Chinese Journal of Physics 56 (2018) 1166–1172

Contents lists available at ScienceDirect

Chinese Journal of Physics

journal homepage: www.elsevier.com/locate/cjph

Hybrid phase transitions of spreading dynamics in multiplex networks

Yanan Huang, Ming Tang, Yong Zou, Jie Zhou*

School of Physics and Materials Science, East China Normal University, Shanghai, 200241, China

ARTICLE INFO

Keywords:
Complex networks
Multiplex networks
Spreading dynamics

ABSTRACT

In this paper, we study the spreading dynamics of social behaviors and focus on heterogenous responses of individuals depending on whether they realize the spreading or not. We model the system with a two-layer multiplex network, in which one layer describes the spreading of social behaviors and the other layer describes the diffusion of the awareness about the spreading. We use the susceptible-infected-susceptible (SIS) model to describe the dynamics of an individual if it is unaware of the spreading of the behavior. While when an individual is aware of the spreading of the social behavior its dynamics will follow the threshold model, in which an individual will adopt a behavior only when the fraction of its neighbors who have adopted the behavior is above a certain threshold. We find that such heterogenous reactions can induce intriguing dynamical properties. The dynamics of the whole network may exhibit hybrid phase transitions with the coexistence of continuous phase transition and bi-stable states. Detailed study of how the diffusion of the awareness influences the spreading dynamics of social behavior is provided. The results are supported by theoretical analysis.

1. Introduction

The studies of complex networks have attracted increasing research interest since it provides a powerful tool to describe various real complex systems [1–6]. One of the important topics is the study of spreading dynamics on complex networks, including epidemic spreading [7], rumor spreading [8], and opinion dynamics [9,10], have received great attentions due to their important values both in theoretical and practical aspects [11–18]. A pioneer finding of this topic is about the threshold of epidemic spreading in heterogeneous networks in which the infection threshold appears to vanish and an epidemic may be prevalence with infinitesimal infection rate [19]. Further, various factors were studied, such as restricted vaccine source [20], effect of cooperation [21], multiple seeds [22], individual mobility [23,24], and immunization protocols [25].

A commonly used model for describing the spreading dynamics is the susceptible-infected-susceptible (SIS) model [19]. Though this model is originally to describe the epidemics, it is also effective in describing other spreading dynamics. An important feature of SIS model is that for a susceptible node even only one of its neighbor is infected, it is still possible to be infected through this infected neighbor. Here, we refer to this kind of transition as simple transition mechanism. There is another kind of transition mechanism in which a susceptible individual may be infected only when a certain number of its neighbors are infected. This number normally is larger than one and we refer to it as multiple transition mechanism. This mechanism is commonly used where individuals need more friends to persuade so as to take a social behavior. A typical model for this mechanism is the threshold model [26]. A key difference of the dynamics between these two kinds of transition mechanisms is that for the SIS model the fraction of infected nodes undergoes a

* Corresponding author.
E-mail address: jzhou@phy.ecnu.edu.cn (J. Zhou).

https://doi.org/10.1016/j.cjph.2018.04.020
Received 3 March 2018; Received in revised form 23 April 2018; Accepted 23 April 2018
Available online 27 April 2018
0577-9073/

continuous phase transition, whereas in the threshold model the phase transition is discontinuous. Such property is also reflected in variations of the SIS model, for example the SIR model [27,28], and in extensions of the threshold model, such as the effect of memory [29], the effect of non-redundant information [30], and individual heterogeneity [31].

Recently, increasing research interesting of spreading dynamics turns to the situation that the spreading of social behavior co-evolves with the diffusion of the news about it. For example, the co-evolution of epidemic spreading and diffusion of its awareness is studied in Ref. [32]. Specifically, when an individual is aware of the epidemics, it will take preventive measures for protection. This effect will impede the spreading of the epidemic and thus induce negative correlation between the epidemic spreading and the diffusion of the awareness. Further, the effect of mass media is investigated, which shows that the final infection density may be strongly influenced by the broadcast of mass media [33]. After then, more detailed effects are further studied under this framework, for example the awareness cascade [34], weighted links [35], cooperation [36,37], competition [38], degree heterogeneity [39], and degree of trust [40]. An important feature of the co-evolution of spreading dynamics on multiplex networks is that the reacting dynamics of an individual could be severely different depending on whether it is aware of the spreading or not.

