Application-Oriented Performance Comparison of 802.11p and LTE-V in a V2V Communication System

Mengkai Shi, Yi Zhang*, Danya Yao, and Chang Lu

Abstract: In recent years, the Vehicle-to-Vehicle (V2V) communication system has been considered one of the most promising technologies to build a much safer and more efficient transportation system. Both simulation and field test have been extensively performed to evaluate the performance of the V2V communication system. However, most of the evaluation methods are communication-based, and although in a transportation environment, lack a V2V application-oriented analysis. In this study, we conducted real-world tests and built an application-oriented evaluation model. The experiments were classified into four scenarios: static, following, face 2 face, and crossing vertically, which almost covered all the V2V communication patterns on the road. Under these scenarios, we conducted experiments and built a probability model to evaluate the performance of 802.11p and LTE-V in safety-related applications. Consequently, we found out that improvements are still needed in Non-Line-of-Sight scenarios.

Key words: Vehicle-to-Vehicle (V2V) communication; connected vehicles; performance evaluation; intelligent transportation system; application-oriented field test

1 Introduction

Vehicle-to-Vehicle (V2V) communication, which is the most important part of the V2X (e.g., V2V, Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and so on) system, has garnered increasing attention from both research institutes and automobile manufacturers. V2V communication is considered a key approach to improving the performance of

the current transportation system, especially when it comes to safety issues under the circumstances of road traffic, based on the fact that traffic accidents lead to severe casualties and financial losses. The accident statistics published by the Ministry of Public Security of China showed 7.42 million reported accidents, 187 781 of which resulted in death or injury (i.e., 58 022 people were killed and 199 880 people were injured), causing a direct property loss of 1.04 billion yuan. The inability of the drivers to be fully aware of the potential crash played a key part in these accidents. V2V communication is an effective method of improving the situation awareness of the drivers by sharing the vehicle position and speed and reducing traffic accidents.

Dedicated Short Range Communications (DSRC) are one of the most popular and promising communication standards that deal with the complex topology and mobility of vehicular environment communication. To fulfill this standard, the Federal Communications Commission of the U.S. allocated 75 MHz bandwidth from 5.850 GHz to 5.925 GHz for DSRC use. 75 MHz

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of the spectrum is divided to six service channels and one control channel. Each channel equally has 10 MHz bandwidth. Except for the spectrum, IEEE has already published a series of protocols for the whole vehicular communication system, named Wireless Access for Vehicular Environments (WAVE). The WAVE stack is mainly composed of two parts: IEEE 1609.x and IEEE 802.11p. IEEE 802.11p, usually used to refer to the entire WAVE stack, is modified from 802.11a, and defines the physical layer of the WAVE stack and part of the Medium Access Control (MAC) layer. The IEEE 1609 Family of Standards for WAVE defines the architecture, resource management, security services, networking services, multi-channel operations, and physical access for high-speed low-latency short-range communication in vehicular environments[1]. As the standards of WAVE have already been published, several companies (e.g., Cohda Wireless, DENSO, etc.) have also released devices that can communicate through the WAVE standards. Universities and research institutes also conducted many performance evaluations of the WAVE standards.

Although 802.11p has many advantages in vehicular environment communication, it still faces some shortcomings, such as limited radio range, unbounded delay under congestion circumstance, and lack of pervasive roadside infrastructures that can communicate through 802.11p[2]. The above mentioned concerns have motivated interest in Long Term Evolution (LTE) as an alternative communication standard in vehicular environments. LTE is the most pervasively deployed wireless broadband technology that can provide high-speed low-latency mobile communication. Its massive deployment provides the world an opportunity to build the connected vehicle system and, hence, deploy the V2X system[3].

As for the development of LTE-V, the Ministry of Industry and Information Technology of China approved the Shanghai Intelligent Connected Vehicle Pilot Area in Jiading District in July 2015. In October 2015, the Shanghai International Automobile City released its initial plan to test 1000 LTE-V2X-enabled vehicles in an area of 90 km^2 in 2018 – 2019. To respond to this situation, 3GPP is actively conducting the study and the specification work on LTE-based V2X. A study item on LTE-based V2X services was approved by 3GPP in which PC5-based V2V had been given the highest priority. This Radio Access Network (RAN) feasibility study has completed the

part of the PC5 transport for the V2V services. The RAN study concluded that the LTE PC5 interface with the necessary enhancements could make it feasible to support V2V services. Moreover, the combination of Uu and PC5 is also recommended to achieve the maximum efficiency of the V2X services by properly selecting the operation scenario[4].

