The “Value” of Reputation in Peer-to-Peer Networks

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***Abstract*—Peer-to-peer networks need to have self-organization properties because of the lack of a centralized authority. This implies that nodes should self-manage and cooperate to sustain the availability of the resources in the system. In this context reputation management schemes have been proven in the past to be a useful tool to foster cooperation.**

In this paper we discuss the importance for a node to build and use its reputation value. We propose a game-theoretical framework, based on the generalized form of the Iterated Prisoner’s Dilemma, to model the interactions of rational and selfish nodes in distributed systems. We study how a node takes into account the change of its reputation when deciding its behaviour in a transaction and discuss the Nash Equilibrium in the system. Then, we also simulate nodes’ interactions under different strategies to analyze how cooperation and reputation evolve in the system.

I. INTRODUCTION

Peer-to-peer systems (P2P) are characterized by heterogeneous components that interact to achieve their specific goals and to sustain the scalability of the system. However, the difficulty in establishing direct relationships might reduce the participation of the nodes and the quality of the communication in systems formed by “strangers”. If the survivability of P2P networks relies on the nodes’ willingness to fulfill their obligations, the system might not function properly: non-cooperative (selfish) behaviour will be privileged and predominant. This occurs because individual rational nodes are incentivized at maximizing their own use of the resource while the costs of the service are shared between all those to whom the service is available. As a result of this “tragedy of the commons” [8], selfish nodes do not share their resources if they cannot increase their *utility*.

In un-managed and fully distributed systems where there is no authority to force nodes to follow an altruistic behaviour, incentive mechanisms leading to “reciprocal altruism” are required to foster cooperation among nodes. In social and economic science numerous works discuss the impact of reciprocate behaviour for node’s interaction in virtual communities [3], [11]. Cooperation upon previous successful experience is applicable if the same nodes interact frequently during their lifetime. However, such approach proves to be ineffective in large distributed communities as nodes sporadically meet. Another approach is based on indirect collaboration of nodes, which implies that indirect reciprocity relationship can be established. But it requires the transactions in the system to be monitored and the result of this observation shared among the nodes [11].

To foster cooperation, solutions based on service differentiation have been proposed: nodes that contribute more will get better services. This solution leads directly to the adoption of reputation management schemes. Reputation is defined to give an estimation of the expected cooperation level of the nodes. Many reputation schemes have been proposed in literature and have been deployed for different contexts ranging from P2P or content distribution networks [5] to mobile ad-hoc networks [10]. These schemes rely on the dissemination of trust information gathered through transactions between nodes so that past experience can be evaluated and generalized to predict the behaviour of the node.

But, the question how *building* reputation is important for a node’s future interactions or how a node *values* its reputation has not been clearly addressed. Previous works assume reputation as a metric to define *cooperation strategy* or to implement a differential service incentive scheme. This is not sufficient to explain why a node should increase its reputation value and to reason on the adoption of reputation management systems from the nodes point of view. Furthermore, if we consider rational nodes, in the sense that they strategize to increase their expected utility from the system, there is no clear understanding of the role of reputation in selecting a specific action/strategy. In most cases nodes want to collaborate to keep their trust value above a certain threshold that allows them to consume system resources at the minimum “price”.

A closer analysis of reputation management systems from an interdisciplinary perspective is needed as, in our opinion, reputation systems are at the boundary between social and economic sciences as well as evolutionary biology and computer science. In our formalization, we discuss the evolution of the system under the enforcement of a reputation management scheme. Herein, we concentrate on incentives and punishment and propose a trust economic model based on the Iterated Prisoner’s Dilemma for P2P systems. Moreover, we derive conclusions from the adoption of specific economic theories to model P2P systems and discuss how cooperation can be enforced in autonomous distributed systems formed by selfish agents.

Sec. II discusses related works. Sec. III presents the network model and Sec. IV gives notions on game theory that will be used to formalize the model. In Sec. V we define the Reputation Game and derive the Nash Equilibrium. Sec. VI discusses experimental results and Sec. VII concludes the paper and gives guidelines for future work.

II. Related Works

A considerable amount of research has focused on the exploitation of economic theories to model nodes' interactions. Most of this effort has been centered to analyze how selfish behaviour impacts the performances of P2P and ad-hoc networks [1].

In [2], the authors propose an approach based on game theory to define and analyze a differential service incentive scheme to improve system's performances. They study the Nash Equilibria for a homogeneous setting and quantify the benefit for nodes to enter the system. The Equilibria are found to be stable in the repeated game setting when nodes report truthfully their own contribution. A revisited version is presented in [4] where whitewashing (nodes that change their identities to clean their history) and collusion are studied. Feldman et al. introduce the concept of indirect reciprocate-based scheme and through simulations they find that these schemes are effective to foster cooperation mainly in the presence of large population size, dynamic membership and infrequent interactions between the nodes.