In reality, when people learn the negative evaluation of a behavior, they will be reluctant to adopt it. In this situation, it may require more friends to persuade or influence them to adopt the behavior. With this consideration, in this paper, we study the spreading of social behaviors which co-evolves with the diffusion of the awareness of the spreading. In order to study the different responses between the awareness and unawareness, we consider the scenario that when an individual is unaware of the social dynamics, its behavior will follow SIS model, while when it is aware of the social dynamics, its behavior will follow the threshold model. Owing to the distinct dynamical features of these two kinds of models, intriguing phenomena of hybrid phase transitions emerge.

2. Model and theory

We use two-layer multiplex networks to model spreading dynamics of social behavior and the diffusion of the awareness (see Fig. 1). The upper layer represents individuals' awareness of the social behavior, and the lower layer corresponds to intimate contacts between individuals where social behavior propagates. The both layers contain the same set of individuals (nodes), and every node in one layer has a counterpart in the other. For the sake of simplicity, we assume the network is unweighed and indirected.

In the upper layer, i.e. the awareness layer, we use UAU model to describe the diffusion of the awareness where every individual can be in two states: if it is not aware of the social dynamics, its state is unawareness (U); if it is aware of the dynamics, its state is awareness (A). In each time step, a U state individual may change to A state by two reasons: (i) influenced by its A state neighbors where each A state neighbor may tell the news to it at a rate α; (ii) spontaneously changes to A state if it has accepted the social behavior in the intimate contact layer. Besides, an A state individual may return to U state at a rate δ because of forgetting the news, referred as the forgetting process.

In the intimate contact layer, individuals could be in one of the two states S or I, where the state I (S) denotes that an individual

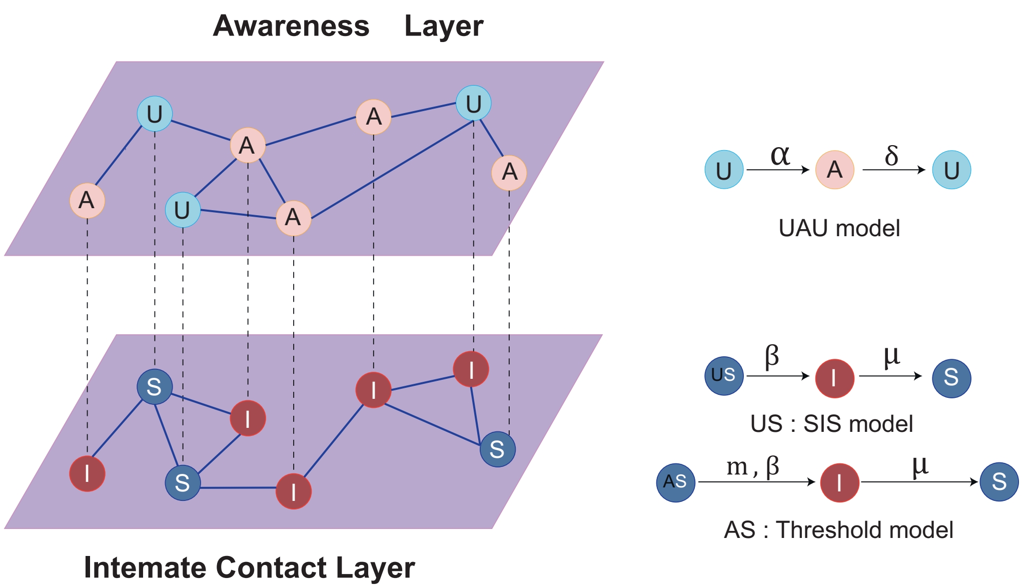

Fig. 1. Schematic representation of a multiplex network. The upper layer is the awareness layer where the diffusion of awareness happens, nodes in this layer represent individuals, which are in two kinds of states: unaware (U) and aware (A). The lower layer is the intimate contact layer where the spreading of social behavior happens, nodes in this layer have two kinds of states: unadopted (S) and adopted (I). Dynamics of the individuals in the upper layer is described by the UAU model. In the lower layer, if an individual is unaware of the spreading, its dynamics will follow the SIS model, otherwise it will follow the threshold model.