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Influence maximization of informed agents in social networks

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ABSTRACT

Control of collective behavior is one of the most desirable goals in many applications related to social networks analysis and mining. In this work we propose a simple yet effective algorithm to control opinion formation in complex networks. We aim at finding the best spreaders whose connection to a reasonable number of informed agents results in the best performance. We consider an extended version of the bounded confidence model in which the uncertainty of each agent is adaptively controlled by the network. A number of informed agents with the desired opinion value is added to the network and create links with other agents such that large portion of the network follows their opinions. We propose to connect the informed agents to nodes with small in-degrees and high out-degree that are connected to high in-degree nodes. Our experimental results on both model and real social networks show superior performance of the proposed method over the state-of-the-art heuristic methods in the facet of opinion formation models.

1. Introduction

Network science has attracted much attention in recent years, which is mainly due to the recent advances in graph theory and availability of huge datasets [1]. Sociology has benefited from these advances in network science and many scholarly works have been carried out on social networks analysis and mining. Suppose that we are about to market a new product, to promote an innovation or to debate the candidacy of a novice in the parliament. Or even in other applications, such as controlling a set of dynamical systems, in which, similarly each person is considered as a single dynamical system and the whole environment is a complex network, different systems start to affect each other [2]. All of which, explicitly or implicitly, contain an opinion formation process within the interference in a social network of people in which some kind of consensus process happens between the agents. In this literature, researchers have designed a suitable and accurate system that in which feedback loops, instabilities and cascade effects are considered in order to simulate a natural system. In such a paradigm, called complexity science, models and eventually results would be more realistic. [3]. The ultimate goal is to efficiently model this phenomenon and find the best strategy to propagate a desired opinion between the individuals with the lowest possible cost. Such a goal can be achieved by employing informed agents in the society [4]. The society is considered as a graph in which nodes represent individuals (or agents) and edges represent the interactions between them. Every agent has a value indicating his/her interest, taste or tendency toward an objective. This value is referred to as the *opinion* of the agent.

As two persons meet and interact, they make their opinions closer by some kind of update process. Opinion formation is a generic form of information diffusion, information cascade or innovation propagation which is proposed to mathematically

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describe the concepts observed in real-world networks. There are several applications regarding such models such as community detection [5], large-scale non-convex optimization [6], analysis of opinion formation by informed agents [4], and forecasting final opinions in a social network [7]. In this work, we consider each person as a particle and propose a measure for selecting the individuals maximizing the desired diffusion. The result of this study could be useful in influence maximization in terms of economics, targeted virus immunization and finding the optimal strategy in social advertisements. A number of methods have been proposed to model this opinion formation process [8]. For instance, Voter model represents selection between two distinct opinions; a political electoral system among two parties is of this kind [9,10]. Likewise, there are other models for opinion dynamics in the literature that are based on binary opinions [11–16]. In more recent models, opinions are represented as the outcome of social or cultural traits of the people who live together as discrete [17] or continuous values [18,19]. Related to this, one can also mention co-evolutionary games that integrate cooperation between competitive agents and concepts of network consensus [20,21]. These methods provide a theoretical framework to cover the phenomena, such as herding effects, social shifts and interactions among living organisms [22]. The viewpoint of these game theoretical methods sheds more light on several cooperation problems. For instance, in the Prisoner's Dilemma game, this knowledge could be used to find the optimal maximal degree warranting the best information exchange among influential players [23].

In this manuscript, we aim at finding the best communication strategy in order to maximize the influence of informed agents on the opinions of other agents. Given the structure of a social network, we would like to determine a subset of agents whose connecting to the informed agents will cause the best consensus properties (e.g., largest portion of the agents getting into a consensus towards the desired opinion) in the network. In this regard, there are some heuristic methods such as high-degree, high-betweenness and high-closeness nodes [24,25], and even more sophisticated metrics that we take into account [26]. In this manuscript, we introduce a heuristic algorithm and show that it outperforms a number of other algorithms. This model involves agents with continuous opinions in a range between two boundaries and a synchronous discrete time update scheme based on bounded confidence model. The model is numerically simulated on both artificially generated and real social networks and the results reveal its effectiveness.

2. Background

2.1. Opinion formation with social power

A class of opinion formation models is defined based on continuous opinion values and a special opinion update rule [27–34]. In these models, each individual takes two deterministic continuous values: the opinion and the uncertainty. Each agent updates his/her opinion through communications with his/her neighbors. The opinion of agent i can change over a range as [28]

$$[x_i - u_i, x_i + u_i], \tag{1}$$

where x_i is the opinion of node i and u_i is its uncertainty. The uncertainty can model personal characteristics of the agents. For instance, sociable agents have higher values of uncertainty than unsociable ones.

Let us consider a directed network on which the individuals interact with each other. These individuals discuss their opinions, and if they meet some criteria, their opinion values will be updated [30,35]. Deffuant et al. introduced an opinion formation model, denoted as bounded confidence model, that has an iterational process [28]. In each iteration, a node and one of its neighbors are selected randomly. If they have close enough opinions, they will make their opinions closer to each other. In general, two sets of information are important in updating the opinion values: neighborhood between the individuals and the difference between their opinion values. Individuals are affected only by those with a direct link on the network, i.e., their neighboring nodes. Furthermore, an agent influences the opinion of its neighbors if the distance between their opinions is less than a certain threshold. Let us consider a network of size N. At each step, one of the existing links between nodes i and j having the opinions x_i and x_j (that each can take a value in the range $[-1, +1]$) is randomly chosen. If the difference between the opinions of the two neighboring agents is less than a specified threshold, commonly called uncertainty of the one who is influenced, i.e., $|x_i - x_j| < u_i$, they will influence each others' opinions through the following opinion update equations

$$\begin{cases} x_i(t+1) = x_i(t) + \mu[x_j(t) - x_i(t)] \\ x_j(t+1) = x_j(t) + \mu[x_i(t) - x_j(t)] \end{cases}, \tag{2}$$

where t indicates time-step of the simulation process. If the bounded confidence condition does not hold, i.e., the difference of the opinions is larger than u_i indicating the uncertainty of agent i, no update will be made in the opinion values. μ is the convergence rate (opinion change rate) parameter, which often takes a value between 0 and 1. We implement a synchronous update scheme for the agents and perform the numerical simulations with large enough iterations to ensure that the maximum possible consensus has happened. We then monitor the final opinion values. In this way, we make sure the method is converged as the opinion trend do not change dramatically afterwards.

In the original bounded confidence model, all of the agents have the same influence on their neighbors. However, in real networks, people have different social capabilities, political situations, incomes, or physical features, and thus different *social*