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# A NOVEL INCENTIVE MECHANISM BASED ON DEBT THEORY FOR P2P FILE-SHARING NETWORKS

HaiMei XU[1,2,*] XianLiang LU[1] Lin LI[1]

1.College of computer science and engineering, University of Electronics Science and Technology of China(UESTC), ChengDu, Sichuan, P.R.China,610054
2.College of ChongQing Communication, ChongQing, P.R.China,400035

Email:xuhaimei@uestc.edu.cn Email:xlu@uestc.edu.cn Email:lilin@uestc.edu.cn

***ABSTRACT***

*In order to solve "free rider" and "tragedy of the commons" problems in Peer-to-Peer(P2P) file sharing networks, this paper proposes a novel incentive mechanism based on debt theory and use game theory to analyze its efficiency. While trying to maximize its own utility subjected to individual rationality, every peer allocates bandwidth resources efficiently according to its debt relationships with competing peers. The more contribution to the system, the better services the creditor will receive from his debtors. In contrast with most of the existing incentives, the whole distributed structure of the system and the practical locating algorithm avoid most of the complexities. Simulations show that the proposed mechanism increase the social utility of the whole P2P system significantly while isolating malicious peers from the network effectively.*

***Keywords*** *Debt Relationship, Non-cooperation Game, Pareto Efficiency, Social Utility, Individual Utility*

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## 1. INTRODUCTION

Lack of incentives in traditional P2P networks lead to free riding and tragic of the commons [19]. The study of Gnutella [18] shows that nearly 70% of users do not share any file in a P2P system and nearly 50% of all file-searching responses come from the top 1% of information sharing nodes. Eigentrust [2] and PeerTrust [3] are both traditional reputation models to solve free-riding problem. Every peer have a global trust value based on file trade, high value means high quality of service(QoS) .But every file trade will trigger complex computing and communication overhead . And it is vulnerable to collusion and whitewash attacks. In [4], Micropayment is firstly introduced to solve incentive issues. Because of without money without service, there is no free rider. But Micropayment requires a central infrastructure for complex accounting which introduces a single point of failure. Other proposals are discussed in [12] [13] [14] [15][17].

As an alternative, we structure the system as an approximately fair exchange. Every peer uses a fleshed out tit-for-tat strategy based on reciprocity. Little data is required to store on every peer. And the practical structure can stimulates cooperation among self-interested peers.

In P2P file sharing networks, every peer benefits from downloading files and contributes to the system through uploading files. The upload capacity is more likely to be the resource bottleneck than the download capacity. When many peers request files from the same peer, peers with more contribution should get more download bandwidth. But in the competing peers' game, every rational peer acts to maximize its own utility while not concern for others' benefit. Thus, lack of incentive will disrupt P2P systems. So how to design a game to stimulate selfish users' cooperation is an effective solution. Our incentive mechanism has been proposed to achieve the following goals:

**a. Fairness:** The more the peer contributes to the system, the more benefit it should get.

**b. Efficient resource allocation:** The resource allocation can achieve Pareto efficiency.

**c. Incentive compatible:** The incentive can maximize expected social utility while guarantee Individual benefit.

**d. Adaptability and scalability:** The incentive can adapt to highly dynamic system. And it performs as well as the system scales up.

The rest of paper is organized as follows. In section 2, we describe the structure of debt theory. In section 3, we use the repeated non-cooperative game model to analyze its efficiency. Firstly, we describe how the peers interact in the game. Secondly we prove in the game, peers can adjust their decisions to reach an equilibrium which means the social utility and individual utility are optimal. In section 4, we show it is a strong incentive resistant to attacks. Simulations are shown in section 5. In section 6, we conclude our work.

## 2. DEBT THEORY

**Definition 1:** Debt relationship: when peer i has downloaded one file successfully from peer j, a debt relationship forms between debtor i and creditor j, we denote $i \prec j$ and describe it by one directed edge from vertices i to j as shown in Fig.1.