Marti et al. [9] propose a game theoretic approach to model auctions in P2P systems. This study provides interesting results about the formation of the reputation value but differs mainly from the approach we propose as in our case providers will deliver the entire service. However, we exploit their definition of variable price. Gupta et al. [7] define the service game where nodes decide whether to serve other nodes with a probability that depends on the serving node' reputation. In their work they show that in *equilibrium* the behaviour of nodes is similar in providing services.

III. Network Model

We assume an autonomous P2P network formed by selfish and rational nodes who want to maximize their own interests from participating in the system activities. Moreover, we assume that 1) the system population is composed by a fix number of nodes (N) with the same capabilities 2) nodes do not participate in a collusion and 3) the identities of the nodes are fixed during the game. Nodes are defined to be rational and strategic: at each interaction they can choose the action, which will influence the outcome of the system. An action can be either cooperation or defection.

We identify two possible network models that are worth investigating for the applicability of reputation management systems in P2P networks: (1) an interaction between nodes is defined as a simultaneously exchange of services; (2) interactions can be asymmetric as nodes have different roles (there is a node that requests a service and a serving node that decides to satisfy the request).

Herein, we analyze the second model: the serving node has to decide on the service provision and the receiving node should decide whether to reward the action of the provider. This results in a *non-cooperative* game, as nodes want to maximize their utility. The game is played in multiple stages and nodes follow a strategy (set of actions). We further assume that nodes will be present in the system for the whole duration of the game and that the end of the game is not know to the nodes and, thus, it is supposed to run infinitely.

TABLE I

Generalized Form of the Prisoner's Dilemma game: payoff matrix. Temptation, Reward, Sucker, Punishment

		Receiver	
		Cooperate	Defect
Serving	Cooperate	(R_s, R_r)	(S_s, T_r)
	Defect	(T_s, S_r)	(P_s, P_r)

We assume a system where at each stage there is a resource request and requests are satisfied at the same rate during the evolution of the game. At the end of each period of time, the results of the interaction are made available to the system population and the utility functions of the nodes are updated. The utility of a node depends on the resources or services it can access and the cost to provide or obtain them. Thus, it is function of the actions the other nodes in the system take. At each node is also associated a reputation value which is updated after every transaction to keep track of nodes behaviour and it is assumed to be common knowledge.

IV. Definitions of non-cooperative games

In this section we introduce key notions on non-cooperative games and the formalism that will be used for the rest of the paper. We model the P2P system by using definitions and results based on the Prisoner's Dilemma [6], [12]. In this game two nodes decide simultaneously whether cooperate or defect without knowing a-priori the choice of the other player. If both cooperate, they receive a specific reward (R). If both defect, they receive a punishment (P). If one defects and the other cooperates, the player who defects receives a larger reward, temptation (T), and the other receives a larger punishment, the sucker's payoff (S).

Table I shows the strategic form of the game represented in a bi-matrix where the rows and the columns are the available strategies for the two players and each box specifies the payoff to each player, respectively for player (S)erving and (R)eceiving, when the strategy profile corresponding to that cell is played. The Prisoner's Dilemma is a non-cooperative and simultaneous game where in its generalized form the payoffs are not identical for the players. To create the dilemma, mutual cooperation must provide higher payoff than other strategies and defection should be the dominant strategy. Therefore, the following conditions must hold:

$$T > R > P > S \tag{1}$$

$$R_s + R_r > P_s + P_r \tag{2}$$

In the single stage game, the best choice for the players is to defect, $(Defect, Defect)$, as it is always the best response to the opponent strategy [6]. More interesting is the iterated version of the game where nodes play against each other repeatedly and track the history of the game. In this setting, nodes can be punished for their defection in past interactions. In the iterated version of the game, the payoff of the players are computed by summing the single stage payoff over all the stages played. However, to maintain the dilemma in the iterated version, the following inequality must also be valid:

$$R_s + R_r > S_s + T_r \text{ and } R_s + R_r > T_r + S_r \quad (3)$$

Conditions (3) states that alternation between $(Defect, Cooperate)$ and $(Cooperate, Defect)$ does not give higher payoff than mutual cooperation. However, in the finite iterated version of the game, defection at the last movement gives higher payoff. But, if the game is iterated infinitely (it is sufficient to assume that nodes do not know when the game will end) cooperation results in a Nash Equilibrium of the game, where no player has incentives to deviate **unilaterally** from its best response strategy.