In another technical report[5], the 3GPP described in detail the three types of V2X namely V2V, V2I, and V2P. The basic functions of UE and E-UTRAN in the V2X system were defined in the report according to the three types. More than 20 use cases were also defined in detail in this report, including description, pre-conditions, service flows, post-conditions, and potential requirements. Take the Forward Collision Warning (FCW) as an example. In the potential requirements of the FCW, the report specifies some metrics, including a maximum latency of 100 ms and a message size of 50 – 300 bytes.

The LTE-V standards were not that developed as the DSRC; hence, no off-the-shelf product communicates based on LTE-V. Most of the research works on LTE-V focused on surveying, modeling, and simulating. Aside from the technical reports released by the 3GPP, some researchers alse surveyed LTE-V-related publications. Araniti et al.[6] discussed the advantages and disadvantages of applying LTE-V in the V2X system. Tseng[7] provided a more detailed description of LTE-V in V2X. Vinel[8] compared the performance of LTE and 802.11p by a simulation. Phan et al.[9] and Trichias[10] also performed a simulation work on the LTE-V performance.

Many research works were conducted to figure out to what extent that 802.11p and LTE-V could support V2V communications. Modeling and simulation were predominant in these research works[11–17]. However, the vehicular environments are so complex that all modeling and simulation must ignore some aspects to fulfill the research. This kind of ignorance makes the modeling and simulation to not precisely reflect the performance of V2V communications under real-world circumstances. A large number of real world field tests were conducted in the recent years based on those concerns. Some of the real-world tests aimed to verify the model or simulation result. Biddlestone et al.[18] performed an experiment at the Transportation Research Center in East Liberty, OH, USA to verify the simulation of the 802.11p WAVE protocol. However, the experiment only included a few static scenarios.

Some other tests aimed to figure out whether the communication technique could support the V2V system. Chen and Yao[19] conducted a real-world test to compare the performances of 802.11n, 802.1.1p, and 3G. Wang et al.[20] performed an evaluation of the 802.11p-based V2V communication in a typical urban expressway to evaluate the communication performance in real traffic flow. They found that the reliability of communication was not stable because of the changing LOS conditions. Liu et al.[21] implemented a V2V system and evaluated the performance of 802.11p, LTE, and Wi-Fi. The listed tests and some other researches[22–27] provided performance evaluation results under real-world circumstances, but were not application-oriented. In other words, if we want to know whether V2V applications (e.g., FCW) can be realized based on these communications, we cannot directly find the answer in these research works.

This study intended to demonstrate the communication performance under typical V2V application scenarios. According to the definition in the application layer standard draft proposed by Society of Automotive Engineers of China, the V2X application system has 17 basic scenarios, including safety-related V2V scenarios (e.g., FCW and intersection collision warning), and non-safety-related V2I scenarios (e.g., traffic light optimal speed advisory, traffic sign in car). Accordingly, we classified the driving pattern in mentioned 17 scenarios into four categories (e.g., static, face 2 face, crossing vertically, and following) to better evaluate the application-oriented communication performance in safety related V2V applications (Fig. 1).

We developed a device that integrated with GPS and LAN adapter as the upper computer. The tested devices were Cohda Wireless Mk5 and LTE-V communication devices developed by Datang Telecom Technology (DTT). The experiment was conducted at the National Intelligent Connected Vehicle (Shanghai) Pilot Zone in Jiading District, Shanghai. We used two vehicles equipped with experiment devices and deployed with test programs. The two vehicles drove as in the scenarios shown in Fig. 1. During the process, we collected driving information (e.g., speed and position) and the communication information (e.g., message sequence and time that the messages were sent and received). The data were classified into four categories according to the scenarios in Fig. 1. We calculated the latency and Packet Delivery Rate (PDR) as the
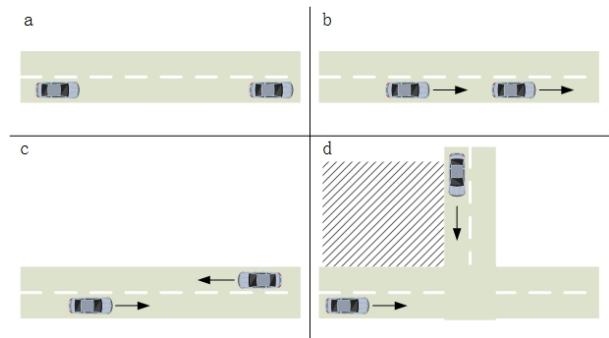

Fig. 1 Driving patterns: Scenario a denotes two static vehicles; scenario b denotes one vehicle following the other vehicle; scenario c denotes two vehicles driving face to face; and scenario d denotes two vehicles driving to the crossing from vertical directions, with an obstacle (described as the shadow area) making the scenario non-line-of-sight.

main metrics to evaluate whether the performance could support the applications.

