Analysis on the vehicle-induced path loss for millimetre-wave V2V communication

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Abstract
Millimetre wave (mmWave) has great potential in vehicle-to-vehicle (V2V) communication to provide wide bandwidth and low latency. However, the biggest challenge for the use of mmWave is the high propagation path loss and susceptibility to blockage among vehicles, especially in urban streets. Vehicle shadow fading is quite common in the actual V2V communication. The non-line-of-sight scenarios are considered and the impacts of blocking vehicles on the characteristics of the V2V wireless channels are studied. The measurements are conducted for two scenarios. For the first scenario, a blocking truck is placed between transmitting and receiving cars. For the second scenario, a car is added as a reflector beside the truck. Based on the measurement results, a path loss model for the V2V communication is developed. In order to further verify the effects of building scattering, a simulation is setup and the results are consistent with the measured results.

1 | INTRODUCTION

In the past few decades, mobile cellular technologies have developed rapidly. The previous four generations of cellular technology have solved the communication between people. As a new generation of mobile communications, 5G aims to allow a ubiquitous connection between people and people, people and things, or between things.

Vehicle communication is one of the primary applications in 5G, which is changing the way of human transportation and communication, and promoting the development of vehicles to be networked and intelligent [1–4]. With the development of vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) telecommunication, the high data rate is required for exchange of massive amounts of raw sensor data. Accordingly, Millimetre wave (mmWave) with a wide-band spectrum has great potential in vehicle communication [5–9]. However, the biggest challenge for the use of mmWave is the high propagation path loss and susceptibility to blockage among vehicles [10–16].

In V2V communications, the line-of-sight path between transmitting and receiving vehicles may be blocked by buildings or other vehicles. In particular, if there are other vehicles between the receiving and the transmitting vehicles, the metal shell of the vehicle would cause extra shadowing loss to the communication signal, which is known as the vehicle shadow fading (vehicle non-line-of-sight [NLOS]). In recent years, with the explosive growth of the number of domestic vehicles, road traffic has become overcrowded, so vehicle shadow fading appears quite common in actual V2V communications. It is crucial to attach great importance to it and study the effects of the block vehicles on V2V wireless channels. Recently, several studies focused on the blockage characteristics for mmWave channels. Bai et al. proposes a mathematical framework to model random blockages and analyze their impact on cellular network performance [13]. Park et al. investigated mmWave blockage characteristics based on measurements collected in a typical V2V environment at 28 GHz, and observed signal fluctuations during periods of blockage [14–16].

The environment of V2V communication is complex and changeable, and there are a large number of antiscatter bodies around the communication links. Therefore, the mmWave propagation characteristics of the V2V environment are different from the channels of the macro cell of the traditional cellular network. Accordingly, it is urgent to conduct an in-depth research on the V2V wireless propagation channel and it is helpful to the design of the V2V wireless communication system.
At present, the industry is very concerned about such a problem: whether a large vehicle is driven between two vehicles, such as a truck, will cause a large insertion loss, which has a significant impact on the link stability of wireless communication. The NLOS scenarios are considered, the effects of the truck blockage, car reflection and building reflection for typical V2V scenarios are measured and theoretically analyzed.

2 | EXPERIMENTAL SETUP

The test instrument and equipment are shown as in Table 1.

Two UWB omnidirectional antennas are installed on two cars respectively. In one of the cars, the antenna is connected to the microwave signal generator through the microwave power amplifier, and the car serves as the transmitting car. In another car, the antenna is connected to the spectrum analyzer, and the car serves as a receiving car. Place a truck or a truck and a car between the transmitting and receiving cars, and observe the effects of the truck blockage and car reflection for typical V2V scenarios.

For the single antenna system in the transmitting and receiving cars, the positions of the antennas will affect the radio wave propagation. Taking the antenna gain into consideration, it is believed that placing the antenna on the roof of the vehicle will have the smallest blockage and the highest transmission reliability. In addition, as the autonomous driving system relies on roof cameras, various sensors, etc., the future roof will integrate an electronic cabin, and the mmWave antenna will be part of this electronic cabin. Accordingly, we place the Tx and Rx antennas in the outside of the sunroof and place the receiving and transmitting system inside the car, as shown in Figure 1.

