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Models of network excitation control

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Abstract

This paper studies models of centralized, decentralized and distributed control of excitation in a network of interacting purposeful agents. As examples, we analyze models of threshold behavior and mob control.

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1. Introduction

Consider a set of interconnected agents having mutual influence on their decision-making. Variations in the states of some agents at an initial instant accordingly modify the state of other agents. The nature and character of such dynamics depend on the practical interpretation of a corresponding network. Among possible interpretations, we mention propagation of excitation in biological networks (e.g., neural networks [21]), failure models (in the general case, structural dynamics models) in information and control systems and complex engineering systems, models of innovation diffusions, information security models, penetration/infection models, consensus models and others, see an overview in [3].

The control problem of purposeful "excitation" of a network possesses the following statement. Find a set of agents to apply an initial control action such that a network reaches a required state. This abstract setting covers informational control problems in social networks [3], [6], control problems for collective threshold behavior [1], [11], [12], information security problems [3], etc. For definiteness, further exposition runs in terms of social networks.

Let $N = \{1, 2, ..., n\}$ stand for a finite set of *agents*; they form a *social network* described by a directed graph $\Gamma = (N, E)$, where $E \subseteq N \times N$ denotes the set of arcs. Each agent is in one of two states, "0" or "1" (passivity or activity, being unexcited or excited, respectively). Designate by $y_i \in \{0; 1\}$ the state of agent i ($i \in N$) and by $y = (y_1, y_2, \ldots, y_n)$ the vector of agents' states. For convenience, transition from passivity to activity is called the "excitation" of an agent.

Assume that, initially, all agents appear passive and the dynamics of the network is described by a mapping Φ: $2^N \to 2^N$. Here $\Phi(S) \subseteq N$ indicates the set of agents having state "1" at the end of the transient process caused by network "excitation"; the latter represents the variation (switching from passivity to activity) in the states of agents from the set (*coalition*) $S \subseteq N$, which takes place at the initial instant. We emphasize that control actions are applied singly.

Concerning the mapping $\Phi(\cdot)$, suppose that it enjoys the following properties:

A.1 (reflexivity). $\forall\ S \subseteq N$: $S \subseteq \Phi(S)$;

A.2 (monotonicity). $\forall\ S, U \subseteq N$ such that $S \subseteq U$: $\Phi(S) \subseteq \Phi(U)$.

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A.3. (convexity). $\forall$ S, $U \subseteq N$ such that $S \cap U = \varnothing$: $\Phi(S) \cup \Phi(U) \subseteq \Phi(S \cup U)$.

For a given mapping $\Phi(\cdot)$, it is possible to define a function $\hat{G} = \{0; 1\}^n \to \{0; 1\}^n$, which associates the vector y of initial states of agents with the vector of their final states:

$$\hat{G}_i(y) = \begin{cases} 1, \text{if } i \in \Phi(\{j \in N \mid y_j = 1\}) \\ \quad 0, \text{otherwise.} \end{cases}.$$

Similarly, we easily define the states of agents "excited indirectly":

$$G_i(y) = \begin{cases} 1, \text{if } \hat{G}_i(y) = 1 \text{ and } y_i = 0 \\ \quad 0, \text{otherwise} \end{cases}, \ i \in N.$$

The paper is organized as follows. Section 2 poses the centralized control problem of network excitation and focuses on a special case with threshold behavior of agents. Section 3 gives a formal statement of the decentralized control problem when agents make independent decisions on their "excitation." Moreover, the issue of implementability of efficient or given states of a network is investigated from the game-theoretic view. The problem of mob control serves as a possible application. The conclusion outlines promising research directions for models of network excitation control.

2. Centralized control problem

Consider given functions C: $2^N \to \Re^1$ and H: $2^N \to \Re^1$. The former characterizes the costs $C(S)$ of initial variation in the states of agents from a coalition $S \in 2^N$, while the latter describes the income $H(W)$ from the resulting "excitation" of a coalition $W \in 2^N$. The subjects incurring these costs depend on a specific statement of the problem.

The goal function of a control subject (a *Principal*) is the difference between the income and the costs. For the Principal, the *centralized control problem* lies in choosing a set of initially excited agents to maximize the goal function $v(S)$:

$$v(S) = H(\Phi(S)) - C(S) \to \max_{S \subseteq N} . \tag{1}$$

In this setting, the Principal incurs the costs and receives the income.

In the general case (without additional assumptions on the properties of the functions $C(\cdot)$ and $H(\cdot)$, and on the mapping $\Phi(\cdot)$), obtaining a solution $S^* \subseteq N$ of the discrete problem (1) requires exhausting all 2^n possible coalitions. The design of efficient solution methods for this problem makes an independent field of investigations (we refer to [17], [23], [29], etc. for several successful statements of optimization problems for system's staff, which employ rather simple algorithms). The state S^* of the social network, maximizing the goal function (1), will be called *efficient*.

A special case engages the cost function and income function being additive with respect to agents:

$$u(S) = \sum_{i \in \Phi(S)} H_i - \sum_{j \in S} c_j , \tag{2}$$

where $(c_i, H_i)_{i \in N}$ are known nonnegative constants. For the time being, we deal with the additive case (2) for simplicity.

In the centralized control problem, agents (network nodes) are passive in some sense. Notably, the Principal "excites" agents from a set S, and then this excitation propagates according to the operator $\Phi(\cdot)$.

Alternative formulations of the control problem are possible, e.g., income maximization under limited costs (the so-called knapsack problem if the cost function and income function enjoy the additive property with respect to agents) or costs minimization for a given income.

Discrete problems of the form (1) demonstrate high computational complexity for large networks (i.e., networks with very many agents). Therefore, in such cases networks are treated as random graphs with specified probabilistic characteristics [1], [1], [7], [8] and the control problem is stated in terms of expected values (e.g., optimization of the expected number of excited agents), see [1].

Example: threshold behavior. Agents in a certain network have mutual *influence* on each other. Arc (i, j) from node i to node j corresponds to the influence of agent i on agent j (we believe that loops are absent). Denote by $N^{in}(i) = \{j \in N \mid \exists$

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