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Theory of rumour spreading in complex social networks

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Abstract

We introduce a general stochastic model for the spread of rumours, and derive mean-field equations that describe the dynamics of the model on complex social networks (in particular, those mediated by the Internet). We use analytical and numerical solutions of these equations to examine the threshold behaviour and dynamics of the model on several models of such networks: random graphs, uncorrelated scale-free networks and scale-free networks with assortative degree correlations. We show that in both homogeneous networks and random graphs the model exhibits a critical threshold in the rumour spreading rate below which a rumour cannot propagate in the system. In the case of scale-free networks, on the other hand, this threshold becomes vanishingly small in the limit of infinite system size. We find that the initial rate at which a rumour spreads is much higher in scale-free networks than in random graphs, and that the rate at which the spreading proceeds on scale-free networks is further increased when assortative degree correlations are introduced. The impact of degree correlations on the final fraction of nodes that ever hears a rumour, however, depends on the interplay between network topology and the rumour spreading rate. Our results show that scale-free social networks are prone to the spreading of rumours, just as they are to the spreading of infections. They are relevant to the spreading dynamics of chain emails, viral advertising and large-scale information dissemination algorithms on the Internet.

Keywords: Structure and dynamics of complex social networks; Rumour models; Critical phenomena

1. Introduction

Rumours are an important form of social communications, and their spreading plays a significant role in a variety of human affairs. The spread of rumours can shape the public opinion in a country [1], greatly impact financial markets [2,3] and cause panic in a society during wars and epidemics outbreaks. The information content of rumours can range from simple gossip to advanced propaganda and marketing material. Rumour-like mechanisms form the basis for the phenomena of viral marketing, where companies exploit social networks of their customers on the Internet in order to promote their products via the so-called 'word-of-email' and 'word-of-web' [4]. Finally, rumour-mongering forms the basis for an important class of

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communication protocols, called gossip algorithms, which are used for large-scale information dissemination on the Internet, and in peer-to-peer file sharing applications [5,6].

Rumours can be viewed as an "infection of the mind", and their spreading shows an interesting resemblance to that of epidemics. However, unlike epidemic spreading quantitative models and investigations of rumour spreading dynamics have been rather limited. An standard model of rumour spreading, was introduced many years ago by Daley and Kendal [7,8]. The Daley–Kendal (DK) model and its variants, such as the Maki–Thompson (MK) model [9], have been used extensively in the past for quantitative studies of rumour spreading [10–13]. In the DK model a closed and homogeneously mixed population is subdivided into three groups, those who are ignorant of the rumour, those who have heard it and actively spread it, and those who have heard the rumour but have ceased to spread it. These groups are called ignorants, spreaders and stiflers, respectively. The rumour is propagated through the population by *pair-wise* contacts between spreaders and others in the population, following the law of mass action. Any spreader involved in a pair-wise meeting attempts to 'infect' the other individual with the rumour. In the case this other individual is an ignorant, it becomes a spreader. In the other two cases, either one or both of those involved in the meeting learn that the rumour is 'known' and decide not to tell the rumour anymore, thereby turning into stiflers [8]. In the Maki–Thompson variant of the above model the rumour is spread by *directed* contacts of the spreaders with others in the population. Furthermore, when a spreader contacts another spreader only the *initiating* spreader becomes a stifler.

An important shortcoming of the above class of models is that they either do not take into account the topology of the underlying social interaction networks along which rumours spread (by assuming a homogeneously mixing population), or use highly simplified models of the topology [11,12]. While such simple models may adequately describe the spreading process in small-scale social networks, via the word-of-mouth, they become highly inadequate when applied to the spreading of rumours in large social interaction networks, in particular, those which are mediated by the Internet. Such networks, which include email networks [14–16], social networking sites [17] and instant messaging networks [18] typically number in tens of thousands to millions of nodes. The topology of such large social networks shows highly complex connectivity patterns. In particular, they are often characterized by a highly right-skewed degree distribution, implying the presence of a statistically significant number of nodes in these networks with a very large number of social connections [14,15,17,18].

A number of recent studies have shown that introducing the complex topology of the social networks along which a rumour spreads can greatly impact the dynamics of the above models. Zanette performed simulations of the deterministic MK model on both static [19] and dynamic [20] small-world networks. His studies showed that on small-world networks with varying network randomness the model exhibits a critical transition between a regime where the rumour "dies" in a small neighbourhood of its origin, and a regime where it spreads over a finite fraction of the whole population. Moreno et al. studied the stochastic version of the MK model on scale-free networks, by means of Monte Carlo simulations [21], and numerical solution of a set of mean-field equations [22]. These studies revealed a complex interplay between the network topology and the rules of the rumour model and highlighted the great impact of network heterogeneity on the dynamics of rumour spreading. However, the scope of these studies were limited to *uncorrelated* networks. An important characteristic of social networks is the presence of assortative degree correlations, i.e., the degrees of adjacent vertices is positively correlated [14,15,23,24]. Furthermore, the mean-field equations used in Ref. [22] were postulated without a derivation.

In this paper we make several contributions to the study of rumour dynamics on complex social networks. First of all, we introduce a new model of rumour spreading on complex networks which, in comparison with previous models, provides a more realistic description of this process. Our model unifies the MK model of rumour spreading with the susceptible-infected-removed (SIR) model of epidemics, and has both of these models as its limiting cases. Secondly, we describe a formulation of this model on networks in terms of interacting Markov chains (IMC) [25], and use this framework to derive, from first-principles, mean-field equations for the dynamics of rumour spreading on complex networks with arbitrary degree correlations. Finally, we use approximate analytical and exact numerical solutions of these equations to examine both the steady-state and the time-dependent behaviour of the model on several models of social networks: homogeneous networks, Erdős–Rényi