The Peer's Dilemma: A general framework to examine cooperation in pure peer-to-peer systems

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The exploration of social dilemmas is being considered a major foundation for encountering the enforced necessities of cooperation in self-organizing environments. Such environments are characterized by self-interested parties and the absence of trusted third parties. Recent approaches apply evolutionary socio-inspired games to formally prove the existence and further prolongation of cooperation patterns within communities. For instance, the Prisoner’s Dilemma game has thus provided a rich opportunity to examine self-interested behaviors in pure peer-to-peer networks. However, assuming a total absence of coalitions, incentives and punishment mechanisms, several works argue against a durable maintenance of cooperation neither at single-shot nor repeated-scenarios. In this article, we formally and experimentally demonstrate a counterexample for the latter by applying evolutionary game theory and a particular instance of the Rock–Scissors–Paper game. Our framework proves that the cyclic dominance of certain type of nodes within a P2P system has an impact and introduces a strategic aspect to the evolution of the overall community.

1. Introduction

The emergence and evolution of cooperation within self-organized networking transactions is being currently addressed by different research directions. As most networking services heavily rely on node cooperation, the need to study and explore this type of behavior represents a major concern for system sustainability. Traditionally, cooperation has been tightly linked to incentive and reputation mechanisms. These mechanisms have evolved to high levels of sophistication and complexity incurring in excessive overheads and very high deployment and maintenance costs. Thus, in the current context there is the need to identify alternative ways to force the emergence of cooperation from a more natural and spontaneous participation.

Recent approaches have taken inspiration from a number of biological phenomena allowing self-organizing behaviors to naturally emerge [24,36]. In addition, investigations on the social order have also been extensively used to justify common behavioral patterns (as those referred to as the Tragedy of the Commons) and also to explore novel strategic structures for cooperation in dynamical networks [32,21]. Other papers in the literature have analyzed the effect of non-cooperation—mostly in the form of free-riding in the context of peer-to-peer (P2P) systems, by constructing a simple economic model of user behavior [7].

Game theoretical results have widely been applied to the study and formal analysis of cooperative behavior in ad hoc networks [34]. In this context, P2P systems have also been analyzed as a game scenario. Peers’ interactions have been generally represented as repeated instances of the same two-player game and analyzed by considering a Cooperate/Free-ride Social Dilemma, equivalent in many ways to the well known Prisoner’s Dilemma (PD) [18,5].

In general terms, this dilemma imposes the non-cooperative behavior over cooperative, i.e., non-cooperation always...
produces a greater benefit against cooperation. Indeed, cooperative peers are prone to exploitation and invasion by non-cooperative peers.

1.1. Our approach

In this article, we study the peers' RSP dilemma as a mechanism to allow cooperation to emerge naturally, without external incentives. This is particularly suitable for pure P2P file sharing networks where no other more sophisticated cooperation-based mechanisms can be implemented. Our approach serves to prove that peer's optional participation in the Cooperate/Free-ride Social Dilemma suffices to maintain acceptable levels of network performance in large P2P communities. The introduction of loner nodes is sufficient to reach a stable equilibrium between selfish anonymous peers. A cyclic dynamics results in the stable coexistence of various types of behavioral patterns.

This article offers the following main findings contributing to any previous related work as follows:

1. A new dilemma: We define the Peer's Dilemma as a new concept characterized by the elimination of the enforcement on peers to participate in the traditional Cooperate/Free-ride Dilemma. We experiment with the Peer's Dilemma modeled as the Rock–Scissors–Paper¹ game (RSP). P2P environments will be represented by nodes repeatedly interacting playing the RSP game. We will show that the payoff matrix for the traditional RSP game can be used to model some decentralized P2P communities.

2. P2P-RSP simulation framework: We evaluate the Peer's Dilemma defining a P2P-RSP simulation framework which will serve to prove that peer's voluntary participation in the Cooperate/Free-ride social dilemma suffices to maintain peer's cooperativeness and ensures acceptable levels of network performance. Our proposal implements the notion of a RSP cyclic competition, based on co-evolutionary learning² as a way to study peer-strategy evolution. Thus, we model a P2P system as a large population consisting of three different types of peers' behavioral strategies, namely cooperators, non-cooperators and loners. The global objective is to prove that the non-cooperative strategy is not able to invade and destroy the community, even if:

- Nodes interactions are not repeated,
- Nodes are fully anonymous,
- Nodes have no recollection of previous interactions with other peers,
- Nodes are neither externally incentivized to cooperate nor punished and,
- Nodes can play the role of providers and requesters indistinctively.

