Li et al. *EURASIP Journal on Wireless Communications and Networking* (2016) 2016:172
DOI 10.1186/s13638-016-0667-4

EURASIP Journal on Wireless Communications and Networking

RESEARCH Open Access

Influence of node mobility on virus spreading behaviors in multi-hop network

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Abstract

Multi-hop network has received growing attention recently with the widely use of wireless network communication technology. At the same time, the security of multi-hop network is facing more serve challenges. Unfortunately, classic techniques for computer virus spreading model cannot be applied to multi-hop network because of ignoring dynamic topology of network. In this paper, classic susceptible-infected (SI) model, susceptible-infected-susceptible (SIS) model and susceptible-infected-removed (SIR) model are applied to multi-hop network based on random way-point (RWP) model, and contact duration of virus is introduced. Virus spreading behaviors are examined through contact duration of virus, communication radius of node, distribution density of node, and the number of initial infected nodes. Simulation results show that node mobility has significant effect on virus spreading behaviors. In particular, a special node speed that can lead network to appear the fastest-spreading virus phenomenon is found. The special speed is approximately equal to the ratio of communication radius of node to contact duration of virus. Distribution density of node and the number of initial infected nodes almost do not affect the special speed.

Keywords: Multi-hop network, Node mobility, Virus spreading, Contact duration of virus

1 Introduction

The widely use of mobile computing and communication devices (e.g., cell phones, laptops, handheld digital devices, personal digital assistants) is driving a revolutionary change in our information society. Now alternative ways to deliver the services are focused around wireless network [1, 2], which can make terminals connect to each other in the transmission range through automatic configuration. The wireless arena has been experiencing exponential growth in the current. Users can use their mobile phone to check e-mail and browse internet; travelers with portable computers can surf the internet in public locations; researchers can exchange information by portable computers via wireless network while attending conferences. These examples of spontaneous, wireless communication between devices might be loosely defined as multi-hop network, which allows devices to establish communication, anytime and anywhere, without the aid of a central infrastructure. Actually, multi-hop network as such is not new, but the setting, usage, and players are. In the past, the notion of multi-hop network was often associated with communication on combat fields and at the site of a disaster area; now, as novel technologies such as Bluetooth materialize, the scenario of multi-hop network is likely to change, as is its importance. As wireless network continues to evolve, multi-hop network is expected to become more important and popular technology solution. Multi-hop network enables two or more mobile nodes to communicate using standard network protocols. Nodes are free to move randomly and organize themselves arbitrarily. Each node is equal, which operates not only as an end-system but also as a router. Since they can forward packets on behalf of other nodes and run user applications, they are connected via wireless links without using the existing network infrastructure or centralized administration. Each node can only communicate directly with other nodes, which is in the transmission range. Nodes can communicate with other nodes that are not in direct transmission range by multi-hop fashion. Multi-hop network has broad application prospects in many fields [3] such as industry, agriculture, transportation, and military. In addition, multi-hop

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network has some concrete application in wireless Internet access, wireless sensor networks, and disaster relief operations. Especially, the growing popularity of multi-hop network makes it increasingly attractive to 5G. Multi-hop network will maybe become an important form of 5G in the future.

Short-range, point-to-point communications for mobile users enjoy increasing popularity, particularly with the rise in Bluetooth-equipped mobile devices. However, the growth of mobile networks is leading to new security challenges. Virus writers have begun exploiting lax security in many mobile devices and subsequently developed virus exploiting proximity-based propagation mechanisms. Viruses are self-replication malicious code which can propagate through network terminals without any human intervention. The multi-hop network has no centralized administration and fixed network infrastructure. And nodes in multi-hop network are resource-restrained devices with low defense capabilities. At the same time, the hardware conditions of virus spreading are satisfied with the configuration improvement of intelligent terminal. Therefore, multi-hop network becomes attractive targets for viruses and is facing some serious challenges [4–6]. Now, viruses are active not only in the wired network but also in the wireless network. They are rapidly occupying global mobile devices. In 2000, the first mobile phone virus "VBS. TimoFonica" appeared in Spain, which sent abusive messages to users via the carrier's internal system. The "torrent" virus was found in China in 2002 that can make the phone automatically shut down when user was reading message. Cabir Cell Phone Worm which was found in 2004 is really a mobile phone virus. Cabir Cell Phone Worm infects phones which run the Symbian operating system. It continually scans for other Bluetooth-enabled devices and tries to infect device which enters the scanning range. Cabir Cell Phone Worm is found in some countries and has more than 20 variants in the current. After the emergence of Cabir Cell Phone Worm, the number of mobile phone virus appears to speed up significantly. About 1.75 Cell Phone Virus appears within a week lasted for 18 months. In 2005, MMS (Multimedia Messaging Service) viruses appeared which are transmitted through MMS, or other ways. MMS is a messaging protocol that allows sharing of media and programs between mobile phones within minutes and across the world. Thus, an MMS virus can send a copy of itself in a short time frame to all the phone numbers found in a phone's address book, resulting in a long-range spreading pattern. In 2006, the number of mobile phone viruses increased by 45 % compared with its number in 2005, and the number of growth was 180. In 2010, more than one million cell phones in China were infected by the "Zombie" virus, which can automatically send text messages. Juniper Networks Mobile Threat Center released its 2011 Mobile Threats Report in February 2012, which showed that mobile malware increased by 155 % compared with the number from the previous year. With the widely use of mobile applications, about 7.521 million mobile terminals were attacked by Trojan within a week in 2014. Virus chain of intelligent terminal has caused the loss of 1 billion yuan to users each year. At present, the diversity of virus species and the complexity of transmission ways make the frequency of security incidents increase in wireless mobile network.

