Characterization of Packet-Level Measurements for Vehicular Wireless Networks

Yuhao Wang, Xing Xing, and Yan Zhang

School of Information Engineering
Nanchang University, 330031, China
wangyuhao@ncu.edu.cn

Abstract **─** A comprehensive understanding of the fading effect on vehicular communications is essential for reliable intelligent transportation system (ITS). Dozens of experiments were performed in the real urban area to collect various types of vehicular wireless data measurements. Then a simulation model of radio link between double mobile nodes was proposed. Based on the real measured data, the proposed model, and the existing model are all applied to the simulator for comparison. It is shown that by evaluating the packet level performance for double mobile vehicles in an urban area, the proposed model performed better. Significant realism can be added to existing systems with clear implications on the design of upper layer protocols by modeling the fading characters for vehicular communications.

Index Terms **─** Communication performance, measurements, radio channel, radio propagation, vehicular wireless networks.

I. INTRODUCTION

Vehicular wireless networks, as the key part of the intelligent transportation system (ITS), which can achieve traffic warning [1-3] and provide the driver with specific route dependent information, will be widely used in the future. Furthermore, from [4-7], the increasing demand for mobile computing and quality of service (QoS) will have future vehicles equipped with a high data rate access to the internet. Various multimedia applications, such as video on demand, games, email, etc., will also be available. Due to the dynamics of high-speed mobile vehicles and the variety of the road conditions, it is difficult to build a complete analytical model to study the network performance, and from [8-9], experimental measurement becomes important in characterizing the channel fading effect in such a dynamic vehicular communication environment. An important factor of vehicular channel model is the mobility [10-12] by including the mobility of nodes and the channel variability. Channel variability, is not well modeled in today's wireless vehicle networks. In [13], simplistic models may not be practical and it is also different to draw conclusions on the real performance of the upper layers. Designers require statistical models that can accurately capture the characteristic of propagation behavior observed at both mobile vehicles [14].

Currently, free space and two ray ground channel models are the most popular propagation models for simulation in vehicular wireless networks [15]. For the free space channel model, it describes an ideal propagation characteristic, and the received power depends on the transmitted power, the gain of antenna, and the distance of the transmitter-receiver. While for the two way ground model, it assumes that the received signal is the sum of the direct line of sight path and the reflected path from the ground. However, the model does not take obstacles into consideration. It is also too ideal for short transmitter-receiver separation distances, as it assumes that signals have a perfect 250m radius range. On the other hand, QualNet supports open-space propagation as well as stochastic propagation models such as Rayleigh, Rician, and log-normal fading, in which all models describe the time-correlation of the received signal power. The Rayleigh model considers indirect paths between the transmitter and the receiver, while the Rician model considers when there is one dominant path and multiple

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indirect signals. OPNet supports open-space propagation models as well as an enhanced open-space model that accounts for hills, foliage, and atmospheric affects [16]. Furthermore, obstacle effects are combined in [17, 18, 19], but the propagation characteristic is limited to line-of-sight. In [20], a radio planning tool is applied and the evaluation for the impact of a more realistic propagation by a set of measurements is validated.

In a dense urban area, path loss, shadow fading, and short-term variants are the main factors affecting the communication quality. Path loss and shadow fading determines the effective communication distance between two adjacent vehicles, while multi-path and Doppler spectrum caused by the sum of absolute speeds of individual nodes affect the quality of service (QoS) in inter-vehicle networks. However, it is noted that some of these effects can be avoided, such as by increasing the height of the antenna and the inerratic variations is just relative to the distance between transmitter and receiver. Here, the model is focused on the short-term variants, especially for the Doppler spectrum model caused by both high mobile vehicles. The Doppler spectrum models in [21, 22] for wireless cellular network cannot really be used for link between double mobile nodes. Akki and Haber [23] consider a Doppler spectrum model for radio link between double mobile nodes in a two-dimensional (2-D) uniform scattering environment. It is a deterministic channel model without considering the specific characteristics, such as the effect of antenna and dynamic distribution of received multi-path wave.