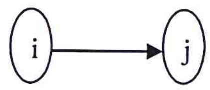

**Figure1.** Form a debt relationship

**Definition 2:** The size of the set $D_{out} = \{k \mid k \succ i\}$ is the total debt for peer i as a debtor, denoted by $out_i$. And the size of the set $D_{in} = \{k \mid i \succ k\}$ is the total debt for peer i as a creditor, denoted by $in_i$. Every peer maintains a database of its creditors. For example in Fig. 2., for $1, D_{out} = \{2,3\}, out_1 = 2, D_{in} = \{4\}, in_1 = 1$ peer 1 maintains a database of its creditors shown in Table. 1.

**Table 1.** The logical directed graph of debt relationships.

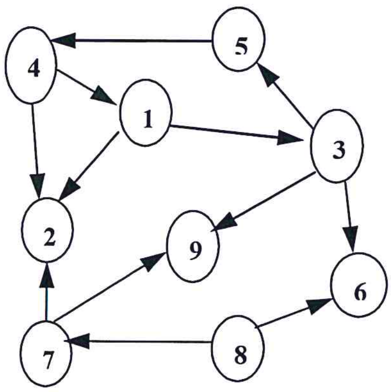


**Figure2.** The database structure of peer 1's creditors.

With the database, when remote peers request a local file services, the peer can choose to pay the debt through direct path or n-step path as shown in Fig.2. For example, there is a direct path from peer 4 to peer 1 and a two-step path from peer 4 to peer 3.

It is clear that any path of length n represents a feasible file transfer. The debt relationship possesses the following properties:

**a. Transitive Relations:** If $3 \succ 1, 1 \succ 4$, as shown in Fig.2., then there is an indirect path from 4 to 3, which mean 4 can pay the debt to 3 instead of 4's creditor 1.

**b. Directed Debt Graph can Guarantee QoS:** For Example, in Fig.2, when peer 2,9,8 simultaneously request file download from 1, 1 query its database and its creditors' database and creditors' creditors iteratively , find a direct debt path from 1 to 2，an indirect debt path from 1 to 9 and no path from 1 to 8.Then 1 can provide the best service to his creditor 2, better service to his creditor's creditor 9 and no service or service to 8 if it has spare capacity. Once peer 1 pay off debt successfully to 2, 9 and provide generous file services to 8 initially, the debt paths are erased. And 2, 9, 8

| |
|---|
| ID for Peer 2 |
| Attributes for the debt from peer 1 to 2 |
| ID for peer 3 |
| Attributes for the debt from peer 1 to 3 |

automatically enroll 1 as their direct creditor to maintain good relationship. In this case, Fig.2. Changes to Fig.3..

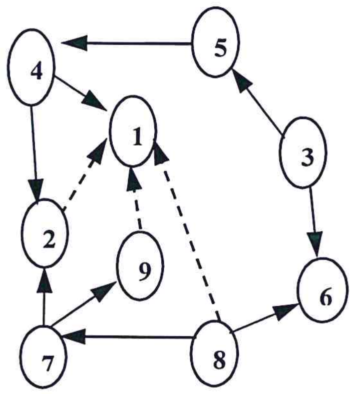


**Figure3.** After payoff debt, trusted relationship still be kept among cooperative peers (dashed path represent new path)

***Lemma 1:*** The larger the indegree $D_{in}$ of the peer, the greater probability($P$) it will receive good services，i.e.,

$$P \propto D_{in} .$$

For example in Fig.2., peer 2 can receive services from his debtors 1,3,4,5,7,8 in the future, but 8 can receive no services.

***Lemma 2*** **:** For each peer, we assume P1 as the probability that its direct creditor provide services to him in the future, P2 as his indirect creditor,P3 as strangers, then P1>P2>P3 .

***Remarks:*** Each peer gives highest priority to his direct creditors, higher priority to indirect creditor. Such strategy will keep good relationships among cooperative peers based on reciprocity. Just as in social networks, we choose to trust our friends firstly and friend's friend secondly and strangers finally. Friends tend to keep long term cooperative relationship. In order to gain benefit from the system, strangers have to take part in cooperation.