With the increasing attention to multi-hop network, it may become one of the main targets of viruses attack in the future. Faced with attack from viruses, it is important to master virus spreading behaviors in multi-hop network. It can help us to take measures to reduce the loss caused by viruses attack. Therefore, devising virus spreading models for multi-hop network is an important research area. In this paper, classic susceptible-infected (SI) model, susceptible-infected-susceptible (SIS) model, and susceptible-infected-removed (SIR) model are applied to multi-hop network based on random way-point (RWP) model [7–9] to analyze virus spreading behaviors. Simulation results show a special node speed that can lead network to appear the fastest-spreading virus phenomenon is approximately equal to the ratio of communication radius of node to contact duration of virus. Distribution density of node and the number of initial infected nodes almost do not affect the special speed. Simulation results of this paper are of practical value for the analysis of virus spreading and give a deeper understanding of virus spreading behaviors in multi-hop network.

The remainder of the paper is organized as follows. Section 2 introduces the related work. Section 3 provides an introduction to mobile model and virus spreading model. Section 4 illustrates the marked difference of virus spreading behaviors that generated by our model. Especially, a special node speed that can lead network to appear the fastest-spreading virus phenomenon is found. Influence factors of virus spreading are analyzed in Section 5. Using the background discussed above, In section 6, SIS model and SIR model are applied to multi-hop network based on RWP model. Section 7 concludes this paper.

2 Related work

Virus spreading models [10–12] and control strategies in mobile environments attract much attention. So far, many efforts have been recently made to model virus spreading among computer network. Scholars mainly reference traditional infectious disease models (e.g., SI, SIS, SIR) in biological engineering [13]. And then they combine with the characteristics of computer virus to form computer virus spreading model [14, 15]. Multi-hop network has the characteristic of dynamic topology. Viruses can spread through short-range radio (i.e., Bluetooth and WiFi) in multi-hop network. However, traditional computer virus spreading models cannot be applied in multi-hop network. Nodes move with variable velocity in [16] are provided to demonstrate the failure of computer virus spreading model in mobile environments. The failure of computer virus spreading model is largely due to its strict reliance on the average connectivity statistic and has no conception of node speed. Computer network is homogeneous network. Node mobility introduces non-homogeneous connectivity distributions that cannot be described using a simple average. It is inappropriate for modeling virus spreading in non-homogeneous mobile networks. Spreading models for mobile networks must treat the movement of devices as a first-class concern. Recently, scholars begin to explore the modified models which are applied to model virus spreading in mobile environments. Robert G firstly used the SIS model to study worm spreading behaviors in ad hoc network [17]. He considered the impact of worm propagation delay and bandwidth constraint on its spread but ignored the impact of human actions. A SIR/WS model [18] is proposed to describe virus spreading in wireless sensor networks. The relationship with the infection rate and immunization rate is proposed. The author in [19] focused on smart phone malware spreading model, in order to understand the spreading behavior of smart phone malware. This paper extensively surveyed the smart phone malware spreading models based on generic epidemic models. A modified SIS epidemic model is proposed to study the dynamics of virus spread in wireless sensor networks in [20]. And the model can be applied to different types of networks such as wireless networks, computer networks, and social networks. Dynamics of worm spreading in the Bluetooth environment is studied in [21], and it also shows the possibility of large-scale worm outbreaks by experiment. Xia Wei built SIS model of smart phone virus and discussed the influence of node mobility to virus spreading [22]; unfortunately, specific mobile model was not pointed out. Node mobility is considered in [23, 24], but mobile devices are attacked by virus from fleeting in-contact wireless devices with short-distance communication range. However, some existent researches do not go far enough. Most models depend almost entirely on the technology of differential equations and fail to take into account the conditions of virus spreading (e.g., ignoring dynamic topology of nodes or contact duration of virus). Virus spreading behaviors in multi-hop network have to be carefully considered through reliable models, although it is complex and challenging to establish practical and appropriate models on virus spreading dynamics. Xu et al. [25–27] proposed a framework processing mobile social media data based on crowdsensing method.

3 Mobile model and virus spreading model

Virus spreading can be regarded as certain actions that obey some spreading rules of networks. A reasonable mobile model can provide us with a more clear recognition to virus spreading behaviors. Mobile models are characterized by the movement of their constituents. The nature of movement—its speed, direction, and rate of change—can have a dramatic effect on protocols and systems designed to support mobility. Mobile models in simulation-based studies are important building blocks. It is designed to describe how their velocity and location change over time. These models that model multi-hop network are categorized as Random Mobility Model and Group Mobility Model. At present, the most widely used mobile model is the RWP model, which was originally proposed for studying the performance of ad hoc routing protocols by Johnson and Maltz [28]. This mobile model is a simple and straightforward stochastic model of multi-hop network. It can describe the movement behavior of node in multi-hop network. Every node in RWP model is described by three parameters: current location, speed, and pause time. The RWP model operates in this paper as follows: In the model, nodes travel within a square area. The total number of nodes is N in the area. Each node independently picks up a random destination. Node travels the destination on a straight line at the chosen speed v. The node may also remain stationary for a random pause time before starting its movement towards the next destination. And then node picks another random destination and move speed. Each node will repeat the process until the end of simulation. The diagram of RWP mobility model is shown in Fig. 1. A paper by Perkins, Hughes, and Owen [29] shows that

