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Epidemic process on activity-driven modular networks

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HIGHLIGHTS

- We study the impact of community structure in epidemic spread on activity-driven networks.
- The epidemic threshold on activity-driven networks can be theoretically drawn.
- The epidemic threshold only involves with the value of the spread rate and the recovery rate.
- The infected-driven vaccination model is presented.

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ABSTRACT

In this paper, we propose two novel models of epidemic spreading by considering the activity-driven and the network modular. Firstly, we consider the susceptible–infected–susceptible (*SIS*) contagion model and derive analytically the epidemic threshold. The results indicate that the epidemic threshold only involves with the value of the spread rate and the recovery rate. In addition, the asymptotic refractory density of infected nodes in the different communities exhibits different trends with the change of the modularity-factor. Then, the infected-driven vaccination model is presented. Simulation results illustrate that the final density of vaccination will increase with the increase of the response strength of vaccination. Moreover, the final infected density in the original-infected-community shows different trends with the change of the response strength of vaccination and the spreading rate. The infected-driven vaccination is a good way to control the epidemic spreading.

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1. Introduction

Infectious diseases, such as the smallpox and human immunodeficiency virus, continues to significantly impact morbidity, mortality, and economic outcomes in many population [1–4]. Numerous studies have discussed epidemics on various types of networks [5–12], but the epidemics of behaviors in societies remain less understood. In many social, biological, and physical systems the interactions among the elements of the system are rapidly changing and are characterized by processes. The timing and duration of those systems are defined on a very short time scale [13,14]. In recent years, there have been extensive research activities on time-varying networks, which evolve on a time scale comparable to the timescale of the propagation process [15,16]. The time-vary structure of link activations affects the network dynamics, from disease contagion to information diffusion [17,18]. The role of individuals' behavior in the spreading of epidemic

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diseases is becoming increasingly important due to increase travel activity on both short and long space and time scales [19,20]. Zhang et al. [21] investigated the susceptible–infectious–susceptible contagion in time-varying networks with identical infectivity. The results proved that targeted immunizations are more efficient than random immunizations independently of the infectivity. Rizzo et al. [22] studied the effect of individual behavior on epidemic spreading in activity-driven networks. Their results suggested that behavioral changes could have a beneficial effect on the disease spreading, by increasing the epidemic threshold and decreasing the steady-state fraction of infected individuals. Liu et al. [23] investigated the contagion processes in activity-driven networks. They derived the critical immunization threshold and assessed the effectiveness of three different control strategies.

Real networks have obvious community structure (such as Facebook [24] and Twitter [25]) where the links are dense in the same community but sparse between communities [26,27]. Recent empirical work suggested that modular structure might, counter-intuitively, facilitate information diffusion [28]. Azadeh et al. [29] studied the impact of community structure on information diffusion with the linear threshold model, the results showed strong communities can facilitate global diffusion by enhancing local, intra-community spreading. The community structure in complex networks also plays an important role in the dynamics of epidemics [30]. Epidemic spreading could be hindered by the presence of communities or modular structure, since this helps confining the epidemics in the community of origin [31]. In Ref. [32], the authors considered an adaptive scale-free network with community structure in which neighbors of an infected node can move to other communities with a certain probability. Wu et al. [33] found that the efficiency of epidemic spreading in their model depends mainly on the degree of community. Gong et al. [34] studied the efficient immunization strategy for community networks, and they presented an algorithm that can properly identify the targets to immunize without knowing the global structural information.

An effective approach to suppress epidemic spreading is the vaccination. However, under the complexity of human mobility and interaction [35–38], the individuals decide whether or not to vaccinate mainly results from a tradeoff between their cost and the potential risk [39]. Zhang et al. [40] investigated the Braess's Paradox in epidemic game, the results verified that improve the successful rate of self-protection does not necessarily downsize the epidemic or increase the whole society payoff. Zhang et al. [41] proposed two models to report the impact of the rational decision-making of individuals on voluntary vaccination. Results indicated that the rational behavior of individuals may increase individuals utility but decrease the total utility of social.

Motivated by the above discussion, in this paper, two novel models of epidemic spreading are presented by considering the activity-driven and the network modular. In the first place, we consider the *SIS* contagion model, and the epidemic threshold is derived analytically according to the mean-field theory. Our results show that the epidemic threshold only has the relationship with the value of the spread rate and the recovered rate. Moreover, with different modularity-factor, the final refractory density of infected individual in the different communities presents various trends. Furthermore, we give an infected-driven vaccination model. According to numerous simulations, the results illustrate that if people strengthen their response strength of vaccination against the disease (that is to say, if the nodes find their infected neighbors and immediately take vaccination), the epidemic can be curbed effectively. Moreover, the final infected density in the original-infected-community presents different trends with the change of the response strength of vaccination and the spread rate.

The rest of the paper is organized into three sections. In Section 2, we define the modular network with activity-driven. In Section 3, the two different kinds epidemic spread models are introduced in detail. We present an analytical approach to predict the epidemic threshold. Section 4 presents the conclusions and the relevant discussions.

2. The activity-driven modular networks

Many systems such as protein interaction and gene-regulatory networks, ecological networks and human interactive networks dynamically evolve with time in reality. In this paper, we research an activity-driven modular network. Activity-driven models consider heterogeneous populations where each node i is characterized by a specific activity rate x_i. Variables x_i do not change in time and are independent and identically distributed realizations of a random variable x, with a probability density function $F(x)$. According to Ref. [42], we consider a heavy-tailed density function of the form $F(x) \propto x^{-\gamma}$, with $\gamma \in [2, 3]$. Realizations x_i of the random variable x are constrained as $\xi < x \leq 1$, where ξ is a cutoff value that is suitably chosen to avoid the possible divergences of $F(x)$ close to the origin. In the following, a class of nodes is defined as the nodes that have the same activity rate.

Community structure plays an important role in the dynamics of epidemics. In general, communities are defined as special clusters of nodes. The concentration of edges within these clusters is high and that between clusters is relatively low. In this paper, we assume the nodes are unvarying in one community, however, the concentration of edges could change by adjusting some parameters. To be sure, the nodes that have the same activity rate are in the same class, but not always in the same community.

To systematically investigate the impact of community structure, we prepare an ensemble of network with two communities A and B. We consider a network of $2N$ nodes; the epidemic model on activity-driven modular networks can be described as follows.

(1) A disconnected network with $2N$ nodes is generated.

(2) Half of the nodes are randomly selected and assigned to community A, and the other half are assigned to community B.

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