Worm spreading model on two-dimensional ad hoc communication networks

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Abstract

In this paper, we model the worm spreading in the ad hoc communication network on a two-dimensional triangular lattice. The medium access control mechanism used to reduce interference among transmitting nodes causes a side-effect on worm spreading. It increases threshold of epidemics and reduces the prevalence of infected nodes in the network.

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1. Introduction

Since the models of small-world [1] and scale-free networks [2] were proposed, people in the physical community have paid much attention to the study of complex networks. A complex network can be developed by nodes representing individuals in a real system and by links representing interactions between them. Topological effects on dynamic behaviors in a network such as synchronization [3-5] and epidemic spreading [6] have been investigated widely. Most previous study on complex networks focuses on topological properties of them ignoring the geometric distance between nodes, which is reasonable for some networks such as food web [7], citation networks[8], metabolic networks [9] etc. However, in some real problems involving transportation systems [10, 11], the Internet [12, 13], WWW [14], power grids [15, 16] and mobile ad hoc communication networks [17, 18], geometric distance is very important for the functions of them. With more in depth research on complex networks, physicists gradually take it into account. Rozenfeld [19] proposed a method for embedding scale-free networks in regular Euclidean lattices accounting for geographical properties. Xie et al. [20] proposed a growing network model based on an optimal policy involving both topological and geographical measures. Xulvi-Brunet et al. [21] introduced several network-generating mechanisms relative to the constraints that geography imposes on the evolution of large-scale network systems in physical space. A review of geographical networks by Yang et al. has appeared recently[22].

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On the other hand, mobile ad hoc networks have become an attractive topic in the field of technology, because of their potential applications in the battle field, disaster relief providing, outdoor assemblies and other settings in temporal use. In such a network which is different from the Internet, there is neither infrastructure nor central authority as seen in the existing cell phone networks. Each of mobile nodes serves not only as a host but also as a router forwarding packets for other ones [23]. The topology of the ad hoc network changes with time since nodes in it keep moving randomly. Therefore, to take collective duties effectively, the network should self-organize into a dynamically stationary network by certain local protocols as needed. A key ingredient for the operation of the ad hoc network is transmission range of mobile nodes. It is a circle with radius \( r \) from the center where a node is located. The energy consumption of a node is proportional to the square of \( r \) [24]. Any other nodes inside this circle can communicate with it directly, while nodes outside it need to be connected by successive indirect transmissions (multi-hop links). It seems easier to realize the global connection with larger transmission range \( r \) than with smaller ones. However, it would consume more energy of nodes which is difficult to be recharged when they are in motion. Moreover, large range may cause strong interference in wireless communication. Inversely, smaller range \( r \) would reduce the possibility of direct connection and demand more multi-hop steps of linking, which increase the probability of network breaking. Therefore, at a fit transmission range \( r \), the network can maintain a balance between both sides. With the useful information transmission in the global connection network, virus may attack the network. Worm and virus attacks on the Internet have been investigated from kinds of angles such as empirical, theoretical and simulation studies. These studies have greatly contributed to our understanding of the impact of network topology on the properties of virus spreading [25-27] and have inspired the design of more effective immunization strategies to prevent and combat Internet epidemics. However, there have been very limited studies on worm spreading in these fresh ad hoc communication networks.

In this paper, we model the two-dimensional (2-D) plane on which nodes move randomly with a triangular lattice, and determine distance-dependent connection by the transmission range. Demanding global connection of the mobile ad hoc network, we investigate the worm transmission through its geometric distance-dependent controlling mechanism. The increase of epidemic threshold and the reduction of long-term stationary worm prevalence are found out by numerical simulations.

2. MODEL

2-D triangular lattice with periodic boundary condition is used to model 2-D plane for the mobile ad hoc communication networks. The total number of the sites on it is \( N = L \times L \). The length of the edge between two nearest geometric adjacent sites is defined as \( r_0 \). We assign \( n_0 \) (\( n_0 < N \)) nodes to the lattice randomly and define the occupancy \( \sigma \) of sites by mobile nodes as \( n_0/N \). Each site of the triangular lattice can be occupied by one node at most. Every node has its transmission range \( r (r > r_0) \). It can gain links to other nodes within its transmission range. To simplify our study, we assume that every node in the network has the same transmission range. And it is noted that a node cannot connect with itself, and two neighbor nodes just can have one link between them, since it makes no sense to communicate with itself or to have multiple channels between any two direct communicated nodes. Case \( r = 2r_0 \) is shown in Fig. 1 as an example. Suppose that node 1 occupies a site of the lattice, its transmission range is denoted by the blue circle around it. Every node inside the circle can directly link to it. Scaling behavior of the connectivity is found in the triangular lattice model [28]. The model serves as a sort of geometric distance-dependent site percolation on dynamic complex networks. When the occupancy \( \sigma \) is near the threshold \( \sigma_c \), individual nodes self-organize into a globally connected dynamic small world network relative to geometric distance. For our triangular lattice model with \( L=200 \), \( \sigma_c =0.37, 0.21, 0.13, 0.09 \), and 0.065 for \( r=2r_0, 3r_0, 4r_0, 5r_0 \), and \( 6r_0 \), respectively. In these cases, averaged degree \( \langle k \rangle =7.56, 7.8, 8.1 \), and 8.19, clustering coefficient \( C = 0.55, 0.56, 0.57 \), and 0.57 for transmission range \( r=3r_0, 4r_0, 5r_0 \), and \( 6r_0 \), respectively[28].

