IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 6, 2017, accepted December 14, 2017, date of publication December 28, 2017, date of current version February 14, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2784845

Connectivity Modeling and Analysis for Internet of Vehicles in Urban Road Scene

JIUJUN CHENG[1], HAO MI[1], ZHENHUA HUANG[1], SHANGCE GAO[2], (Senior Member, IEEE), DI ZANG[1], AND CONG LIU[3]

[1]Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China
[2]Faculty of Engineering, University of Toyama, Toyama 930-8555, Japan
[3]Department of Computer Science, Shandong University of Science and Technology, Qingdao 266590, China

Corresponding authors: Zhenhua Huang (huangzhenhua@tongji.edu.cn), Shangce Gao (gaosc@eng.u-toyama.ac.jp), Di Zang (zangdi@tongji.edu.cn), and Cong Liu, (liucongchina@sdust.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61472284, in part by JSPS KAKENHI under Grant JP17K12751, and in part by the Natural Science Foundation of Shanghai under Grant 17ZR1445900.

ABSTRACT The connectivity of a large-scale heterogeneous Internet of Vehicles (IoV) is an important challenge for the environment of urban road scenes, which feature crossroads, buildings, and communication devices. The uneven density and wide distribution of vehicles in the city, the building barriers, and the interference of other communication technology will make the connectivity weaker. To the best of our knowledge, there is no formal method to model and analyze connectivity by considering the environment of urban road scenes. This paper presents such a theoretical method to investigate four connectivity properties—i.e., possibility, data forwarding time, link forwarding capability, and packet error rate—and deduce a connectivity model. Using experiments, we prove that the proposed model can ensure that the connectivity is effective and reliable in an urban road scene, and it can be used to accurately evaluate the network connectivity of a highly dynamic IoV.

INDEX TERMS Connectivity, Internet of Vehicles, large-scale heterogeneous network, urban road.

I. INTRODUCTION

The characteristics of an urban road scene determine that the IoV is a large, complex, heterogeneous network system composed of different hierarchical networks. How to effectively use the IoV to scientifically plan and distribute the network space-time resources and effectively solve the connectivity problem represents an urgent issue to be resolved. Its resolution plays an important role in efficiently solving such problems as traffic congestion, traffic safety, haze management, information transmission and other social services.

In recent years, some existing work on the connectivity of the IoV has paid more attention to a particular scene or been based on certain assumptions. They mainly focused on end-to-end connectivity [1]–[6] and overall network connectivity [7]–[10]. The former is mainly used to study the connectivity probability between two nodes in a dynamic network environment. It can be modeled as 1-D network space. As shown in Fig. 1, according to a certain node distribution model—e.g., Poisson distribution—the relationship between the probability of connectivity and vehicle density is analyzed. The latter is mainly based on the percolation theory to analyze the changes of the network static connectivity with vehicle density but does not consider node mobility.

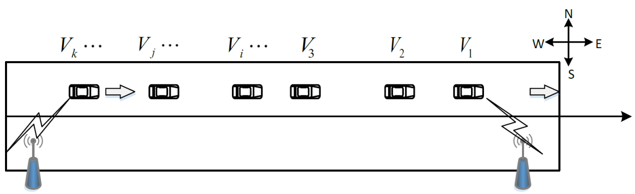


FIGURE 1. End-to-end connectivity of one-dimensional network topology model.

At present, the research on vehicle interconnection in an existing urban scene is focused Vehicular ad-hoc network (VANET) and VANET with a road side unit (RSU) [11]–[15]. In an urban road scene, [16] analyzed the connectivity of VANET and VANET with RSU. Many studies have investigated the potential factors impacting connectivity, including topology, traffic signals and vehicle traffic [17]–[19]. However, without considering the characteristics of an urban road scene, existing research cannot effectively solve the connectivity problems in a large-scale heterogeneous IoV.

2169-3536 © 2017 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

The existing vehicle connectivity modeling and analysis techniques cannot be applied directly to a large-scale heterogeneous IoV given an urban road scene because they have the following characteristics different from those of a conventional IoV:

1) Urban roads are covered widely with crisscrosses, junctions and sections.
2) Vehicle density distribution is uneven, and low vehicle density leads to cases in which vehicles cannot be connected to the IoV by vehicle to vehicle.
3) A large-scale heterogeneous vehicle network is composed of vehicles, base stations, RSUs and other facilities distributed in an urban scenario.
4) Existing vehicle connectivity methods focus on a small network. If we directly apply them to a complex network in an urban scene, we encounter problems such as low packet delivery rate and high end-to-end delay.

In this paper, by considering these four characteristics, we first introduce a large-scale heterogeneous IoV scene in the context of an urban road scene, and then we discuss the modeling and analysis approaches for its connectivity.

The remainder of this paper is organized as follows. Section II discusses the related work. Section III presents a large-scale heterogeneous IoV in an urban road scene. In Section IV, four connectivity properties are proposed and analyzed. Section V describes a connectivity model under an urban road scene. Finally, Section VI provides simulations to show the proposed approaches. Section VII offers the conclusion.

II. RELATED WORK

We summarize the existing work related to IoV connectivity.

A. CONNECTIVITY OF END-TO-END

Ng *et al.* [1] assumed that the vehicle arrival probability on an expressway belongs to a Poisson distribution process and deduced the probability of network connectivity between source and target RSUs. Liu *et al.* [2] established the vehicle connectivity model for an expressway scene, and their analysis shows that the position of the network node satisfies the gamma distribution. They deduced the mathematical relationship among end-to-end connection probability, vehicle density, and transmission distance. Shao *et al.* [3] studied and analyzed the relationship among network connectivity probability, vehicle node coverage and RSU coverage for the two scenarios of Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I). Zhang *et al.* [4] considered the randomness of vehicles and vehicle spacing and assumed expressway vehicle speed to be static. The value of network connectivity probability with network evolution based on exponential random geometric graphs is deduced. The above research assumed that the distribution of vehicle nodes satisfies a mathematical distribution model and found the relationship between end-to-end connectivity probability as the node density in an expressway segment or an urban area. Xiong and Li [5] abstracted the expressway as a 1-D network scene to determine network connectivity based on the presence or absence of isolated nodes, studied the impact of spatial and temporal vehicle distribution on network connectivity, and proposed a probabilistic analysis algorithm to calculate the 1-connectivity necessary condition of end-to-end nodes. Yan *et al.* [6] proposed the necessary and sufficient conditions for the k-connection of IoV and gave the k-connected probability between two nodes and the maximum number of departure vehicles that can be tolerated.

B. CONNECTIVITY OF WHOLE NETWORK

To find the overall connectivity of a network, the existing work focuses on the relationship between connectivity and node density based on Percolation theory. In [7], for IoV characteristics, an actual network is abstracted as a 1-D linear network model and 2-D plane network model. First, it proves theoretically that one-dimensional VANET has no percolation characteristics. Because of the existence of network vacancy, the network connectivity is poor in the case of small node density, and the connectivity of a 2-D large-scale network based on fixed-point connectivity and percolation theory is used to describe the connectivity conditions under which some areas are covered. Based on the percolation theory discussing the state transformation of IoV connectivity, Dousse *et al.* [8], [9] discussed the effect of interference on the connectivity of a large-scale IoV and the critical value of λ at the time of cluster connectivity. Jin *et al.* [10] used the theory of infiltration from the perspective of two-dimensional study of network connectivity to theoretically quantify the relationship between vehicle density and wireless transmission distance.