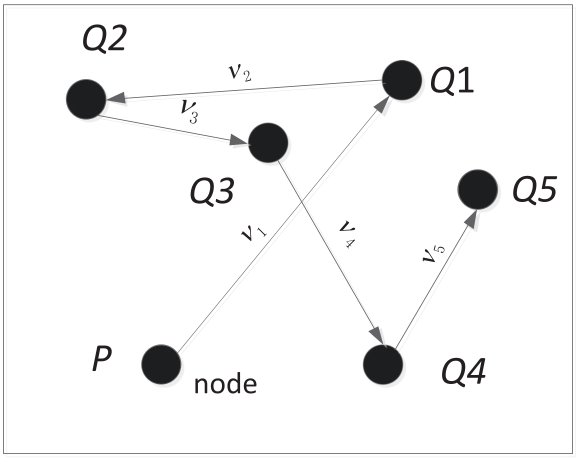


Fig. 1 Diagram of RWP mobility model

node speed, pause time, network size, and the number of sources can affect the performance of routing protocols. Node speed is shown to be a significant factor, while pause time is not. Thus, it can be set to 0 s in order to study smoothly. As simulated time progressed, more nodes move across the center of simulation region [30, 31]. And RWP model does not have a steady state with different node speed; thus, the mobility scenario poses different connectivity properties.

For the virus spreading models, we focus on the most popular models, the SI model, SIS model, and SIS model. In this paper, the main research object is SI model, which is the basis of SIS model and SIR model. In SI model, nodes are divided into two statuses: susceptible (S) and infected (I). The susceptible nodes are attacked by viruses, and initially, only a small number of nodes are infected. The virus spreads itself to its neighbor nodes by continuously communicating during a given stretch of time. Then susceptible node will become infected node with infection rate β. The infected neighbor nodes repeat the process to their respective neighbor nodes, until all nodes become infected nodes. Infected node cannot be recovered from virus. It is only capable of spreading virus to susceptible nodes. The status transition of SI model can be seen from Fig. 2. The SIS epidemic model resembles a flu-like virus, where nodes have no immunity. In SIS model, nodes are also divided into two statuses: susceptible (S) and infected (I). Two parameters in SIS model are also referred to as the birth rate (β) and death rate (γ) of the virus. Different from SIS model, the infected node can recover from virus to become a susceptible node with a recovery probability γ, and this susceptible node will probably be infected again. Status of every node will repeat the process until the end of simulation. The status transition of SIS model can be seen from Fig. 3. In SIR model, nodes are divided into three statuses: susceptible (S), infected (I), and removed (R). Susceptible node can become removed node with an immune probability δ; infected node can be become removed node with an immune probability μ, too. Once a node becomes a removed node, it will not be infected again. The status transition of SIR model can be seen from Fig. 4. In addition, the Table 1 shows the definitions of various symbols in this paper.

In this paper, MATLAB software is used to study virus spreading characteristics in multi-hop network. Where the unit time of node moving is 1 s (i.e., dt = 1 s), total simulation time is 400 s (i.e., $T = 400$ s). Each node can automatically communicate with adjacent nodes though wireless networks. In this paper, all simulation experiments are carried out on the basis of the above conditions. Note that every simulation result represents the average of 100 times.

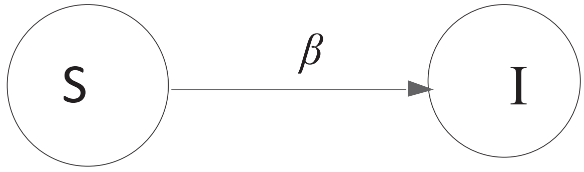


Fig. 2 Status transition in SI model

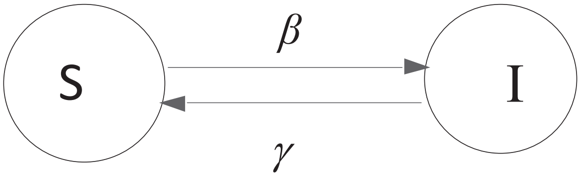


Fig. 3 Status transition in SIS model

4 Different virus spreading behaviors

The dynamic topology of multi-hop network is its important feature. It is of great significance to explore the relationship between virus spreading behaviors and node speed, which can help us to master virus control strategies. The value of node speed determines the fluctuation degree of multi-hop network topology and also influences virus spreading behaviors. Figure 5 explores virus spreading behaviors in the multi-hop network based on RWP model by using the SI model. If $\Delta T = 0$ s, virus spreading is from fleeting in-contact wireless devices with short-distance communication range. Susceptible node will become infected node with infection rate β, when susceptible node is in communication range of infected node. The $i(t)$ increases to a steady value with the increasing v. This is because nodes in net_{fast} (network in which nodes move quickly) are "better mixed" than nodes in net_{slow} (network in which nodes move slowly). The faster node velocity speeds up the changes of neighbor nodes. Infected nodes will have more opportunities to communicate with susceptible nodes, and then virus transmission is speeded up. When node speed increases to a certain value, frequent change of neighbor nodes cannot speed up virus spreading. By then, the spatial distribution of infected nodes and susceptible nodes determines virus spread behaviors. In a word, node mobility plays an important role in virus spreading.