For global connection, an ad hoc network can guarantee successful packets transmission. Meanwhile, with the communication, worm may attack nodes in the network. Nekovee[29] studied the worm epidemics in the two-dimensional random geometric graph (RGG) modeling the ad hoc networks. Threshold behavior and dynamics of worm epidemics in these networks are greatly affected by a combination of spatial and temporal correlations which characterize these networks. Every node in the network acts as a base station to relay message to other participants within its limited transmission range so that a packet can arrive at its destination via successive inter node transmissions. Worm can infect the nodes who participate in the propagation of packet. It is evident that the nodes transmitting message in the same moment interfere with each other. To reduce the interference effect of
transmission, there is a coordination mechanism called the medium access control (MAC) which demands all nodes inside the transmission range of a speaking node keep silent at that moment. To avoid interference, a node needs to check whether all neighboring mediums are free or not before transmission a package, and if anyone is busy the transmission cannot continue. It introduces novel spatial and temporal restriction in the dynamics of data communication which is absent in Internet communications.

Fortunately, MAC mechanism can induce a side-effect of inhibiting worm spreading. We consider the susceptible-infected-removed (SIR) model that provides a more realistic description of real worm epidemics which enables us to obtain final stationary infected ratio of nodes impacted by MAC. Any node in the network can be in one of the following three states: susceptible, infected or immune. Infected nodes transmit the worm with probability \( \lambda \) to their neighboring nodes which are susceptible. An infected node becomes immune with the action of specific software at rate \( \delta \). \( S(t) \), \( I(t) \), \( R(t) \) can be used to denote the proportion of susceptible, infected, immune nodes, respectively, in the network. To simplify, We set \( \delta = 1 \) as usual. Not all infected nodes can work as effective infection sources because of the operation of the MAC mechanism on the ad hoc network. When an infected node can get a chance to transmit a package hence a worm, all the other infected nodes as its neighboring sources can’t work at the same time.

3. RESULT

We define a quantity \( R_\infty \) to describe the epidemic prevalence in the networks.

\[
R_\infty = \lim_{t \to +\infty} R(t)
\]

In figure 2, the epidemic prevalence in the ad hoc network is shown as a function of the infection rate \( \lambda \). We simulate on a triangular lattice for different transmission mechanisms: MAC and non-MAC. Either with MAC or without MAC, the function of \( R_\infty \) with \( \lambda \) is almost independent of transmission ranges \( r \). For different transmission ranges \( r \), the topology of networks looks similar, which lead to the results of \( R_\infty (\lambda) \). With two mechanisms, \( R_\infty \) has critical thresholds \( \lambda_c \) below which a worm cannot spread in the network and above which it infects a finite fraction of the nodes. For the MAC mechanism which represents spatial-temporal restriction, the threshold \( \lambda_c \) is obviously higher than the values without it in the networks. If two or more infected nodes connect with each other as the nearest neighbors, only one of these nodes can be as an effective infection source, which reduces the probability of worm transmission. The presence of the MAC regulation not only affects \( \lambda_c \) but also results in the reduction in the
epidemic prevalence. For the limit $\lambda = 1$, we demonstrate that not all nodes in the network can be infected by the worm because of the function of MAC mechanism, which is illustrated by solid symbols in Fig. 2.

Next, we discuss the propagation dynamics of worm in the ad hoc networks. As shown in Fig. 3, taking $r=5r_0$ at the critical global connectivity as an example, one can find the velocity of worm spreading with MAC mechanism is slower than the velocity without it when $\lambda = 0.1$. The cause of slow velocity is temporal correlations in the spreading dynamics by the MAC mechanism. Neighboring nodes compete to be the propagation source slows down the overall progress of the epidemics. In Fig. 4, we simulate the fraction of immunized nodes versus time, which repeats demonstrating that the impact of spatial and temporal restriction on the worm prevalence in the ad hoc network.

![Fig2](image1)

**Fig2**: The epidemic prevalence $R_\infty$ as the functions of the infection rate $\lambda$ in the triangular lattice model both in the absence and presence of the MAC mechanism.

![Fig3](image2)

**Fig3**: Time evolution of the fraction of infective nodes $I(t)$ when $r=5r_0$. The result of simulations are shown both in the absence and presence of MAC.
Fig 4: Time evolution of the fraction of recovered/immunized nodes $R(t)$ when $r=5r_0$. The result of simulations are shown both in the absence and presence of MAC.

4. DISCUSSION and CONCLUSION

Our study on worm transmission of the mobile ad hoc communication network is based on observables of the system—the transmission ranges, and a real mechanism-MAC. A 2-D triangular lattice is a good model to resemble the circle of transmission range. The study of worm transmission is at the critical state of global connectivity which consumes less energy and cause less interference. However, in the process of communication, the transmission ranges of nodes should decrease as messages being sent out for themselves and others. Actually, the energy consumption of every node should be different. Therefore, the model with random and changeable transmission ranges to communication is also an interesting one to be investigated.

To conclude, in this paper, we have presented a 2-D triangular lattice as the background for mobile ad hoc communication networks with uniform transmission range and the homogenous distribution of nodes on it. We studied the worm transmission for the network with critical global connectivity. Numerical simulation reveals that MAC mechanism increases the threshold of epidemics, and reduces the prevalence of worm infection in mobile ad hoc networks.

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