C. IoV CONNECTIVITY IN URBAN SCENE

At present, research on connectivity mainly focuses on VANET with and without RSU. There are many studies on potential factors that affect connectivity in an urban scene, including topology, traffic signals and vehicle traffic. For the stopping behavior of traffic, Ho and Leung [17], studied the causes of network congestion and the related factors influencing the connection. Madsen *et al.* [20] explored the correlation between connectivity and mobility in theoretical scenarios. Fiore *et al.* [21] studied the relative velocity and the number of channels affecting the connectivity in a VANET scene.

D. SUMMARY

Recently, research into IoV connectivity has drawn much attention, especially in the area of VANET. However, to provide better services for society, more efforts are required to address their formal modeling, analysis, and optimization issues when facing a large-scale urban road scene.

III. LARGE-SCALE HETEROGENEOUS INTERNET OF VEHICLES ARCHITECTURE IN URBAN SCENES

A large-scale heterogeneous IoV in an urban area is composed of vehicles with wireless communication equipment, IoV intersection gateways (IG) at each intersection, cellular base stations and other infrastructure [22]. On the one hand, IGs can relay messages sent or received by vehicles; on the other hand, they can provide necessary auxiliary information to the vehicles. The vehicles are equipped with a vehicle-to-vehicle (V2V) interface to communicate with each other and with the vehicle-to-intersection (V2I) gateway interface for IG access. At the same time, vehicles are also provided with the function of a cellular network, which means that they can access the mobile Internet through a cellular network. IGs at the intersections are equipped with an I2V interface for vehicle communication, which can access the Internet through fixed wires. The working range of I2V of a single IG is one specified area around its intersection. Clearly, a single IG cannot cover the entire urban area but only its nearby regions. The messages generated by IGs can be relayed many times by multiple vehicles before reaching the IG nearest to the destination vehicle's location. The urban street map can be abstracted as $G(I, R)$. Based on the above concepts, we give the definition of a trunk road network.

Definition 1: The trunk network of IoV is composed of a set of IGs denoted as $I = \{i_1, i_2, \ldots, i_j, i_{j+1}, \ldots, i_m\}$ and a set of roads $R = \{r_1, r_2, \ldots, r_j, \ldots r_{m-1}\}$ that connect IGs, where $r_j \in R$, and connects i_j and i_{j+1} IG, $j \in \{1, 2, \ldots, m-2\}$.

Definition 2: crisscross road complexity: There are several crossroads in an urban road grid. Crossroads have the following characteristics (Pc_i, t_i, D_i):

Pc_i denotes that crossroads can participate in the relay of messages, while the non-repairable probability of the link could be reduced.

t_i represents the time taken by the process of sending messages through crossroads.

D_i represents the time consumption of forwarding information by crossroads.

Definition 3: Vehicle distribution probability density function: Vehicles in the road are subjected to a normal distribution. The number of vehicles in any designated distance is subject to the Poisson distribution with the following expression:

$$f(v) = \frac{(\rho s)^v}{v!} e^{-\rho s}$$

where v represents the number of vehicles in distance s, and ρ represents the vehicle density on the entire road.

IV. FOUR CONNECTIVITY PROPERTIES OF URBAN ROAD SCENE

By acquiring the travel speed of all vehicles in a trunk road network, the transmission range of a wireless communication device for vehicle networking and the vehicle density on these roads, we can model four attributes of trunk road network connectivity: possibility, data forwarding time, link forwarding capability and packet error rate in a certain vehicle density and transmission range.

A. POSSIBILITY OF CONNECTIVITY

Definition 4: The Possibility of Connectivity Pc:

$$\mathrm{Pc} = P(w \cap Q) = P_{w|Q} \times \mathrm{P}_Q$$

where $P_{w|Q}$ represents the conditional probability of connectivity if there are Q chains broken, P_Q represents the probability that Q chains are broken, and Q represents the number of broken chains in the lane.

When vehicles approach a road junction, they will transmit messages through the intersections, and there is no need to be concerned about communication among the vehicles. When vehicles are away from the intersections, because of the long distance between two vehicles on different roads, the road length and communication of vehicles can be ignored. Therefore, we can turn the winding road (A, B, C, D, E) into a straight road with several intersections; as shown in Fig. 2, it is also like a trunk road network.

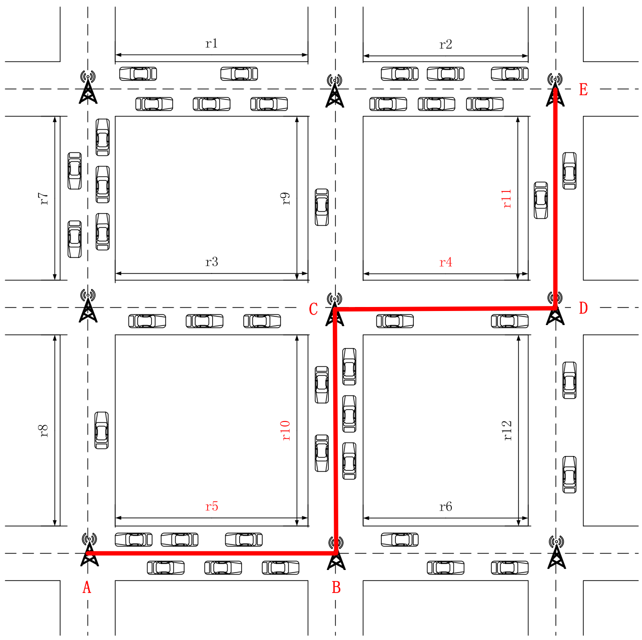


FIGURE 2. **Large-scale heterogeneous network in urban scenes.**

In a trunk road network, vehicles can travel along a road in two opposite directions. As shown in Fig. 2, we can assume that statistical data on each section of the road map can be obtained. These statistical data include i) the average vehicle speed on road r_j (denoted as $\bar{S}$) and ii) the average vehicle density (ρ_w, ρ_e, ρ_s, ρ_n represent the mean density of the west, east, south, and north lanes, respectively). Average vehicle density is defined as the number of the vehicles within a unit length of a single lane.

Denote the connectivity possibility of the trunk road network as Pc. First, we must derive the connectivity possibilities Pc_j of road ($r_j \in \{r_1, r_2, \ldots, r_n\}$ to calculate Pc.

Consider the situation of a two-way single lane, such as road r1 in Fig. 2, where a vehicle can travel along the road

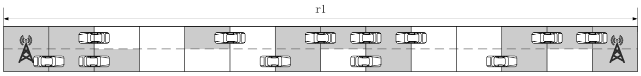


FIGURE 3. The two lanes are divided by the transmission range.

in opposite directions. Each section of the road has east and west lanes, as shown in Fig. 3. In addition, each lane is divided into areas with equal intervals, and each area corresponds to transmission range Tr. Tr is the length of each part of the two-way lane divided according to the vehicle transmission range. The message can be forwarded by the vehicles moving in the same direction or be relayed by the vehicles moving in the opposite direction.