The rest of the paper is arranged as follows: Section 2 introduces the experiment arrangements, including the experiment field, devices, and process; Section 3 briefly describes the evaluation metrics; Section 4 presents a detailed analysis of experiment data; Section 5 demonstrates our model to evaluate the communication performance from the view of application; and Section 6 finally concludes the paper.

2 Experimental Arrangement

2.1 Experiment field

The experiments were conducted at the National Intelligent Connected Vehicle (Shanghai) Pilot Zone in Jiading District, Shanghai. The closed zone has two main roads. One straight road was called Zhongbai Road, which has a length of 1.3 km. The other main road was the arc road shown in Fig. 2. The area has 3 intersections shown on the map. Obstacles were built around the intersection composed of Zhongbai Road and the arc road to imitate the environment of scenario d in Fig. 1.

2.2 Experiment devices

The experiment used two vehicles, both of which sent messages to the other and received messages from the other. We used two types of communication devices (i.e., Mk5 from Cohda Wireless, which realized the 802.11p and IEEE 1609 family, and LTE-V device from DTT, which was a prototype of the standard LTE-V communication device) to compare the performance of 802.11p and LTE-V, as shown in Fig. 3. The detailed
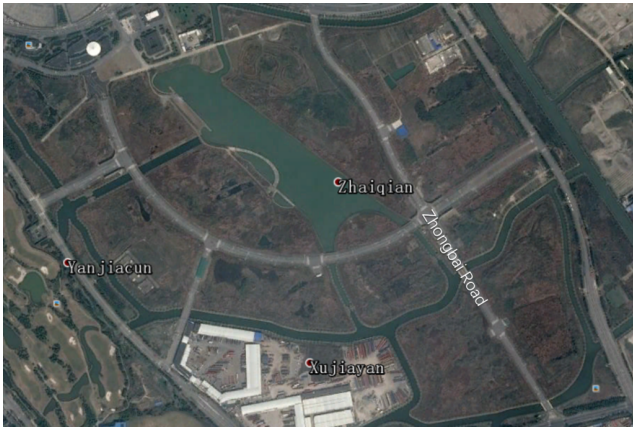
Fig. 2 Map of the experiment field in the National Intelligent Connected Vehicle (Shanghai) Pilot Zone.

Fig. 3 Experiment devices from left to right: Cohda Wireless Mk5, LTE-V device from DTT, and CWAVE-Original from Nebula Link to the upper computer.

information on the devices are listed as follows:

- Communication devices: Cohda Wireless Mk5 and LTE-V device from DTT;
- Upper computer: CWAVE-Original from Nebula Link which integrated a LAN adapter;
- Communication antenna: original binding antenna of the two types of devices;
- GPS module: Ublox MAX-M8Q;
- GPS Antenna: CWAVE-MTSBWY-OAI;
- Vehicles: Changan CS75, MG GS.

2.3 Experiment process

We used CWAVE-Original as the upper computer to more precisely evaluate the latency. The upper computer installed the Linux operation system, and was connected to the communication device with a network line cable. We used the round-trip time to calculate the latency because the computers are not precisely synchronized. We deployed a test program on the upper computer, as is shown in Fig. 4. This program had two threads: one sends test messages, and the other serves as a receiver. The test process is described below.

Each vehicle periodically sends a test message with an interval of 100 ms. First, Vehicle A builds a test frame composed of the frame identity and sequence number. We then add the GPS information to the frame, including position and speed. We used two
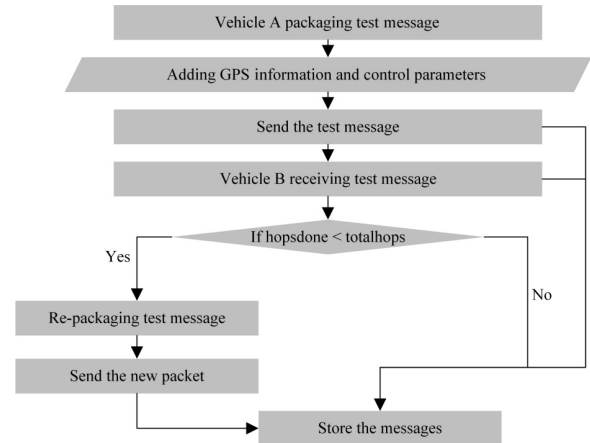

Fig. 4   Flow chart of the test program. Vehicles A and B do the same exact thing in the test.

indicators as the communication control parameters to determine how Vehicle B deals with the message received, totalhops, and hopsdone. The former denotes the total hops the message should be transferred and the latter denotes the times that the received message has already been transferred.