This approach allows the system to be self-adaptive, without any central or external mechanism which monitors and provokes changes in the structure or behavior of the P2P system.

Article organization. The rest of the article is organized as follows: Section 2 presents other formal and experimental frameworks by comparison with our approach. In Section 3 we will provide mathematical soundness to our new analytical formalism and describe the foundations and dynamics of our model where P2P nodes are confronted with the RSP dilemma. Section 4 describes our simulation framework based on evolutionary computation algorithms where the impact of different types of peer's behavior can be measured and studied. Also, this section summarizes the experimental results. Finally, in Section 5 we establish the main conclusions as well as the immediate future work.

2. Related work

In this section, we explore several game theoretical frameworks defined for the formal analysis of incentives and any other mechanism applied to enforce cooperation in P2P systems.

2.1. Game theoretical frameworks for the analysis of incentives and costless signaling

Game theory offers a suite of analytical tools that may be used to predict the outcome of complex interactions among rational entities [34]. For instance, various formal game theoretic models have been proposed to examine the implications of the assumption that peers selfishly act to maximize their own rewards in current P2P systems (free-riding) as well as to analyze equilibria of peer strategies under several incentive-based or reputation-based mechanisms [18,33]. On one hand, in [11] a game of incomplete information is played between peers of different types or utility functions found in several centralized payment mechanisms. This model assumes that all other peers are fixed in their strategies, and then attempt to learn either the payoffs associated with their own strategy or the joint distribution of others' strategies. On the other hand, analysis for cooperation in decentralized dynamical networks are often based on the idea under “cheap talk” in a costless signaling context [12]. In this context, players signal their condition to other players, which can observe a certain information regarding other players’ past actions. Hence, indirect reciprocity applies when benevolence to one user increases the chance of receiving help from others [30].

Additionally, [7] proposed a game-theoretic framework that examines the implication of several incentive mechanisms on the users’ behavior and also on the system performance. In particular, this work analyzed the impact of a punishment mechanism based on excluding those users with the lowest willingness to share resources (like BitTorrent choking as described below). This then implies that users publicly fix a behavioral strategy which reflects their

¹ The Paper Scissors Stone Club was founded in 1842, in England. In 1925, the club reached over 10,000 members and the name was changed to The World RSP Society.

² Co-evolutionary learning is a population-based, stochastic search algorithm that iteratively applies the process of selection, cross-over and mutation on the competing solutions in the population.
generosity to contribute their resources to the system. However, the effectiveness of this type of punishing can be easily subverted if the system allows users to cheaply acquire different identities.

By contrast, our proposal, as other game theoretical approaches which suggest that P2P systems can sustain free-riding in equilibrium [19], demonstrates that, even when a large proportion of the participant peers initially refuses to cooperate (so no incentive is deployed), the system’s stable equilibrium is reached and thereby achieved the socially optimal network outcome. In other words, cooperation emerges naturally and therefore the system survives both, population dynamics and the dilemma of cooperation.

2.2. Repeated settings and evolutionary dynamics

Game theory proves that when players play the PD game repeatedly an indefinite or random number of times, namely the Iterated PD (IPD), cooperation can emerge [1,9]. Further exploration of the IPD has concluded that the strategies that attain better results tend to be optimistic and generous such as tit-for-tat [2] and reciprocal altruism [14]. Consider current BitTorrent (BT) policies as a good example of trying to meet fairness and system stability in a P2P file sharing system in which BT peers adopt the tit-for-tat (TFT) strategy of IPD tournaments [17]. As BT makes each peer’s download rate be proportional to their upload rate, thus peers are likely to exchange file pieces preferentially with others who uploaded them recently. BT then deploys such an incentive mechanism which clearly intends to benefit the peers who contribute (cooperate) more to the system. For instance, to punish or at least discourage free-riders, BT users are capable to temporary refuse to upload which is called choking. BT implements various choking algorithms. We refer interested readers to [4,28,27] for an interesting discussion of the impact of TFT and altruism strategies on the actual robustness and performance of BT clients.