In fact, virus spreading needs a period of time. Therefore, instantaneous state transitions cannot model virus

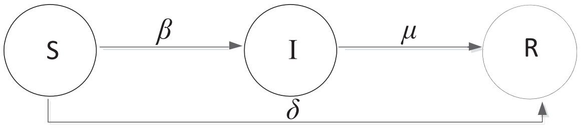


Fig. 4 Status transition in SIR model

Table 1 Symbol definition

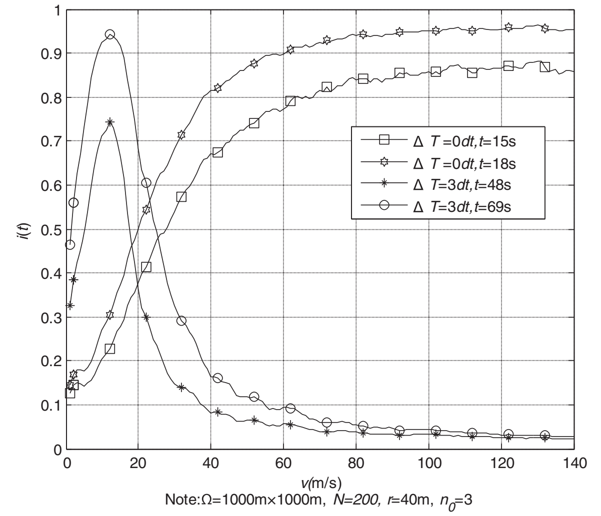
Symbol	Instructions	Symbol	Instructions
Ω	Moving space of node (square area)	ρ	Distribution density of node
v	Node speed	r(t)	The rate of removed nodes at time t
r	Communication radius of node	T	Total simulation time
dt	The unit time of node moving	n_0	The number of initial infected nodes
N	The total number of nodes	ΔT	Contact duration of virus
$I(t)$	The number of infected nodes at time t	$i(t)$	The rate of infected nodes at time t
$S(t)$	The number of susceptible nodes at time t	$s(t)$	The rate of susceptible nodes at time t
γ	Recovery probability (I → S)	β	Infection probability (S → I)
μ	Immune probability (I → R)	δ	Immune probability (S → R)

spreading perfectly. Simulation result in Fig. 5 shows that $i(t)$-v curve has a peak point for the influence of ΔT. It demonstrates contact duration of virus which plays an important role to virus spreading in multi-hop networks. An intuitive explanation for this phenomenon is as follow. Connectivity between nodes is enhanced with the increase of node speed, so viral spreading speed increases. And as node speed continues to increase, the time that susceptible node stays in coverage area of infected node is too short, so that virus cannot finish propagation. Figure 6 shows that three differential curves are almost coincident. It suggests that the variation trend of curve does not change with time. The peak is also same at different time. It corresponds to a special node speed. This speed can lead network to appear the fastest-spreading virus phenomenon. It is called v_{fs} in this paper.

Consider that infection probability β, recovery probability γ, and immune probability μ or δ can only affect the value of $s(t)$, $i(t)$, and $r(t)$ at any moment, while the value of v_{fs} cannot be changed according to the change of these probability. Therefore, we assume they are constant with appropriate generality. In addition, the MAC (Medium Access Control) protocol used by WiFi-based wireless devices follows the IEEE 802.11 standard, which specifies a set of rules that enable nearby devices to coordinate their transmissions in a distributed manner. The MAC is a highly complex protocol. It can control nodes to enter the channel in sequence; thus, MAC can affect the value of $i(t)$ at any moment, and not the value of v_{fs}.

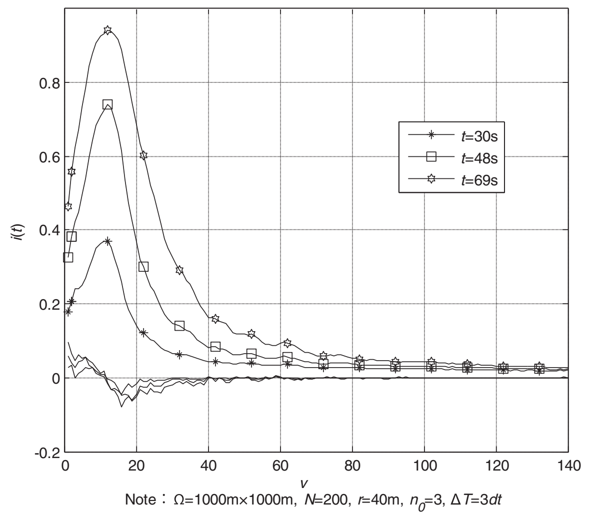
5 Analysis of influence factors

In order to analyze influence factors to v_{fs}, several important parameters are investigated. They are contact duration of virus, communication radius of node, the number of initial infected nodes, and the distribution density of node. Then analyzing different properties of this model with change of parameters; discussing the relation between v_{fs} and these parameters. These studies have greatly contributed to our understanding of the



Note:Ω=1000m×1000m, *N=200,* r=40m, n_0=3

Fig. 5 Different virus spreading behaviors



Note：Ω=1000m×1000m, N=200, r=40m, n_0=3, Δ T=3dt

Fig. 6 The consistency of v_{fs} at different time influence of every factor on virus spreading behaviors. What is more, there is a very important research value to analyze the influence factors, which can help to take corresponding strategies to control virus spreading and improve the security of multi-hop network.

