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Locating the source of spreading in temporal networks

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HIGHLIGHTS

- We propose a method for solving the problem of source location in temporal networks.
- We establish two models to depict the spreading process in temporal networks.
- We adopt four strategies based on nodes' importance to select the observers to improve the accuracy.

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ABSTRACT

The topological structure of many real networks changes with time. Thus, locating the sources of a temporal network is a creative and challenging problem, as the enormous size of many real networks makes it unfeasible to observe the state of all nodes. In this paper, we propose an algorithm to solve this problem, named the backward temporal diffusion process. The proposed algorithm calculates the shortest temporal distance to locate the transmission source. We assume that the spreading process can be modeled as a simple diffusion process and by consensus dynamics. To improve the location accuracy, we also adopt four strategies to select which nodes should be observed by ranking their importance in the temporal network. Our paper proposes a highly accurate method for locating the source in temporal networks and is, to the best of our knowledge, a frontier work in this field. Moreover, our framework has important significance for controlling the transmission of diseases or rumors and formulating immediate immunization strategies.

1. Introduction

Epidemic dynamical behavior can be observed in many real networks. Prototypical examples include epidemics transmission through social networks, virus propagation in communication networks, rumor transmission on the Internet, the cascading failure of power networks, and crises contagion through financial networks. Throughout history, epidemic outbreaks have brought about enormous losses for economies and society, from SARS in 2003 to the recent H7N9 flu outbreak. Therefore, many significant studies have examined the dynamics of epidemic outbreaks on networks [1–5]. However, these studies have focused on the forward problem of the diffusion process and its dependence on the rate of infection. Another challenging question regarding the diffusion process is the inverse problem of inferring the original source in a huge network relying on relatively limited observed nodal states. This problem has received considerable attention in recent years [6–9]. In 2012, Pinto et al. established a likelihood function connecting the real infected time lags with theoretical time lags, enabling the source to be located from relatively few observations [10]. To locate the source,

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Brockmann and Helbing identified an effective transmission distance to calculate the spreading time between nodes [11], whereas Fabrizio et al. constructed a Bayesian conditional probability model of all nodal states, and found the source using marginal probabilities via belief propagation [12].

The traditional analysis of source location is conducted on static networks, where it is assumed that the speed of a network's evolution is slower than the information transmission rate. Actually, most real networks are dynamic and temporal. There are many methods for modeling such temporal networks. In 2010, Martin and Bergstrom divided the observation window into periods and abstracted the temporal network into a static network in each period [13]. And Casteigts et al. used time-varying graphs to study temporal networks [14]. However, these methods are restricted by the limitations of static networks. To break away from this constraint, Holme and Saramaki proposed the idea of using line graphs to describe temporal networks [15], before Nakamura and Tanizawa introduced a linear model of time-varying properties that could be transformed into a network structure [16]. Recently, the special characteristics of temporal networks have attracted considerable attention [17]. With the development of research on temporal networks, the consideration of propagation dynamics has increased. Many scholars have studied the influence of "burstiness" on the spreading process [18]. In 2011, Karsai et al. derived a Poisson distribution to describe a network, and proposed a transmission ratio between this Poisson distribution and a power-law distribution based on the SI (susceptible–infected) model [19]. Similarly, a number of researchers have investigated other characteristics of temporal networks that have an impact on information propagation [20]. However, research into locating the source of the spreading process in temporal networks is inadequate. To this end, Liu et al. recommended an algorithm for optimizing particle swarms with scale-free interactions to find the optimum or hub nodes in the evolution process [21]. And Antulov-Fantulin et al. proposed a statistic method for finding the spreading source based on the time information of all nodes is known [22].

In this paper, we focus on depicting the spreading process and locating the transmission source in a temporal network. To the best of our knowledge, this is the first work in this field. In Section 2, we propose a diffusion process and consensus dynamics to model the spreading process based on the definition of a temporal network. We then propose a backward temporal diffusion process (BTDP) to effectively locate the spreading source in the temporal network. We also improve the strategy of selecting the observed nodes by expanding the indexes that measure the nodes' importance to the temporal network, such as the degree, closeness centrality, and PageRank. Our framework for locating the source in a temporal network is shown to be highly accurate and widely applicable. We believe this work has considerable significance to the problem of source location, and has the potential to drive the study of temporal networks.

2. The spreading process in temporal networks

Methods of modeling the dynamical behavior of propagation are generally based on the networks' topological structure, such as the diffusion model and consensus dynamics. In a static network, the process of information spreading happens in a fixed structure. In fact, the network structure changes with time, and we refer to this as a temporal network. In this paper, we assume that the scale of the network is constant and that linkages between nodes change over time. Thus, the dynamical spreading process is influenced by the time limit of the linkages. As we wish to study the dynamical spreading process in a temporal network, we should first to learn how to depict these networks.

2.1. Depicting a temporal network

Generally, a network can be expressed by a binary group $G = (V, E)$, where V is the set of all nodes and E is the set of all links. A temporal network considers the time of the interactions between the nodes on the basis of a static network. We define these interactions between individuals as events. An edge is only active when an event happens. Because every edge can have more than one event, the spread of information should satisfy the time limitation and the order. In a temporal network, the edges can be represented as tetrads $e_{ij} = (i, j, t_{ij}, \Delta t_{ij})$, which means that nodes i and j interact at time t for a period of Δt_{ij}. or example, in a mobile phone network, user A called user B at t_1 and finished the call at t_2. This event can be expressed as $(A, B, t_1, t_2 - t_1)$. As every call can be expressed by a tetrad in this format, the sequence of tetrads can be used to express the temporal mobile phone network. If these interactions between individuals are instantaneous or the duration can be ignored, the events can be simplified to the triple $e_{ij} = (i, j, t_{ij})$. Fig. 1 shows an example of an instantaneous temporal network and a non-instantaneous temporal network. Thus, we can also use $G = (V, E)$ to represent temporal networks, where V is still the set of nodes, but E is the set of events $e_{uv} = (u, v, t_{uv}, \Delta t_{uv})$. In temporal networks, the spread of information is limited to the period of active interaction and the propagation delay, so information can only be spread through effective temporal paths. An effective temporal path between nodes means that information from one node can spread to another node through some sequence of events $e_{v_0v_1}, e_{v_1v_2}, \ldots, e_{v_{n-2}v_{n-1}}, e_{v_{n-1}v_n}$. These events must satisfy the condition that the occurrence time of later events is greater than the sum of the earlier event's occurrence time and propagation delay, $t_{e_{v_{i-1}v_i}} \geq t_{e_{v_{i-2}v_{i-1}}} + \Delta t_{e_{v_{i-2}v_{i-1}}}, \forall 1 \leq i \leq n$. In general, if there are several effective paths between two nodes, we define the smallest amount of time over these paths as the shortest temporal distance.

2.2. Modeling the dynamical spreading process

There are two classical methods of modeling dynamical spreading, a diffusion process and consensus dynamics. These methods can also be used in temporal networks. Because any spreading process, like epidemic spreading in a population,

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