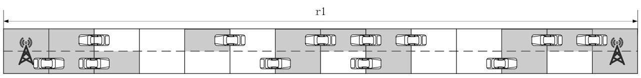


FIGURE 4. Repairing the broken chain by opposite direction vehicles or intersection gateway.

When the vehicle is traveling on the road, data packets propagate along the travelling direction of vehicles in priority. As shown in Fig. 4, the opposite direction vehicles in the two-way lane can be used to increase the possibility of connectivity. IG can also be used to relay a message around an intersection. With such a design, a broken chain is defined as the link between two vehicles V_k and V_{k+1} travelling in the same direction on road r_j when the length between them $D_k > Tr$. The broken chain can be repaired if there are oncoming vehicles or IG can contact V_k and V_{k+1} within the transmission range.

Variables v_w and v_e denote the number of vehicles in each interval of Tr on west and east lanes, respectively. It is assumed that the vehicles in the two lanes obey the normal distribution, while v_w and v_e obey the Poisson distribution. We have the following probability mass function:

$$f(v_w) = \frac{(\rho_w Tr)^{v_w}}{v_w!} e^{-\rho_w Tr} \tag{1}$$

$$f(v_e) = \frac{(\rho_e Tr)^{v_e}}{v_e!} e^{-\rho_e Tr} \tag{2}$$

Since the two opposite lanes have equal status, we take westward-moving vehicles as an example. Use P_{nf} to denote the non-repairable probability due to no vehicle on the westbound lane.

$$\begin{aligned} P_{nf} &= f(v_e = 0) \\ &= e^{-\rho_e Tr} \end{aligned} \tag{3}$$

Considering that the gateway can participate in the relaying of messages, the non-repairable probability of the link should be reduced to P'_{nf}:

$$P'_{nf} = \begin{cases} P_{nf} \times \dfrac{\alpha - 2}{\alpha}, & \alpha > 2 \\ 0, & \alpha \le 2 \end{cases} \tag{4}$$

where $\alpha = \frac{L}{Tr}$, and L is the length of the road.

We define the repairable probability of a broken link between the two same-direction vehicles V_k and V_{k+1} as P_f:

$$\begin{aligned} P_f &= \left(1 - P'_{nf}\right)^{\left\lfloor \frac{D_k}{Tr} \right\rfloor} \\ &= \begin{cases} \left(1 - \dfrac{\alpha - 2}{\alpha} e^{-\rho_e Tr}\right)^{\left\lfloor \frac{D_k}{T_r} \right\rfloor}, & \alpha > 2 \\ 1, & \alpha \le 2 \end{cases} \end{aligned} \tag{5}$$

The vehicle in each interval of the westward lane obeys the Poisson distribution, and the distance D_k between V_k and V_{k+1} obeys the exponential distribution with parameter ρ_w. To calculate Pc_j, considering that there may be redundant broken chains, variable Q represents the number of broken chains in the west lane. If all Q chains can be repaired, road r_j can be considered as being connected. $P_{w|Q}$ expresses the connective condition probability with Q broken chains:

$$\begin{aligned} P_{w|Q}(q) &= P_f^q, \quad q \in \{0, 1, \ldots, N-1\} \\ &= \begin{cases} \left(1 - \dfrac{\alpha - 2}{\alpha} e^{-\rho_e Tr}\right)^{\sum_{i=0}^{q} \left\lfloor \frac{D_k}{Tr} \right\rfloor}, & \alpha > 2 \\ 1, & \alpha \le 2 \end{cases} \\ &= \begin{cases} \left(1 - \dfrac{\alpha - 2}{\alpha} e^{-\rho_e Tr}\right)^{\alpha - \frac{(N-1-q)}{\gamma_w Tr}}, & \alpha > 2 \\ 1, & \alpha \le 2 \end{cases} \end{aligned} \tag{6}$$

where N_j is the number of vehicles on the westward lane of r_j.

To obtain the total connectivity probability of r_j, we should also abtain the probability quality function $P_Q(q)$ of Q. According to the definition, a broken chain means that the distance between two same-direction vehicles is greater than Tr. P_b represents the probability of the broken link. The distance between any two vehicles traveling in the same direction obeys the exponential distribution, so its expression is

$$P_b = P_r\{D_k > Tr\} = e^{-\rho_e Tr} \tag{7}$$

For $N_j - 1$ chains, the probability for q broken chains obeys the binomial distribution:

$$P_Q(q) = \binom{N_j - 1}{q} \times P_b^q \times (1 - P_b)^{(N_j - 1 - q)} \tag{8}$$

Therefore, the total connectivity possibilities of road r_j can be expressed as

$$Pc_j = \sum_{q=0}^{N_j - 1} P_{w|Q}(q) \times P_Q(q) \tag{9}$$

Finally, the connectivity possibilities of a trunk road network formed by n roads can be given as

$$Pc_R = \prod_{j=1}^{n} Pc_j \tag{10}$$

B. DATA FORWARDING TIME

Definition 5: The data forwarding time is represented by T, which is summed by T_j of n roads, where T_j is the time taken for data to be transmitted on the road network $r_j \in \{r_1, r_2, \ldots, r_j, \ldots r_n\}$.

Once a trunk road network is connected, the data forwarding time can be characterized by the time taken by any data packet to travel from a source vehicle to a target vehicle. Trunk road network R consists of n sections of roads, and the data forwarding time of road r_j is T_j. T can be expressed as

$$T = \sum_{j=1}^{n} T_j \tag{11}$$

The data forwarding time depends on the number of vehicles N_j traveling on r_j and the time required for a message to travel between V_k and V_{k+1} traveling on the road or between vehicles and intersections. The time required for a data packet to be transferred from V_k to V_{k+1} depends on a message forwarding strategy. On the one hand, if V_k uses greedy forwarding, then the data forwarding time, expressed as t_p, is the time taken to process and send messages. On the other hand, if V_k uses a carry-forwarding strategy, the message carried by V_k travels at the same speed S_k as the vehicle. Thus, the data forwarding time depends on S_k and the distance traveled by V_k until it can forward the message to the next car V_{k+1}—that is, when it enters the transmission range.

Theorem 1: T is an additive metric.

Proof: Let $T(r_i, r_j)$ be a metric for link (r_i, r_j). For any path $r = (r_i, r_j, r_k, \ldots r_m)$, where r is one of the trunk roads, $T(r)$ can be denoted as follows:

$$T(r) = T\left(r_i, r_j\right) + T\left(r_j, r_k\right) + \ldots + T(r_{n-1}, r_n)$$

It is easy to see that these conditions satisfy additive metric rules [24]. This completes the proof.

To estimate the data forwarding time, two cases are considered:

If the road length L is less than the transmission range $Tr(\alpha \leq 1)$, the data forwarding time of the road is t_p, which denotes the time for processing and sending messages of the vehicle or IG, as Fig. 5 shows.

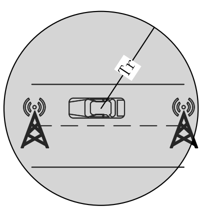


FIGURE 5. Road length is shorter than the communication transmission range.