This paper addresses a fast fading channel model for radio link between double mobile nodes in a three-dimensional (3-D) scenario (3-D scatter fading channel model). It is a stochastic model relative to the antenna, the probability distribution of the multi-path wave and the relative speed of the two mobile nodes [24]. The random phase of received wave is assumed to be uncorrelated. The necessity of the proposed method is demonstrated by using real-life experiments conducted in an urban area of Wuhan city, China. The experiment involves two cars, one for transmitter and one for receiver, driving on different time and road conditions in the Wuhan city to create a broaden wireless measurement database. We obtain the analytical expressions of the Doppler spectrum for double mobile nodes, and then integrate the Doppler spectrum model with a path loss model as the physical module in OMNet++ platform to evaluate packet level performance for the link of vehicular wireless networks. The real-life vehicular wireless measurement is used to validate the proposed channel model and the results are compared with that of the conventional two ray ground model.

The rest of the paper is organized as follows. Section 2 describes the experiment and the measured wireless data. The packet-level statistical performance of the measurement is also given. Section 3 describes the proposed channel model by analytic expression of Doppler spectrum for radio link between double mobile nodes in 3-D scenario. Section 4 analyzes the packet level statistical performance of the proposed model, and compares the performance with the Gans Doppler model. Results and conclusions are given in Sections 5 and 6, respectively.

II. EXPERIMENTS AND MEASUREMENTS

The experiments were performed on LuoYu and ZhongNan roads, Wuhan city, China. There were two mobile vehicles used in the experiments as a transmitter (TX Vehicle) and a receiver (RX Vehicle), respectively. Both vehicles contain embedded-PCs (EPC) built with a Mini-ITX board, an automotive power supply, a Celeron processor, storage devices and GPS devices. The used parameters of vehicular wireless experiment network are given in Table 1.

Table 1: The parameters of Vehicular Wireless Network in measurements

Parameters	**Detailed information**
The high of antenna	3.2 m
Antenna type	Omni-direction
The gain of antenna	8 dBi
Wireless LAN chip	Intel@2200BG
Network adaper power	100 mW
Network model	Ad Hoc
Modulation	BPSK
MAC protocol	802.11b
Transmission Platform	StarEast

The transmitter broadcasted 100 User Datagram Protocol (UDP) packets per second with 100 bits per packet at 1 Mbps (the lowest rate). The UDP payload consists of a 32-bit sequence number that is incremented by the transmitter for every successive packet and local GPS record. The receiver sniffs the packets from the wireless interface and keeps a trace of the lost ones by checking the UDP packet sequence numbers, as shown in Fig. 1(a) and Fig. 1(b). We adopted packet loss rate (PLR) which is the ratio of the missing number packets in radio link to the total number packet sent by the TX vehicle as the indicator.

(a) Vehicle in the experiments

(b) PC in the vehicle

Fig. 1. Experimental vehicular system.

Dozens of measurements were obtained from real road tests. In Fig. 2 is plotted the cumulative density functions (CDF) of PLR when the distance between two vehicles varies from 10-20 meters, 20-30 meters, and 30-40 meters, respectively. From these figures, it is observed that: a) The inter-vehicle distance has an direct impact on link quality of vehicular wireless network. The distribution of PLRs become flatter as the inter-vehicle distance becomes larger. b) The PLRs with the same inter-vehicle distance almost follow the same distribution, no matter if the traffic is heavy (8 am), or light (2 pm and 9 pm). From the measurements, it is observed that we can use the same distribution function to express the different packet loss samples for the same inter-vehicle distance.

