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Hybrid resource allocation and its impact on the dynamics of disease spreading

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HIGHLIGHTS

- We propose a hybrid resource allocation model in suppressing the disease spreading.
- The more globally the resources are allocated, the more efficiently the disease can be suppressed.
- The strategy of resource allocation can alter the phase transition on heterogeneous networks.
- Hysteresis loops appear on both homogeneous and heterogeneous networks.

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ABSTRACT

Efficient utilization of limited resources is crucial in controlling disease outbreaks. Usually, in the process of disease control, medical resources are either controlled globally by the government or allocated locally among individuals. Here, to explore systematically which of the two strategies is more efficient in suppressing the outbreaks of disease, a hybrid strategy is proposed, in which, a tunable parameter is introduced to tune the preference of global and local resource allocation. By studying the interplay between the resource allocation and disease spreading based on a generalized susceptible–infected–susceptible (SIS) model, we show that the global resource allocation has more advantages in controlling disease than local allocation. Besides, the hybrid resource allocation has significant influence on the dynamics of disease spreading. There is first order phase transition of the final infected fraction of nodes on homogeneous networks, however, the transition type changes from hybrid transitions to first order transition at a critical value of the tunable parameter on heterogeneous networks. When considering the initial conditions, hysteresis loops appear on both homogeneous and heterogeneous networks. Using mean-field approximation and a generalized dynamical message passing (GDMP) approach, we calculate exactly the fraction of infected nodes at the steady state, as well as the epidemic thresholds and the phase diagram of the disease on the homogeneous networks and heterogeneous networks respectively.

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1. Introduction

We are now living in a modernized world, in which the mobility of populations are global and the contact between individuals are frequent. At the same time, the frequent mobility and contact of individuals greatly facilitate outbreaks of malicious diseases, such as the SARS [1], Ebola virus [2], which induces a great shortage of medical resources [3]. A challenging problem we are faced nowadays is how to optimally allocate the scarce resources of treatment and vaccination so as to suppress the disease effectively or mitigate the outbreaks of epidemics to the most extent.

The available of the large-scale data sets largely promotes the development of complex network science [4]. Many systems in real world can be described as networks with nodes denoting individuals and edges representing interactions among them [5–9]. Examples include technical networks like the internet [10] or traffic networks like subway and airline networks [11] and a wide range of socioeconomic and financial systems [12,13]. The dynamics of the networks, such as cascading failure of interdependent networks [14], and the dynamics on the networks, such as the epidemic spreading on contact networks have now been studied extensively in recent years [15–20]. Especially, the epidemic spreading on complex networks can be used to describe many dynamical processes, for example, the spreading of computer virus [21], rumours [22]. To study the underlying mechanisms of epidemic spreading, many models have been proposed, such as the susceptible–infected–susceptible (SIS) and susceptible–infected–recovered (SIR). A seminal work that motivated large amounts of following studies was conducted by Pastor-Satorras and Vespignani [23], they found the absence of an epidemic threshold its associated critical behavior on scale-free networks, which can guide us to develop effective immune strategies. After this work, many works focused on the interplay between the network topology and epidemic spreading [24–29].

Inspired by these researches, the immunization strategies that depend on the network structure recently received extensive studies [30–34]. The simplest immunization strategy is the random immunization [35], but is inefficient for many complex spreading circumstance. Later on, many more effective immunization strategies were proposed, such as the targeted immunization based on node degree [36] or betweenness centrality [37] and acquaintance immunization [38] and so on [39,40].

Moreover, researches of epidemic spreading on multiplex networks are attracting increasing interest [41–43] in recent years. Multiplex structures are ubiquitous in real systems, and researches of disease spreading on multiplex networks are essential to understand the mechanism of spreading dynamics in real world, and can provide more effective immune strategies to suppress the spreading and diffusion of disease and rumours etc. For example, Chen et al. [43] studied the interplay between the resource allocation and disease spreading on multiplex networks. They focused on the effects of local resource allocation in social networks on the dynamics of disease spreading, and found that there are hybrid phase transitions of the final infected nodes fraction [44], which is different from the classical epidemic models. These findings inspires us to develop strategies to allocate resources reasonably in disease controlling. Besides, authors in Ref. [28] studied the impact of preferential resource diffusion on disease spreading on multiplex networks. They found optimal strategies of resource allocation on social networks that can suppress disease spreading to the most extent. The interplay between the resource allocation and disease spreading has now been an attracted topic. In addition to the researches on multiplex networks, many other works have been conducted and guide us to develop efficient resource allocation strategies to suppress the disease spreading [45,46].

The previous studies only focused on global or local allocation of resources, but there is no systematically research of which way is more efficient in suppressing disease. In this paper, we proposed a hybrid resource allocation model based on the susceptible–infected–susceptible (SIS) epidemic model. In our model, a bias parameter p is introduced to tune the relative preference of global and local resource allocation. To theoretically analyze the dynamics of epidemic spreading, we use mean-field approximation and a generalized dynamical message passing (GDMP) approach on homogeneous networks and homogeneous networks respectively. We show that the hybrid resource allocation has significant impact on the dynamics of epidemic spreading. Specifically, the final infected fraction versus epidemic transmission rate exhibits first order phase transition on homogeneous networks, while it changes from hybrid phase transitions to first order transition at a critical value of p on the heterogeneous networks. When considering the initial conditions, the hysteresis loops occur. Most importantly, we find when there is a large preference to the local resource allocation, the epidemic threshold decreases exponentially with the increment of p, which indicates that the global resource allocation has more advantages in suppressing the disease spreading than the local resource allocation, and when resources are mainly locally allocated the disease cannot be suppressed effectively.

2. Model descriptions

We consider the susceptible–infected–susceptible (SIS) model on an undirected network with degree distribution $P(k)$ and N nodes. The structure of the network is described by the adjacency matrix A. If there is an edge between nodes i and j, the element of matrix A is $a_{ij} = 1$ otherwise $a_{ij} = 0$. Each node in the SIS model is in either infectious or susceptible state at any time steps. Disease transmits between the infected nodes and their susceptible neighbors with rate β. At the same time, each infected node i recovers to susceptible state with recovery rate $\mu_i(t)$, which is dependent on the amount of resources, and varies from node to node. The recovery process of an infected node always consumes some resources, which are provided from the susceptible nodes that are regarded as healthy nodes. Since resources can promote the recovery of infected nodes,