i(c_i)=1, a_j(c_j)=0, i \neq j$. According to the analysis of one-stage game mentioned above, we have $c_i < c^{'} < c_j$. In the second stage, the payoff of the player whose type is $c^{'}$ can be written as: $1-c^{'}$, if he provides resources in the first stage ; or 1 if he provides nothing in the first stage.

On the basis of analysis of equilibrium in the second stage game, here, the equilibrium conditions between two stages will be analyzed. According to the analysis of total expected utilities of players in two-stage game and the payoff results of players in second stage. We know that the $c^{'}$, the separation point about whether or not to provide resources, satisfies the following formula

$$(1-c^{'})+\delta[F(c^{'})\frac{F(c^{**})}{F(c^{'})}+(1-F(c^{'}))(1-c^{'})]=F(c^{'})+\delta[F(c^{'})+(1-F(c^{'}))(1-c^{'})] \tag{8}$$

The left of formula (8) is the total expected discount utility of two-stage game in the condition of player providing nothing in the first stage. The right is the total expected discount utility of two-stage game in the condition of the player providing resources in the first stage. By combining the formula (7) and (8), the equality (9) can be obtained. So the equality (9) is the equation $c^{'}$ must satisfy.

$$1-F(c^{'}) = c^{'} + \delta F(c^{'})c^{**} \tag{9}$$

According to expressions (2) and (9), we have $c^{*} + F(c^{*}) = 1$ and $c^{'} + F(c^{'})(1+\delta c^{**}) = 1$. Because of the strict increasing function $F(c)$ about c and $\delta > 0, c^{**} > 0$, there exists $F(c^{'}) > F(c^{*})$ if $c^{'} > c^{*}$ .Then $c^{'} + F(c^{'})(1+\delta c^{**}) > c^{*} + F(c^{*})$, that is $1 > 1$, so we have $c^{'} < c^{*}$.

According to the analysis mentioned above, the perfect Bayesian-Nash equilibrium can be concluded. If the type of player $c \in (c^{'}, c^{*})$, then player should provide resources in the first stage and it is not necessary to provide resources in the second stage; if $c \ge c^{*}$, then player need not to provide resources in the two stages; or if $c \le c^{*}$, then player should provide resources in the two stages. In the interactions among the peers, the expected utilities of the players will be optimal if they obey the process mentioned above.

4. The IIDGTrust Algorithm

According to the analysis mentioned above, the interaction among the peers can be briefly divided into the following seven steps.

(i). If $l = 1$, namely, player i enter the network for the first time. Let initial trust of the player i be random number between 0 and 1, and the initial strategy be $a_i(c_i) = 0$. Or access step (ii).

(ii). Player i interact with any player j , and i gets the type of c and observe the action of player j and inquire the value of $a_j(c_j)$ whether equals 1.

(iii). There are three cases that player i updates the prior trust to the player j on the basis of the Bayesian law.

- If two players don't provide anything in the last stage, that is $a_i(c_i)=0,\ a_j(c_j)=0, i \neq j$. Then the players get the new trust value based on formula (5).
- If both players do provide resources in the last stage, that is $a_i(c_i)=1,\ a_j(c_j)=1, i \neq j$. Then the player gets the new trust value based on formula (7).
- If player i provides resources and j provides nothing in the last stage, that is $a_i(c_i)=1,\ a_j(c_j)=0, i \neq j$. Then they will decide whether to provide resource on the basis of the analysis in case 3 of 3.3 and the last two cases.

(iv). According to the result of step (iii) and the analysis of formula (8), we can get the game's refine Bayesian-Nash equilibrium, which is the region with the separation of $c^{'}$ and c^{*} .

(v). Player i will choose the better strategy on the basis of the refine Bayesian-Nash equilibrium.

- If the type $c \le c^{*}$ of player i hold, he will provide resources in every stage.
- If $c \in (c^{'}, c^{*})$ holds, player i will provide resources in current stage, but provide nothing in the second stage.
- If $c \ge c^{*}$ holds, player i will provide nothing in every stage.

(vi). End the current interaction, if the game over, access (vii), or enter the next stage game and access (ii).

(vii). End the algorithm.

The interaction among the peers is briefly described by the algorithm. Algorithm also reflects the problem of updating the trust of the players by applying the Bayesian law and describes the strategies choice based on the new trust. All of these illustrate the uncertainty and dynamic of trust relationship among peers in networks.

5. The Experimental Result and Analysis

We here simulate the effectiveness of the IIDGTrust avoiding too many free-riders in network. The simulation is based on the software NetLogo 4.1. The peers are indicated by turtles, and the green patches stand for resources. Let the total peers in the P2P network is 1000, and there exists three types of players as follows:

(1). Contributors (CP) who always provide resources no matter what happens. Their percentage is q.