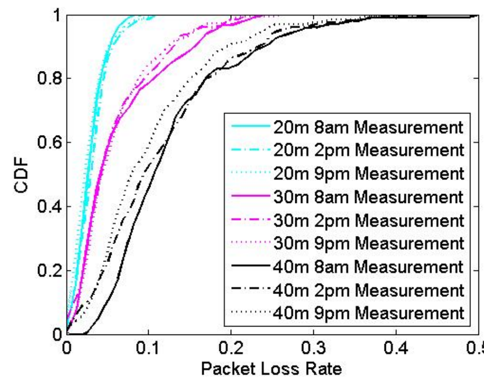

Fig. 2. The CDF of PLR for different inter-vehicle distances and different measured time

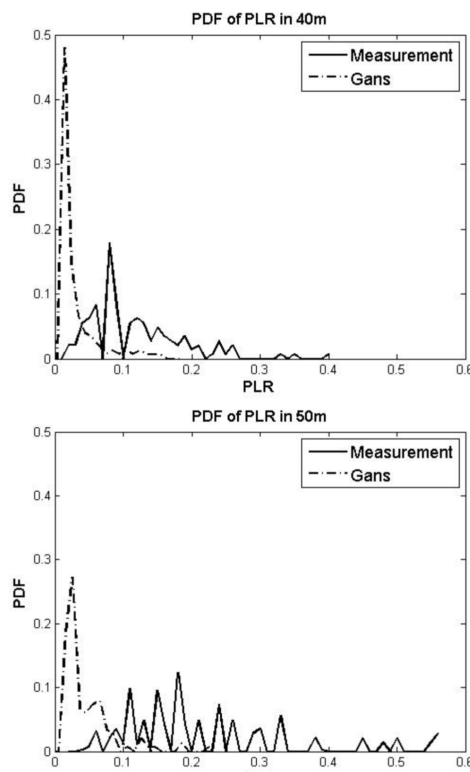

Fig. 3. The PDF of PLR for both measurement and Gans Doppler model.

Figures 3 and 4 depict the probability distribution function (PDF) and cumulative distribution function (CDF) of PLR for the Gans Doppler model and the measurements. Apparently, the Gans Doppler model does not fit the measurements. The reason is that the Gans Doppler model only considers the Doppler Effect caused by one mobile node, which is used in wireless cellular networks. However, for vehicular wireless networks, all vehicles are in motion, and the mobility of all vehicles should be incorporated into the propagation model. Therefore, it is necessary to propose a propagation model for double mobile nodes in vehicular networks.

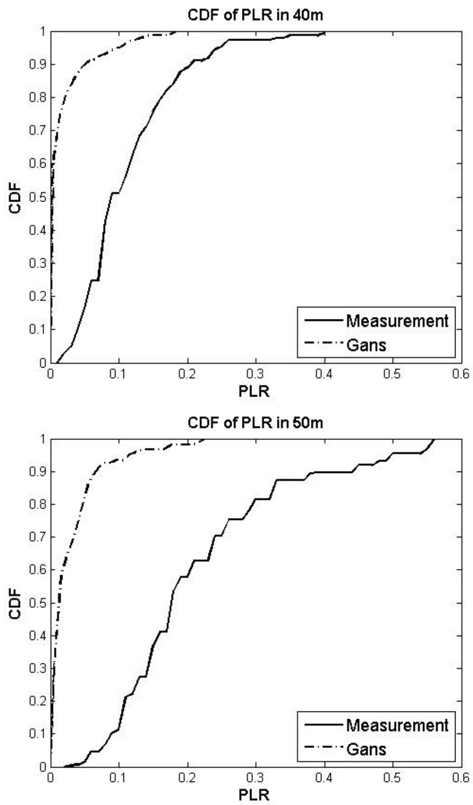

Fig. 4. The CDF of PLR for both measurement and Gans Doppler model.

III. PROPAGATION MODEL FOR DOUBLE MOBLE NODES

Considering a two ray ground model may not be practical for the vehicular application, as it assumes that signals have a perfect 250m radius range, here we proposed to integrate the channel model with a short-term fading channel model as the propagation model for vehicular wireless networks for short-term fading [24], a new fading model for a radio link between double mobile nodes in 3-D scenario. In the following sections, more significant results will be presented.