V. THE REPUTATION GAME

This section describes the reputation game which is based on the Iterated Prisoner's Dilemma. At each stage of the game two nodes, picked at random, are considered for the game: one node is acting as resource[1] provider and the other as resource consumer. Their role in the system is interchangeable, i.e., a node who is service provider at time t_i might be service receiver at time t_j. The two available actions are collaborate (provide the service) or defect (ignore the request) for the serving node and collaborate (reward) or defect (do not reward) for the receiving node. We are interested in showing how the decisions affect nodes utility and reputation values in the long run of the game.

A. Introducing reputation in the game

First we define the role of reputation in the game. A provider node pays a cost for providing the service, but this cost is compensated by the increase in its reputation I and by the "monetary" reward obtained from the receiving node. A receiver pays the requested service but it increases its reputation value as result of fulfilling its commitment.

After each transaction, the reputation value is updated, based on the reputation calculated at the previous stage and the outcome of the single stage game. The updating function is defined as

$$I_{t+1} = \begin{cases} 0, & \text{if } t = 0 \\ I_t * (1-\alpha) + v * \alpha, & \text{if } t > 0 \end{cases} \quad (4)$$

with $0 \leq \alpha \leq 1$ and $v \in \{0, 1\}$, thus, $0 \leq I_t \leq 1$.

This means that if a node cooperates, it will increase its reputation by a factor determined by the constant[2] α, which models the importance of the new interaction for the computation of the reputation, and v, a binary parameter that indicates if cooperation has taken place. Nodes with high reputation values are considered trustworthy in the system.

B. The reputation model

The reputation game evolves as follow, where steps $2.a$ and $2.b$ are simultaneous:

1 The requesting node identified as N_r has an associated reputation value I_r. It sends a request for a specific service to other nodes[3] in the system by offering a reward B.

2.a The serving node N_s has two possible actions: 1) cooperate and send the service or 2) defect and ignore the request.

2.b The receiving node N_r has also two possible actions: 1) cooperate and send the promised reward or 2) defect and fail to meet the commitment.

3 The single stage game ends and the nodes update their utility functions and reputation values.

The dilemma for N_s consists in deciding if: 1) afford the cost of serving the file and behave correctly obtaining the reward R_s if N_r cooperates or the punishment S_s if N_r defects; 2) ignore the request obtaining the reward T_s without having sent the file if N_r fulfills its commitment or the punishment P_s if N_r defects as well (see Table I). N_r has to face a similar dilemma but with different payoffs.

The payoffs for a generic serving node N_s and requesting node N_r at a specific iteration of the game t are given as follows:

$$\pi_s^{t+1} = \begin{cases} -C + B - C_p(I_r) + f(I_s^t), & R_s \\ -C - C_p + f(I_s^t), & S_s \\ B + f(I_s^t), & T_s \\ f(I_s^t), & P_s \end{cases} \quad (5)$$

$$\pi_r^{t+1} = \begin{cases} -B + S + g(I_r^t), & R_r \\ -B + g(I_r^t), & S_r \\ S + g(I_r^t), & T_r \\ g(I_r^t), & P_r \end{cases} \quad (6)$$

where C is the cost for providing the service, B is the reward for serving nodes with $(B - C) > 0$, S is the value of a service for the requesting node with $(S - B) > 0$, $C_p(I_r) = B/(1 + e^{5I_r})$ is the punishment factor and $f(I_s^t) = B * [I_s * (1-\alpha) + \alpha * v]$ and $g(I_r^t) = S * [I_r * (1-\alpha) + \alpha * v]$ are the benefit for the nodes in terms of *future payments* based on their level of cooperation, respectively for the serving and receiver node (refer to (4) for the update function of the reputation). The punishment factor $C_p(I_r)$ is inserted to reduce payoff of serving nodes when providing services to untrustworthy nodes.

The game is a Prisoner's Dilemma if the conditions introduced in Sec. IV hold. From condition (1) we can derive for N_s that $f(I_s)_{\text{def}} > f(I_s)_{\text{coop}} - C_p(I_r) - C$ and $B > C + C_p(I_r)$. This means that the benefit in serving must compensate the direct cost and the cost derived from the punishment of serving less trustworthy nodes. Hence, lower

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[1] We use the general term resource as it can represent a file in the case of content distribution networks, a request to cache a file in distributed caching systems, a job execution request and so on.

[2] α is a system parameter and depends on network conditions. If transactions are infrequent, a low value of α is desirable whereas when transactions are frequent, a high value is desirable.