If the road length is longer than the transmission range $(\alpha \geq 1)$, the message is forwarded along the road via a multi-hop technology, as Fig. 6 shows. The random variable denotes the number of vehicles on the corresponding intervals of length Tr on the two lanes. Similarly, v is subject to Poisson distribution and has the following probability density function:

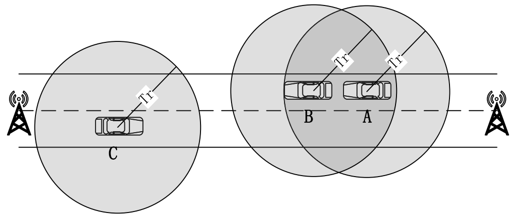


FIGURE 6. Road length is longer than the communication transmission range.

$$f(v) = \frac{((\rho_w + \rho_e) Tr)^v}{v!} e^{-(\rho_w+\rho_e)Tr} \tag{12}$$

To calculate the data forwarding time on a road, the strategy for message forwarding should be considered. If a message is forwarded hop by hop, the data forwarding time on the link is the same as in the first case. For another, if the message is carried and forwarded by a vehicle, it is necessary to estimate the part of the road denoted as β without any vehicles forwarding a message. In this case, the last car that receives the message on the part carries the message along until it enters the transmission range of another vehicle and then forwards the message. As Fig. 6 shows, vehicle A passes the message to vehicle C. Vehicle A passes it to B via hop-by-hop forwarding, while B cannot receive it directly because of the limit of communication radius, and B must carry the message until the next forwarding. The expression for β is

$$\beta = f(v = 0) = e^{-(\rho_w+\rho_e)Tr} \tag{13}$$

Because vehicles can realize message forwarding through IG at an intersection, this part should also exclude the situation in which vehicles are in an IG communication range:

$$\beta' = \begin{cases} \beta \times \dfrac{\alpha - 2}{\alpha}, & \alpha > 2 \\ 0, & \alpha \leq 2 \end{cases} \tag{14}$$

In this case, the average data forwarding time can be calculated by the average vehicle speed of road r_j. As mentioned above, N_j is the total number of vehicles on road r_j. Thus, the average data forwarding time of road r_j is

$$T_j = \begin{cases} t_p, & \alpha \leq 1 \\ \alpha \cdot t_p, & 1 < \alpha \leq 2 \\ \alpha\left(1 - \beta'\right) t_p + \beta' L/\bar{S}, & \alpha > 2 \end{cases} \tag{15}$$

where the average speed of vehicles on the road is

$$\bar{S} = \frac{\sum_{v=1}^{N_j} S_v}{N_j} \tag{16}$$

C. LINK FORWARDING CAPABILITY

Obviously, trunk road network connectivity cannot be infinite;the packet transported in the trunk road network will consume the network connectivity. We can define this consumption as the link forwarding capability. For a given trunk road network R, the link forwarding capability on road r_j can be expressed by the number of vehicles transmitting the packet, which is related to the road length L and the transmission range Tr of vehicles travelling on this road. If $L < Tr$ $(\alpha \leq 1)$, there is no need to tranmit the message through the vehicle.If a vehicle is within th coverage of the junction gateway, the message will be forwarded to the junction gatewa. If $L > Tr$ and the vehicle is not within the communication coverage range of the junction gateway $(\alpha \geq 2)$, then the message is transmitted hop by hop or carried with forwarding. Therefore, the average link forwarding capability for the traffic in road r_j is

$$D_j = \begin{cases} 0, & \alpha \leq 1 \\ 1, & 1 < \alpha \leq 2 \\ \alpha\left(1-\beta'\right)+\beta' N_j, & \alpha > 2 \end{cases} \tag{17}$$

Correspondingly, the link forwarding capability for trunk road network formed by n roads can be given by

$$D = \sum_{j=1}^{n} D_j \tag{18}$$

Theorem 2: D is an additive metric.

Proof: This proof is similar to that of Theorem 1. Let $\mathrm{D}(\mathrm{r_i}, \mathrm{r_j})$ be a metric for link $(\mathrm{r_i}, \mathrm{r_j})$. For any path $r = (r_i, r_j, r_k, \ldots r_m)$, where r is one of the trunk roads, T(r) can be denoted as follows:

$$D(r) = D\left(r_i, r_j\right) + D\left(r_j, r_k\right) + \ldots + D(r_{n-1}, r_n)$$

It is easy to see that these conditions satisfy additive metric rules [24]. This completes the proof.

D. PACKET ERROR RATE

In the process of data packet tranmission in a trunk road network, some data bits maybe damaged or lost. This situation leads to some unreliability in the trunk road network connectivity. We use the error rate to represent the trunk vehicle network packet error rate in an urban scene. The error rate is mainly affected by the transmission range. As the transmission range increases, the error rate increases because of channel fading and interference. According to [23], thepacket error rate between two consecutive vehicles is

$$BER_l = \frac{1}{2}\left(1-\sqrt{\frac{2\sigma_f^2\alpha_1 P_t/z^2}{P_{\text{therm}}+2\sigma_f^2\alpha_1 P_t/z^2}}\right) \tag{19}$$

where α_1 and α_2 are constants, P_t is the transmission power, $\mathrm{P_{therm}} = \alpha_2 R_b$ is the thermal noise power, R_b is the data transfer rate, $2\sigma_f^2$ is the signal envelope mean square described by the Rayleigh density function, and z is the distance between two vehicles. Given that the distancez between two vehicles obeys the exponential distribution, the probability density of z can be written as follows:

$$f(Z) = \begin{cases} \dfrac{\rho e^{-\rho z}}{1-e^{-\rho Tr}}, & if\ 0 \leq z \leq Tr \\ 0, & else \end{cases} \tag{20}$$

which represents the conditional probability of the distance between two vehicles traveling in the same direction, and the distance between them is less than or equal to the transmission range Tr. Therefore, the mathematical expectation of error rate can be calculated as follows:

$$E\left[BER_l(Z)\right] = \int_0^{T_r} BER_l(z) f_z(z) dz \tag{21}$$

Moreover, the road packet error rate UR_j of road r_j is

$$UR_j = 1-(1-E[BER_l(Z)]) \tag{22}$$

Finally, the packet error rate of a trunk road network consisting of n roads is given by

$$UR = \prod_{j=1}^{n} UR_j \tag{23}$$

Theorem 3: UR is a multiplicative metric.

Proof: Let $UR(r_i, r_j)$ be a metric for link (r_i, r_j). For any path $r = (r_i, r_j, r_k, \ldots r_m)$, where r is one of the trunk roads, $UR(r)$ can be denoted as follows:

$$UR(r) = UR\left(r_i, r_j\right) \times D\left(r_j, r_k\right) \times \ldots \times D(r_{n-1}, r_n)$$

It is easy to see that these conditions satisfy multiplicative metric rules [24]. This completes the proof.

V. CONNECTIVITY MODEL

In a vehicle network with infrastructure under an urban scene, the connectivity problem of two vehicles (source and target vehicles) is also a trunk road network connectivity issue. As mentioned above, a trunk road network includes infrastructure junction gateways $i_1 - i_m$ where road junctions $r_1 - r_n$ are connected. The intersection gateway i_1 is the first of the source vehicle connections in a trunk road network, and i_m is the last one, which connects to the target vehicle.