The radio link considered here is between two vehicles moving with speed $V_i, i=1,2$ in 3-D scenario. The left one in Fig. 5 shows the coordinate system of the mobile vehicles and the right one in Fig. 5 displays the referenced coordinate system. According to the radio propagation model for the 2-D wide area with one mobile node [25], the channel time-variant transfer function for radio link between double mobile vehicles in a 3-D scenario can be defined as

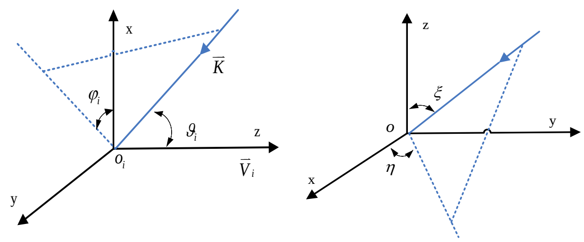

Fig. 5. The coordinate system of mobile vehicles.

$$h(f_0;\vec{r}) = \sum_{k=1}^{N} a_k F_1(\overrightarrow{K_{1k}}) F_2(\overrightarrow{K_{2k}}) e^{j\phi_k - \vec{k_1}\cdot\vec{r_1} - \vec{k_2}\cdot\vec{r_2} - 2\pi f_0 \tau_k}, \quad (1)$$

where $\sum_{k=1}^{N} a_k F_1(\overrightarrow{K_{1k}}) F_2(\overrightarrow{K_{2k}})$ is the relative amplitude, and $\vec{k_1}\bullet\vec{r_1}+\vec{k_2}\bullet\vec{r_2}$ is the phase caused by the double mobile nodes. Setting

$$2\pi f_{dk} = \vec{k_1}\cdot\vec{r_1}+\vec{k_2}\cdot\vec{r_2} = \left|\vec{k_1}\right|\left|\vec{r_1}\right|\cos\vartheta_{1k} + \left|\vec{k_2}\right|\left|\vec{r_2}\right|\cos\vartheta_{2k}, \quad (2)$$

where $\vartheta_{ik} (i=1,2; k=1,2,...,N)$ is the angle between $\vec{V_I}$ and $\overrightarrow{K_{ik}}$. The Doppler frequency shift is thus

$$f_{dk} = \frac{f_0 V_1 t}{c}\cos\vartheta_{1k} + \frac{f_0 V_2 t}{c}\cos\vartheta_{2k} = f_{d1}\cos\vartheta_{1k} + f_{d2}\cos\vartheta_{2k}, \quad (3)$$

where $f_{d\max} = f_{d1} + f_{d2}$ is the max Doppler shift caused by the two mobile vehicles. Substituting (3) into (1), we have

$$h(f_0;\vec{r}) = h(f_0;t) = \sum_{k=1}^{N} F_1(\overrightarrow{K_{1k}}) F_2(\overrightarrow{K_{2k}}) e^{j\phi_k - 2\pi f_{dk} - 2\pi f_0 \tau_k}. \quad (4)$$

Assume that the phases are uncorrelated; the time-autocorrelation function of the channel transfer function can be written as

$$R_H(\tau) = E\{h(f_0;t)h^*(f_0;t+\tau)\}$$
$$= \sum_{k=1}^{N} E\{F_1^2(\overrightarrow{K_{1k}})\}E\{F_2^2(\overrightarrow{K_{2k}})\}E\{e^{j2\pi f_{dk}\tau}\}, \quad (5)$$

$\{\overrightarrow{K_{ik}}\}$ and f_{dk} are independent identically distributed. Therefore, (5) can be further written as

$$R_H(\tau)=E\{F_1^2(\overrightarrow{K_{1k}})\}E\{F_2^2(\overrightarrow{K_{2k}})\}E\{e^{j2\pi f_{dk}\tau}\}$$
$$=\int_0^{2\pi}\int_0^{\pi}\int_0^{2\pi}\int_0^{\pi} F_1^2(\vartheta_1,\varphi_1)F_1^2(\vartheta_2,\varphi_2)e^{j2\pi f_d(\vartheta_1,\vartheta_2)\tau} p_{\vartheta_1,\varphi_1}(\vartheta_1,\varphi_1)\, p_{\vartheta_2,\varphi_2}(\vartheta_2,\varphi_2)\,\mathrm{d}\vartheta_1\mathrm{d}\vartheta_2\mathrm{d}\varphi_1\mathrm{d}\varphi_2, \quad (6)$$