[3] The selection of the service provider is out of scope of this paper and we suppose there is a mechanism based on node's reputation I_s to choose the server.

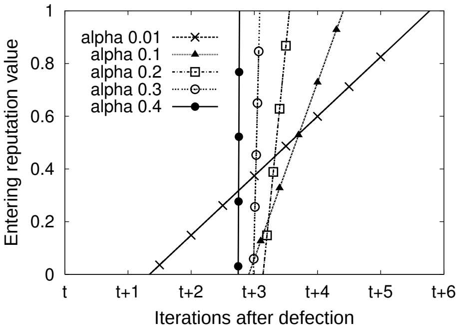

Fig. 1. Nash Equilibrium for the reputation game: the defecting player has greater payoff from always cooperation ($\pi = \sum R_i$) rather then cooperation defection ($\pi = \sum^t R_i + T_{t+1} + \sum_{t+2} P_i$) (this is represented by the points below the curves when $t = 10$ is the last cooperative interaction.) The Nash Equilibrium depends from the reputation value at the beginning of the game.

is the reputation I_r greater is the punishment N_s will receive, thus, it is more tempted to defect. For the requesting node N_r, it is sufficient to have that $g(I_r)_{\text{def}} + B > g(I_r)_{\text{coop}}$ as we have assumed $(S - B) > 0$. The dilemma is kept in the iterated version of the game (3) if $S > C + C_p(I_r)$ as we assume the utility, derived from future payments, be greater in case of cooperation.

C. *Nash Equilibrium for the reputation game*

In this section we demonstrate the effectiveness of the reputation game and we show how Nash Equilibrium is obtained by analyzing the impact of actions at each stage on the reputation value. We use a reputation management system on top of a P2P network to simulate nodes interactions. The parameters' settings and decision metrics that we use to evaluate the results obtained from the simulations are summarized in Table II and they are defined in accordance with the conditions of the Iterated Prisoner's Dilemma, introduced in Sec. IV.

In the repeated game strategy, reputation is sufficient to sustain cooperation if the players are patient. Let's consider the repeated game with a trigger strategy where the serving node N_s and the receiving node N_r cooperate for t transactions and at time $t+1$ node N_s *unilaterally* defects triggering an-open loop for N_r to defect in subsequent interactions. After iteration $t+1$, the *best response* for N_s is to defect.

The curves in Fig. 1 show when the payoff resulting from this action is equal to the payoff earned for cooperating all the time. This is summarized in (7). The inequality indicates after how many x iterations, with x defined after iteration t, *always cooperation* is the best strategy with respect to the entering reputation value $I_s(t=0)$.

$$I_s(t=0) \leq \frac{10x + 15(2-\alpha)[(1-\alpha)^t - 1] - 15(1-\alpha)^x}{25(2-\alpha)(1-\alpha)^t} + \frac{15/(1+e^{5*\{(1-\alpha)^t[I_r(t=0)-1]+1)\}})}{25(2-\alpha)(1-\alpha)^t} \tag{7}$$

The plot shows that the defecting player has no incentive for being uncooperative at time $t+1$ as the *Temptation* reward cannot compensate future *Punishment* rewards. For different choices of the parameter α (used to update reputation as defined in (4)) and for the reputation value $I_s(t=0)$ the defecting node N_s had at the beginning of the game, it is more advantageous to cooperate when $I_s(t=0)$ is below the curves (see (7)) as it is the case after 5 interactions (iteration $(t+6)$), for all considered values of α. Thus, we have defined that if nodes are *sufficiently* patient, cooperation is a Nash Equilibrium for the *reputation* repeated game. The same result can be derived for the receiver as defecting node.

TABLE II
PARAMETERS' SETTING

Number of Nodes	1000	Network Topology	random
Initial transactions	1000	Number of iterations	9000
Experiments run	5	Service value [S]	25
Benefit [B]	15	Cost [C]	5

TABLE III
STRATEGIES AVAILABLE TO PLAYERS

Average	A node decides for cooperation if the opponent reputation value is greater than the average reputation.
Adaptive	A node considers its reputation value, the correspondent reputation value and the average reputation in the system to decide for cooperation or defection.
Relative	A node cooperates if its reputation value is below the correspondent reputation value.
Discriminant	A node decides for cooperation if the correspondent reputation value is above a fix threshold (if not specified the threshold is set to 0.5).
Random	A node decides randomly if cooperate (this is the only strategy that is not based on reputation).

