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The maintenance of cooperation in multiplex networks with limited and partible resources of agents

Zhaofeng Li, Bi Shen, Yichuan Jiang *

Distributed Intelligence and Social Computing Laboratory, School of Computer Science and Engineering, Southeast University, Nanjing 211189, China

HIGHLIGHTS

- Agents play iterated public goods game in multiplex networks with limited and partible resources.
- High degree diversity in one layer promotes cooperation in multiplex networks.
- Degree differences between conjoint nodes encourage cooperative behaviors.
- A greedy-first mechanism that facilitates the emergence of cooperation is proposed.

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ABSTRACT

In this paper, we try to explain the maintenance of cooperation in multiplex networks with limited and partible resources of agents: defection brings larger short-term benefit and cooperative agents may become defective because of the unaffordable costs of cooperative behaviors that are performed in multiple layers simultaneously. Recent studies have identified the positive effects of multiple layers on evolutionary cooperation but generally overlook the maximum costs of agents in these synchronous games. By utilizing network effects and designing evolutionary mechanisms, cooperative behaviors become prevailing in public goods games, and agents can allocate personal resources across multiple layers. First, we generalize degree diversity into multiplex networks to improve the prospect for cooperation. Second, to prevent agents allocating all the resources into one layer, a greedy-first mechanism is proposed, in which agents prefer to add additional investments in the higher-payoff layer. It is found that greedy-first agents can perform cooperative behaviors in multiplex networks when one layer is scale-free network and degree differences between conjoint nodes increase. Our work may help to explain the emergence of cooperation in the absence of individual reputation and punishment mechanisms.

1. Introduction

One of the most critical problems in evolutionary dynamics is to find the reason for the maintenance of cooperative behaviors when defective behaviors can lead to larger short-term benefits [1,2]. Recently, the empirical resolution of different linking types has been improved [3,4], and the real social systems can be described as a superposition of several complex social networks, which is commonly named as multiplex networks [5–9]. Many studies have generalized evolutionary games into multiplex networks and accounted for the positive effects of multiplex structure on evolutionary

* Corresponding author.
E-mail addresses: lizhaofeng@live.cn (Z. Li), sbshenbi@gmail.com (B. Shen), yjiang@seu.edu.cn (Y. Jiang).

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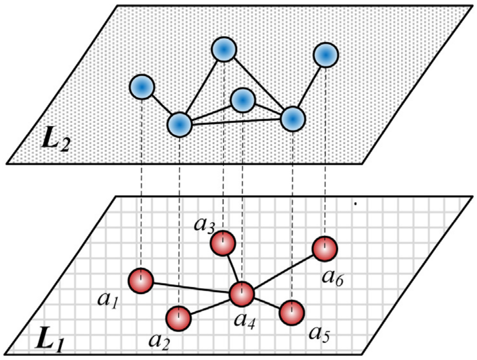

Fig. 1. Illustration of multiplex networks.

cooperation [10–17]. Some studies also consider several ways of linking different networks, which focus on the effects of the interconnections among different layers [18,19]. In conjoint layers of multiplex networks, each agent is usually expected to cooperate in multiple games simultaneously. However, few works have considered the "payment capability" which indicates the maximum disposable resources (costs) of the agent and the restriction between costs of multiple games. The limited resources of agents are common restrictions in many multi-agent systems [20,21] and real social systems [3].

This raises a fundamental problem for evolutionary cooperation in multiplex networks: *How do the limited resources of agents affect the positive effects of multiplex structure on cooperation evolution*? Because of larger short-term benefits, defective behaviors can be easily imitated. Therefore, can cooperative behaviors finally disappear if some agents have to defect in partial interactions due to the unaffordable costs of cooperation in all the interactions?

In this case, there are two defective temptations that can inhibit cooperative behaviors in a certain layer. The first temptation is the higher temporal payoffs of defective neighbors, which is inherent in the maintenance of evolutionary cooperation [1,2,22]. Most present studies focus on network reciprocity of multiplex structure which means that cooperative behaviors can exist and diffuse if agents can aggregate into cooperative clusters [23]. The second temptation originates in different payoffs of allocated resources in multiple layers, which may lead to the disappearance of cooperation in the lower-payoff layers. To ensure the non-zero payoff in some layers, agents should contribute parts of resources in multiple layers or adopt biased allocation strategies in different layers. Therefore, it is necessary to design efficient mechanisms to induce proper strategies of resource allocation in multiple layers.

Our work utilizes the effects of network structure and designs evolutionary mechanisms to ensure the cooperative behaviors in iterated public goods games (PGGs) with limited and partible resources of agents. First, to defeat the temptation of defective neighbors in a certain layer, we generalize degree diversity [24] into multiplex networks. Second, we design a greedy-first evolutionary mechanism to prevent the disappearance of cooperation in the lower-payoff layer. The greedy-first agents prefer to imitate the allocation strategies of neighbors in the higher-payoff layer. Correspondingly, a generous-first mechanism, that means agents tend to improve the payoffs in the lower-payoff layer, is also proposed to highlight the effect of greedy-first mechanism.

Specifically, we give specific conditions to analyze how degree diversity and greedy-first mechanism can promote cooperative behaviors in multiplex networks. It is worth noting that Santos et al. [24] firstly introduce the degree diversity in PGGs, which is played in the single-layer network with binary contributions of resources. In this paper, we further extend the close relationship between degree diversity and the maintenance of cooperation from two additional perspectives. First, cooperative behaviors in multiplex networks can be promoted if degrees of nodes in one layer are highly diverse. Second, evolutionary cooperation can also be facilitated by the differences between degrees of conjoint nodes in multiple layers. Moreover, greedy-first mechanism utilizes the human instinct of searching higher benefits and may help to understand the emergence of cooperation. In particular, our work suggests that cooperative behaviors can be controlled by varying the degree diversity in multiplex networks.

2. Model statement

2.1. Topology and agent

Multiplex networks consist of two or more layers. In our model, we only consider the case of duplex networks which have two layers denoted by L_1 and L_2, and each layer indicates one type of relationship between humans. Parallel graphs, which are conjoint by cross-layer paths, are usually used to represent multiplex networks [8,9]. As shown in Fig. 1, each agent represents a pair of conjoint nodes and is linked with different sets of agents in the duplex layers. For agent i, the notation $N_i^{L_1}$ ($N_i^{L_2}$) denotes the set of i and its neighbors, and $k_i^{L_1}$ ($k_i^{L_2}$) denotes the degree of i in L_1 (L_2), respectively.

Agent i possesses a constant amount of resources R_e. For the sake of simplicity, R_e is identical for all the agents and set as one unit. The notations $c_i^{L_1}$ and $c_i^{L_2}$ indicate the percentage of resources that are allocated in each layer. Thus, $c_i^{L_1} \geq 0$,