5.1 Contact duration of virus

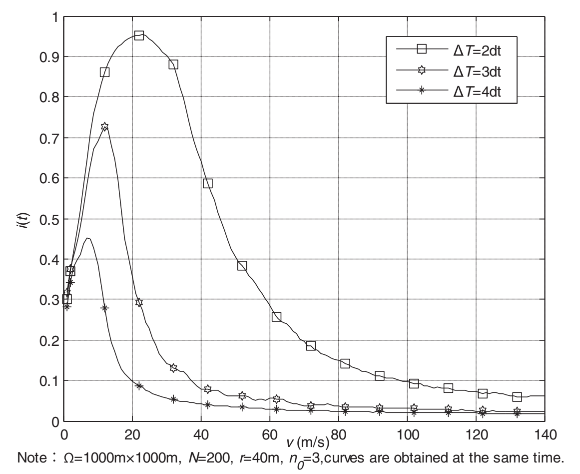
In general, contact duration of virus is often ignored in order to simplify the virus spreading model. However, contact duration of virus has important impact to virus spreading. Figure 7 shows the relation between v and $i(t)$ with different ΔT. It can be seen from Fig. 7, $i(t)$ decreases with the increasing ΔT. Reasons for this phenomenon are as follows: the increase of ΔT extends the time of finishing virus transmission; on the other hand, enough contact time between nodes cannot be guaranteed with the increasing ΔT. Therefore, the probability of finishing virus transmission is reduced and then leads to the decrease of $i(t)$. At the same time, simulation result shows as follows: (1) v_{fs} decreases with the increasing ΔT, (2) when $v < v_{\mathrm{fs}}$, $i(t)$-v curve rises slowly if ΔT is greater, and when $v > v_{\mathrm{fs}}$, $i(t)$-v curve decays rapidly if ΔT is greater. Virus spreading needs to meet the requirements of connectivity and ΔT. The increase of v can improve connectivity but increase the difficulty of meeting ΔT. Therefore, when other parameters are constant, there is the phenomenon: the greater ΔT, the lower v_{fs}. When $v < v_{\mathrm{fs}}$ (i.e., enough contact time between nodes can be guaranteed.), connectivity of multi-hop network can be effectively improved with the increasing v. Improvement of connectivity makes virus spread rapidly. And the improvement is more obvious if ΔT is smaller, so $i(t)$-v curve rises rapidly. When $v > v_{\mathrm{fs}}$ (i.e., enough contact time between nodes cannot be guaranteed.), contact time between nodes becomes short. Reduction of contact time makes virus spread slowly. Especially for the greater ΔT, this influence is more obvious, and then $i(t)$-v curve decays rapidly.

5.2 Communication radius of node

Communication radius of node is a very important factor whether in the network connectivity or virus spreading. Figure 8 shows the relation between v and $i(t)$ with different r. It can be seen from Fig. 8, $i(t)$ increases with the increasing r. Reasons for this phenomenon are as follows: on the one hand, the increase of r expands communication range; on the other hand, more contact time between nodes can be provided with the increasing r in multi-hop network. Therefore, the probability of finishing virus transmission is improved and then leads to the increase of $i(t)$. At the same time, simulation result shows as follows:(1) v_{fs} increases with the increasing r; (2) when $v < v_{\mathrm{fs}}$, $i(t)$-v curve rises rapidly if r is greater; when $v > v_{\mathrm{fs}}$, $i(t)$-v curve decays slowly if r is greater. According to theoretical analysis, r has the opposite effect on virus spreading compared with ΔT. The increase of ΔT increases the difficulty of finishing virus transmission. On the contrary, the increase of r can expand communication range of node and increase contact time. Therefore, when other parameters are constant, there is the phenomenon: the greater r, the higher v_{fs}; $i(t)$-v curve rises rapidly and decays slowly with the increase of r.

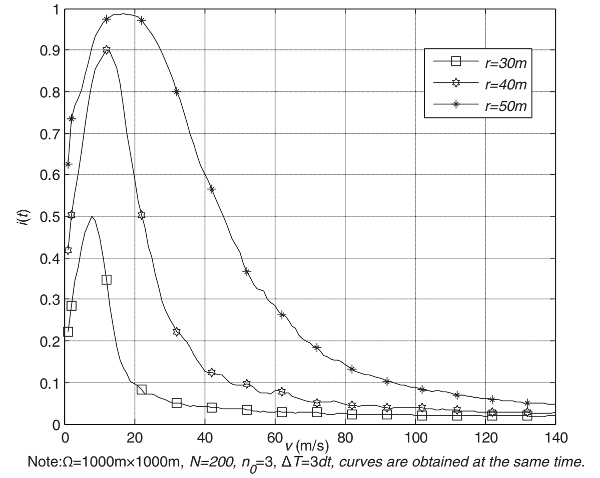
5.3 The number of initial infected nodes