The connectivity problem of a trunk road network can be transformed into a problem of finding the optimal or near-optimal trunk road network. Such a network consists of intersection gateway sequences, which meets the highest possible connectivity under the constraints of data forwarding time, link forwarding capability and packet error rate of tolerable connectivity. The data forwarding time constraints can be converted to an upper limit, and the value depends on the needs of a source vehicle's network application. For example, low T_{th} is assigned to real-time sensitive applications, while high T_{th} applies to non-time-sensitive ones. The link forwarding capability and packet error rate also have corresponding upper limits D_{th} and UR_{th}.

In a vehicle network with infrastructure under an urban scene, data packets are sent from a source vehicle and forwarded by some vehicles via hop-by-hop forwarding and carry forwarding modes until the target vehicle is reached. The goal is to meet the highest probability of connectivity *Pc(R)* under the data forwarding time $T(R)$, link forwarding capability $D(R)$ and packet error rate *UR(R)* of tolerable connectivity. The trunk network connectivity model R consisting of the passing roads and intersections can be expressed in the following form:

$$C\left(v_s, v_d\right) = max_R Pc(R) \tag{24}$$

Subject to

$$T\left(R\right) = \sum_{j=1}^{n} T_j(R) \le T_{th} \tag{25}$$

$$D\left(R\right) = \sum_{j=1}^{n} D_j(R) \le D_{th} \tag{26}$$

$$UR\left(R\right) = \prod_{j=1}^{n} UR(R) \le UR_{th} \tag{27}$$

where $C(v_s, v_d)$ is the connectivity of a data packet from source vehicle v_s to target vehicle v_d. *Pc(R)* is the connectivity probability of trunk road network R. T_{th}, D_{th} and UR_{th} represent the thresholds for the data forwarding time, link forwarding capability and packet error rate of the tolerable connectivity in the trunk road network, respectively, according to a vehicle's network application requirements of the source vehicle.

According to the theorem in [24], the threshold problem composed of n additive measures and k multiplicative measures is an NP-complete problem. In the vehicle-connected model with infrastructure in an urban scene, there is a multi-threshold problem constituted by two additive measures and a multiplicative measure. Therefore, the concerned model connectivity problem is NP-complete.

VI. SIMULATION AND EXPERIMENTAL VERIFICATION

The accuracy of this connectivity model depends on the accuracy to predict the probability of connectivity, data forwarding time, link forwarding capability and packet error rate compared with the real world. Not all vehicles in an actual urban scene are equipped with communication devices. To verify these properties, this paper uses a simulation experiment to simulate the IoV in an urban scene to obtain the relevant statistical data. A series of calculations are made on the model by using a software tool, and we compare the statistical data obtained from the simulation experiment and the prediction results of the related properties in the vehicle connectivity model with the infrastructure in an urban scene to verify the accuracy of the proposed model.

To verify the vehicle network connectivity model in an urban scene, as shown in Fig. 2, we design a 5-km bi-directional single-lane scene where the path is r5-r10-r4-r11. There is fixed infrastructure at a crossroads, where A is called the source gateway responsible for initiating a ping connection, and E is the target gateway, which is the target of the ping connection. The vehicles equipped with communication devices of a vehicle network V2V maintain a certain average speed in this bi-directional single lane. We take a greedy edge of the stateless routing protocol to determine the connectivity between vehicles and relay the ping packets sent by the source gateway via greedy forwarding.

The related connectivity thresholds and associated communication parameters used in a simulation process are essentially derived from multiple experiments and existing literature. Specific simulation parameters are set as shown in Table 1.

TABLE 1. Units for magnetic properties.

Parameter name	Value
Maximum sending power	20 mW
Frequency	2.4 GHz
Spread model	Two-way ground reflection model
Signal attenuation threshold	-110 dBm
Simulation time	30 min
Application types	Ping
Target of ping	Target gateway
Interval of ping	1 s
Timeout value of ping	1 s
Simulation time interval	1 s

Since the packet error rate is mainly based on the bit error rate, and the bit error rate has been verified in [23], the following is mainly the verification for the possibility of connectivity, data forwarding time and link forwarding capability.

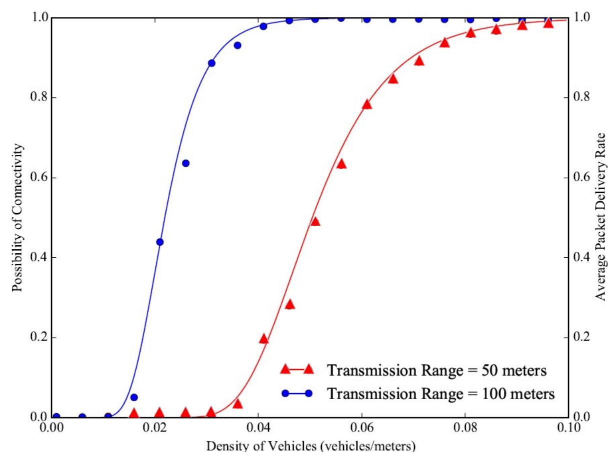


FIGURE 7. The possibility of transmission range of 50 m and 100 m and the relationship between GPSR average delivery rate and vehicle density.

First, as shown by blue dots and red triangles in Fig. 7, the simulation experiment is carried out under different vehicle densities, and the average delivery rate of the GPSR protocol is calculated according to the loss rate of ping packets.

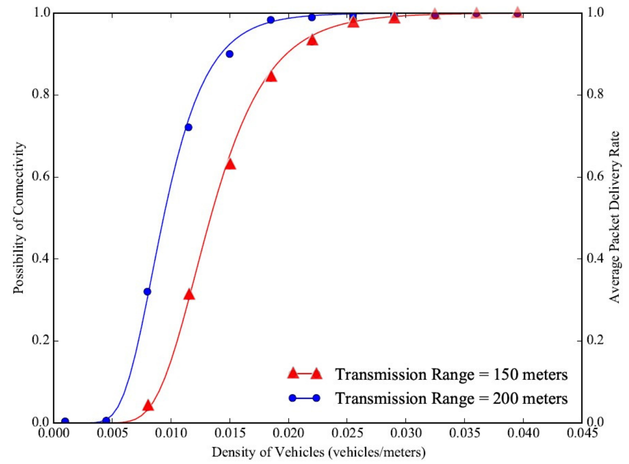


FIGURE 8. **The possibility of transmission range of 150 m and 200 m and the relationship between GPSR average delivery rate and vehicle density.**

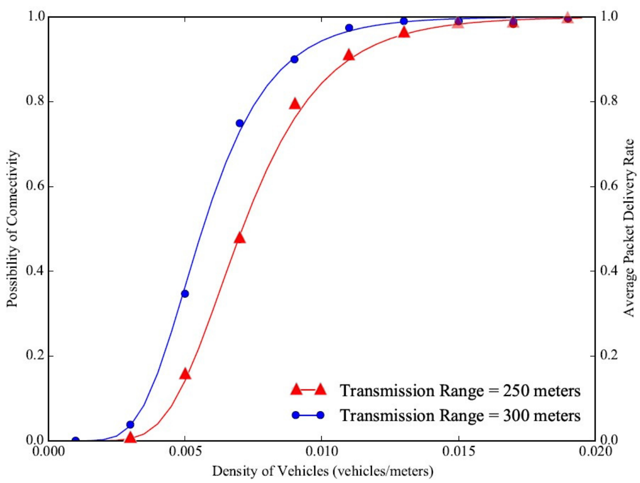


FIGURE 9. **The possibility of transmission range of 250 m and 300 m and the relationship between GPSR average delivery rate and vehicle density.**

