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Power-law distributed temporal heterogeneity of human activities promotes cooperation on complex networks

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HIGHLIGHTS

- A modified evolutionary Prisoner's dilemma game on complex networks.
- Temporal heterogeneity of players' activities facilitates cooperation.
- Hubs play important role in the maintenance of cooperation.

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ABSTRACT

An evolutionary prisoner's dilemma game (PDG) with players located on Barabási–Albert scale-free networks is studied. The impact of players' heterogeneous temporal activity pattern on the evolution of cooperation is investigated. To this end, the normal procedure that players update their strategies immediately after a round of game is discarded. Instead, players update strategies according to their assigned reproduction time, which follows a power-law distribution. We find that the temporal heterogeneity of players' activities facilitates the prosperity of cooperation, indicating the important role of hubs in the maintenance of cooperation on scale-free networks. When the reproduction time is assigned to individuals negatively related to their degrees, a fluctuation of the cooperation level with the increase of the exponent β is observed.

1. Introduction

Cooperation plays an important role in the real world, ranging from biological systems to economic and social systems [1–3]. Understanding the emergence and persistence of cooperation among selfish individuals remains an important topic of game theory [4–7]. Among the many games, the prisoner's dilemma game (PDG), has attracted most attention in theoretical and experimental studies [8–10].

The standard PDG is described by the following set of rules [8]. When two players play a PDG, each of them can choose to cooperate (C) or defect (D). Each player will gain a payoff depending jointly on his choice and the opponent's choice. A cooperator receives R when playing with a cooperator, and S when playing with a defector, while a defector earns P when playing with a defector, and T against a cooperator, with $T > R > P > S$. Given this payoff ordering, in a well-mixed (unstructured) population where each agent interacts with all other agents (or a representative sample of the population composition), defectors are fitter and thus the fraction of cooperators asymptotically vanishes.

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Since cooperation is abundant and robust in nature, considerable efforts have been extended trying to understand the evolution of cooperation on the basis of the PDG. One of the proposed mechanisms to explain this phenomenon is network reciprocity. In Refs. [11,12], dramatic improvement in the maintenance of cooperation is observed when considering an evolutionary PDG on scale-free network structures. In these systems the competition between the cooperative and defective hubs (players with large number of neighbors) provides a mechanism enforcing the boom of cooperators. The claim is further confirmed in the study of the coevolution of strategy and network [13–15]. Remarkable increase of cooperation is also observed for those systems where the inhomogeneous imitation activity is introduced artificially to characterize the asymmetric and different influence of players to each other [16,17]. To sum up, the heterogeneity in either spatial structure or social influence strongly affects the evolution of games and favors the emergence of cooperation.

Recent empirical studies indicate that the human activities display a heavy-tailed nature that cannot be well characterized by the Poissonian approximation [18,19]. Examples include the email communication [20], the cell-phone communication [21], the short-message communication [22], the web page visits [23] and some other online activities [19,24]. Attempts have already been made to understand the influence of the heterogeneity and burstiness of human dynamics on the dynamics of information diffusion [25] and epidemic spreading [26] as well. These phenomena lead to a natural and interesting question: what influence will the temporal heterogeneity of players' activities has on the evolutionary games?

In general, there are two time scales in the game dynamics, one is interaction time scale, which characterizes how frequently the individuals interact with each other, and the other is strategy-selection time scale, which depicts how frequently they modifies their strategies. Most previous researches assume the two time scales are identical, i.e., the individuals immediately update their strategies after one round of game. However, it has been reported that if the two time scales are nonidentical, the final evolutionary results can change dramatically compared to identical cases [27–29]. Take [28] for example, Wu et al. studied the diversity of reproductive time scale on the evolution of cooperation, and found a remarkable increase of cooperation through the introduction of a bimodal distribution of reproduction rate of players.

In the present work, focusing on the influence of the inhomogeneous human activity pattern on the game dynamics in complex networks, we extend the work in Ref. [28] by proposing a new update rule: players update their strategies not immediately after a round of game, but according to their assigned reproduction time which follows a power-law distribution. Our investigation shows that the combination of the spatial effect and the inhomogeneous reproductive time scale boosts cooperation, indicating the important role of high-degree hubs in the maintenance of cooperation on scale-free networks. On the other hand, the cooperation may be affected or even inhibited when the impact of individuals with smaller connectivity is enforced. We believe such consideration would gain more instructive insights in understanding the evolution of cooperation in real world.

In the following section, we define our evolutionary PDG model. In Section 3, we present our numerical results and analysis. Conclusions are given in Section 4.

2. Model

We study the PDG with pure strategies: the players can either defect (D) or cooperate (C). The players are disposed on Barabási–Albert scale-free networks, and each player interacts only with its nearest neighbors and collects profits depending on the payoff parameters. Unless otherwise stated, the accumulated payoff f_x (gain from all interactions of player x [11,12]) is adopted as the payoff of player x in each generation. Following common studies, the PDG is rescaled such that it depends on a single parameter, i.e., the parameters are chosen to be $R = 1, P = S = 0$, and $T = b$, representing the advantage of defectors over cooperators (or the temptation-to-defect). The same as in Refs. [30,31], the best-takes-over update rule is used determining the transformation of player's strategy. That is, whenever an individual node is updated, the strategy of one of its neighbors (including the node itself) with the highest payoff in the last round will be imitated.

Since our main focus is to evaluate how the heterogeneity of players' activity affects the evolution of cooperation, we discard the normal procedure that individuals update their strategies immediately after one round of game. Instead, we consider the situation that the interaction and the strategy-selection time scales for the individuals are nonidentical. This is realized in Ref. [27] through the introduction of a parameter representing the ratio between the selection and interaction time scales, whereas in Refs. [28,29] by implementing probabilistic strategy updating.

Scientists, from both theoretical and experimental aspects, have pointed out that Poissonian individuals with different acting rates and periodical activity can lead to heavy-tails in the population level [32,33]. Hence, in our PDG model, each player is firstly assigned a constant updating rate in terms of its reproduction time Δt. Δt varies with different individuals, following a power-law distribution. During one round of the game, each player interacts with its nearest neighbors and collects profits. Here, we implement the synchronous strategy-updating dynamics [34]. What is different with the classic approach is whether a player updates its strategy or not in one round of the game depends on its reproduction time. For example, suppose the ith player is assigned with a reproduction time $\Delta t_i = 3$, then it updates its strategy only at the rounds (or time steps) $3, 6, 9, \ldots$. The payoff of every player is set to zero after each round of the game.

To avoid some strikingly long time scales, we set a cell limit M, and the task turns to be the generating of the following probability function

$$P(k) \propto k^{-\beta}, \tag{1}$$