substituting (3) into (6), we have

$$R_H(\tau)=\delta^2 g_1(\tau)g_2(\tau), \quad (7)$$

where $\delta^2=R_H(0)$ is the average power of the multi-path scattering component, which is the channel variance, and

$$g_i(\tau)=\int_0^{\pi} p_i(\vartheta_i)e^{j2\pi f_{di}\tau\cos\vartheta_i}\mathrm{d}\vartheta_i \ \ (i=1,2), \quad (8)$$

$$p_i(\vartheta_i)=\frac{\int_0^{2\pi}F_i^2(\vartheta_i,\varphi_i)p_{\vartheta_i,\varphi_i}(\vartheta_i,\varphi_i)\,d\varphi_i}{\int_0^{\pi}\int_0^{2\pi}F_i^2(\vartheta_i,\varphi_i)p_{\vartheta_i,\varphi_i}(\vartheta_i,\varphi_i)\,d\varphi_i d\vartheta_i}, \quad (9)$$

where $p_i(\vartheta_i)$ is the PDF of the antenna gain when the K-th multi-path arrived or transmitted with an-. gle ϑ_i. Taking the Fourier transform of $R_H(\tau)$, we have the Doppler spectrum

$$S_H(\upsilon)=\delta_H{}^2G_1(\upsilon)*G_2(\upsilon), \quad (10)$$

where $G_i(\upsilon), i=1,2$ is the Fourier transform of $g_i(\tau)$ Since we have $f_{di}\cos\vartheta_i=y$,

$$G_i(\upsilon)=F[\int_0^{\pi}p_i(\vartheta_i)e^{j2\pi f_{di}\tau\cos\vartheta_i}d\vartheta_i]$$
$$=\frac{1}{f_{di}}\int_{-f_{di}}^{f_{di}}\frac{p_i(\arccos\frac{\upsilon}{f_{di}})}{\sqrt{1-(\frac{\upsilon}{f_{di}})^2}}\sigma(v-y)dy, \vartheta_i\in[0,\pi], \quad (11)$$

If the range of ϑ_i is extended from $[0,\pi]$ to $[2n\pi,2(n+1)\pi]$, where n is the natural number, (11) can be further written as

$$G_i(\upsilon)=\frac{1}{f_{di}}\int_{-\infty}^{\infty}\frac{p_i(\arccos\frac{\upsilon}{f_{di}})}{\sqrt{1-(\frac{\upsilon}{f_{di}})^2}}rect(\frac{y}{2f_{di}})\sigma(v-y)dy$$
$$=\frac{p_i(\arccos\frac{\upsilon}{f_{di}})}{\sqrt{1-(\frac{\upsilon}{f_{di}})^2}}rect(\frac{y}{2f_{di}}), \quad (12)$$

where $rect(\frac{y}{2f_{di}})=1$ when $\frac{y}{2f_{di}}<\frac{1}{2}$, and 0 otherwise. And the Doppler spectrum becomes

$$S_H(\upsilon)=\frac{a}{f_{d2}^2}\cdot\frac{p_2(\arccos\frac{\upsilon}{f_{d2}})}{\sqrt{1-(\frac{a\upsilon}{f_{d2}})^2}}*\frac{p_2(\arccos\frac{\upsilon}{f_{d2}})}{\sqrt{1-(\frac{\upsilon}{f_{d2}})^2}}, \quad (13)$$

where $a=f_{d1}/f_{d2}, 0<a<1$, and f_{d2} is the Doppler shift caused by one vehicle. The analytical expressions of the Doppler spectrum for double mobile channel proposed here is a random variable of the antenna, relative speed of the two mobile vehicles, and the probability distribution of the received and transmitted multipath wave.