With locally stored creditors' database, it is easy to find one n-step debt path through iteratively searching. Let G be the directed graph of debt relationships of the whole P2P system. How to choose the value of n in such a potentially enormous graph to guarantee the system's efficiency and each peer's benefit? It is a useful way to have each peer gain a view of the network wider than its own experience. However locally stored creditors' database still reflect a subgraph of G.. In order to get a wider view, peer i wish to ask his creditors' creditors. If it continues in this manner, he will have a complete view of G. For example, in Fig.2., only after 3 iterations, peer 1 knows he should pay the debt to 2,3,4,5,6,9. Because of no path between 1 and 7,8, 1 can reject services to 7,8 unless it has spare capacity.

Fortunately, we have empirically determine the number of iterations n. Small World theory [1] [7] [20] [21] and Six Degrees of Separation [5]] theory indicate that in such a directed graph like social networks, the average path length between any two vertices is 6. Simulation in section 5 verify if n>6(see section 5) don't substantially improve the social utility where n=6, 6 is sufficient. The debt path searching algorithm is given in algorithm 1.

```
Definitions:
•peer k: the source peer
•A: Set of peers which have request files from peer i
•Count: the size of A
• B: Set of peers which are direct creditors of peer i
•PathSet: Set of debt path between peer i to A[j]
Algorithm:
N=6;  initialize the number of the searching iterations
Repeat {
 for (each A[i] in A)
 {for (each B[j] in B)
 {if (A[i] = =B[j])
 {Store debt path from k to A[i] to PathSet;
 Update B;
  Delete A[i] in A;
  Count=Count-1;
 }endif
 }endfor
 Replace B with B's direct creditors;
 N=N-1;
 } until (n=0 or Count=0);
 Pay the debt according to PathSet;
 Delete the debt according to PathSet;
 Create new debt Path according to PathSet
```

**Algorithm 1.** The iterative algorithm of searching debt path.

## 3. INCENTIVE-COMPATIBLE GAME MODEL

Before we present our game model for P2P file sharing system, we give the necessary notations:
N represents the number of peers in P2P system.
$X_i$ (t) represents the bandwidth allocated to peer i when i request a file transfer at time t.
$u_i$ represents the maximal upload bandwidth of peer i.
$d_i(t)$ represents the maximal download bandwidth of peer i at time t.
For ease of discussion , we drop the time dependent notation, we use $x_i$ instead of $x_i(t)$, $d_i$ instead of $d_i(t)$.

Fig.4. illustrates file transfer process. Peers 1...4 request file download from peer k at rate $d_1 ... d_4$

respectively, the actual rates assigned by peer k are $x_1 \ldots x_4$. The transfer bandwidth allocation depends on the debt relationships between peers 1…4 and K.

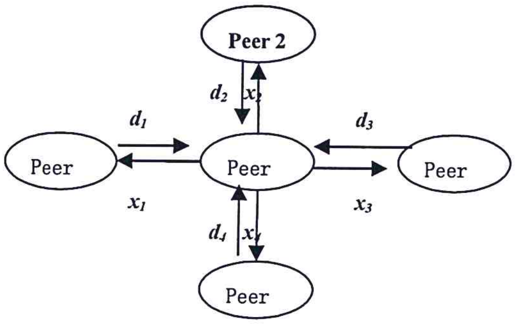


**Figure4.** Peers 1…4 compete for bandwidth from peer K.

The interactive behaviors among competing peers belong to repeated non-cooperative game problem [6] with incomplete information [16]. Peers can't know others' strategies before they choose their own ones between cooperation (pay the debt to the creditor or contribute) and disoperation (free-riding or occasionally contribute). Peers can adjust their strategies in the game process. After repeated games, the systems will reach an equilibrium which means that the social utility and the individual utility are both optimal. Simulation in section 5 shows the system converges to equilibrium after repeated games.