Recent analysis, however, such as [27,29] have demonstrated that BT is not a Nash equilibrium. By conducting a measurement study of real BT swarms, these works address the so called BitTorrent Dilemma game, i.e., the one-sided version of the PD which does not have a dominant strategy and deals with direct reciprocity and unconditional cooperation. Their results show that there exists a strategic BT peer behavior which makes all peers contribute (being altruistic in terms of the upload capacity) to the system even when they do not directly improve their performance. In this article, we also question the need of incentives for inducing cooperation and present a game-theoretic model, namely P2P-RSP model, that aims to capture the Peer’s Dilemma. We formally and empirically validate our model by conducting experiments on our own simulation tool (described in sections below). Our simulator can be configured with different payoff matrices as to evaluate and examine other related dilemmas.

Furthermore, other works concentrate on the analysis of the stability and evolution of P2P populations comprised of multiple peer types. As in our approach, in [37] peers are modeled according to the strategy or type they play at a time slot. For each time slot, the whole system is defined by a vector which establishes the fraction of the different type peers. Dynamics of that vector depend on a general gain and loss model which assigns probabilities to the services received and provided. In addition, a learning process allows peers to switch (or adapt) to another strategy, namely the highest performance strategy, at each time slot. From their conducted experiments, a probabilistic TFT policy leads to the system collapse whereas the optimal overall performance was achieved when peers of type “reciprocators”—which make decisions according to the reputation of requesters, dominate [23]. Our approach, however, optimizes peers adaptation by applying a co-evolutionary algorithm.

2.3. Discussion

In all those formalisms, incentives, reputation, as well as cooperation levels, are parameters which are represented either as participants’ payoff values or as probabilistic values. The formal analysis then focuses on the computation of the expected payoff value for each participant node at the end of the game. However, all previous works present two common drawbacks:

- The impossibility to represent and model coalitions of nodes and estimate their behavior, and
- The impossibility to represent and model the unpredictable deviations from the game.

To this regard, our model differs from the previous as:

- **Peers are assumed not to have memory.** Or recollection of previous instances of the game so coalitions cannot be formally structured.
- **Unpredictable deviations from the game cannot take place.** As the game is a static game played in only one turn and the set of actions only three.
- **Mutual cooperation pays equals to mutual defection.** In traditional PD and IPD, always mutual cooperation pays more than mutual defection. By contrast, the RSP matrix (see Fig. 1 right) assigns equal payoffs to mutual cooperation and mutual defection. This feature is of special interest to us and represents one of the kernels of our work. On one hand, it completely eliminates the existence of any kind of preconceived incentive strategies intrinsic to the application. Hence, we can model those settings in which nodes are oblivious to the actual semantic of the interaction. On the other hand, this feature also allows us to represent users of a file sharing P2P system perceiving the service required on equal terms as it is provided in terms of consumed resources, quality of service (QoS), or costs. For example, put simply a P2P setting in which a requester who receives a file gains, in terms of quality of service, the same as its provider.
- **Modeling peers’ behavior.** Depends on a large number of parameters such as bandwidth, network topology and data availability, to name a few. Our model serves to represent those P2P systems in which there exists different characteristics or variables regarding nodes'
3. Our game theoretical framework

In this section, we detail the foundations of the formalism we propose.

3.1. Evolutionary game theory: basic concepts

While traditional game theory has been a powerful tool for the analysis of many interactive systems, the basis and the assumptions underlying evolutionary game theory\(^5\) are more appropriate for modeling and studying the dynamic behavior of P2P systems.

Consider each P2P node interaction as a two-player game where both players are rational and have common knowledge about the structure of the game including the game’s rules and the payoff functions for players (i.e. a game of complete information). Additionally, consider that each P2P player cannot correctly forecast the play of an opponent (also known as a game of imperfect information, since a player does not know exactly what actions other players took up to that point). Evolutionary game theory states that the players are individuals with genetically encoded strategies, which fully determine the player’s behavior and are, for instance, subject to the force of natural selection (i.e. reproduction and mutation), playing by turns a finitely/infinitely repeated game. This approach, based on co-evolutionary learning, allows the system to self-adapt, without any central or external mechanism which monitors and provokes changes in the structure or behavior of the P2P system.