Figure 9 shows the relation between v and $i(t)$ with different n_0. It can be seen from Fig. 9, $i(t)$ increases with the increasing n_0. The reason for this phenomenon is that infected nodes have more chances to communicate with susceptible nodes with the increasing n_0. Therefore, the probability of finishing virus transmission is improved and then leads to the increase of $i(t)$. At the same



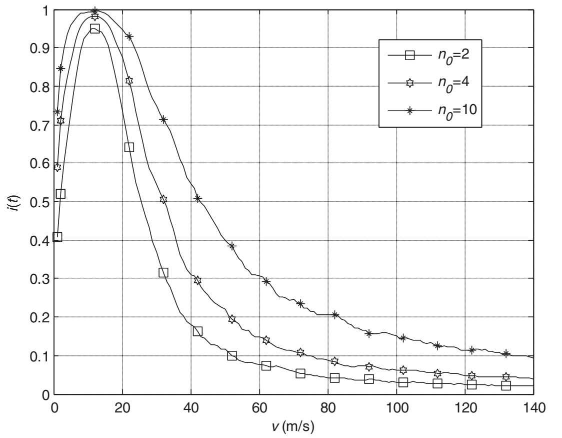
Note：Ω=1000m×1000m, N=200, r=40m, n_0=3,curves are obtained at the same time.

Fig. 7 Relation between v and $i(t)$ with different ΔT



Note:Ω=1000m×1000m, N=200, n_0=3, ΔT=3dt, curves are obtained at the same time.

Fig. 8 Relation between v and $i(t)$ with different r



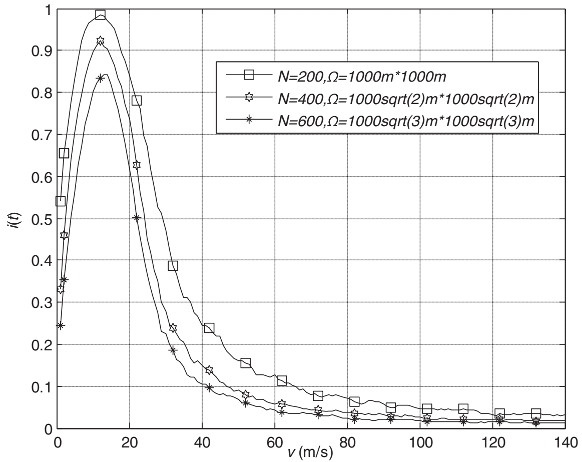
Note：Ω=1000m×1000m, *N=200, ΔT=3dt, r=40m, curves are obtained at the same time.*

Fig. 9 Relation between v and $i(t)$ with different n_0

time, it is shown that (1) n_0 almost does not affect v_{fs}; (2) when $v < v_{\mathrm{fs}}$, $i(t)$-v curve rises rapidly if n_0 is greater; and when $v > v_{\mathrm{fs}}$, $i(t)$-v curve decays slowly if n_0 is greater. This is because n_0 cannot affect connectivity and ΔT. In fact, n_0 can be seen as a part of $I(t)$ ($i(t) = I(t)/N$). Therefore, n_0 affects only the value of $i(t)$, and not the value of v_{fs}. The increase of n_0 can significantly boost virus transmission. And this improvement is more obvious with the increase of n_0, so $i(t)$-v curve rises rapidly and decays slowly.

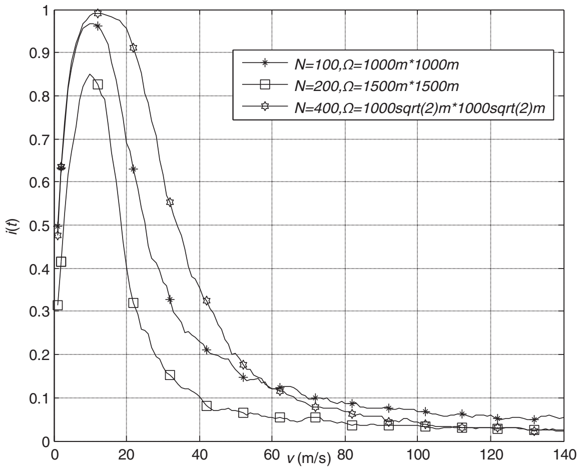
5.4 Distribution density of node

Figures 10 and 11 show the relation between v and $i(t)$ with same or different ρ. It can be seen from Fig. 10, $i(t)$ is different although the same ρ. This is because almost the same number of susceptible nodes is infected during a unit time in different scenarios with the same ρ. Therefore, the total number of infected nodes is the same at every moment in different scenarios. When N is greater, $i(t)$ ($i(t) = S(t)/N$) is smaller. It can also be seen from Fig. 11, $i(t)$ increases with the increasing ρ. Reason for this phenomenon is that connectivity is enhanced due to the increase of ρ, so that there are more opportunities to communication between susceptible nodes and infected nodes. Therefore, the probability of finishing virus transmission is improved. At the same time, Figs. 10 and 11 show that with or without change of ρ almost does not affect v_{fs}. Virus spreading needs to meet the requirements of connectivity and ΔT. Although different ρ changes connectivity, such the change on connectivity is for network under all speeds. In fact, ρ can indirectly represent the total number of nodes N because of $i(t) = I(t)/N$ and $\rho \approx (N/\Omega)$. Therefore, ρ affects only the value of $i(t)$, and not the value of v_{fs}.



Note：*r*=40m, Δ*T*=3*dt*, *n0*=3, curves are obtained at the same time.