For each peer i, denote the number of files downloaded successfully from the system per unit time by $f_{get}$, we propose the following individual utility function:

$$U_i(T) = \int_{t_0}^{t_0+T} f_{get}(t) \qquad \forall T>0 \quad (1)$$

For each peer i, $f_{offer}$ represent the number of files it contributes to the system per unit time. We propose the social utility function:

$$su(T) = \sum_{i=1}^{N} \int_{t_0}^{t_0+T} f_{offer}(t) \qquad \forall T > 0 \quad (2)$$

In the game, rational individual maximizes his own benefit. When peer 1…n request file transfer at maximal rate $d_i$ from the same peer k, k can maximize his benefit by bandwidth distribution $\vec{x} = [x_1, x_2 \cdots x_n]$, i.e.,

$$F(T) = \arg\max \ (\sum_{i=1}^{n} U_i(T) \quad s.t. \sum_{i=1}^{n} x_i \le u_k \quad (3)$$

From equation(1),

$$U_i(T) = \int_{t_0}^{t_0+T} f_{get}(t)dt = \int_{t_0}^{t_0+T} a_k x_i dt \quad \forall a_k > 0 \quad (4)$$

In equation(4), $\alpha_k$ denotes the transform factor from $x_i$ to $f_{get}(t)$.

To maximize its self benefit, every peer will allocate bandwidth efficiently. For Example: In Fig.2, we assume $u_1$=8.0, $d_2$=3.0, $d_9$=4.0, $d_8$=4.0. When peer 2, 9, 8 request file download from peer 1 simultaneously, peer 1's bandwidth allocation should be $x_2$=3.0, $x_9$=4.0, $x_8$=1.0. Which lead to the optimum solution to equation (3).

***Theorem 1***: After long-term repeated games, the number of files every peer downloaded successfully from the system is equal to those he contributed to the system, i.e.,

$$\lim_{T\to\infty} \left( \int_{t_0}^{t_0+T} f_{get}(t)dt - \int_{t_0}^{t_0+T} f_{offer}(t)dt \right) = \lim_{T\to\infty} F_{get}(T) - F_{offer}(T) = 0 \quad (5)$$

***Proof:*** From lemma 1, we see that when $T \to \infty$, the files the peer i get from the system depend more and more on his contribution. More contribution, more benefit. By lemma 2, Good relationships are always kept between the active debtor and creditor based on reciprocity. Which is more like a fleshed out Tit-For-Tat strategy taken by every peer .To get more files from the system, the dominant strategy in a long-running repeated game for every peer is to offer good file services to others. So, it is a fair file exchange for every peer after a long time.

***Theorem 2:*** The optimum solution to equation(3) leads to maximization of social utility after repeated games.

***Proof :*** From equation(2), the system problem is defined as

$$\operatorname{argmax}\sum_{i=1}^{N}\int_{t_0}^{t_0+T} f_{offer}(t)dt \quad \forall T>0 \quad (6)$$

By theorem 1,

$$\lim_{T\to\infty}\operatorname{argmax}\sum_{i=1}^{N}\int_{t_0}^{t_0+T} f_{offer}(t)dt=\sum_{i=1}^{N}\lim_{T\to\infty}\operatorname{argmax}\int_{t_0}^{t_0+T} f_{offer}(t)dt$$

$$=\sum_{i=1}^{N}\lim_{T\to\infty}\operatorname{argmax}\int_{t_0}^{t_0+T} f_{get}(t)dt \qquad (7)$$

Then, the solution to equation (3) is also the optimal solution to equation (6) after repeated games. Which mean it is incentive compatible .Simulation in section 5 will verify it.

A resource allocation is Pareto efficient if there is no other allocation in which some other peers is better off and no peer is worse off. In file sharing networks, seeking Pareto efficiency is a local optimization strategy in which pairs of counterparties sees if they can improve their benefit together. By theorem 2, such strategy leads to global optimization.