To this regard, a key concept is that of an evolutionary stable strategy or ESS [22], i.e., a population strategy that yields a higher reward than any other feasible strategy [16]. However, there are games that have no ESS but do have a fixed point of a particular best-response correspondence. This is the case of the RSP game where the unique Nash equilibrium strategy is mixed in the proportion \(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}\) to play each possible action (rock, scissors, paper). Hence, the key objective is to specify the evolutionary stability of this strategy (which imposes a challenge specially for multi-party games).

3.2. The Peer’s Dilemma as a Rock–Scissors–Paper (RSP) game

We define the Peer’s Dilemma as a new concept to reason about the uncertainty of P2P file sharing systems’ users, perceiving the service required on (at least) equal terms that it is provided. As we stated before, the application of the PD scheme establishes only two strategies, namely cooperate and defect, and two non-concurrent roles, namely requester and provider. However, some knowledge is missing here. For instance, deliberately disconnections are not strictly considered and the possible concurrence of roles either. Hence, in this article we demonstrate that the model becomes more natural when, on one hand, a third option is introduced into the traditional peer’s dilemma, namely the exit option, also called withdrawal from playing and, on the other hand, two possible simultaneous roles are involved as in real P2P systems.

To encounter the former, our proposal introduces a new type of node, called the loner.\(^6\) The loner option differs from defection in that the latter has a malicious nature and tries to defeat others, whereas loners do not act maliciously. Therefore, peers are given three different strategies in each individual interaction and for each possible role. Nodes must choose between cooperate, non-cooperate or temporarily disconnect. Furthermore, games should be

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\(^{4}\) A bayesian game is one of imperfect and incomplete information in which players’ typeology and classification will play a role.

\(^{5}\) Evolutionary game theory was first introduced as a method to explain the equality of sex ration in mammals, realizing that the fitness of each individual as well as the future of the species depended on the distribution of males and females in the population [8].

\(^{6}\) Others have used the term “loner” e.g. in a voluntary public-good game [14] but slight differences appear here when nodes can play two simultaneous roles.
played twice per round and node, i.e. requesting a content and serving contents, so our model distinguish between these two different roles: provider and requester. Nodes encountering only one role can adopt the loner strategy for one of the roles in one or more rounds of the game.

More formally:

**Definition 3.1** (The loners option). A loner is a node who, being risk adverse, rationally decides to disconnect from the system at several chosen rounds aimed at maximizing its own benefits (e.g. saving own resources such as bandwidth or connection cost).

**Proposition 3.1** (Player roles). Each node plays two simultaneous roles, Provider and Requester, at any round of the game. Therefore each interaction takes the form of an instance of a RSP game.

Therefore, on the sole assumption that peers aim at maximizing their own individual payoff (being rational peers), if nodes are given the option to disconnect at certain periods of time (this seems to be a reasonable assumption), the following cyclic phenomenon takes place from both, a provider and a requester’s point of view:

- Once non-cooperative strategies\(^7\) increase within the community and start invading cooperative ones\(^8\) over a period of time, the loner option (disconnecting) becomes increasingly attractive (a more beneficial strategy, see the payoff matrix in Fig. 1 right) for cooperative peers. In other words, well behaved nodes will seek to escape from exploitation/wasting resources, by temporarily quitting the community. For the sake of illustration, put simply an honest provider who, overwhelmed with requests, decides to save its own bandwidth.
- However, as soon as the loner strategy dominates the system, non-cooperators begin to starve and cooperation becomes the most profitable option for them (see payoff matrix in Fig. 1 right). In other words, non-cooperators in any role, aimed at maximizing their individual payoff, will then change their strategy and display a cooperative behavior.
- Finally, when cooperators dominate the community, loner peers are rationally forced to join the community again with a non-cooperative behavior, as this becomes the most profitable strategy.

Therefore, cooperator escape to loner, loners escape to non-cooperator and non-cooperators escape to cooperator. Fig. 1 left represents the cyclic dominance of the three possible strategies in iterated scenarios that yields a self-organizing pattern. This way, each underlying interaction between peers can be modeled as a RSP Dilemma, in which each peer has three possible actions: Loners (equivalent to playing Scissors), Non-Cooperators (equivalent to playing Paper) and Cooperators (equivalent to playing Rock).