The relationship of the vehicle connectivity model between the probability of communication and the vehicle density with different transmission ranges in an urban scene is then plotted as the blue and red curves shown in Figs. 7-9. The small dots in the figure represent the average delivery rates of the GPSR protocol, and the curves represent the theoretical predictions of the connectivity possibilities. Through the position of small dots and curves, we can see that the prediction of communication possibility corresponds well to the simulation results. In the different transmission ranges, the probability of connectivity is close to 0 when the vehicle density is insufficient, and when the vehicle density rises to a certain threshold, the connectivity probability begins to increase until the vehicle density is sufficiently large. These two thresholds are related to the transmission range. When the range is within 50 meters, the connectivity probability will reduce. While the connectivity probability will not change significantly as the range increases when it is over 100 meters. As shown in Fig. 7, when the transmission range is 50 m, the vehicle density threshold is approximately 0.03/m, and the probability of communication is close to 1. When the density reaches 0.095/m, the average delivery rate of GPSR is greater than 99.5%. When the transmission range is 100 m, the vehicle density threshold is approximately 0.015 vehicles/m, which is half the value of 50 m. When the vehicle density reaches 0.045 vehicles/m, the communication probability is close to 1, which is 0.47 times the value of 50 m, and the average delivery rate of GPSR is greater than 99.5%. We can see that the average rate of increase of the GPSR is slightly faster than 50 m when the transmission range is 100 m, which can also be supported by the rising predicted connectivity possibility curve in Fig. 7. When the transmission range is larger, there is no significant difference among the growth rates of connectivity possibilities. The main difference is that the larger the transmission range, the smaller the vehicle density threshold and the smaller the fully connected vehicle density threshold, which corresponds to the average delivery rate of GPSR in different transmission ranges.

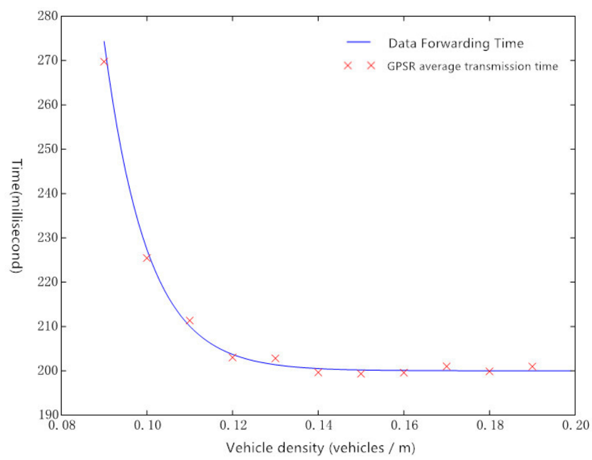


FIGURE 10. **Data forwarding time and GPSR average transmission time when transmission range is 50 m.**

The average transmission time of ping packets transmitted by GPSR is statistically analyzed with different vehicle densities at an average speed of 30 km/h and compared with the predicted data forwarding time, as shown in Figs. 10 and 11. Since GPSR itself does not support the carry-forwarding mode, we have added it to conform to the data forwarding time design. When GPSR cannot find the next relay vehicle, it stores the data packet in the buffer zone temporarily. The data packet is carried by the vehicle for a certain period until the GPSR finds an available vehicle that can forward or the time runs out and the data packet is discarded.

In Fig. 10, the transmission range is 50 m. When the vehicle density is 0.09/m, the GPSR average transmission time is 270 ms, and with the increase of vehicle density, the GPSR average transmission time rapidly declines. The study of the transmission situation finds that with increasing vehicle density, the average delivery rate of GPSR increases, i.e., the number of discarded data packets becomes increasingly

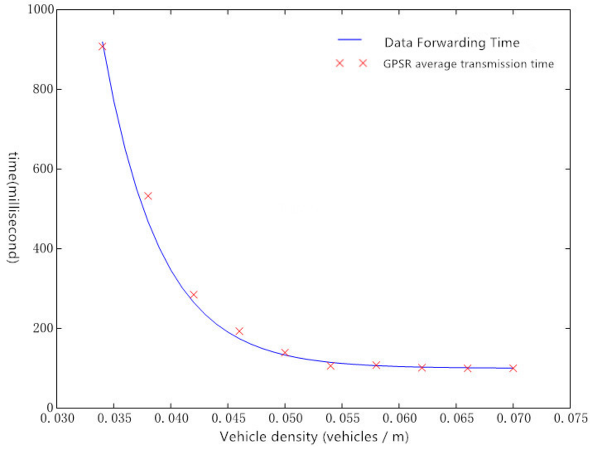


FIGURE 11. Data forwarding time and GPSR average transmission time when transmission range is 100 m.

less, corresponding to the lower number of packets to be carried in real-time connectivity. When the vehicle density is sufficiently high, the data forwarding time predictive curve of connectivity does not change significantly. This trend can be confirmed from the statistical results of the average transmission time of GPSR, and the data forwarding time estimated value of connectivity is consistent with the simulation results. Similarly, in Fig. 11, when the vehicle density exceeds 0.055/m, the average transmission time of GPSR is stabilized at approximately 100 ms. Since the average delivery rate of GPSR is very close to 1, there is nearly no packet loss, and the transmission time is mainly due to data packet forwarding. The real-time prediction curve of the connectivity in the figure confirms the simulation results as well.

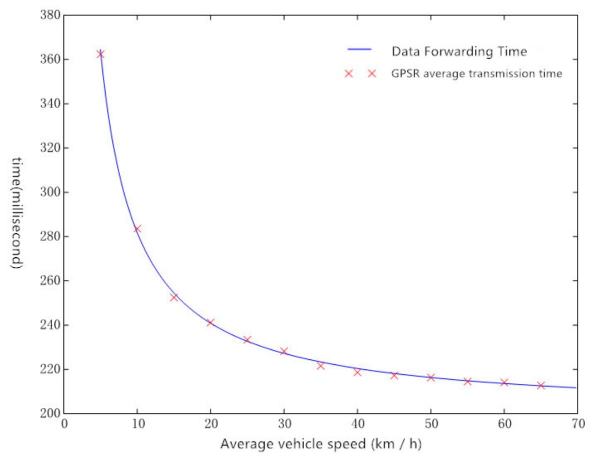


FIGURE 12. Data forwarding time and GPSR average transmission time when transmission range is 50 m (vehicle density is 0.1/m).