In this experiment, we initially set the parameter totalhops as 2, indicating that Vehicle B will send the message back to Vehicle A after it receives the test message. Hopsdone was initially set as 0. After putting all the test information into the test frame, we are almost ready to send the message to the communication. The last procedure before sending the message was to add the exact sending time. We used the system standard function get time of day, which provided an accuracy of up to $1\,\mu s$. Once Vehicle B receives the test message, it immediately records the time, then it parses the data and increases the control parameter hopsdone by 1. The program then compares the parameter hopsdone and totalhops. If hopsdone is less than totalhops, Vehicle B's position and speed are added, and the message is sent back after attaching the time; otherwise, the message is locally stored.

We conducted the experiment as follows after all programs and devices were deployed:

- Scenario a in Fig. 1: Vehicle A parked at the south end of the Zhongbai Road, and Vehicle B parked at some points along this road. The distance between these points and Vehicle A ranged from 100 m to 800 m, with an interval of 100 m between every two points.
- Scenario b: Vehicle A drove back and forth along the Zhongbai Road with speeds of 20 km/h, 40 km/h, 60 km/h, and 80 km/h, followed by Vehicle B with the same speed.

● Scenario c: Vehicle A drove back and forth along the Zhongbai Road with speeds of 20 km/h, 40 km/h, 60 km/h, and 80 km/h. Vehicle B drove on the same road with the same speed but facing Vehicle A.

● Scenario d: Vehicle A drove back and forth along the Zhongbai Road with speeds of 20 km/h and 40 km/h. Vehicle B drove along the arc road with the same speed. In this scenario, the two vehicles must arrive at the intersection at the same time. In comparison, another static NLOS scenario was conducted.

Every scenario was repeatedly performed, such that we could have enough data to evaluate the communication performance.

3   Evaluation Approach

As mentioned earlier, we used two main metrics to evaluate the communication performance: end-to-end latency and PDR. Before calculating the latency and the PDR, we divided the data into some categories according to the data characteristics in different scenarios, such that we could analyze the performance in different scenarios. The data, which could not be classified, was the bad data that needed to be knocked out.

3.1   Data classification

First, we found out that the messages could hardly be received when the distance between the two vehicles was larger than 700 m. Hence, only the entries with a distance less than 700 m were considered in all cases. The vehicles' position and speed had different features in different scenarios, and we classified the data into different categories based on these differences. The data was sorted according to the rules below:

$$d \in \begin{cases} S_a, & \text{if } v_A < 0.1\,\text{km/h}, v_B < 0.1\,\text{km/h}; \\ S_b, & \text{if } |\theta_A - \theta_B| < 15°; \\ S_c, & \text{if } 165° < |\theta_A - \theta_B| < 195°; \\ S_d, & \text{if } 75° < |\theta_A - \theta_B| < 105°, \\ & \quad \text{or } 255° < |\theta_A - \theta_B| < 285° \end{cases} \quad (1)$$

where, S_a, S_b, S_c, and S_d denote the set of data in scenarios a, b, c, and d, respectively; v_A and v_B are speeds of vehicles A and B, respectively; θ_A and θ_B are directions of vehicles A and B, respectively.

3.2   PDR and latency measurement

The PDR and the latency were measured herein according to the scenarios. In scenario a, the PDR and the latency were given per 100 m because the data was recorded every 100 m. In scenarios b, c, and d, the PDR and the latency were calculated according to the speed. The PDR was calculated using Eq. (2) while the latency was calculated using Eq. (3).

$$\text{PDR} = \frac{N_{\text{received}}}{N_{\text{sent}}} \quad (2)$$

$$t = \frac{t_{\text{received}} - t_{\text{sent}}}{2} \quad (3)$$

4   Performance Analysis

We analyzed the performance under each scenario after data classification. The upper figure in Fig. 5 shows the comparison of the PDR of 802.11p and LTE-V in scenario a, while the lower one shows that of the latency.

As for scenario b, in which one vehicle was followed by another and there are risks that a rear-end crash could happen, Fig. 6 shows the comparison of the PDR and the latency. In this scenario, the distance between the two vehicles was about 100 m and it had little effect on the PDR and the latency. The figure presents that although the PDR declined as the speed increased, it was rather high overall. Moreover, the latency was very stable and low.