VI. EXPERIMENTAL RESULTS

In our experiments we use the parameters listed in Table II and we run 1000 initial transactions to bootstrap the reputation management system. Each node can be either service provider or service receiver and, in each stage, two nodes are selected randomly. During the game nodes follow strategies defined in Table III and the strategy is the same in each experiment.

Fig. 2 shows the impact of the different strategies in terms of fraction of cooperative interactions. The *discriminant* strategy gives better results compared to the others, but this strategy heavily depends on the threshold for the reputation value chosen to differentiate between cooperation and defection.

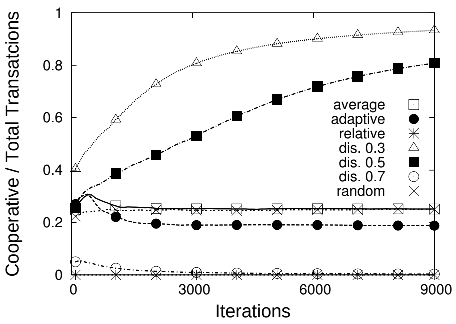

Fig. 2. Number of cooperative transactions (both provider and receiver cooperate) for the available strategies.

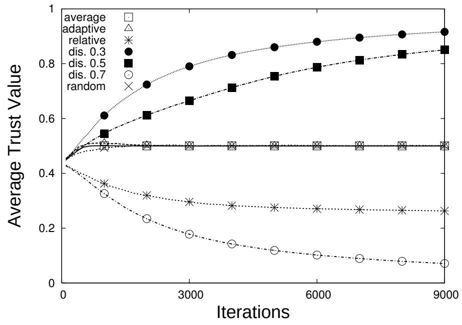

Fig. 3. Average reputation value in the system for the available strategies.

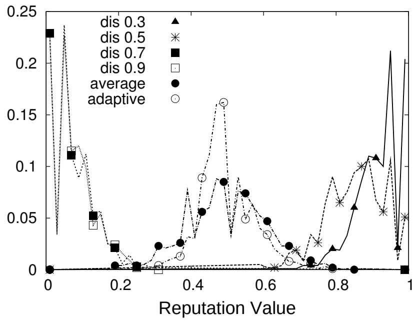

Fig. 4. Probability Distribution Function (PDF) of reputation values in the system with respect to different strategies.

Fig. 3 shows that the discriminant strategy performs better as the average reputation value increases if it is initially above the fixed threshold. An interesting property is associated with the average and adaptive strategies as they maintain the average trust level constant in the system (see Fig. 3) as well as the fraction of cooperative transactions (see Fig. 2). The explanation of this behaviour is associated with the definition of the strategies as they choose cooperation or defection to maintain constant the reputation value.

Fig. 4 shows the distribution of reputation values. As anticipated above, the adaptive and average strategies tend to aggregate the reputation values of the nodes close to 0.5. On the contrary, the discriminant strategy with a low threshold shows a behaviour that can be assimilated to always cooperate. This behavior is function of the initial reputation value of the nodes after bootstrapping the system. Fig. 5 shows the impact of the initial reputation value $I(t = 0)$ on the effectiveness of the strategies. For the discriminant strategy, if the initial reputation value is below the chosen threshold, this strategy will favour cooperation in the system. On the contrary, the adaptive and average strategies work to bring the system to a stable operating point that has the average reputation value close to 0.5. This behavior is shown in Fig. 5 for an average initial value close to 0.7 and 0.3.

VII. CONCLUSIONS AND FUTURE WORK

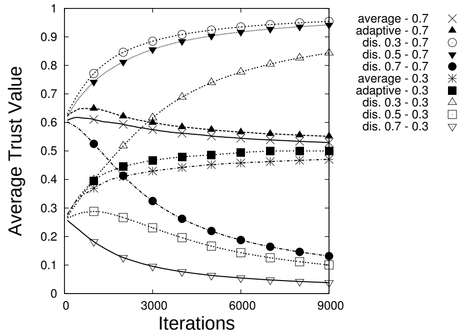

Fig. 5. Average reputation value considering different conditions of the system at the bootstrap. Initial training transactions are cooperative with a probability of 0.7 or 0.3.

In this paper we propose a game theoretic approach based on the Iterated Prisoner's Dilemma to study reputation management systems. We derive the Nash Equilibrium for the reputation game and we show that reputation is sufficient to sustain cooperation if players are *patient*. Unlike other approaches we define a framework to study how reputation is valuable for a node and we study the evolution of reputation in the system. As future work, we are in the process of enhancing our reputation model by considering the impact of different strategies. This includes the definition of adversarial models for rational and malicious nodes.

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