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Cooperation and strategy coexistence in a tag-based multi-agent system with contingent mobility

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ABSTRACT

Understanding how to enhance cooperation and coordination in distributed, open, and dynamic multiagent systems has been a grand challenge across disciplines. Knowledge employed in such systems is often limited and heuristic in nature such that cooperation-promoting mechanisms based on trust or reputation become largely unreliable. Although recent studies within the context of tag-based systems reported the emergence of stable cooperation in such uncertain environments, they were limited exclusively to only static interaction structures. Consequently, it remains unknown whether and under what conditions tag-based interactions can promote cooperation in dynamic mobile systems. We herein combine the methods of game theory, evolutionary computing, and agent-based simulation to study the emergence of tag-mediated cooperation in a mobile network with resource diversity. In a series of extensive Monte Carlo simulations, we find that tag-based interactions can give rise to high levels of cooperation even in the presence of different types of contingent mobility. Our model reveals that agent migrations within the system and the invasion of new agents from the outside can have similar effects on the evolution of dominant strategies. Interestingly enough, we observe a previously unreported coexistence of conditional and unconditional strategies in our tag-based model with costly migrations. Differently from earlier studies, we show that this mobility-driven strategy coexistence in our model is not affected by resource limitations or other game-specific factors. Our findings highlight a striking robustness of tag-based cooperation under different mobility regimes, with important consequences for the future design of cooperation-enforcing protocols in large-scale, decentralized, and self-organizing systems such as peer-to-peer or mobile ad-hoc networks.

1. Introduction

For decades, evolutionary economic games have played a major role in the study of strategic decision making and cooperative behavior in social dilemmas [1]. Advanced mathematical and computational models, originally dedicated to the exploration of theories of cooperation and coordination in biological and social systems, have attracted much recent attention in applied information sciences and knowledge-based information technology [2–4], whenever cooperation among constituent units of a system is necessary for its functioning but is missing or difficult to maintain due to an ever-present incentive for selfish behavior [5,6]. Indeed, improving the management of common-pool resources [7] and the design of associated cooperation-enforcing protocols [2,3,8] is highly desirable in most engineered, large-scale, and distributed systems such as peer-to-peer (P2P) networks [9], mobile ad-hoc networks (MANETs) [10], multi-agent robotic systems [11], delay-tolerant networks (DTNs) [12], social networking technologies [13], or other related networks of opportunistic contacts [14].

Although various protocols for enforcing cooperation in these systems have been proposed [8,15,16], those relying exclusively on game-theoretic principles [4–6,17] are surprisingly rare. One type of such protocols employing game theory is based on tags, discernible phenotypic markings, that are harnessed for similarity-based interactions [18–31]. By using tags, individuals naturally direct cooperative acts towards sufficiently similar tag-mates, while simultaneously channeling their benefits away from dissimilar opponents. This behavior ultimately leads to a stable assortment of cooperators which is not necessarily confined to a physical space. Instead, the clustering of tag-based altruists in the virtual space of phenotypes [22] is entirely sufficient for the emergence

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of global cooperation. Tag-mediated interactions can thus generate substantial levels of cooperation even in aspatial interactions [22,25,32] which are otherwise known as detrimental to cooperative behavior [33].

Similarly to simple heuristics [34], tag-based strategies for cooperation are highly robust [19], cognitively effortless [18], and computationally simple [5], as they only partially employ the available information in the environment relying instead on a single cue, without the need for storing that information for its subsequent processing [35]. Consequentially, neither the memory for previous encounters nor the explicit knowledge of relatedness among interactors is required for the emergence and sustenance of cooperation in tag-based systems. Tag-mediated interactions may therefore particularly be useful in promoting cooperation in the absence of trust [6,9] and reputation [4,36] mechanisms, i.e., when individuals are unable to gain information about the actions of others [18], as in one-shot interactions [26]. Additionally, as has been observed previously with other mechanisms [37], tags combined with spatial structure and memory [28] can give rise to surprisingly novel dynamics, by restoring cooperative behavior in an otherwise detrimental environment or by further elevating cooperation levels when conditions are already favorable.

Most of these advantages of tag-based cooperation are also desirable in other large-scale, decentralized, and mobile networks of wirelessly linked devices such as MANETs, whose ad-hoc network protocol performance critically depends on the type of mobility exhibited by the system [38]. Over the last two decades, many models of mobility in cooperative systems have been advanced, with either random [39,40] or non-random, contingent migratory behaviors [35,41–43]. Nevertheless, in spite of their abundance, the overall findings of these theoretical studies remain rather inconclusive, as they have often revealed not only facilitatory, but also inhibitory effects of mobility on cooperation. In line with theoretical reports, more recent empirical investigations [44,45] further corroborate these mixed findings, indicating that precise conditions under which diverse types of migratory behaviors can foster cooperation are yet to be identified. Indeed, movement can lead to exaggerated separation [46] and the associated global defection by dissolving cooperation-sustaining clusters, but it can also give rise to strong patterning and dominant cooperation via deletion of unsatisfactory connections and the reduced competition for resources [39].