In Fig. 6 is plotted the Doppler spectrums of the proposed double mobile channel model and the conventional Gans model with single mobile node. It illustrates that the Doppler spectrums for two links are different. As the values of vehicle speed ratio (values of frequency shift ratio caused by vehicles) a decreases from 1 to 0, the vertical asymptotes move nonlinearly from the center of the graph to the outside. The curve becomes similar to the Doppler spectrum for link of a single mobile node, and the Doppler spectrum gap shrinks as $a\to 0$. When $a=0$, that is

$$f_{d2}=0, S_H(\upsilon)=p_1(\arccos\frac{\upsilon}{f_{d1}})/(f_{d1}\sqrt{1-(\frac{\upsilon}{f_{d1}})^2}). \quad (14)$$

It is similar to the analytical expression Doppler spectrum for single mobile node, which reveals that our models are more comprehensive.

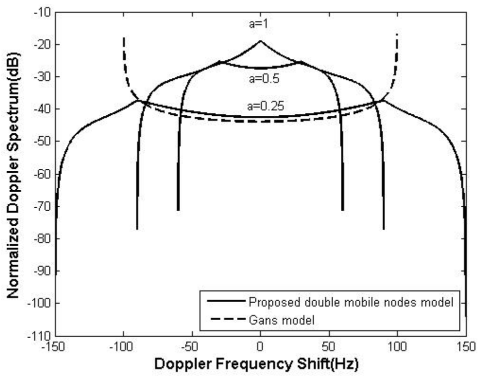

Fig. 6. Doppler spectrum.

IV. PACKET-LEVEL PERFORMANCE EVALUATION

The architecture of mobile nodes used here is depicted in Fig. 7. We use OMNET++ [26] as the simulation tool.

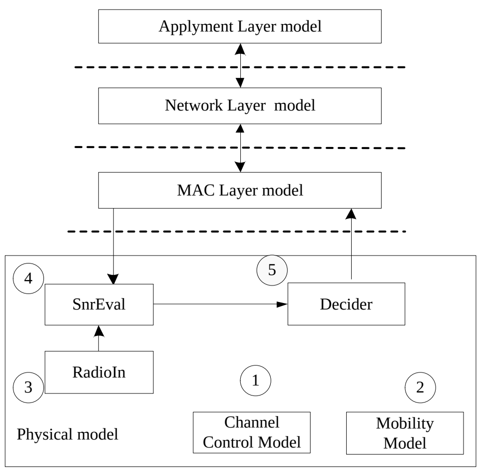

Fig. 7. The architecture of the mobile nodes.

In the simulation, the applyment layer module broadcasts 100 packets per second. The network-layer module is necessary for nodes accessing Internet network. The MAC-Layer module uses the 802.11b communication protocol. The physical module integrates the information of node mobility, received power, background noise and modulation to decide whether a transmitter ground is received correctly. Here, we focus on the SnrEval and Decider modules which are used to control the propagation characteristic. We integrate the proposed Doppler spectrum model with the two ray ground channel model to calculate the received power.

Figures 8 and 9 show the PDF and the CDF of the PLR, which is an important measure for statistical performance of packet level. Apparently, the proposed model fits the measurements quite well compared to the Gans Doppler model. The proposed 3-D scatter fading channel model for double mobile nodes is useful to express the actual radio propagation performance in a dense urban environment. The fading caused by two mobile vehicles is more severe than that caused by single mobile vehicle, and this effect has to be taken into consideration. For different inter-vehicle distances, the proposed model can provide a reasonable match to the measurements.