In scenario c, the two vehicles drove face to face. Figure 7 shows the PDR of 802.11p and LTE-V while
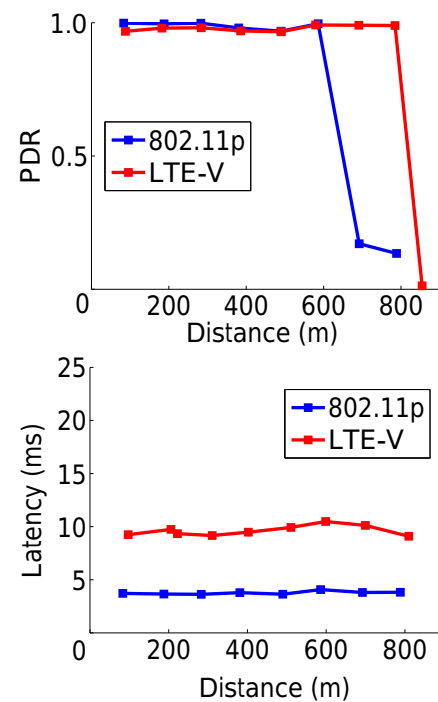

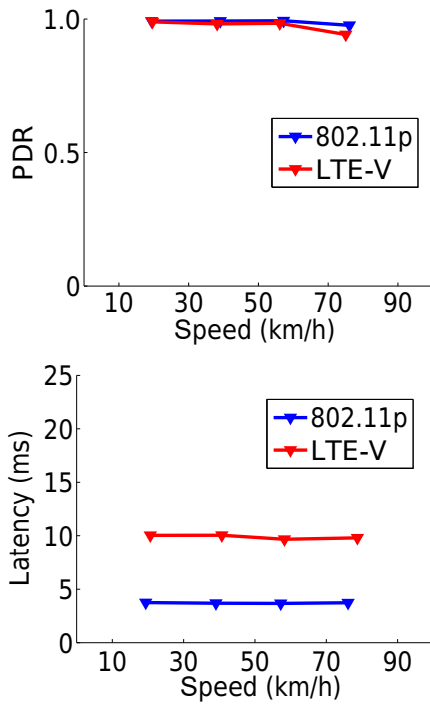**Fig. 5   PDR and latency in the static scenario of 802.11p and LTE-V.**

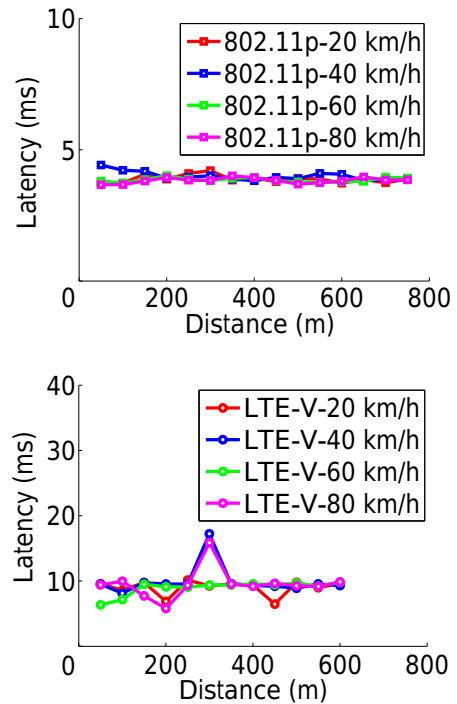**Fig. 6 PDR and latency in scenario b, with the comparison of 802.11p and LTE-V.**

Fig. 7 PDR in scenario c, with the comparison of 802.11p and LTE-V.

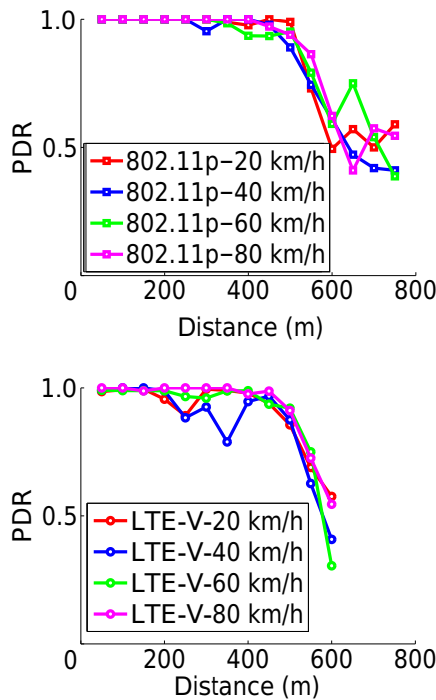**Fig. 8 Latency in scenario c, with the comparison of 802.11p and LTE-V.**

Fig. 8 depicts the latency of 802.11p and LTE-V. The relation between the PDR and the speed is not very tight, and so was the relation between the latency and the speed. Figure 8 illustrates that the relations between

the distance and the two metrics were quite different. The latency was still weakly correlated to distance. In contrast, the PDR was quite significantly correlated to distance. A rapid decline was observed when the distance exceeded 500 m. In comparison to the PDR in scenario a, an access time was observed before the two vehicles got connected. Furthermore, the access time of LTE-V was a little bit longer than that of 802.11p.