However, even though tags can either establish or further enhance cooperative behavior, their cooperation-promoting potency under mobile regimes is still unknown. To the best of our knowledge, tag-based cooperation has not been studied previously in the context of mobile systems, which is hence the task that we enthusiastically undertake in the present paper, as the first-ever study on tag-mediated cooperation with migrations. More specifically, since many technological networks are inherently mobile and the effects of migrations on cooperation are generally difficult to anticipate [39], the question remains whether and under what conditions tag-based interactions can promote cooperation in distributed, large-scale, multi-agent systems even in the presence of mobility.

Long-range or global migrations [47] are often regarded as highly detrimental to cooperation as they knowingly generate a well-mixed state in the studied population, typically favoring defectors over cooperators. Nevertheless, opposite findings with positive effects of long-range mobility on cooperation have also been reported recently [48]. Differently from most earlier studies which established cooperation-promoting effects of only local migrations, we hypothesized that tag-mediated interactions in our multiagent-based model can promote cooperation under both local and global mobility regimes. We further expected that cooperation in a tag-based mobile system should depend not only on the internal, within-system migrations and the actual movement radius, but also on the rate at which new agents are entering the system from the outside.

To address these assumptions, we institute an evolutionary, multiagent-based model of tag-mediated cooperation with mobility structure and limited resources. In a series of computer-based Monte Carlo simulations, we investigate the effects of two different migration types, the role of the migration radius, and the effects of the invasion rate of newcomer agents on the evolution of four competing strategies. Importantly, earlier models of tag-based cooperation (e.g. [19,26,27,49,50]) typically assumed that only a single-agent invasion can occur at each time step, ignoring thereby the possibility of realistically larger immigration rates. Common to these models is their convergence on the finding that largely one single strategy, namely, conditional 'ethnocentric' cooperation, robustly dominates over all other competing strategies. In our present model, on the other hand, in addition to internal migrations we study the role of immigration by systematically varying the rate at which new agents invade the simulated system. We thus address not only the internally dynamic, fluid nature of intra-network connections, but we also consider the fact that complex networks represent inherently open systems [51] subject to a continuous growth and linking to new incoming units, which is a hallmark of real-world technological networks.

With respect to variable resources that were implemented in our model, their heterogeneity was previously shown to enhance cooperation [52] and produce coexistence of unconditional strategies [53]. However, in a model with mobility structure, two unconditional strategies, and no tags [54], migratory behaviors were found to prevent such strategy coexistence in the long term. Moreover, earlier studies suggest that coexistence of strategies seems to be restricted to only certain types of evolutionary games such as the snowdrift [24], cyclic [55], and public goods games [56], and is a rather unstable, transient phenomenon.

We were therefore wondering if our tag-mediated cooperation model with variable resources, costly migrations, and different immigration rates could give rise to a stable coexistence of both unconditional and conditional strategies, and whether such coexistence can emerge also independently of resource limitations in our model with prisoner's dilemma-like interactions. Such a finding would allow us to shift away from previous theories of ethnocentric dominance [18,19,22,27,49] and to move towards a better understanding of conditions under which alternative evolutionary scenarios can emerge in tag-based systems [23,29].

Variability and re-growth of resources in our computational model can be interpreted in the context of P2P networking sites for file-sharing: Renewable resources can roughly be seen as files and their updates that can be shared and downloaded by registered users of a P2P network. If a certain number of users are detected as free-riders (i.e., they download the files provided by others but do not upload and share their own files in return), it would be natural to punish them and restrict their downloading capacity in the system. Earlier investigations [5,57], however, suggest that such resource restrictions or other centralized measures may not be necessary in tag-based systems with static structures, where one should instead harness tags and the associated tag-mediated strategies to enhance cooperation among generous peers and to drive it away from selfish defectors. Nevertheless, it remains unclear if tags alone are sufficient for free-rider neutralization also in mobile systems, where users are more frequently exposed to changes of their interaction partners and consequentially more susceptible to exploitation, or whether a combination with other mechanisms (including limited resources) is required under such dynamic conditions.

We employ the agent-based framework [58–63] because the multi-agent paradigm can easily be superimposed on the archi-

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