To further compare these models, we consider the mean error (ε), relative mean error ($\bar{\varepsilon}$), and mean square standard deviation of error (σ_{MSE}).The mean error reflects the approximation degree between simulation and measurement results; while the mean-square standard deviation of error reflects the extent of the error and the stability of method.

$$\varepsilon = \frac{1}{N}\sum_{t=1}^{N} | x(t) - x_r(t) |, \; \bar{\varepsilon} = \frac{\varepsilon}{\frac{1}{N}\sum_{t=1}^{N} x_r(t)},$$

$$\sigma_{MSE} = \sqrt{\frac{1}{N}\sum_{t=1}^{N}[x(t) - x_r(t) - \varepsilon]^2}. \qquad (15)$$

Table 2 summarizes the results of the proposed model and the Gans model. The mean error ε is between -0.05 - +0.05 when the transmitter-receiver distance is 20m, 30m, 40m, 50m, while that of Gans model is much larger. The relative mean error $\bar{\varepsilon}$ of the proposed channel is under 50%, compared to that of Gans model, which is almost 80%. The proposed model is found to be more accurate based on measured data and can be used to estimate the packet-level performance of vehicular wireless networks in a dense urban environment. However, we also found that as the distance increases, the mean-square standard deviation of error σ_{MSE} increases. The larger distance between transmitter-receiver may result in a larger mean-square standard deviation of error.

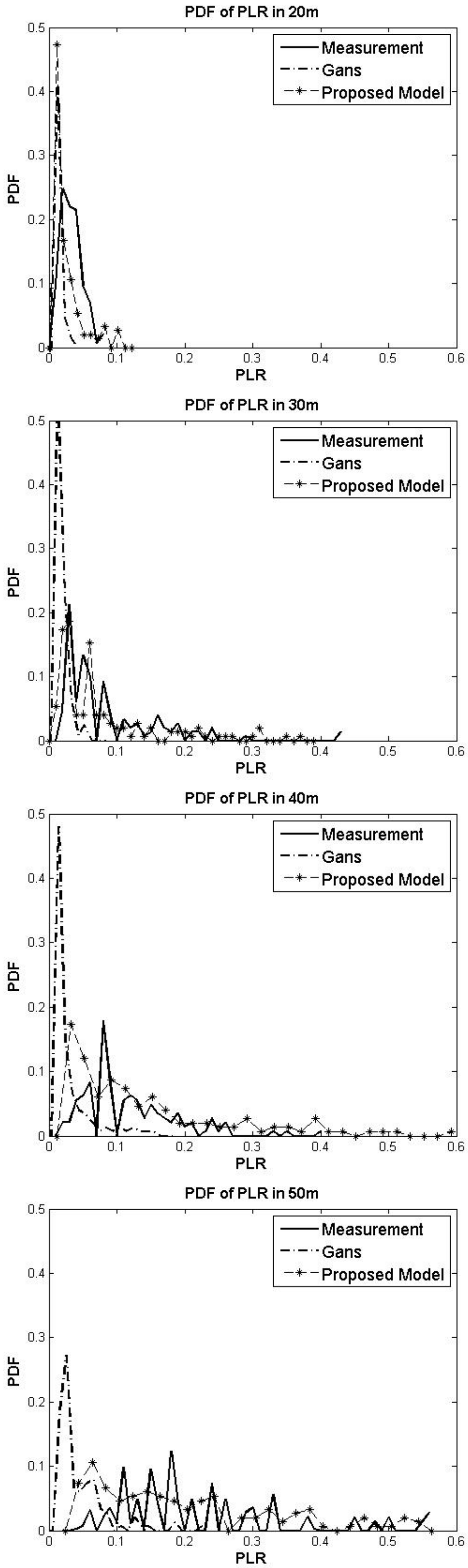

Fig. 8. Comparison in PDF of PLR with inter-vehicle distance 20m, 30m, 40m, and 50m.