In order to improve the reliability of the test data and observe the effect of frequency selection, the test frequency is setup as 26.75–27.25 GHz (11 frequency points, the frequency interval is 50 MHz), and 38.75–39.00 GHz (6 frequency points, the frequency interval is 50 MHz).

The common technical requirements are shown as below:

1. The transceiver antennas are placed on the top of the transmitting and receiving cars through the sunroofs, and the sunroof gap is as small as possible.
2. The bottom of the transceiver antenna is 10 cm above the sunroof.
3. The automatic test system is adopted, 600 readings for each frequency point are taken to calculate the time-domain characteristics of the receiving level.
4. The test scenarios are setup as shown in Table 2.

In addition, according to the information provided by the antenna manufacturer, the antenna height is 13 cm, and the phase centre is at the centre of the antenna. When the frequency is above 26 GHz, the main radiation is concentrated in a small space in the phase centre. Therefore, when the antenna bottom is 10 cm above the roof, the main radiation centre height is 16.5 cm.

In our test, the vehicles were not moving. We have also tried to do the measurement while the vehicles are moving, but there are some difficulties in the following aspects. (1) It is difficult to keep the distance of the vehicle stable. (2) As the automatic test program is controlled by the LAN port, the movement of the vehicle makes the control network cable easily broken. Even so, we believe that the measurement with the vehicles in the static state is of reference value, and the measurement data is worth sharing with you.

The antennas could be equivalent to a half-wave dipole antenna in the measured frequency band, accordingly the transmitting and receiving antenna gain are expressed as $G_\text{t}$ and $G_\text{r}$, respectively, and both are 2.15 dBi. Assume the transmit power is $P_\text{t}$ (dBm) and the receive power is $P_\text{r}$ (dBm), then the V2V channel path loss ($L_{\text{V2V}}$) is defined as:

$$L_{\text{V2V}} = (P_\text{t} - P_\text{r}) + (G_\text{t} + G_\text{r})$$  \quad (1)

The V2V channel path loss without the block is recorded as $L_{\text{V2V,F}}$. And the path loss when adding a block is written as

| Instrument and equipment | Parameters |
|--------------------------|------------|
| Microwave signal generator | The maximum transmit power is 15 dBm, and the frequency range is 9 kHz~40 GHz. |
| Coaxial cable | The loss is about 6 dB. |
| Spectrum analyzer | The test frequency is up to 40 GHz. If RBW is small enough (such as less than 10 kHz) and the input power is larger than $-125$ dBm, the test results will be credible. |
| Two UWB omnidirectional antennas | 1.6–50 GHz. The gain is around 2 dBi in the whole band. |
| Microwave power amplifier | 26~40 GHz Output power is 46 dBm. |
| Coaxial cable and adapter | 2.92 mm coaxial cables and adapters |
| Two laser collimators | Green laser |
| Truck | One |
| Car | Three |
Therefore, the additional loss induced by the block (extra loss $L_E$) is defined as:

$$L_E = L_{V2V-B} - L_{V2V-F}$$  \hspace{1cm} (2)

$L_{V2V-F}$ is the fitting model of V2V transmission loss without blocking vehicle based on the measurement results, which is shown in Equation (3).

$$L_{V2V-F} = 32.45 + 20\log D[m] + \gamma \log F[\text{GHz}]$$  \hspace{1cm} (3)

In the free space model, $\gamma = 1$, and in this study, $\gamma = 1.08$. The measurement results indicate that the transmission loss in this measurement is within the dynamic range of the

| Scenario no. | Technical consideration | Scenario description |
|--------------|-------------------------|----------------------|
| 1            | The distance is 50 m. There is a blocking truck between the transmitting and receiving cars (Tx and Rx). There are three position states. (1) The blocking truck is placed in the middle of the Tx and Rx. (2) The distance between the midpoint of the truck and Tx is about 10 m. (3) The distance between the midpoint of the truck and Rx is about 10 m. | ![Scenario 1 Diagram](image1) |
| 2            | The distance is 50 m. There is a blocking truck between the transmitting and receiving cars (Tx and Rx). And a car is added as a reflector beside the truck. The distance between the reflector and the adjacent car is 2 m. | ![Scenario 2 Diagram](image2) |

**TABLE 2** Test scenarios of V2V path loss (the distance in the table is considered as the distance between two antennas)

**FIGURE 1** Car antenna installation

**FIGURE 2** Picture for scenario 1

**FIGURE 3** Example curve in time domain: V2V Tx-Rx distance 50 m, one blocking truck 38.901 GHz, one blocking truck in the middle Tx-Rx
measurement system and the data is valid. Equation (3) is derived from our fitting of the measured data without blockers. Because of the limitation of space, these measured data are not listed.

