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Epidemic dynamics on information-driven adaptive networks

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ABSTRACT

Research on the interplay between *the dynamics on the network* and *the dynamics of the network* has attracted much attention in recent years. In this work, we propose an information-driven adaptive model, where disease and disease information can evolve simultaneously. For the information-driven adaptive process, susceptible (infected) individuals who have abilities to recognize the disease would break the links of their infected (susceptible) neighbors to prevent the epidemic from further spreading. Simulation results and numerical analyses based on the pairwise approach indicate that the information-driven adaptive process can not only slow down the speed of epidemic spreading, but can also diminish the epidemic prevalence at the final state significantly. In addition, the disease spreading and information diffusion pattern on the lattice as well as on a real-world network give visual representations about how the disease is trapped into an isolated field with the information-driven adaptive process. Furthermore, we perform the local bifurcation analysis on four types of dynamical regions, including healthy, a continuous dynamic behavior, bistable and endemic, to understand the evolution of the observed dynamical behaviors. This work may shed some lights on understanding how information affects human activities on responding to epidemic spreading.

1. Introduction

The spreading dynamic is one of the core issues in network science [1–3], where most of the related researches focus on epidemic spreading and information diffusion in recent years. Much of the work to date focuses on the analysis of these two processes independently, such as the spread of single contagion [4–6] or concurrent diseases [7,8], and the diffusion of various kinds of information (e.g., news [9], rumor [10], innovation [11].). However, the epidemic spreading process is closely coupled with the corresponding disease information diffusion (or saying individuals' awareness of the disease) in the real world. For instance, during the severe acute respiratory syndrome (SARS) outbreak in China in 2003, overwhelming number of disease reports have been posted. These kind of information about SARS may affect the individuals' behavior in keeping away from SARS and thus help to make the disease under control [12,13]. Therefore, disease information diffusion may play an important role in the control of the epidemic outbreak, but it is not easy to quantitatively measure the strength of its impact [14].

Nowadays, some models have been proposed to model the interaction between epidemic spreading and information diffusion on complex networks [14–17]. The fundamental assumption is that, when a disease starts to spread in the population, people may get the disease information from their friends or media before the advent of the epidemic and take some preventive measures to keep away from being infected [15,18,19]. By depicting preventive measures as the reduction of transmitting probability [20,21] or particular states of individuals (immune or vaccination) [22], previous models showed that the disease information diffusion indeed inhibits the epidemic spreading significantly (reduce the epidemic prevalence as well as enhance the epidemic threshold) [15,23]. Therefore, the emergence of mutual feedback between information diffusion and epidemic spreading [14] exhibits the intricate interplay between these two types of spreading dynamics. The interplay between these two types of spreading dynamics is similar to the competing epidemics [24,25] to some extent, that is to say, there is a competitive mechanism between epidemic spreading and the information diffusion. Most of aforementioned studies of such complex interacted spreading dynamics are based on static network,

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i.e., the network structure stays fixed when the two processes are spreading on the network. However, individuals would sometimes cut off the connections with the infected ones when they become aware of the disease, leading to the change of network structure. Consequently, how to characterize the mutual spreading process on the adaptive networks is a crucial issue we want to address in this work.

Generally, the network dynamic researches could be classified into two lines: (i) one is the *dynamics of the network*, which focuses on the time evolution of network structure [26–28]; (ii) the other is considered as the *dynamics on the network*, which concerns the state change of the nodes (or interactions) on networks, such as the epidemic spreading and information diffusion process [29,30], the evolutionary game [31] and so forth. Currently, researchers became to study how the epidemic would spread on adaptive networks, i.e., considering one epidemic spreading process on dynamical changing networks [32]. In [32], the author proposed a model by considering that the susceptible individuals are allowed to protect themselves by rewiring their links from the infected neighbors to some other susceptible ones [33–35]. Many researches indicate that segregating infected (or susceptible) individuals with the adaptive behavior is an efficient strategy to reduce the fraction of susceptible-infected (*SI*) interactions, as well as hinder the outbreak of the whole epidemic spreading [36–38]. In addition, abundant temporal behaviors are presented to illustrate the spreading dynamics on the adaptive network, such as the coexistence of multiple stable equilibrium and the appearance of an oscillatory region, which are absent in the spreading dynamics on static networks [32,39]. Besides the edge rewiring strategy, the link cutting or temporarily deactivating is also a commonly used rule in the adaptive models [40,41].