Figs. 12-14 show the change of the data forwarding time and GPSR average transmission time with increasing average vehicle speed under a certain vehicle density. Because the speed limit of vehicles on urban roads in our country is 70 km/h, the average speed of vehicles in the experiment

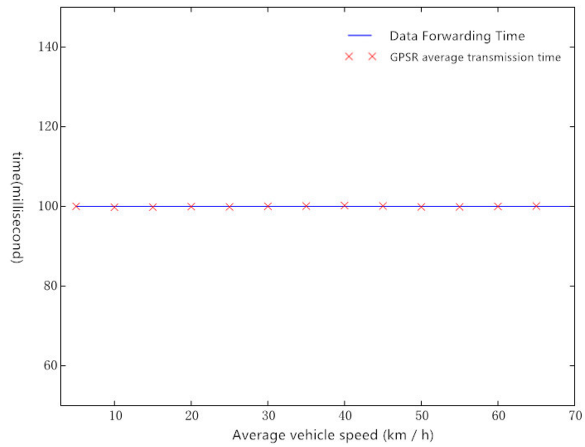


FIGURE 13. Data forwarding time and GPSR average transmission time when transmission range is 100 m (vehicle density is 0.1/m).

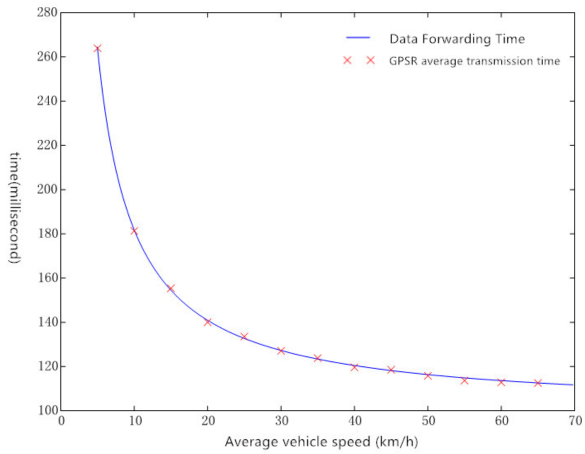


FIGURE 14. Data forwarding time and GPSR average transmission time when transmission range is 100 m (vehicle density is 0.05/m).

is set from 5 km/h to 70 km/h. In the case when the transmission range is 50 m as shown in Fig. 12, the data forwarding time with the vehicle density of 0.1/m and the average transmission time of GPSR decreases when the average speed of the vehicle increases, and both are consistent. This change indicates that GPSR relies on vehicles that carry and forward data packets. In Fig. 13, the transmission range increases to 100 m with the same vehicle density, and the average transmission time of the GPSR protocol remains constant at any vehicle speed. This is consistent with the corresponding data forwarding time curve. The reason for this phenomenon is that since the vehicle density is sufficiently large, GPSR does not need to forward data packets through the carrying forwarding. Therefore, the average transmission time does not change with the change of vehicle traveling speed. To verify this, in Fig. 14, the vehicle density in the same transmission range is reduced to the half the original—that is, 0.05/m. Under this vehicle density, GPSR must begin to rely on vehicles to carry data packets and wait for the chance to forward them. Therefore, the average transmission time varies with the average vehicle speed. The experimental results are consistent with the corresponding data forwarding time predictive curves and verify the effectiveness of data forwarding time.

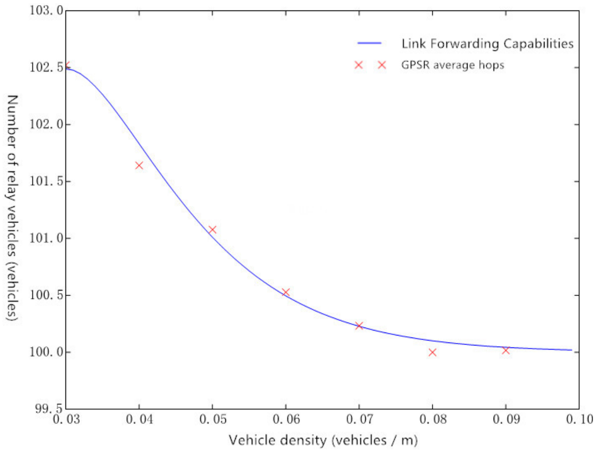


FIGURE 15. The link forwarding capabilities and GPSR average number of hops when transmission range is 50 m.

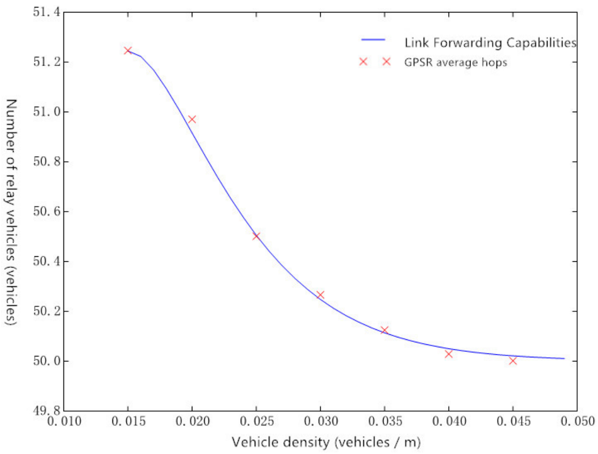


FIGURE 16. The link forwarding capabilities and GPSR average number of hops when transmission range is 100 m.

Finally, the average hop count of ping packets transmitted via GPSR is computed with different vehicle densities, corresponding to the link forwarding capability curve, as shown in Figs. 15 and 16. It can be seen that when vehicle density is low, the link forwarding capability is relatively high. When it rises, the link forwarding capability begins to decrease, with smaller and smaller rate, eventually close to a constant—that is, the minimal link forwarding capability. From the results of the simulation experiment, we can see that the link forwarding capability is higher when the vehicle density is low. This is because the data packets in some forwarding paths must be relayed to the vehicles traveling in the opposite direction, and the average hop count for data packets transmitted by GPSR decreases with increasing vehicle density. When the number of vehicles in the same lane is sufficiently high, the average hop count is essentially invariant and tends to a constant. Therefore,the link forwarding capability is consistent with the results of the simulation experiments.

In summary, the predictions of connectivity probability, data forwarding time, link forwarding capabilities, and packet error rate through the proposed vehicle connectivity model are consistent with simulation results of the vehicle-based network in an urban scene. Therefore, the results of this connectivity model using these properties are accurate and credible and can be applicable to vehicle networks with infrastructure in an urban scene.

VII. CONCLUSIONS

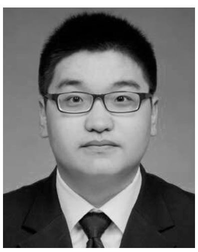
In this paper, we studied the large-scale heterogeneous networks of a vehicle network in an urban scene. Through the establishment of four types of connectivity, we obtained the connectivity model of an urban vehicle network. Based on the comparison between the predicted values of the properties through the proposed model and the actual results of vehicle network simulation, we concluded that the model is suitable for a vehicle network with infrastructure in an urban scene. The connectivity results were effective and reliable, and we could use the model to assess the connectivity of a dynamic vehicle network.