***Theorem 3:*** The bandwidth allocation based on debt theory is Pareto efficient.

***Proof*** : For any source peer k, there are two cases for bandwidth allocation when peer 1..n request files simultaneously .One is when its aggregate requestors' bandwidth $\Sigma_{i=1}^{n} b_i \le w_k$ .In this case, $x_i = b_i$ , all peers gain max benefit . The second case is that some indirect creditors or strangers receive no file transfer, but the bandwidth is fully utilized. By lemma 2, such strategy can give reward to good creditor and punishment to strangers, which can incentive peers cooperative at later time. In this case no other strategy can improve the utility of one peer without reducing the utility of another peer.

## 4. THREAT MODELS

Discussion and analysis in section II and III show that our incentive protocol is a fleshed out Tit-For-Tat protocol .In [8][9][10], Robert Axelrod has proved that tit-for-tat protocol can get started with a small cluster, spread in the population rapidly, and counter non-cooperative models.

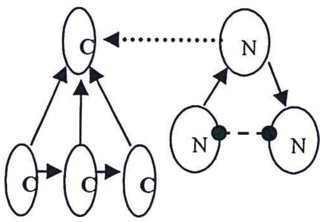


**Figure5.** Weak connection forms between malicious collective(C) and normal peers (N).

### 4.1 Malicious Individual

When selected as download source, malicious peers always provide an inauthentic file or just free ride others. That means there are few debtors to provide services to them in the future just as tit-for-tat.

### 4.2 Malicious Collectives

Malicious pees form a malicious collective by claiming other malicious peers are good creditors. Because normal peers receive few file services from malicious collective, there are few debt paths between normal peers and malicious collective. They are almost two isolated subgraphs. Just as in Fig.5. Malicious collectives have no chances to receive good services from normal peers. In contrast with Maxflow algorithm [17], our incentive mechanism avoids huge computing overhead to resist collusion.

4.3 **Whitewash Attack**

In most P2P system, identities are zero-cost. That allows malicious newcomers to escape punishment for misbehaviors by switching to new identities. Our incentive mechanism possesses a "stranger adaptive" property. With the system running, peers will become stingier and stringer to strangers (newcomer) if strangers are stingy. But they will be more and more generous to strangers if strangers show generosity. So, the incentive mechanism is inherently strong to counter whitewash attack.

## 5. EXPERIMENTS AND SIMULATIONS

In this section, we will assess the performance of the incentive mechanism. We simulated a small file-sharing network like the Query-Cycle Model [22] with 500 nodes. 20% of the nodes are selfish, 20% of them are Altruistic and the rest of them are Mixed. Selfish nodes do not share any resource just free riding others. Altruistic nodes share resource. There is no fixed model for Mixed nodes. We have done the same experiment for ten rounds. Every experiment lasted for 100 minutes. Then we figured out the three following main factors:

**a. Social utility of the whole system:** the aggregate number of files computed by equation(2), which can reflect the degree of the incentive mechanism's efficiency. In Fig.6. and Fig.8. We take the average values of the ten experiments as social utility.

**b. Successful Downloads Ratio (SDR):** SDR=the sum of successful downloads /the sum of downloads, which represents the results of file download requests. This can reflect the degree of QoS of nodes. In Fig.7, we take the average values of the ten experiments as SDR.

**c. Convergence:** whether the system can reach an efficient equilibrium and how quickly the system will converge? They both reflect the degree of the incentive mechanism's efficiency.

Firstly, we compared the social utility of the whole P2P system with and without incentive mechanism.

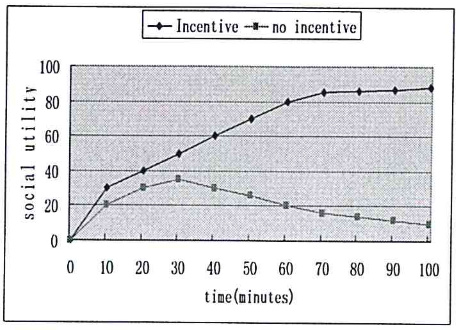


**Figure6.** Social utility varied with time

From Fig.6, we see that social utility of the P2P system with incentive mechanism increased rapidly. Without incentive mechanism, the social utility increased in the beginning 30 minutes and then decreased quickly for free-riding discouraged the sharing behaviors of Mixed peers and Altruistic peers.