3 | EXPERIMENTAL RESULTS

A. Scenario 1: One blocking truck exists betweenTxandRx.
The picture for scenario 1 is shown in Figure 2.
The test frequencies are 26.75–27.25 GHz (11 frequency points), and 38.75–39.00 GHz (6 frequency points). And 600 readings for each frequency point are obtained. As an example, for 39.101 GHz, when the blocking truck is placed in the
middle of the Tx and Rx, the path loss and probability density are shown in Figure 3.

For the most critical median of path loss of all the frequencies, the results are shown in Figures 4 and 5.

According to the above parameter definitions, to calculate the extra loss caused by vehicle blocking, the basic method is to calculate the difference between the median time-domain path loss at a certain frequency and the calculated value of Equation (3). The extra median path loss values are shown in Figures 6 and 7. From Figures 4–7, ‘Truck’ refers to the position of truck midpoint, ‘Truck in the middle’, ‘Truck to Tx 10 m’, ‘Truck to Rx 10 m’ refer to three measured path loss curves for three different positions, and ‘Modelling’ refers to the calculated path loss curve without blocking truck based on Equation (3).

The data is divided into 26.75–27.25 and 38.75–39.00 GHz frequency bands, and the data of frequency points in each frequency band are averaged and the standard deviation is calculated. The results are shown in Tables 3 and 4.

The extra loss introduced by the blocking truck is about 6–20 dB. This result is mainly caused by the scattering of ground, trees, and the building. Especially for buildings with
reinforced concrete structures, the scattering is relatively strong. As shown in Figures 4 and 5, the measurement results may show obvious differences at adjacent frequency points at a distance of 50 MHz, while the calculation curve based on Equation (3) is relatively flat. Generally, it is believed to be caused by multipath effect.

The position status of the three tests described in Tables 3 and 4 is described in Table 2. Actually, the blocking truck is at different positions of the Tx-Rx connection.

From the average of the measurement results of the three cases shown in Table 3, there is no significant difference between the additional insertion loss caused by the blocking truck in the 27 GHz and 39 GHz frequency bands. As shown in Figures 3 and 4, the additional insertion loss is generated by comparison with the model of Equation (3). It can be seen from Figure 3 that the reference path loss described by Equation (3) is frequency-dependent, and the free space loss in the 39 GHz is greater than that in the 27 GHz.

B. Scenario 2: There is a blocking truck exists between two cars and there is a car as a reflector beside the truck.

The picture for scenario 2 is shown in Figure 8.

For the most critical median of path loss, the results are shown in Figures 9 and 10. The extra median path losses are shown in Figures 11 and 12.

The test data is divided into 26.75–27.25 GHz and 38.75–39.00 GHz frequency bands, and the data of frequency points in each frequency band are averaged and the standard deviation is calculated. The results are shown in Tables 5 and 6.

Compared to the result of scenario 1, the extra path loss is significantly reduced due to the introduction of a reflective car. Statistically speaking, the reason is that reflective vehicles introduce a new multipath with a high probability.

4 | V2V PATH LOSS MODEL DEVELOPMENT

Based on the measurement results, the model is studied. For a statistical point of view, from the average of the three scenarios shown in Table 3, the data in Table 5, and the comparison of the standard deviation data, we cannot conclude that there is significant difference in the extra loss between the 27 GHz band and the 39 GHz band. Considering the usability of the model, the conditions for merging scenarios can be appropriately simplified, and a relatively unified and simplified model can be developed as Equation (4).

$$L_{V2V-B} = L_{V2V-F} + L_E + N(0, \sigma_E)$$

frequency ∈ [26.75 GHz, 39 GHz] (4)

where $L_E$ is the extra loss introduced by the blocking car and blocking building. $N(0, \sigma_E)$ is a Gaussian distributed random

| Frequency (GHz) | 26.75–27.25 GHz | 38.75–39.00 GHz |
|-----------------|-----------------|-----------------|
| One blocking truck with a reflecting car, in the middle Tx-Rx | 2.3 | 6.6 |

| Frequency (GHz) | 26.75–27.25 GHz | 38.75–39.00 GHz |
|-----------------|-----------------|-----------------|
| One blocking truck with a reflecting car, in the middle Tx-Rx | 3.9 | 3.8 |