**3.3. Principles of the game**

In the next propositions we will assume a pure P2P community which can be modeled using the paradigm just described. In particular,

**Proposition 3.2** (Even rewards). Two interacting nodes with similar type of strategies result in a draw on the payoffs attained by each interacting node. Therefore \((C,C), (NC,NC), (L,L)\) yield \((0,0)\) to each player node.

Each value is considered in terms of QoS, resources or any other cost (e.g. bandwidth usage or payment per-MB connection) wasted or saved at each interaction, in comparison with the QoS, resources or any other cost that rival nodes used, saved or wasted at the same time, and the impact that those interactions have, in terms of resources accumulated or used, along the life of the P2P community. In traditional PD and IPD, always mutual cooperation pays more than mutual defection. But contrast, the RSP matrix, which is zero sum, assigns equal payoffs to mutual cooperation and mutual defection. Our experiments will show that this configuration gives the system stability.

**Proposition 3.3.** (Non-cooperators’ advantage). Non-cooperative behavior against a cooperative action always renders better value for the non-cooperative node in terms of resources/costs used in the interaction. In other words, exploiting other peers resources is always more profitable than using a peer own ones. This is represented by payoffs \((-1,1), (1,-1)\) corresponding to interactions \((C,NC)\) and \((NC,C)\) respectively.

**Proposition 3.4** (Loners’ advantage). Non-cooperative behavior against a loner strategy \((NC,L)\) and \((L,NC)\) incurs in lost for the non-cooperative while the loner save and accumulate its resources and costs.

**Proposition 3.5** (Cooperators’ advantage). Finally, \((C,L)\) and \((L,C)\) interactions leave loners in a disadvantageous position with respect to the cooperative ones. Loners’ temporary disconnections yield a lost of opportunity to interact with cooperative nodes. By contrast, for cooperative strategies it represents accumulated resources for the future.

Although a few variants are included, this will constitute the basis of our approach:

**Corollary 3.1.** (Basis of our approach). Loners prevent the community from being invaded by non-cooperators. So cooperation emerges naturally without the need for incentives.

**3.4. Equilibrium of the Peer’s Dilemma**

Now, we elaborate on the equilibrium of the Peer’s Dilemma (as defined in Section 3.2):

**Definition 3.2** (Strategy). In a game, a strategy for player \(i\), denoted by \(s_i \in S_i\) where \(S_i\) is the set of all possible strategies, is a complete contingency plan for player \(i\). It describes the series of actions that this player would take at each possible decision point in the game.
Definition 3.3 (Strategy profile). A strategy profile in a two player game is a tuple \((\sigma_1, \sigma_2)\) dictating players 1 and 2 how to play and therefore determining the outcome of the game. Therefore, player 1 plays strategy \(\sigma_1\) and player 2 plays strategy \(\sigma_2\) in the game.

Definition 3.4 (Nash equilibrium of the one-shot Peer’s Dilemma). In the one-shot Peer’s Dilemma the strategy profile \((\sigma_1, \sigma_2)\) which constitutes the Nash equilibrium is the one in which the strategies \(\sigma_1 = \sigma_2 = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)\). We denote this strategy profile as \(\sigma_{\text{NSP}}\).

In other words, both players choose each possible action \((\text{NC}, \text{C}, \text{L})\) with probability \(\frac{1}{3}\) each. When examining the iterated version of the Peer’s Dilemma from a game theoretical point of view, the following result is obtained [35]:

Definition 3.5 (Evolutionary Stable Strategy of the iterated Peer’s Dilemma). In the iterated version of the Peer’s Dilemma the strategy profile \(\sigma_{\text{ESP}}\) from Definition 3.4 is a stable solution of the game, with the following properties:

- \(\sigma_{\text{ESP}}\) is a weakly evolutionary stable strategy: It does not protect cooperators from small incursions from the non-cooperative players but it does prevent total invasion.
- \(\sigma_{\text{ESP}}\) is a proper equilibrium: The profile protects every individual player from incurring in fatal and lethal cost, even when players with the strategy of never-cooperate are part of the game.
- \(\sigma_{\text{ESP}}\) allows players to be more alert to possible deviations from the profile, although it allows small trembles.