Fig. 10 Relation between v and $i(t)$ with the same ρ



Note：*r=40m,* Δ*T*=3*dt, n0*=3, curves are obtained at the same time.

Fig. 11 Relation between v and $i(t)$ with different ρ

5.5 Relation between v_{fs} and two parameters: communication radius of node and contact duration of virus

Fundamentally, v_{fs} varies mainly depending on r and ΔT. Where σ^2 is the variance, it represents the fluctuations on the value of v_{fs} around $r/\Delta T$. According to Table 2, when (r, ΔT) is (40 m, 3 s), (80 m, 6 s), (60 m, 4 s), and (30 m, 2 s), the values of variance are as follows: $\sigma_1^2 = 0.56$, $\sigma_2^2 = 0.34$, $\sigma_3^2 = 0.25$, $\sigma_4^2 = 0.45$. If r and ΔT are constant, the conclusion can be obtained that v_{fs} is almost the same although ρ and n_0 in constant change. In fact, the value of v_{fs} almost does not change as long as $r/\Delta T$ is a constant value (as shown in Table 2, (r, ΔT) is (40 m, 3 s) or (80 m, 6 s); (r, ΔT) is (60 m, 4 s) or (30 m, 2 s)). Such as, $r/\Delta T = 40$ m/3 s or 80 m/6 s, the variance is 0.46; $r/\Delta T = 60$ m/4 s or 30 m/2 s, the variance is 0.38. It is noted that the value of v_{fs} is strongly

Table 2 The special node speed

r(m)	ΔT (s)	N	Ω (m^2)	$\rho = N/\Omega$	n_0	v_{fs}(m/s)
40	3	200	2000×2000	5.00×10^{-5}	3	14.0
		100	$1000\sqrt{2} \times 1000\sqrt{2}$	5.00×10^{-5}	3	12.5
		300	1500×1500	1.33×10^{-4}	3	14.9
		100	$500\sqrt{3} \times 500\sqrt{3}$	1.33×10^{-4}	3	13.3
		400	2000×2000	1.00×10^{-4}	3	13.1
		100	1000×1000	1.00×10^{-4}	3	12.5
		250	2000×2000	6.25×10^{-5}	2	13.4
		250	2000×2000	6.25×10^{-5}	6	12.8
		250	2000×2000	6.25×10^{-5}	10	14.0
80	6	200	2000×2000	5.00×10^{-5}	3	13.3
		100	$1000\sqrt{2} \times 1000\sqrt{2}$	5.00×10^{-5}	3	13.6
		300	1500 m × 1500 m	1.33×10^{-4}	3	14.5
		100	$500\sqrt{3} \times 500\sqrt{3}$	1.33×10^{-4}	3	13.4
		400	2000×2000	1.00×10^{-4}	3	13.1
		100	1000×1000	1.00×10^{-4}	3	12.8
		300	2000×2000	7.50×10^{-5}	1	14.5
		300	2000×2000	7.50×10^{-5}	5	13.8
		300	2000×2000	7.50×10^{-5}	9	13.0
60	4	150	1000×1000	1.40×10^{-4}	3	15.0
		300	$1000\sqrt{2} \times 1000\sqrt{2}$	1.40×10^{-4}	3	14.8
		140	500×500	5.60×10^{-4}	3	15.5
		100	$500\sqrt{3} \times 500\sqrt{3}$	5.60×10^{-4}	3	15.1
		200	2000×2000	5.00×10^{-5}	3	15.1
		100	$1000\sqrt{2} \times 1000\sqrt{2}$	5.00×10^{-5}	3	14.7
		200	1000×1000	2.00×10^{-4}	3	16.1
		200	1000×1000	2.00×10^{-4}	6	14.2
		200	1000×1000	2.00×10^{-4}	9	15.3
30	2	500	3000×3000	5.56×10^{-5}	5	14.2
		250	$1500\sqrt{2} \times 1500\sqrt{2}$	5.56×10^{-5}	5	15.0
		300	2000×2000	7.50×10^{-5}	5	14.6
		150	$1000\sqrt{2} \times 1000\sqrt{2}$	7.50×10^{-5}	5	13.8
		100	400×400	6.25×10^{-4}	5	14.5
		400	800×800	6.25×10^{-4}	5	16.3
		200	2000×2000	5.00×10^{-5}	1	14.4
		200	2000×2000	5.00×10^{-5}	6	14.8
		200	2000×2000	5.00×10^{-5}	11	15.2

dependent on the value of $r/\Delta T$ according to the analysis of above conclusions. Besides, according to the above simulations, the phenomenon can be found as follows: if $v \leq v_{fs}$, $i(t)$ increases as $v \rightarrow r/\Delta T$; if $v \geq v_{fs}$, $i(t)$ decreases to zero as $v \rightarrow \infty$. Therefore, a series of prevention-cure strategies of virus are drawn: (1) when $v < v_{fs}$, considering decreasing node speed to control virus spreading; (2) the number of mobile nodes with the velocity v_{fs} should be reduced as much as possible, and (3) when $v \geq v_{fs}$, considering increasing node speed to control virus spreading.