Figure 9 shows that in scenario d, an obvious reduction of the communication performance can be found at the intersection with an obstacle. The effective communication range rapidly decreased to 200 m because of the non-line-of-sight. Similar to that in scenario c, the communication performance in scenario d was weakly correlated to speed. The PDR was strongly correlated to distance, and the decline happened when the distance exceeded 150 m, while the latency remained quite stable as the distance varied.

5 Application-Oriented Evaluation

In Section 4, we presented the experiment results. However, these results were not directly sufficient; hence, we cannot conclude whether the performance could satisfy the application need. We need to more specifically evaluate the performance from an application point of view to more directly
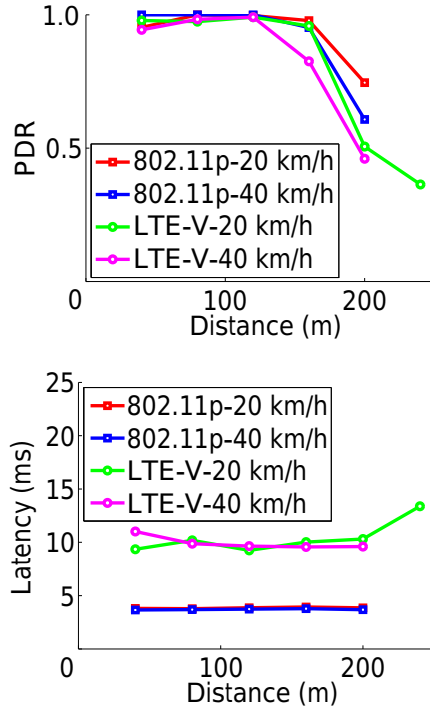
Fig. 9   PDR and latency in scenario d, with the comparison of 802.11p and LTE-V.

demonstrate the communication performance by building a connection between the metrics and the application.

For this concern, we proposed a probability model to describe the application reliability. As analyzed earlier, the PDR was strongly correlated to distance. Thus, we used distance as a major metrics. Let $P(d)$ be the probability that a vehicle can successfully receive one message at least before the distance between the two vehicles becomes less than d. $P(d)$ is correlated to the distance d, speed v, latency t_l, and PDR.

$$P(d) = f(d, v, P_d, t_l) \tag{4}$$

P_d represents the PDR. Although the PDR was influenced by many factors, we simplified the PDR herein based on the analysis in Section 4. P_d was only correlated to distance, as shown in Eq. (5).

$$P_d = f(d) \tag{5}$$

The functions had different forms in different scenarios. We would demonstrate the function in detail here.

5.1   Rear-end collision

A rear-end collision happened when the two vehicles drove one after another, similar to that in scenario b. Let us assume that Vehicle A is travelling after Vehicle B with a uniform speed v_0, and Vehicle B is travelling

at a uniform velocity v_B. A rear-end collision might happen in case of $v_0 > v_B$. Let d_s represent the safe distance:

$$d_s = (v_0 - v_s)t_r + \frac{(v_0 - v_s)^2}{2a} \tag{6}$$

t_r is the reaction time of the driver, which generally ranges from 0.75 s to 1 s; v_s is the safe speed (i.e., $v_s = v_B$); and a is the acceleration of Vehicle A. We simplified the deceleration process. During this process, Vehicle A decelerated to the safe speed with a uniform acceleration. Although a was correlated to the wind, friction coefficient, and other factors, we neglected all the factors aside from the friction coefficient. Hence, we had $a = \mu g$, where μ is the friction coefficient, and g is the gravitational acceleration. We can then rewrite Eq. (6) as

$$d_s = (v_0 - v_B)t_r + \frac{(v_0 - v_B)^2}{2\mu g} \tag{7}$$

where f_s is the sending frequency, and $T_s = 1/f_s$ is the time interval between two consecutive messages. Initially, the distance between the two vehicles is d_0 at moment t_0 which was beyond the effective communication range. We then obtain the following:

$$P(d > d_s) = 1 - \prod_{d \in (d_s, d_0)} [1 - P_d(d)] \tag{8}$$

In the process of the two vehicles approaching from d_0 to d_s, the messages were sent every T_s. t_i represents the time that the i-th message was sent. Considering the latency, the moment that the i-th message arrived is denoted as $t_i + t_l$, if the message has been successfully delivered. The distance between the two vehicles can then be described as follows:

$$d = d_0 - (v_0 - v_B)(t_i + t_l) \tag{9}$$

Corresponding to the safe distance d_s, we define the parameter safe time, t_s, as

$$(v_0 - v_B)(t_s + t_l) < d_0 - d_s < (v_0 - v_B)(t_{s+1} + t_l) \tag{10}$$

We can then rewrite Eq. (8) as

$$P(d > d_s) = 1 - \prod_{0 < i < s} [1 - P_d(d_0 - (v_0 - v_B)(t_i + t_l))] \tag{11}$$