Note that, although the dynamics of the nodes within the P2P community have been modeled using the symmetric payoff matrix shown in Fig. 1 right, an important feature of the iterated version of the Peer’s Dilemma is that the two players can adopt two different roles (Provider and Requester). Thus, the evolution of a P2P community is not only dependent on the choice of strategies, but also dependant on the proportion of requesters and providers.

To this regard, some previous experimental work has revealed that increasing the number of possible strategies for each peer to \(\{\text{honest-requester}, \text{dishonest-requester}, \text{loner}, \text{honest-provider}, \text{dishonest-provider}\}\) does not lead to a recognizable cycle of dominant strategies, thus not been able to draw any further conclusions. Our proposal, therefore, preserves the main RSP three-action game at the same time as it creates strategy profiles for every possible peer role.

4. Our experimental framework

In our experimental phase, the evolution of a community of peers is simulated applying an evolutionary process (a genetic algorithm in our case) to a population of potential solutions. The coevolution process searches for increasingly better solutions without a fixed training set, i.e. the population itself is the training set that changes during the learning process.

Thus, in this section we briefly describe the design foundations of the experimental framework we developed to directly control the necessary system and co-evolutionary parameters. Furthermore, a pre-built executable version is accessible from SourceForge.net projects at https://sourceforge.net/projects/thepeersdilemma. Finally, we evaluate the Peer’s Dilemma by analyzing the main factors which directly have an effect on the system dynamics and stability.

4.1. Our P2P-RSP simulator

Current version of the developed framework allows us to specify the following functionalities:

- **P2P communities’ nature**: A random number \(N\) of nodes engage in a \(\text{RSP cyclic competition}\) in which peers interact in pairs, playing the Peer’s Dilemma. The experimental framework allows us to run simulations varying the initial proportion of the node types, e.g. initially balanced populations (33% each type) and also unbalanced communities such as those initially dominated (70%) by a certain type.
- **Rounds and generations**: In our model, a round \(r\) will be considered a point in time in which the peers of a community simultaneously interact in pairs. A generation consists of a number \(k\) of rounds. A fixed number of generations will be performed to examine the evolution of peer communities.
- **Overlay**: Given a fixed number of \(N\) peers, we use a matrix \(E \in \mathcal{M}_{N \times N}\) to denote what pair of peers interacts at each generation, where \(e_{ij} = 1\) if peers \(i\) and \(j\) play against each other, and \(e_{ij} = 0\) otherwise (also note that \(e_{ii} = 0\) \(\forall i = 1, \ldots, N\)). A percentage of the values of this matrix changes according to a mutation rate parameter. For example, a mutation rate of 0.2 represents a weakly randomized overlay matrix as only 20% of the peers change opponent at each generation. By contrast, a high mutation rate of 1 represents a random overlay matrix which constantly changes over the life of the P2P community.
- **Peer representation and strategies**: Peers are represented as individuals by an encoded \(k\)-bit string, equivalent to its genetic code or chromosome, dictating the actions to be taken for both roles, provider and requester, at \(k\) consecutive rounds. Individuals’ chromosomes are randomly initialized with the action for all \(k\) rounds. We define \(A = \{\text{non-cooperative}, \text{cooperative}, \text{loner}\}\) as the set of possible actions for each peer at any given round \(r\).
- **Peers interactions**: Peers communications are inherently probabilistic, but do rely on peers’ chromosomes to play any action within the set \(A\) at any round \(r\) and for both roles. However, our model does not depend on any agent having any capacity to recognize other agents or remember past actions. At an intuitive level, since no memory and no referrals for previous nodes identities are considered, Sybil attack is not applicable.
- **Selection**: At the end of each generation, the payoff obtained by a peer will be computed as the total arithmetic sum of individual payoffs encountered at each round. The best chromosomes, those who are chosen to pass their gene-inherited knowledge to the next generation, should be selected assuming the **Survival of the...**
fittest principle [15]. We apply the Fitness Proportionate Selection (FPS) as the selection process by which the probability for selecting a given individual for reproduction is proportional to its fitness value.

- Reproduction: Two basic genetic operators take place in the reproduction process: crossover and mutation [10]. On one hand, we use the single point crossover operator which consists of selecting a crossover point on both parents’ chromosomes. The offspring's genetic code copies the beginning of one parent’s chromosome to the designated crossover point, and the rest (from the crossover point up to the end) from the second parent. On the other hand, mutation involves nature to take part.

