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Measuring edge importance to improve immunization performance

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HIGHLIGHTS

- The influence of edge heterogeneity in disease spreading is studied.
- An edge importance index based on the gravity model is proposed.
- The efficiency of the modified high-risk immunization strategy is evaluated.
- The weak ties should be more valued to get better immunization efficiency.

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ABSTRACT

The edge heterogeneity has a remarkable influence on disease spreading, but it has seldom been considered in the disease-controlling policies. Based on the gravity model, we propose the edge importance index to describe the influence of edge heterogeneity on immunization strategies. Then the edge importance and contact weight are combined to calculate the infection rates on the I–S (Infected–Susceptible) edges in the complex network, and the difference of the infection rates on strong and weak ties is analyzed. Simulation results show that edge heterogeneity has a significant influence on the performance of immunization strategies, and better immunization efficiency is derived when the vaccination rate of the nodes in the weak I–S edges is increased.

1. Introduction

Many real systems, e.g. communication systems, social systems, etc., can be depicted as networks with nodes (or vertexes) representing individuals and edges (or links) standing for interactions among the nodes. Heterogeneity exists widely in these real systems. For instance, the fans number of different users in Facebook varies greatly. Generally, Facebook users with tens of thousands fans can be more influential than the ones with only a few fans. Therefore, node heterogeneity indeed affects the spreading process, and should be considered in the modeling of spreading dynamics on real networks. Based on this, the hubs, individuals with high centrality, are often identified to accelerate information spreading [1] or slow down disease propagation [2]. Various methods are developed to find these influential nodes based on different measures, such as k-shell [3], degree centrality [4,5], eigenvector centrality [6] and betweenness centrality [7,8]. However, the application of these methods normally requires global information about the network topology structure which is impractical to be collected for large-scale networks [9]. Therefore, strategies based on local information are proposed. The acquaintance immunization strategy is such an example of using local information to select the influential nodes [10].

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At the same time, edge heterogeneity is also a universal phenomenon in the networks. On one hand, relationships, which are represented by edges, vary largely in types. In MSN, a social network, the types of relationships are diverse and different relationships have distinct roles in the spreading process of the same information [11]. On the other hand, interactions, which are also represented by edges, vary greatly in the interacting strengths. In scientific collaboration networks, the number of coauthored papers between two scientists or the number of mutual authors between two papers is highly heterogeneously distributed [12]. Thus edges cannot be treated equally and they are often assigned with weights to describe their heterogeneity. For example, in airport networks, edge weight is used to denote the number of flights or seats [13–15], or the number of passengers [16] between two airports. Other examples include the reaction rate in metabolic networks [17], the frequency of coexistence between two words in language networks [18], and so on. Different relationships have different effects on information spreading and behavior influence. People are always willing to keep in close touch with their friends and accept friends' recommendations and suggestions. Thus the weight distribution of network edges will have a remarkable effect on the spreading process. As Yang's study [19] stated, more heterogeneous weight distribution results in lower epidemic prevalence on regular random networks. Yan got similar conclusions in the scale-free networks that larger weight dispersion of networks leads to slower spreading, and epidemic spreads faster on unweighted networks than on weighted ones under the same conditions [20]. The edge heterogeneity does have significant influences on the spreading process, and it may be of great help to control the epidemic spreading. While the node heterogeneity is often considered in the disease-controlling policies, there is a need for the research on a policy considering edge heterogeneity.

Aiming at part of the population, vaccination is usually accepted as an effective and cost-saving method to block the epidemic propagation. To achieve the highest immunization efficiency, the selection of nodes to be vaccinated is of vital importance. However, most previous studies just identify the nodes for vaccination based on the node heterogeneity and edge heterogeneity has seldom been considered. This paper explores the influence of edge heterogeneity on immunization strategies and defines the edge importance metrics as the guidance to vaccinate the nodes. We divide the disease spreading period into three stages, including nodes immunization, nodes contact and nodes infection. And three indices, namely, edge importance, contact weight and infection rate, are proposed to depict the edge heterogeneity in three different stages. Our results demonstrate that edge heterogeneity has a big impact on the performance of immunization strategies. We also find that such impact is two-sided. Incorporating edge heterogeneity can bring either positive or negative influence on the immunization results. Moreover, when the nodes in weak ties are given increasing access to vaccination, the efficiency of the immunization strategy will be gradually improved.

The rest of this paper is arranged as follows. In Section 2, we briefly describe the proposed mode and indices. The edge importance, contact weight and infection rate are presented in detail in Sections 2.1–2.3 respectively. We investigate the influence of edge heterogeneity on immunization strategies and give the simulation results in Section 3. Section 4 gives the conclusions.

2. Model and analysis

The classic Susceptible–Infected–Removed (SIR) model is used to study the effect of edge heterogeneity in the complex network. SIR model is a kind of compartment model where the individuals are divided into three states, namely S (Susceptible), I (Infected) and R (Removed). In this paper, we only analyze three types of homogeneous networks: regular, random and small-world networks. They are all generated by the Watts–Strogatz (WS) small-world network model [21]. In the WS network, if the rewire probability is 0, small-world networks would degenerate into regular networks; else, if rewire probability grows to 1, small-world networks would become random networks.

The infectious diseases, such as the seasonal influenza, are not easy to be eradicated and may spread for many seasons or periods. Inspired by prior studies [20,22], a spreading period is divided into three stages in this paper. And we produce an iterative sequence of the three-stage period on top of a network. The first stage is immunization. In this stage, people are evaluated separately whether to be vaccinated or not before the disease spreading for the present period, and the edge heterogeneity is represented by an edge importance index. The edge importance index describes how important an edge is to its vertexes. Apart from the subjective closeness of the relationships, edge importance index can incorporated other immunization influencing factors, such as the node degree. The gravity model is employed to measure the edge importance which is the basis to choose the network nodes for vaccination. The second stage is nodes contact. In this stage, individual will have contact with their neighbors and such contact action may result in disease infection. Different from the standard SIR model [23], in the present model, each infected individual will generate k contacts at each time step where k is the node degree of the infected individual. For each contact, individuals often preferentially make contact with other individuals with closer relationships. The subjective closeness of the relationships is defined as contact weight index to describe the edge heterogeneity in this stage [24]. A widely accepted general form of similarity indices [25,26], namely the number of mutual neighbors, is used to represent the contact preference. The third stage is nodes infection, where infected nodes would infect their contacted unimmunized neighbors with a certain probability. And the infection rate from the infected nodes to their susceptible neighbors is given to describe the edge heterogeneity in this stage.

Let λ denote the initial spreading rate at which a susceptible individual becomes infected after contacting with an infected neighbor once, after contacting with infected nodes for x times, the probability for a susceptible node being infected would be $1-(1-\lambda)^x$. For very small λ, it will be approximately equal to λx [1]. At the same time, γ is defined as the recovering probability from state I to R.