The sending frequency in scenario b was 10 Hz; hence, T_s was 0.1 s. The friction coefficient was empirically set as 0.6. The reaction time of the driver t_r was 1 s. We first analyzed the applicational performance of 802.11p. According to the experiment result in Section 4, the latency was constant (i.e., 5 ms). The safe distance and $P(d)$ are shown in Fig. 10 based on these parameters. In this scenario, there is very little chance that a collision will occur when the distance between the
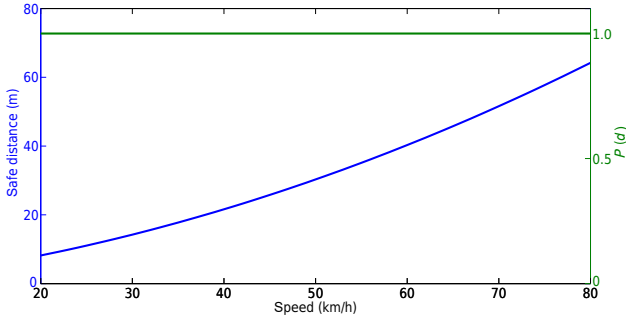
Fig. 10   **Safe distance and $P(d)$ in scenario b: the speed here is the relative speed of vehicles A and B.**

two vehicles exceeds 300 m. Moreover, within 300 m, the PDR was weakly correlated to distance. Hence we lose this metrics to a quite low value, with a PDR of 0.9, which was less than the minimum value in the experiment. According to the calculation, the rear-end collision would still be avoided in case of V2V system deployment.

The result for LTE-V was exactly similar to that in Fig. 10. The rear-end collision warning application could be perfectly realized.

5.2   Frontal collision

In scenario c, the two vehicles travelled face to face. A frontal crash may happen at an intersection or when overtaking at a road of the bidirectional two roads. In this scenario, the relative speed of the two vehicles was the sum of both the vehicles' speed. In the worst situation, both vehicles needed to stop to avoid the crash. Hence, d_s was obtained as:

$$d_s = (v_0 + v_B)t_r + \frac{(v_0 + v_B)^2}{2\mu g} \qquad (12)$$

In the worst situation, Vehicles A and B must both successfully receive a message from the other vehicle before the distance reduces to d_s. Hence, $P(d > d_s)$ is obtained as follows:

$$P(d > d_s) = P_A(d > d_s)P_B(d > d_s) \qquad (13)$$

We assume that Vehicle A is under the very same circumstance as Vehicle B, which means $P_A(d > d_s) = P_B(d > d_s)$.

$$P(d > d_s) = \{1 - \prod_{0 < i < s}[1 - P_d(d_0 - 2v_0(t_i + t_l))]\}^2 \qquad (14)$$

Parameters, such as i, s, t_i, t_l, and d_0, were defined similar to those in Section 5.1. In the calculation, the T_s, μ, and t_r values were the same as those in Section 5.1. Different from the rear-end collision situation as shown in Section 4, the PDR was strongly correlated to

distance. Hence, we used a piecewise linear fit method to obtain the detailed PDR.

In case of 802.11p, the analysis in Section 4 showed that the PDR was weakly correlated to speed; we only used the mean value of the PDR of different speeds. Figure 11 shows that $P(d)$ is 100% when the relative speed varies from 10 km/h to 240 km/h. We also analyzed the LTE-V performance, and the result was exactly the same.

5.3   Intersection collision

Intersection collision accidents are also very common, especially at the non-signalized intersection with obstacles, similar to the circumstance in scenario d in Fig. 1. Vehicle B travelled to the intersection in the vertical direction of Vehicle A. The safe distance d_s in this situation is presented as follows:

$$d_s = \sqrt{(v_0 t_r + \frac{v_0^2}{2\mu g})^2 + (v_B t_r + \frac{v_B^2}{2\mu g})^2} \qquad (15)$$

Suppose that vehicles A and B travelled at the same speed, d_s could be simplified as follows:

$$d_s = \sqrt{2}v_0 t_r + \frac{\sqrt{2}v_0^2}{2\mu g} \qquad (16)$$

Both vehicles successfully need to receive messages from the other vehicle successfully in time to avoid the collision, similar to the situation in the frontal collision.

$$P(d > d_s) = P_A(d > d_s)P_B(d > d_s) \qquad (17)$$

We obtained the following formula under the same assumption that Vehicles A and B had equal speed:

$$P(d > d_s) = \{1 - \prod_{0 < i < s}[1 - P_d(d_0 - \sqrt{2}v_0(t_i + t_l))]\}^2 \qquad (18)$$