Secondly, we compared the QoS of the three types of nodes in incentive mechanism.

In Fig.7, at the beginning of the simulation, file exchanges were not frequent. So the directed graph based on debt theory has not been constructed. Because Altruistic peers generously provided services to any type of peers, SDR of three types of nodes could keep a high level. However file exchanges increased gradually after 30 minutes. Because of Selfish nodes sharing no files, no debtors made repayment to guarantee his QoS. After repeated games, the SDR of selfish nodes decrease rapidly .The SDR of Altruistic peers increase gradually to a higher level in the whole game process. After they stopped free-riding behaviors, SDR of Mixed nodes kept an increasing trend.

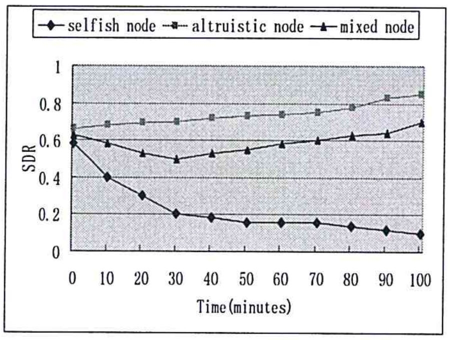


**Figure7.** SDR of three types of peers varied with time

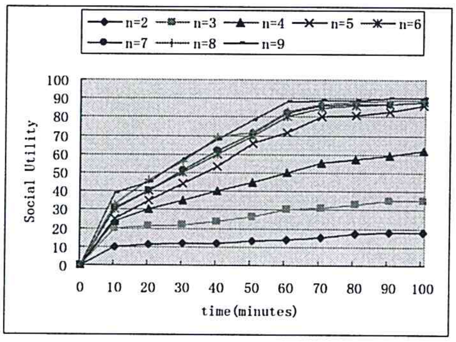


**Figure8.** Social utility with different n varied with time

Thirdly we compared the convergence of the system with different searching length n of debt path.

Fig.8. shows that when n=6 the system performed slight better than n=5 but much better than n= 2, 3, 4. And when n>6 social utility increased very slowly and finally converged to a point with n's increasing. So n=6 is a turning point, we can choose n=6 in general. We also see that after a long time, the repeated game reached an equilibrium point with different n.

Fourthly, we varied the system scale gradually form 500 nodes to 1000 nodes and repeated the experiments as above. The performance of the system remained stable which verified the incentive mechanism is scalable.

Finally we changed the percentages of three different peer types and changed the frequency of nodes joining and leaving gradually. The system performed as well as above which verified the incentive mechanism is adaptable.

## 6. CONCLUSION

In this paper, we proposed an incentive mechanism to address the cooperation problems in P2P systems. Game theory has proved that it is incentive compatible. And resource allocation is Pareto optimal. In contrast with reputation and Micropayment systems, the distributed structure and locating algorithm avoided most of the complexities. Because of its tit-for-tat nature, the incentive is inherently resistant to attacks. Results of simulations showed that the incentive mechanism can stimulate peers to cooperation efficiently. Extending the incentive mechanism to unstructured systems such as Gnutella and structured overlay network like Chord, Tapestry or Pastry is an interesting future topic.

## 7. ACKNOWLEDGEMENTS

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**HaiMei Xu** is a PH.D candidate at College of Computer Science and Engineering, University of Electronic Science and Technology of China (UESTC). Her research interests include distributed system and networks, peer-to-peer networks.

**XianLiang Lu** is a professor and doctoral supervisor at College of Computer Science and Engineering in UESTC. His research interests include Distributed Operating System, Computer Networks and Network Security.

**Lin Li** is a Ph.D. candidate at College of Computer Science and Engineering in UESTC. His research interests include Network Security and computing algorithms.