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Virus-traffic coupled dynamic model for virus propagation in vehicle-to-vehicle communication networks

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ABSTRACT

With the development of connected vehicle technology, virus propagation that exists in a traditional network environment will gradually penetrate vehicle-to-vehicle (V2V) communication networks, thus posing a serious threat to the security of intelligent transportation systems (ITS). Understanding the characteristics of virus propagation through space and time is the key to ensuring the safety of ITS. However, most existing studies on virus propagation have ignored the dynamic relationship between virus transmission and traffic flow based on the assumption that the probability of virus infection is a constant. In light of this, this study proposes a two-layer model, called the virus-traffic coupled dynamic model, to investigate virus propagation in V2V communication networks. First, the dynamics of traffic flow and vehicular mobility are formulated as many update rules between cellular automata in the lower layer; then, due to the similarity between biological epidemic dissemination and virus propagation, an epidemic model called the susceptible-infected-recovered (SIR) was built to model the virus propagation process in the upper layer; finally, the lower and upper layer are connected by the probability of virus infection. Numerical experiments show that the model can accurately reproduce the process of virus transmission over space and time. The experiments also prove that reducing the probability of virus infection can constrain the spread of the virus effectively for both different communication range limits and various traffic densities.

1. Introduction

Over the past few decades, the rising number of vehicles in cities has brought traffic jams and accidents to our daily life [1–3]. The emerging technology of connected vehicles allows information such as speed, location, and direction to be exchanged or shared among vehicles [4,5]. This technology creates a new approach to preventing traffic jams in urban road networks, such as controlling the trajectories of connected vehicles when passing through an intersection to decrease intersection delay [6,7]. However, the flipside is the high possibility of viral infection between connected vehicles. For instance, an attacker may use the vulnerability of vehicle-to-vehicle (V2V) communication networks to infect adjacent vehicles. Further, the virus can spread through inter-vehicle communication to infringe on users' privacy, or directly alter vehicle motion. Based on this, the vulnerability of connected vehicles to virus attack poses serious security threats to the transportation system.

Analyzing the propagation of viruses in V2V communication networks requires a multi-layer framework to describe the interdependencies between virus flow, traffic flow, and V2V communications [8]. Considering that the transmission of a virus between connected vehicles depends on the transmission of normal information such as the speed or location of vehicles, research on virus propagation must be closely related to normal information transmission.

To date, scholars have carried out a great deal of research on the propagation of general information. Due to the complexities caused by the interaction between traffic flow dynamics and V2V communications, one of the classical methods for analyzing the propagation of general information is the simulation-based approach [9,10]. In one such study, E. Spaho et al., [11] reviewed simulation-based approaches in detail and captured the nonlinear relationship between traffic flow, information flow, and V2V communication. In addition, X. Yang et al., [12] constructed an information propagation simulation framework for vehicular net-

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works, and further simulated information transmission among IVC(Inter-vehicle communication)-equipped vehicles on a freeway. Other studies [13–15] constructed a simulation framework by assuming traffic flow was static, and used the simulation results of spatial headway to analyze the constraints of information propagation. However, these simulation methods lack strict theoretical formulation to support theoretical understanding and insight.

Compared with the simulation-based approaches, integrating traffic flow and information flow into different layers of a framework can provide theoretical understanding and insights [16,17]. For example, Y.H. Kim et al., [18] considered the communication constraints generated by traffic flow dynamics to establish the information propagation model formed by the SI model and CTM model. They performed numerical experiments using the speed of information dissemination wave to describe the characteristics of instantaneous information flow propagation. Lili Du et al., [19,20] constructed an information-traffic coupled cell transmission model (IT-CTM) by dividing the road segment into multiple cells to capture the information propagation between inner-cell and inter-cell networks. Jian et al., [21] hold that traffic congestion may impact whether a particular information packet can reach the desired location, and under this assumption, a control strategy for information propagation was proposed to research the effect of this phenomenon on a congested V2V communication environment.