The main parameters had the same values as in Sections 5.1 and 5.2. Figures 12 and 13 present the results.
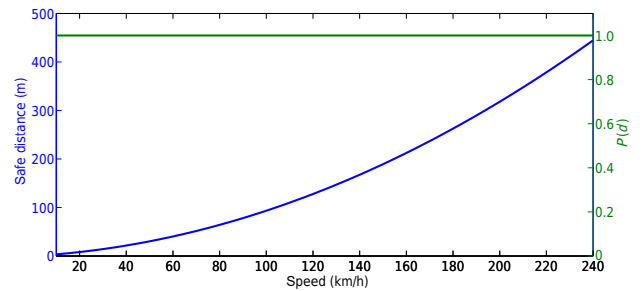

Fig. 11   **Safe distance and $P(d)$ in scenario c: the speed here is the relative speed of Vehicles A and B. Different from scenario b, the range of the relative speed is expanded to 10 – 240 km/h.**
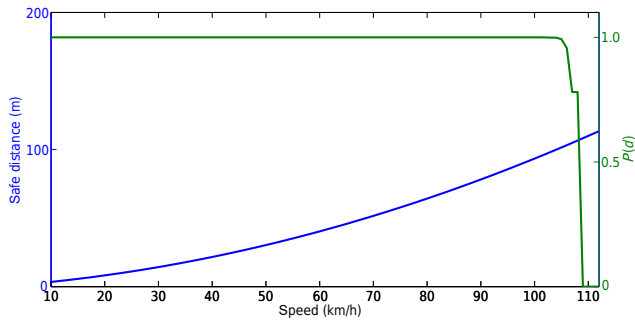
Fig. 12 Safe distance and *P(d)* in scenario d based on 802.11p. The speed here is the relative speed of vehicles A and B, which is the sum of two vectors because the two vehicles were not driving on the same line.
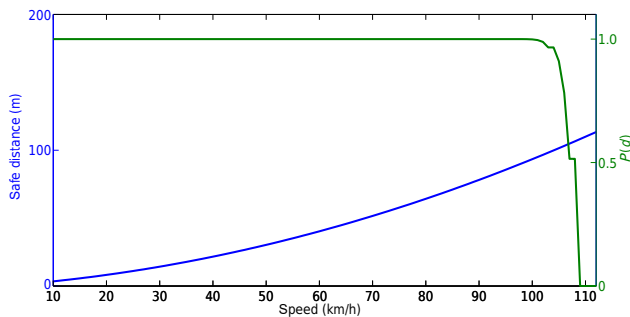

Fig. 13 Safe distance and *P(d)* in scenario d based on LTE-V.

Figure 12 shows the result of 802.11p when the relative speed varies from 10 km/h to 102 km/h. $P(d)$ was 100%. A sharp decline was observed in 102 km/h, and $P(d)$ decreased to 0 at 109 km/h, indicating that in this case, the V2V system could do nothing to prevent the accident. The speed in Fig. 12 was relative; hence, for one vehicle (A or B), the decline happened at 72 km/h. $P(d)$ decreased to 0 when the speed exceeded 77 km/h. Figure 13 shows the analysis of LTE-V, with the result very much similar with that of 802.11p.

6 Conclusion

In this study, we conducted a real-world test in the National Intelligent Connected Vehicle (Shanghai) Pilot Zone according to the application scenarios. Consequently, we found that in most scenarios, the PDR was slightly correlated to speed, but strongly correlated to distance, whereas the latency was weakly correlated to both speed and distance. As long as the message could reach the receiver, the latency remained quite low. In the NLOS scenario, the effective communication range was much shorter than that in the LOS scenarios. The PDR and the latency had the same features as in LOS scenarios.

We also performed an application-oriented evaluation, including rear-end collision, frontal collision, and intersection collision. First, we analyzed the safe distance in the collision scenarios, then built a probability model to analyze the relationship between collision and communication performance. The results showed that in the LOS scenarios, V2V could greatly help in preventing accidents, but in the NLOS scenarios, collision still might happen under some extreme circumstances.

In the present work, the latency was not a constraint factor because the experiment only involved two vehicles. The situation would be very different when the number of communication nodes increases. More experiments, especially experiment of multi-vehicle to study the influence of communication congestion, will be conducted in the future to study the communication performance in a more detailed manner. Improvements will also be proposed and deployed to promote the V2V system performance and make transportation safer.

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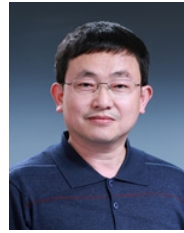
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