4.2. Experimental results

Some preliminary experimentation led us to identify three factors which significantly influenced the outcome of the experiments⁹: (1) the ratio of repeated interactions amongst the same nodes (i.e. dynamism on the overlay), (2) the population size (this is, the number of peers) and, (3) the initial cooperation nature of the population (percentage of cooperator nodes within the community). Our initial hypothesis was that both, highly dynamic overlays and low populated systems would make it less likely to render evolutionary stable communities. We first evaluate the impact of these two factors on the cooperation dynamics. Subsequently, effects of the initial cooperation rate in the population are examined.

Finally, further experiments were carried out changing the payoff matrix, comparing the choice of our game (a

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⁹ Experiments were conducted on a Intel Pentium 4 3 GHz processor, with 1 GB RAM under Windows XP SP2, and Java Runtime Environment using MS.NET Framework 3.5 SP1 development platform.
standard RSP zero sum game) to other arbitrary non-zero sum games.

4.2.1. Impact of the overlay

Extensive experimentation has revealed how the network structure (spatial lattices, random overlays and scale-free networks) affects the level of cooperation in decentralized P2P communities [20]. In several experiments, we analyze the influence of fixed overlay matrices, where peer interactions do not change at all, compared to highly dynamic overlays. The results attained are very intuitive: highly dynamic overlays seem to negatively influence the time needed to evolve into cooperative patterns. The experiments show how P2P networks with frequent and notable overlay changes are difficult to predict and analyze. By contrast, minor changes in the overlay matrix, such as those occurred in BT when establishing optimistic unchokes, render better results being able to predict the development of such networks. Fig. 2a and b compares a weakly randomized matrix such that, at each generation, the overlay changes with probability 0.2 (Fig. 2a), with a random overlay which constantly changes during the life of the P2P community (Fig. 2b). The graph in Fig. 2a shows how the community has no difficulties in persisting over a period of time (500 generations), establishing a sinusoidal pattern for each of the three possible strategies. However, by increasing the overlay dynamism (nodes are not likely to interact with the same nodes in future generations) (Fig. 2b) the system appears non-persistent and it is more easily invaded by dominant non-cooperative or loner strategies.

4.2.2. Size of P2P communities

Next, we evaluate if the initial state of the population, in terms of the ratio of each type of node, has an influence on reaching a stable state. It is worth mentioning that in PD, regardless of the initial configuration of the population, cooperators are bound to go extinct (see [13] web simulators). However, as mentioned in Section 2.2, there exists several works demonstrated that in practice an altruistic contribution on the part of a small minority of high capacity peers can in fact dominate the BT’s performance [27]. Therefore, our starting hypothesis to this regard assumes that even when a large proportion of the population initially refuses to cooperate, the stable equilibrium is to be reached.

Hence, we conduct several experiments for populations with an initial proportion of 70% non-cooperators and 30% cooperators. Fig. 3a shows how the more non-cooperators exist aiming to destroy cooperation, the more proportion of loners appears. Thus, non-cooperators eventually migrate into the cooperation region. Similarly, Fig. 3b illustrates the same phenomenon within an initial mostly cooperative population. Other initial proportions display the same kind of graph.
4.3. Comparison with non-zero sum games

Current version of the developed framework provides an interface to easily specify different values for payoffs. Since real P2P environments may exhibit non-zero sum game behaviors we are then interested in comparing the traditional RSP payoff matrix, which is zero sum, with other non-zero sum matrices. More precisely, we will run experiments with non-zero sum matrices in which different scenarios are modeled such as (i) mutual cooperation pay more than mutual defection, (ii) altruism, (iii) reciprocity, and (iv) punishments.

First, by alleviating Proposition 3.2 we represent file sharing P2P systems in which mutual cooperation renders better results than mutual defection attaining both players a reward of (1, 1). Therefore, the traditional RSP payoff matrix is modified in order to simulate this scenario which is a non-zero sum. As a result, the RSP cyclic competition is unreachable even increasing the initial proportion of cooperators. Fig. 4 depicts our findings which always lead to cooperators defect in early generations. This result confirms the propositions of our model’s foundations.