In this work, we consider a more complicated case that two dynamical processes (i.e., epidemic spreading and disease information diffusion) are spreading on adaptive networks. Therefore, three dynamical processes are coupled in this case, we aim to illustrate how the adaptive behavior can affect the interplay between epidemic spreading and information diffusion. The adaptive behavior is aroused by the individuals awareness of the disease. In this model, those who have been informed of the emergence of disease can break their neighbouring connections to prevent further infection. Additionally, epidemic spreading and disease information diffusion are described by the SI and SIS model, respectively. The disease information generation of the infected individuals is considered to form a mutual feedback loop between these two types of spreading dynamics [20]. Therefore, the effect of information diffusion on epidemic spreading could be interpreted by two aspects: (i) reduce the epidemic spreading probability with protective measures; and (ii) cut off *SI* links with the information-driven adaptive process. Both numerical analyses based on the pairwise approach and simulation results indicate that the information diffusion and the adaptive behavior of the nodes can inhibit the epidemic outbreak significantly. In addition, we present a full local bifurcation diagram to show the abundant dynamical behaviors in the proposed model.

The paper is organized as follows. In Section 2, we give a detailed description of the model as well as mathematical expressions based on the mean-field model and the pairwise model. In Section 3, we first analyze the case of epidemic and disease information spreading on static network, i.e., the case of no adaptive behavior is taken into account. We further give the results of how the epidemic and disease information spreading processes interact with each other on adaptive network. The sensitivity analysis of the parameters and dynamical characterization of the model is given in the end of Section 3. We conclude the paper with some future directions of the work in Section 4.

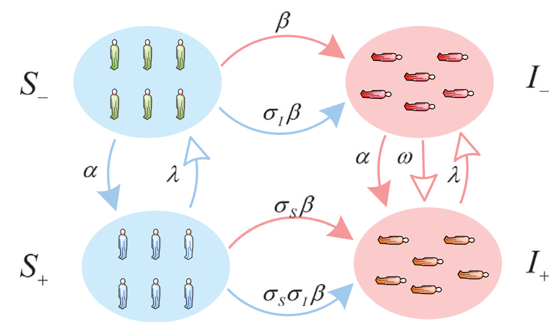

Fig. 1. Transmission diagram of epidemic spreading (*SI* model in the horizontal direction) and disease information diffusion model (SIS model in the vertical direction).

2. Model

2.1. Model description

We give a detailed illustration of our model in Fig. 1. The vertical transformation describes the diffusion of disease information by an SIS model, where individuals can be at one of the two states: (i) + : indicates that the individuals have known the existence of the disease, denoted as the informed ones; (ii) −: indicates that the individuals have not known the existence of the disease. At each time step, the informed nodes will transmit the information to their unknown (−) neighbours with probability α, and each informed individual may forget the information of the disease with a probability λ. Besides, the one who has been infected by the disease will become to know the information of the disease with a corresponding rate ω [14,16].

In the horizontal transformation of Fig. 1, the epidemic spreading is described by an SI model. Each node is at one of two states, susceptible (S) or infected (I). The disease can be transmitted through the SI links, where the S-state individuals could be infected with the probabilities β, $\sigma_I\beta$, $\sigma_S\beta$ and $\sigma_{SI}\beta$ respectively through S_-I_-, S_-I_+, S_+I_- and S_+I_+ links, where σ_I, σ_S and σ_{SI} are the impact factors of the information on epidemic spreading. Generally, when people know the occurrence of the disease (informed individuals), they would like to take some measures to protect themselves, leading to the reduction in infectivity ($0 < \sigma_S, \sigma_I < 1$). In particular, the influence coefficient of the epidemic spreading probability through S_+I_+ links could be calculated as $\sigma_{SI} = \sigma_S\sigma_I$, with the assumption of the independent effect of the infection probability.

Additionally, we consider an information-driven adaptive process which the informed individuals would reduce physical contacts to protect themselves or their friends. That is to say, the informed susceptible individuals (S_+) will keep away from their infected neighbors to protect themselves from being infected, and informed infected individuals (I_+) will also avoid contacting their susceptible neighbors to prevent the epidemic from further spreading. Consequently, the edge-breaking rule of adaptive behavior is adopted [40]. Thus, at each time step, the S_+ (I_+) state individuals will break the links connected to their I (S)-state neighbors with rate r_S (r_I) respectively. Specially, the breaking rate of the S_+I_+ pairs could be interpreted as $1-(1-r_S)(1-r_I)$ with the independent assumption. It is worth noting that the deactivation of *SI* links only represents the avoidance of physical contacts between the *S*- and *I*-state individuals. That is to say, the edge-breaking process will not affect the diffusion of disease information for it can be transmitted through other types of connections such as phone, internet and so forth. The dynamic of the epidemic spreading degen-