Other scholars studied cyber-attacks for connected vehicles. W. Yan et al., [22,23] found that modern malware can completely bypass firewalls and anti-virus (AV) scanners. So, virus propagation that exists in a traditional network environment can also penetrate V2V communication networks. P. Wang et al., [24] proposed an extended car-following model for connected vehicles to capture the impacts from the security attacks. The stability of the proposed model was analyzed and the stable condition was derived accordingly. O. Trullols-Cruces et al., [25] studied the dynamics of vehicle worm epidemics in large-scale road networks and through numerical simulation to analysis the speed delay. S. Hong et al., [26] proposed an epidemic spreading model of complex dynamical network with the consideration of the impact of total number of connections and contact time on the spread of epidemic. Balthrop et al., [27] proposed a control strategy that was not affected by change in network topology by studying the network topologies affected by different virus replication and propagation strategies. Reilly et al., [28] studied the impact on control systems by high-level attacks in freeway systems, and determined the specified attack by simulating the traffic network model. Amoozadeh et al., [29] described the impact of security attacks on communication channels and provided strategies to improve the safety and security of connected vehicles. In terms of virus propagation in networks, Kephart et al., [30] initially developed a comprehensive study about the spread of computer viruses using epidemic models. Z. Chen et al., [31] established a statistical model for malicious information propagation under any network topology based on space-time stochastic processes. H. Okamura et al., [32] proposed a stochastic model for internet worm propagation: Node behavior under virus propagation was regarded as the process of node emergence and extinction, and based on that assumption, the behavior of worm propagation was analyzed.

In addition, research has been conduced on the attacks on the sensors of Cyber–Physical Systems. For instance, R. Ivanov, J. Park et al., [33,34] focused on the impact of attacks on multiple sensors of the Cyber–Physical Systems (CPS), and proposed a secure design method for system design. R. Lee et al., [35] concerned on the disruption made by malicious attacker, and he also developed an accurate algorithm for sensor fusion, which combines the data received from all the sensors.

Most of these studies did not analyze the probability of virus infection specifically, but instead set the probability at a certain value. However, the probability of virus infection directly affects the speed and extent of virus propagation. In our research, we take the characteristics of virus propagation in V2V communication networks into account to put forward a specific calculation method for the probability of virus infection.

To summarize, the probability of virus infection for connected vehicles has not been clearly determined so far, and preventing virus propagation in V2V communication networks remains a challenge. To solve the above challenges, this research introduces a virus-traffic coupled dynamic model to investigate virus propagation over space and time in a connected-vehicle environment where some vehicles are equipped with V2V communications devices, while others are not equipped with these devices. This research assumes that the probability of virus infection is mainly determined by the penetration rate of equipped vehicles, the mobility of the vehicles, and the reliability of virus information transmission. Further, the virus infection probability and virus propagation process are both calculated based on the virus-traffic coupled dynamic model under different scenarios. Results illustrate that the proposed model can accurately reproduce the process of virus propagation over space and time. Therefore, this research provides an effective method for simulating virus propagation in V2V communication networks.

2. A virus-traffic coupled dynamic model

2.1. Notation

Name	Unit	Description
$L_n(t)$	m	position of the nth vehicle (follower) at time t
$L_{n-1}(t)$	m	position of the $(n-1)$th vehicle (leader) at time t
$v_n(t)$	m/s	speed of the nth vehicle at time t
$v_{n-1}(t)$	m/s	speed of the $(n-1)$th vehicle at time t
a_n	m/s^2	maximum deceleration of the nth vehicle
a_{n-1}	m/s^2	maximum deceleration of the $(n-1)$th vehicle
l	m	length of vehicle
t_r	s	reaction time of the driver
$gap_{s,n}(t)$	m	critical value of safe distance of the nth vehicle at time t
$v_{s,n}(t)$	m/s	critical value of safe speed of the nth vehicle at time t
ρ	Veh/cell	density of vehicles
T	–	number of simulation times
r	m	communication range
$S(t)$	veh	number of susceptible vehicles at time step t
$I(t)$	veh	number of infected vehicles at time step t
$R(t)$	veh	number of recovered vehicles at time step t
β	–	probability of virus infection
α	–	probability of recovery
γ	Hz	frequency of wireless communication
Q	veh	total number of vehicles on road
P_{suc}	%	success rate of V2V communications
P_e	%	probability of a cell being occupied by an equipped vehicle