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Research paper

Effects of awareness diffusion and self-initiated awareness behavior on epidemic spreading - An approach based on multiplex networks

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ABSTRACT

In this paper, we study the interplay between the epidemic spreading and the diffusion of awareness in multiplex networks. In the model, an infectious disease can spread in one network representing the paths of epidemic spreading (contact network), leading to the diffusion of awareness in the other network (information network), and then the diffusion of awareness will cause individuals to take social distances, which in turn affects the epidemic spreading. As for the diffusion of awareness, we assume that, on the one hand, individuals can be informed by other aware neighbors in information network, on the other hand, the susceptible individuals can be *self-awareness* induced by the infected neighbors in the contact networks (local information) or mass media (global information). Through Markov chain approach and numerical computations, we find that the density of infected individuals and the epidemic threshold can be affected by the structures of the two networks and the effective transmission rate of the awareness. However, we prove that though the introduction of the *self-awareness* can lower the density of infection, which cannot increase the epidemic threshold no matter of the local information or global information. Our finding is remarkably different to many previous results on single-layer network: local information based behavioral response can alter the epidemic threshold. Furthermore, our results indicate that the nodes with more neighbors (hub nodes) in information networks are easier to be informed, as a result, their risk of infection in contact networks can be effectively reduced.

1. Introduction

The outbreaks of diseases can involve the diffusion of information in regard to the diseases, including the risk of infection, rumors, fears and so on, which can stimulate individuals to take spontaneous behavioral responses to protect themselves, thereby bring profound impacts on the spreading of disease [1–6]. For example, recent outbreaks of the H1N1 flu, the bird flu, and the severe acute respiratory syndrome (SARS) have brought the reduction of going out and the plenty of people wearing face masks. For this reason, there has been an increasing focus on the development of formal models aimed

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at investigating the interplay of epidemic spreading and information-based behavioral responses [7–10]. Such as, based on the assumption that the probability of susceptible individual going to the alter state is proportional to the number of infected neighbors, Sahneh et al., extended the SIS (Susceptible-Infected-Susceptible) model to a Susceptible-Alter-Infected-Susceptible (SAIS) model [11,12], and they found that the way of behavioral response can enhance the epidemic threshold; Meloni *et al.* studied a meta-population model that incorporates several scenarios of self-initiated behavioral changes into the mobility patterns of individuals, and they found that such behavioral changes do not alter the epidemic threshold, but may produce a negative impact on disease, i.e., the density of infection is increased [13]; In Refs. [14–16], authors investigated the effects of the information-based behavioral responses on the epidemic dynamics by designing the transmission rate as a function of the local infected density or the global infected density.

Though the effects of information-based behavioral responses on the epidemic dynamics have been studied by many authors, most of works assumed the spreadings of information and epidemic are in the same network. As we know, with the development of technology, information can fast diffuse through many different channels, such as, the word of mouth, news media, online social networks, and so on. In view of this, recent well-studied multiplex network theory has been used to mimic the interplay of information or related awareness and the epidemic dynamics [17–20]. For instance, Sahneh et al., have shown that the information dissemination spread in another network can help boost the resilience of the agents' population against the spreading and found optimal information dissemination for different topologies [21]; Wang et al., investigated the interplay of the epidemic dynamics and the information dynamics in multiplex network based on the SIR (R-recovery) model, and focused on the two fundamental quantities underlying any spreading process: epidemic threshold and the final epidemic prevalence [22]; Granell et al., established an SIS-UAU model to investigate the competing effects of the spreading of awareness and the epidemic dynamics in multiplex with the transmission rate of awareness as well as the structure of information network [23]. More recently, they further generalized their model by reducing the probability of infected individuals becoming awareness and including the effect of a mass broadcast of awareness (mass media) on the epidemic dynamics [24].

In Refs. [23,24], authors assumed that susceptible individuals can only be informed by other aware neighbors. In reality, individuals may become aware (i.e., self-initiated awareness) when they find that their neighbors are infected. Inspired these factors, in the current work, we study the interplay between the diffusion of awareness by incorporating the *self-awareness* effects and the epidemic dynamics under the framework of multiplex network. In the model, an infectious disease first spreads among population represented by the contact network, and then the outbreak of the disease stimulates some people (infected or susceptible individuals) become aware of the risk of infection, and they take some protections to reduce the probability of infection. Meanwhile, unaware individuals can be informed by other aware individuals through the information network or become *self-awareness* induced by the infected neighbors in contact network or mass media. The finding indicates that the additional self-initiated awareness mechanism can reduce the density of infection, however, which can not alter the epidemic threshold. Moreover, we show that since the hub nodes in information networks are easier to be informed, which can much lower their infection probability in contact networks. The results are verified by the Monte-Carlo simulations and the microscopic Markov chain approach (MMCA).

The layout of the paper is as follows: we introduce the model in Section 2. The simulation results and theoretical analysis are presented in Section 3. Finally, Conclusions and discussions are presented in Section 4. The results for the global information-based *self-initiated* awareness are given in Appendix A.

2. Model

In this work, we generalize the model of Ref. [23,24]. In that model, a multiplex network includes two layers, one is physical layer representing the spreading of epidemic (contact network), and the other is information layer on where the diffusion of the awareness evolves (information network). All nodes represent the same individuals in both layers, but the connectivity is different in each of them. In the contact layer, a Susceptible - Infected - Susceptible (SIS) model is used to mimic the epidemic dynamics. That is to say, a susceptible node can be infected by one infected neighbor with certain probability, and the infected node can return to susceptible state with probability μ. On the information layer, the dynamical process of awareness is assumed to be similar to the SIS model, that is, an unaware node (U) can be informed by an aware neighbor (A) with probability λ, and the aware node can loss awareness and back to unaware state with probability δ. The interplay of the two processes is modelled as follows: once an individual is infected, s/he will certainly become aware, that is, the probability is $\sigma = 100\%$. In addition, to distinguish the protective behaviors between the aware individuals and unaware individuals, let β and $\beta^A = \gamma\beta$ (here $0 \le \gamma < 1$. If $\gamma = 0$, the aware individuals are completely immune to the infection.) be the probabilities of unaware and aware susceptible nodes to get infected, respectively.

From the description of the model, one can find that, on the one hand, the authors assumed that the infected individuals will *automatically* become aware and are willing to inform the disease information. As we know, in many cases, infected individuals are unwilling to tell others since they can be discriminated or isolated by others once others know they are infected by one certain disease. For example, if one person is infected by AIDS or hepatitis B, who may be alienated by his friends. So we assume that infected individuals becoming aware with probability $0 \le \sigma \le 1$. On the other hand, in the model, individuals can *only* be informed by their neighbors through the information network, that is to say, one individual has no chance to become aware once their neighbors are unaware. However, individuals can become *self-awareness* once their friends are infected or they are informed by the mass media, and the probability of becoming awareness increases