(2). Free-riders (FP) who never provide resources. Their percentage is (1-q)t, $0<t<1$. A certain amount of free-riders will meets the actual demand in the P2P systems.

(3). Rational Players (RP) who whether or not to provide resources will depend on the situation of the network. If there are rich resources in network, they will provide nothing, at that time, or they provide some resource. At some time point, RP is taken as CP or FP according to their providing resources or not. Their percentage is (1-q)(1-t).

On the basis of the analysis mentioned above, the following parameters are given as q=0.2， t=0.7, $\bar{c}=2$, and type c obeys a uniform distribution $[0, 2]$, and the distribution function is $F(c)=c/2$. By formula (2), we can get $c^{*}=2/3$, and by formula (6), we get $c^{'}=0$.

The result of simulation without IIDGTrust mechanism, peers interactive randomly. The phenomenon can be illustrated in figure 1. Time is represented by the horizontal coordinates and the change of the all kinds total peers and total available resources over time is represented by the vertical coordinates. When the simulation begins, there are rich in resources in the initial system. The RP do not need to provide anything. So, the RP will be taken as FP under such circumstance. Because CP always provide resources no matter what happens, which make the FP survive. With the system running in Fig. 1, we know that the resources in the system are provided by the CP whose percentage is 20%, which will led to a shortage of resource in network long time, and will prevent the development of the scale of the system.

The result of the simulation after using the IIDGTrust mechanism is illustrated in Figure 2. When the simulation begins, there are rich in resources in the initial system. In the meantime, the total number of FP increases quickly, and the resources in the system decreases sharply. Comparing to the simulation result without using the IIDGTrust mechanism, there is no obvious difference before this time. But in the following periods, because of the IIDGTrust mechanism, when the initial resources decrease sharply, the RP have to provide resources to the system to increase their utilities, so that the number of the CP increases and remains a steady level. The number of the FP also decreases to a steady level. So, the system also maintains a relatively stable state. From the Fig. 2, we know that the percentage of the CP keeps about 59.9%(599/1000 in Fig. 2), which has improved dramatically comparing to about 24%(242/1000) in Fig.1.

Comparing the Fig.2 and Fig.1, we know that the mechanism can decrease the total free-riders (758 in Fig.1 and 401 in Fig.2) effectively in network and establish a good foundation to the stable development of the system.

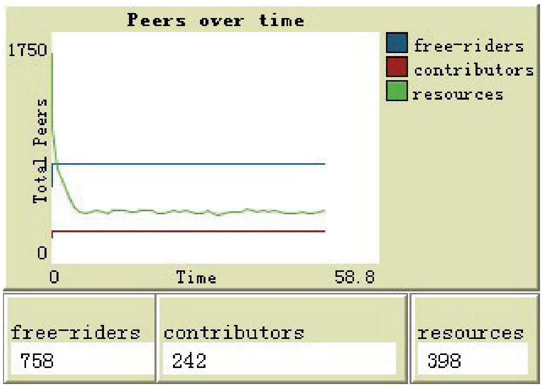

Fig. 1. The result of simulation without the IIDGTrust

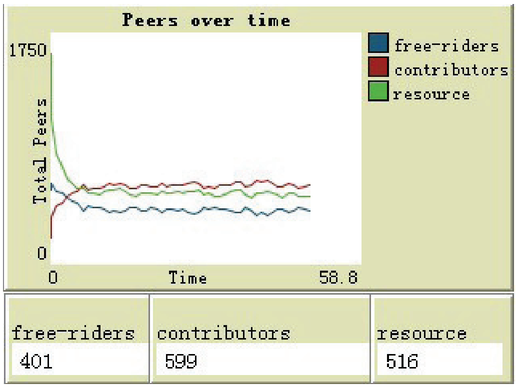

Fig. 2 The result of simulation with the IIDGTrust

6. The Conclusion

There are many free-riders in the P2P networks. At present, to the limitations of study on problem, by analyzing the incompleteness and the dynamics of the trust among the peers in the networks, the paper study the trust mechanism based on the Incomplete Information Dynamic Game. Firstly, we provide the “what if” analysis of the game playing among the players. Secondly, on the basis of the case “Supplying the Public Resources”, the analysis and the deduction of the trust relationship of the game playing among the players are given. The results of the simulation demonstrate that the IIDGTrust mechanism can make the percentage of the peers keep reasonable proportional relationships, which provide a better stability of the network.

Because the trust mechanism is based on the hypothesis, the other attacks such as the collusion, false reports, etc in the P2P networks are not considered in the analysis process. Besides, if the same resources are owed by some player, which player should we choose? The problem also has not been considered. We will research these problems in the future work.

Acknowledgments

This work is supported in part by Chinese National Science Foundation (Grant No. 61063039) and 2011 graduate student scientific research innovation projects in Guangxi(Project Numbers: 2011105950812M20) . We extend our gratitude to the anonymous reviewers for their insightful comments.

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