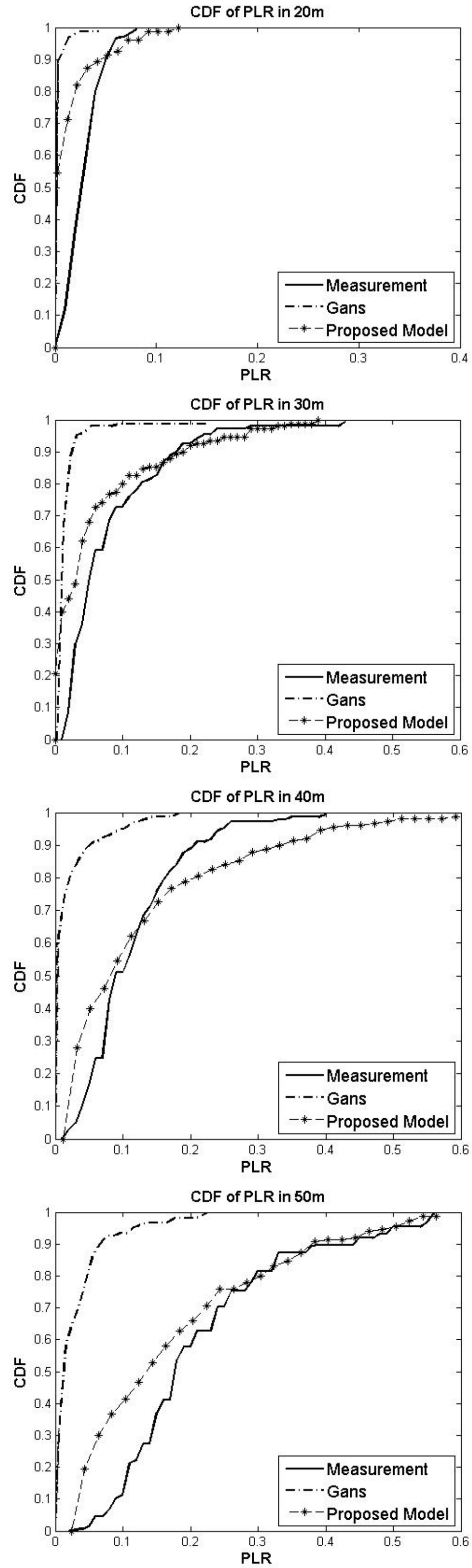

Fig. 9. Comparison in CDF of PLR with inter-vehicle distance 20m, 30m, 40m, and 50m.

Table 2: Comparison of the prediction errors between proposed model and the Gans model

	20m		30m	
	P-model	G-model	P-model	G-model
ε	0.015768	0.028252	0.028747	0.068238
$\overline{\varepsilon}$	0.4693	0.84083	0.35229	0.83625
σ_{MSE}	0.032105	0.058905	0.051324	0.15156
	40m		**50m**	
	P-model	G-model	P-model	G-model
ε	0.043869	0.09113	0.07446	0.1758
$\overline{\varepsilon}$	0.38799	0.80604	0.35035	0.82717
σ_{MSE}	0.077522	0.19414	0.14123	0.37399

V. CONCLUSION

As a key component of the ITS, vehicular wireless networks, has attracted research attention from both the academia and industry of US, EU, and Japan. Although many works have been done on communication and routing protocol, only few models have been developed to characterize the fading effect on vehicular wireless data. This paper presents a real-life experiment conducted in a real environment that collects wireless vehicular measurements to analyze the channel model for vehicular communications and the fading effects. It is shown that the previous Gans Doppler model, which is just based on one mobile node, cannot accurately model the channel variability. To address the problem, a novel channel model based on 3-D scattering fading for radio link between double mobile nodes is developed. The statistical performance of PLR based on the measured data supports the results of the proposed model.

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Yuhao Wang was born in Hubei, China, in 1977. He received the Ph.D. degree in space physics from Wuhan University, China in 2006. He is a Professor with the School of Information Engineering, Nanchang University, China from 2006. His current interests are in the areas of radio measurements, channel modeling, radio link and network simulation, wireless cellular network, VANET and Software Defined Radio (SDR).

Xing Xing was born in An Hui, China, in 1989. He received the B.S. degree from Nanchang University, China, in 2010. His research interests include radio measurements and wave propagation, computational simulation, and wireless networks.

Yan Zhang was born in Jiang Xi, China in 1987. She received the M.S. degree from Nanchang University, China, in 2011. Her research interests include radio measurements and wave propagation, computational simulation, and wireless networks.