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The value of less connected agents in Boolean networks

Daniel Epstein, Ana L.C. Bazzan *

PPGC/Instituto de Informática, Universidade Federal do Rio Grande do Sul (UFRGS), Caixa Postal 15064, 91.501-970 Porto Alegre, RS, Brazil

HIGHLIGHTS

- We consider realistic network topologies, based on preferential attachments.
- Random Boolean networks are used to guide agents in their decision-making.
- Reinforcement learning allows agents to select efficient strategies.
- Agent-based modeling and simulation is used to draw conclusions about individuals.
- Two scenarios: the El Farol Bar Problem and route choice.

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ABSTRACT

In multiagent systems, agents often face binary decisions where one seeks to take either the minority or the majority side. Examples are minority and congestion games in general, i.e., situations that require *coordination among the agents* in order to depict efficient decisions. In minority games such as the El Farol Bar Problem, previous works have shown that agents may reach appropriate levels of coordination, mostly by looking at the history of past decisions. Not many works consider any kind of structure of the social network, i.e., how agents are connected. Moreover, when structure is indeed considered, it assumes some kind of random network with a given, fixed connectivity degree. The present paper departs from the conventional approach in some ways. First, it considers more realistic network topologies, based on preferential attachments. This is especially useful in social networks. Second, the formalism of random Boolean networks is used to help agents to make decisions given their attachments (for example acquaintances). This is coupled with a reinforcement learning mechanism that allows agents to select strategies that are locally and globally efficient. Third, we use agent-based modeling and simulation, a microscopic approach, which allows us to draw conclusions about individuals and/or classes of individuals. Finally, for the sake of illustration we use two different scenarios, namely the El Farol Bar Problem and a binary route choice scenario. With this approach we target systems that adapt dynamically to changes in the environment, including other adaptive decision-makers. Our results using preferential attachments and random Boolean networks are threefold. First we show that an efficient equilibrium can be achieved, provided agents do experimentation. Second, microscopic analysis show that influential agents tend to consider few inputs in their Boolean functions. Third, we have also conducted measurements related to network clustering and centrality that help to see how agents are organized.

1. Introduction

One of the major research directions in adaptive and self-organizing systems is dedicated to learning how to coordinate decisions and actions of multiple agents. Also, it is important to understand whether individual agents' decisions can lead

* Corresponding author. Tel.: +55 5133086823.
E-mail addresses: depstein@inf.ufrgs.br (D. Epstein), bazzan@inf.ufrgs.br (A.L.C. Bazzan).

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to globally optimal or at least acceptable solutions. Our long term research aims at studying the effect of several types of strategies for self-organization of agents in complex systems. The present paper addresses simulation of agents' decision-making regarding a well-known problem in collectives in general [1] and in minority games in particular.

We use two distinct scenarios. The first is the *El Farol* Bar Problem (EFBP), proposed by B. Arthur [2], which has also been the subject of, e.g., Refs. [3,4]. The idea behind this metaphor is that a common situation people face is when one has gone to his/her favorite pub only to find out that it happened to be overcrowded that night, leading to one regretting not to have stayed home.

The metaphor of rewarding the decision that is made by the minority of the players (or agents) is interesting in many scenarios. For instance, in agent-based simulation of traffic, a minority game is clearly useful to model route choice. This leads us to the second scenario, which deals exactly with iterated route choice (IRC) in vehicular traffic networks.

Minority games have been the focus of many works. Regarding the general idea, the most similar works to the present paper have appeared in Ref. [5] and in Ref. [6]. In all these cases, the authors have also considered agents in a kind of social network. However, the connectivity was such that the average number of neighbors with whom each agent interacts was fixed. In the present paper we use a topology with preferential attachment in the sense of Barabási and Albert [7], which basically means that a few nodes have big connectivity while the majority of the nodes are connected to just another node. Also, we go beyond classical minority games such as the EFBP – where the reward is binary – and propose that the use of the RBN formalism can model a wider class of games. Here we discuss the two applications previously mentioned.

The rest of this paper is organized as follows: The next two sections review some works on the EFBP and its more general version, the minority game (Section 2), and explain how the RBN formalism works (Section 3). Following these, in Section 4 our methods are presented. Simulation results and their analysis then follow. Finally, Section 6 discusses several aspects of this work and its future directions, and provides concluding remarks.

2. Related work on minority games, and route choice

Microeconomics and game-theory assume human behavior to be rational and deductive—deriving a conclusion by perfect logical processes from well-defined premises. But this assumption does not hold especially in interactive situations like the coordination of many agents. There is no *a priori* best strategy since the outcome of a game depends on other players. Therefore, bounded and inductive rationality (i.e., making a decision based on past experience) is supposed to be a more realistic description.

In this context, in 1994, B. Arthur introduced a coordination game called the *El Farol* Bar Problem. Every week n players wish to visit the bar *El Farol*. Up to a certain threshold ρ of customers the bar is very comfortable and enjoyable. If it is too crowed, it is better to stay home. The payoff of the game is clear: if the number of visitors is less than the threshold ρ, these visitors are rewarded, otherwise those who stayed home are better off. In the original work, $n = 100$ and $\rho = 60$ were used, but arbitrary values of n and ρ have also been studied, as e.g., in Ref. [4].

The players can only make predictions about the attendance for the next time based on the results of the previous m weeks. For the decision whether to go or to stay home, the player always selects the strategy that predicts the outcome of the last weeks most accurately. Computer simulations have shown that the mean attendance converges to the threshold $\rho = 60$.

Later, the EFBP was generalized to a binary game by Challet and Zhang [3], the so-called Minority Game (MG). An odd number n of players has to choose between two alternatives (e.g., yes or no, or simply 0 or 1). With a memory size m there are 2^{2^m} possible strategies. Each player has a set S of them. These are chosen randomly out of the whole set. In the simplest version of the game, players are rewarded one point if they are in the minority group. Other functions that favor, for instance, smaller minorities were studied by several authors as, e.g., Refs. [8,4].

The MG and the EFBP are gradually becoming a paradigm for complex systems and have been recently studied in detail. We will refer briefly to some of the results.

In their original work, Challet and Zhang [3] have systematically studied the influence of the memory size m and number of strategies S on the performance of the game.

B. Edmonds [9] has investigated the emergence of heterogeneity among agents in a simulation. His paper tackles evolutionary learning as well as communication among agents, which might lead to a differentiation of roles at the end of the run.

Still regarding the EFBP, the most similar work to the present paper has appeared in Ref. [5]. However, the focus there is resource allocation: agents using particular resources are rewarded or punished according to the availability of these resources. Also, agents use a set of strategies to decide which resource to choose, and use a simple reinforcement learning scheme to update the accuracy of strategies. A strategy is a lookup table that suggests to an agent what resource to choose based on the actions of its neighbors at the previous time step. This way, these authors have also considered agents in a kind of social network. However the connectivity is such that the average number of neighbors with whom each agent interacts is fixed. In the present paper we use a topology with preferential attachment [7], which basically means that a few nodes have big connectivity while the majority of the nodes are connected to just another node.

In more general terms, there has been an interesting line of research connecting minority games and collective intelligence such as Ref. [10]. For a discussion see Ref. [1].