6 Virus spreading behaviors in sis model and sir model

In the above sections, classic SI model is applied to multi-hop network based on RWP model to analyze virus spreading behaviors. It is demonstrated that v_{fs} is approximately equal to the ratio of communication radius of the node to contact duration of virus. Distribution density of node and the number of initial infected nodes almost does not affect v_{fs}. Is there this phenomenon in SIS model or SIR model? Using the background discussed above, this section simply discusses SIS model, and SIR model is applied to multi-hop network based on RWP model. Table 3 shows the values of various symbols which are in SIS model and SIR model.

In Fig. 12, virus spreading behaviors are also examined through parameters contact duration of virus, communication radius of node, distribution density of node, and the number of initial infected nodes. According to the simulation result in Fig. 12, SIS model has also this phenomenon: $i(t)$ increases to a steady value with the increasing v, and then $i(t)$ decreases to zero with the continuously increasing v. Note that cures are obtained at the same time. According to cases 1, 2, and 3, simulation results show that v_{fs} is also approximately equal to $r/\Delta T$, although there are changes in contact duration of virus, communication radius of node, distribution density of node, and the number of initial infected nodes. In addition, $i(t)$ increases with the increasing r according to the comparison between case 3 and case 4; $i(t)$ decreases with the increasing ΔT according to the comparison between case 3 and case 5. In a word, SIS model and SI model show similar virus spreading behavior in multi-hop network. Compared with SI model and SIS model, status transition of node in SIR model is relatively complicated. Actually, there is basically the same virus spreading behaviors according to Fig. 13.

Table 3 Simulation parameters

Model	Case	Ω/m^2	N	n_0	r/m	ΔT
SIS	1	1000×1000	200	6	40	2dt
	2	1500×1500	300	10	60	3dt
	3	1000×1000	200	3	80	4dt
	4	1000×1000	200	3	60	4dt
	5	1000×1000	200	3	80	3dt
SIR	1	1000×1000	200	3	80	4dt
	2	2000×2000	300	6	60	3dt
	3	1000×1000	200	3	40	2dt

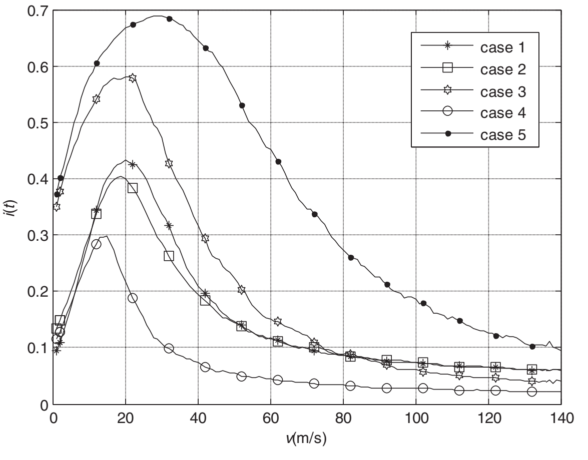


Fig. 12 Relation between *v* and *i*(*t*) with different conditions in SIS model

7 Conclusions

Traditional epidemiological models fail to capture the unique topological properties of mobile networks. Node mobility introduces non-homogeneous connectivity distributions that cannot be represented using a simple average. Virus spreading model that ignores contact duration of virus fails to capture the unique virus spread properties of multi-hop network. Virus spreading behaviors here is obviously different compared with virus spreading behaviors with instantaneous state transitions. An important result from the model in this paper is that virus spreading speed increases first and then decreases with the increase of node speed. The special node speed, which can lead the network appear the fastest-spreading virus phenomenon, is approximately equal to the ratio of communication radius of node to contact duration of virus. The special speed almost has no relation with distribution density of node and the number of initial infected nodes. An understanding of virus spreading characteristics on multi-hop network is of great importance for the design of effective detection and prevention strategies for similar networks. So that people can minimize or prevent the risk of virus spreading. It will be the focus of future research to explore the dynamic expression of virus spreading in multi-hop network based on RWP model. Besides, there are several important areas for future work, such as finding analytical derivations for the mixing rate and the connectivity fluctuation parameter. However, the research of this paper already offers useful and interesting insights into virus spreading in multi-hop network. It will have great significance for the future research.

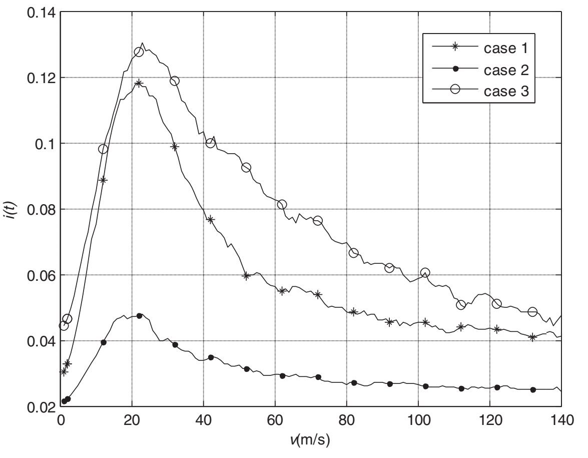


Fig. 13 Relation between *v* and *i*(*t*) with different conditions in SIR model

Acknowledgements

This paper is supported by Natural Science Foundation of Liaoning, China (2015020031), Science and Technology Project of Dalian, China (2015A11GX011), and Science Public-funded Project of Liaoning Science and Technology Department of China (2015003012).

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Received: 13 March 2016 Accepted: 5 July 2016

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