Secondly, consider an example of a P2P network that has at its heart altruism as a positive component of peer utility (see e.g. the scenario presented in [25]). Assuming that one derives altruistic utility from having others benefit from the material one uploads, this results in a non-zero sum game. Payoff matrix depicted in Fig. 5 left represents the aforementioned scenario in which cooperation seems to be always beneficial. However, from our extensive simulations, though contribution persists as shown in Fig. 5 right, the evolution of such communities is not stable over the time.

Additionally, we find another example in the framework proposed in [37]. In this work, authors design and evaluate the stability, robustness and performance of incentive policies by also following an evolutionary approach and assigning nodes three possible strategies. In particular, they conducted an evaluation of the so-called proportional incentive policy, which takes into account service consumption and contribution, and which can lead to a robust and scalable system (their system is based on [6]). Thus, the payoff matrix is modified in our simulation tool as shown in Fig. 6 left. Note that our developed framework does not allow us to simulate the traditional TFT, since this strategy follows some sort of shared history based mechanism. However, we can simulate the reciprocator behavior as in [37] by replacing the semantics of the loner option with a reciprocative behavior which makes providers serving according to a tag-based flag disclosing other players’ action. Our findings agree with those in [37], i.e., at the equilibrium there are still some cooperators in the system while the fraction of defectors converges to zero (see Fig. 6 right).

Finally, punishments such as indirect reciprocity and reputation mechanisms [31] are likely to affect individuals’ willingness to cooperate and to discourage asocial behavior. However, they are generally costly and therefore result in an unselfish behavior [33]. For instance, several studies confirm that punishment can force a population in a

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Fig. 4. Simulation of a non-zero RSP game which gives rewards when playing (C, C).

Fig. 5. Non zero-sum payoff matrix for simulating altruism.
cooperative state, i.e., in the presence of a sufficiently large number of cooperative players, to leave everyone worse off than in an asocial population [3]. We conduct several experiments for initial populations equally distributed as well as increasing the initial proportion of cooperators. We also modify the payoff matrix in order to penalize non-cooperation in any role and strategy (also playing loner). However, our simulations give us equilibria where cooperators are doomed and loners always dominate.

5. Conclusions

From the experiments conducted and the model created, we conclude that the basis for cooperation to naturally emerge is the repeated RSP game which is characterized by its traditional payoff matrix as depicted in Fig. 1 right. Hence, the theoretical framework of our approach is based on the Nash Equilibrium of a game of imperfect but complete information. That means that nodes do not know what strategy other players take but they can estimate their loss and gains as the payoff matrix is fixed and public. On the contrary, in the case of having a payoff matrix which is uncertain, the theoretical framework must then be changed to consider bayesian perfect equilibria in games of imperfect and incomplete information, in which nature and player types will play a role.

In our simulation, however, during co-evolution players do not take into account other players payoffs; nodes solely adapt to the different stages and proportions of the population as they go along. To this regard, the experimental work surely renders different results as the nodes co-evolve and adapt to possibly different environments. Indeed, the use of the RSP matrix provides the system with a distributed self-adapting property, as all nodes are made equally responsible for the global system outcome.

Moreover, our theoretical framework is based on well-known results which apply to the one-shot and repeated shots of the RSP game with no simultaneous roles. In theory, our hypothesis (nodes do not need external incentives to cooperate using the RSP payoff matrix when playing with simultaneous roles and repeated shots) was close enough to the traditional setting to be able to derive similar conclusion. Furthermore, the empirical results validate the theoretical hypothesis of our approach and validate the coevolution dynamics as a plausible way to simulate such P2P networks. For instance, in our model, the initial generation of nodes’ chromosomes, their biological reproductions and mutations, and also the interactions among peers has a certain probability of occurrence. However, if the dynamics of the game changes or the actual payoff matrix of the game changes then results may be different, as shown Section 4.3.

The study and analysis of concrete behavioral patterns, and also the potential influences among themselves, represent the immediate future work. Moreover, it would be interesting to evaluate our co-evolutionary system with some type of fully stochastic and unobservable payoff values. In this case, the main goal might focus on either automatically deriving the optimum payoff matrix or reaching novel game dynamics.

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References


Fig. 6. Non zero-sum payoff matrix for simulating the framework proposed in [37].


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