REFERENCES

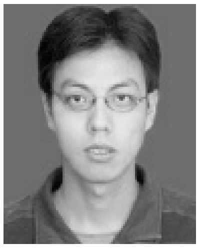
[1] S. Ng, W. Zhang, Y. Zhang, Y. Yang, G. Mao, "Analysis of access and connectivity probabilities in vehicular relay networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 1, pp. 140–150, Jan. 2011.
[2] Y. Liu and G.-X. Wu, "Study on the connectivity model of VANET based on 802.11p/WAVE and its application," *J. Commun.*, vol. 34, no. 6, pp. 85–91, 2013.
[3] C. Shao, S. Leng, Y. Zhang, A. Vinel, and M. Jonsson, "Analysis of connectivity probability in platoon-based vehicular ad hoc networks," in *Proc. IEEE Wireless Commun. Mobile Comput. Conf.*, Aug. 2014, pp. 706–711.
[4] Y. Zhang, H. Zhang, W. Sun, and C. Pan, "Connectivity analysis for vehicular ad hoc network based on the exponential random geometric graphs," in *Proc. Intell. Vehicles Symp.*, Jun. 2014, pp. 993–998.
[5] W. Xiong and Q.-Q. Li, "Prerequisite to 1-connected vehicular ad hoc networks in highway scenarios," *J. Softw.*, vol. 21, no. 11, pp. 2906–2919, 2010.
[6] Z. Yan, H. Jiang, Z. Shen, Y. Chang, and L. Huang, "k-Connectivity analysis of one-dimensional linear VANETs," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 426–433, Jan. 2012.
[7] S. Li, D. L. Zhang, and C. J. Jiang, "On connectivity of vehicular wireless ad hoc network," *J. Syst. Simul.*, vol. 21, no. 3, pp. 888–893, 2009.
[8] O. Dousse, F. Baccelli, and P. Thiran, "Impact of interferences on connectivity in ad hoc networks," *IEEE/ACM Trans. Netw.*, vol. 13, no. 2, pp. 425–436, Apr. 2005.
[9] O. Dousse, P. Thiran, and M. Hasler, "Connectivity in ad-hoc and hybrid networks," in *Proc. 21st Annu. Joint Conf. IEEE Comput. Commun. Soc.*, vol. 2. Jun. 2002, pp. 1079–1088.
[10] X. Jin, W. Su, and Y. Wei, "A study of the VANET connectivity by percolation theory," in *Proc. Consum. Commun. Netw. Conf.*, 2011, pp. 85–89.
[11] W. Viriyasitavat, F. Bai, and O. K. Tonguz, "Dynamics of network connectivity in urban vehicular networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 3, pp. 515–533, Mar. 2011.
[12] N. Akhtar, O. Ozkasap, and S. C. Ergen, "VANET topology characteristics under realistic mobility and channel models," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2013, pp. 1774–1779.
[13] I. W.-H. Ho, K. K. Leung, and J. W. Polak, "Connectivity dynamics for vehicular ad-hoc networks in signalized road systems," in *Proc. 21st Int. Teletraffic Congr. (ITC)*, 2009, pp. 1–8.

[14] N. Loulloudes, G. Pallis, and M. D. Dikaiakos. (Jul. 2010). "The dynamics of vehicular networks in urban environments." [Online]. Available: https://arxiv.org/abs/1007.4106
[15] C. Li *et al.*, "Mobile gateway based forwarding for infrastructure-to-vehicle data delivery in vehicle ad hoc network," *J. Comput. Lang. Chin.*, vol. 35, no. 3, pp. 454–463, 2012.
[16] C. Chen, X. Du, Q. Pei, and Y. Jin, "Connectivity analysis for free-flow traffic in VANETs: A statistical approach," *Int. J. Distrib. Sensor Netw.*, vol. 9, no. 3, p. 598946, 2013.
[17] I. W. H. Ho and K. K. Leung, "Node connectivity in vehicular ad hoc networks with structured mobility," in *Proc. 32nd IEEE Conf. Local Comput. Netw. (LCN)*, Oct. 2007, pp. 635–642.
[18] M. M. Artimy, W. Robertson, and W. J. Phillips, "Connectivity in inter-vehicle ad hoc networks," in *Proc. IEEE Can. Conf. Elect. Comput. Eng.*, vol. 1. May 2004, pp. 293–298.
[19] G. Marfia, G. Pau, E. De Sena, E. Giordano, and M. Gerla, "Evaluating vehicle network strategies for downtown Portland: Opportunistic infrastructure and the importance of realistic mobility models," in *Proc. 1st Int. MobiSys Workshop Mobile Opportunistic Netw. ACM*, 2007, pp. 47–51.
[20] T. K. Madsen, F. H. P. Fitzek, and R. Prasad, "Impact of different mobility models on connectivity probability of a wireless ad hoc network," in *Proc. Int. Workshop Wireless Ad-Hoc Netw.*, May/Jun. 2004, pp. 120–124.
[21] M. Fiore and J. Härri, "The networking shape of vehicular mobility," in *Proc. 9th ACM Int. Symp. Mobile Ad Hoc Netw. Comput. ACM*, 2008, pp. 261–272.
[22] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, "Routing in Internet of vehicles: A review," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2339–2352, Oct. 2015.
[23] S. Panichpapiboon and W. Pattara-Atikom, "Connectivity requirements for self-organizing traffic information systems," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3333–3340, Nov. 2008.
[24] Z. J. Wang, "Quality-of-service routing for supporting multimedia applications," *IEEE J. Sel. Areas Commun.*, vol. 14, no. 7, pp. 1228–1234, Sep. 1996.

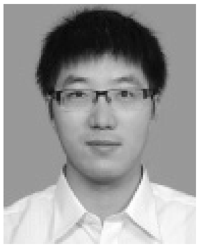
JIUJUN CHENG received the Ph.D. degree from the Beijing University of Posts and Telecommunications in 2006. In 2009, he was a Visiting Professor with Aalto University, Espoo, Finland. He is currently a Professor with Tongji University, Shanghai, China. He has authored over 50 publications, including conference and journal papers. His research interests include mobile computing and complex networks with a focus on mobile/Internet interworking and Internet of Vehicles.



HAO MI received the B.S. degree in software engineering from the Harbin Institute of Technology, Harbin, China, in 2015. He is currently pursuing the master's degree with the College of Electronic and Information Engineering, Tongji University. His current research interests include Internet of Vehicles.



ZHENHUA HUANG received the Ph.D. degree in computer science from Fudan University, China, in 2008. He is currently a Professor with the School of Electronics and Information, Tongji University. Since 2004, he has published over 50 papers in various journals and conference proceedings. His research interests include data warehouses, OLAP application, data mining, and knowledge discovery.



SHANGCE GAO received the Ph.D. degree in innovative life science from the University of Toyama, Toyama, Japan, in 2011. He is currently an Associate Professor with the University of Toyama. He has authored over 90 publications in journals and conference proceedings. His research interests include mobile computing, machine learning, and neural networks. He was a recipient of the Best Paper Award at the IEEE 2016 International Conference on Progress in Informatics and Computing, the Shanghai Rising-Star Scientist Award, the Chen Guang Scholar of Shanghai Award, the Outstanding Academic Performance Award of the IEICE, and the Outstanding Academic Achievement Award of the IPSJ.

DI ZANG is currently an Associate Professor with the Department of Computer Science and Technology, Tongji University, China. Her current research interests include machine learning, pattern recognition, and intelligent transportation signal processing.

CONG LIU received the B.S. and M.S. degrees in computer science and technology from the Shandong University of Science and Technology, Qingdao, China, in 2013 and 2015, respectively. His research interests include the areas of business process mining, petri nets and software process mining, and Internet of Vehicles.