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**FIGURE 11** V2V Tx-Rx distance 50 m, one blocking truck with a reflecting car, extra median path loss (dB), 26.75–27.25 GHz

**FIGURE 12** V2V Tx-Rx distance 50 m, one blocking truck with a reflecting car, extra median path loss (dB), 38.75–39.00 GHz

**TABLE 5** V2V Tx-Rx distance 50 m, one blocking truck with a reflecting car, extra median path loss (dB)

**TABLE 6** V2V Tx-Rx distance 50 m, one blocking truck with a reflecting car, standard deviation of extra median path loss (dB)
variable. The mathematical expectation is 0 and the standard deviation is \( \sigma_E \). For the extra loss vector data of all frequency points measured in the two scenes, after subtracting the average value, we use the Jarque–Bera test with significance level of 0.05 to check separately and confirm that it belongs to the Gaussian distribution. The corresponding mean and standard deviation are shown in Table 7.

In different scenarios, \( L_E \) and \( \sigma_E \) are selected as shown in Table 7.

### 5 | SIMULATION VERIFICATION

The effect of building scattering is further explained by simulation. The simulation is setup based on EastWave software. EastWave is a full-wave electromagnetic simulation software package for accurate 3D simulation of electromagnetic wave interaction problems, which can run on Windows and Linux operating systems. EastWave is based on finite-difference time-domain (FDTD) method which also includes a physical optics (PO) module which may work either alone or jointly with FDTD method for extremely large systems. The PO module is used.

The simulation model is shown in Figure 13, where the transmitting antenna is a dipole antenna with a centre frequency of 27 GHz, and the receiving antenna is set as an electric field probe (E-monitor, size: 10 m × 3 mm × 2 mm). The distance between the transmitting and receiving antennas is set to 45–55 m. A truck (material: PEC, size: 7.2 m × 2.3 m × 2.4 m) is placed in the middle, and a building is modelled next to it. As the glass used in the building is a metal coating material, which has a large impact on the penetration loss, the building material is set to a conductor with a conductivity of 0.01 S/m in the simulation, and the size is 30 m × 0.5 m × 6 m. Comparing with traditional full wave methods, the simulation based on PO module saves storage and possesses a high efficiency. And it is one of the most important tools in analyzing large electric size object.

As the receiving antenna used in the actual test has good polarization characteristics, take the received field strength in the vertical direction from the electric field simulation results. The simulation results of electric field strengths for the situations with a building and without the building could be obtained, respectively.

The received power of an antenna is the power density multiplied by the effective area of the receiving antenna. Based on Equation (5), the relationship between the received power and the strength of the received electric field can be established:

\[
P_r = \frac{E^2}{\eta} \times A_{\text{eff}} = \frac{E^2}{\eta} \times \frac{\lambda^2}{4\pi}
\]

The simulation results of the nonbuilding and the existing building shown in Figure 14 show that the path loss of the nonbuilding changes smoothly with the distance, and the path loss of the building with the distance does not change smoothly. The relatively smooth curve, which fluctuates rapidly with distance, is about −7 to +17 dB. It is generally believed that this is caused by the scattering multipath of buildings. This shows that the V2V mmWave communication system in the urban environment needs to prepare enough fading margin, or use diversity receivers to combat this multipath fading.

### 6 | CONCLUSION

We studied the vehicle-induced path loss for mmWave V2V communication. The NLOS scenarios are considered and the impacts of blocking vehicles on the characteristics of the

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**TABLE 7** V2V path loss model parameters (dB)

| Scenario No | Blockings                                           | \( L_E \) | \( \sigma_E \) |
|-------------|-----------------------------------------------------|----------|--------------|
| 1           | One blocking truck                                  | 10.8     | 6.9          |
| 2           | One blocking truck with a reflecting car           | 3.8      | 4.3          |

**FIGURE 13** Simulation scenario diagram

**FIGURE 14** Simulation results of transmission loss with and without building
V2V wireless channels are studied. The measurements are conducted for two scenarios. For the first scenario, a blocking truck is placed between transmitting and receiving cars. For the second scenario, a car is added as a reflector beside the truck. The results show that the occlusion of a single truck in the middle of the Tx-Rx path is more obvious. Adding reflective vehicles next to it will reduce the occlusion effect. Statistically speaking, the reason is that reflective vehicles introduce a new multipath with a high probability. Furthermore, in the mmWave V2V channel, the blockers will not only block the direct path, but also increase the probability of blocking the scattering path from a statistical perspective. We believe that if you measure in true free space, you can get a relatively convergent “extra loss”, but this measurement is not instructive for practical engineering.

For the measurements, the scattering of road ground, trees and buildings beside the road is inevitable. This is exactly the actual application scenario of intelligent connected cars in the future. Considering the universality of this scenario, it must be recognized that the extra loss introduced by the blockers in the channel will not be a constant, but will have a random distribution. So we give the standard deviation statistics of the measurement results in the frequency domain. This is also proved by simulation. Measurements show that the V2V channel has strong scattering. In theory, MIMO technology or spatial/polarized diversity has higher value in improving system performance and avoiding the effects of channel fading. In general, in a typical urban channel environment, the mmWave band insertion loss introduced by a truck is below 20 dB. Obviously, this adverse effect on the communication link can be overcome. The laws revealed by this paper will undoubtedly enhance the industry’s confidence in using mmWaves in V2V scenarios.

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REFERENCES

1. Husain, S., et al.: The road to 5G V2X: Ultra-high reliable communications. In: IEEE Conference on Standards for Communications and Networking (CSCN), pp. 1–6 (2018)
2. Storek, C.R., Duarte-Figueiredo, F.: A 5G V2X ecosystem providing internet of vehicles. Sensors. 19(3), 550 (2019)
3. Campolo, C., et al.: 5G network slicing for vehicle-to-everything services. IEEE Wirel. Commun. 24(6), 38–45 (2017)
4. ITU-, R, IMT: Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond. ITU-R Recommendation M (2015)
5. Va, V., et al.: Millimeter wave vehicular communications: A survey. Found. Trends Netw. 10(1), 1–113 (2016)
6. Reddy, G.S., Elias, A.A: Range optimization for DSRC and 5G millimeter-wave vehicle-to-vehicle communication link. International Workshop on Antenna Technology (iWAT) (2019)
7. Wang, Y., et al.: MmWave vehicle-to-infrastructure communication: Analysis of urbanmicrocellular networks. IEEE Trans. Veh. Technol. 68(8), 7086–7100 (2018)
8. Perfecto, C., Del Ser, J., Bennis, M.: Millimeter-wave V2V communications: Distributed association and beam alignment. IEEE J. Sel. Areas Commun. 35(9), 2148–2162 (2017)
9. S’anchez, M.G., T’aboas, M.P., Cid, E.L.: Millimeter wave radio channel characterization for 5G vehicle-to-vehicle communications. Measurement. 95, 223–229 (2017)
10. Andrews, J.G., et al.: Modeling and analyzing millimeter wave cellular systems. IEEE Trans. Commun. 65(1), 403–430 (2017)
11. Rappaport, T.S., et al.: Overview of millimeter wave communications for fifth-generation (5G) wireless networks—With a focus on propagation models. IEEE Trans. Antennas Propag. 65(12), 6213–6230 (2017)
12. Baccelli, F., Zhang, X.: A correlated shadowing model for urban wireless networks. Proc. IEEE Int. Conf. Comput. Commun. 801–809 (2015)
13. Bai, T., Vaze, R., Heath, R.W.: Analysis of blockage effects on urban cellular networks. IEEE Trans. Wirel. Commun. 13(9), 5070–5083 (2014)
14. Karthunen, A., et al.: Spatially consistent street-by-street path loss model for 28-GHz channels in micro cell urban environments. IEEE Trans. Wirel. Commun. 16(11), 7538–7550 (2017)
15. Park, J.-J., et al.: Millimeter wave vehicular blockage characteristics based on 28 GHz measurements. IEEE 86th Vehicular Technology Conference (VTC-Fall) (2018)
16. Park, J.-J., et al.: Vehicle antenna position dependent path loss for millimeter-wave V2V communication. 11th Global symposium on millimeter waves (GSMM) (2018)

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