Antenna Performance Test Method and Result Analysis for V2X Communication of Connected Vehicle

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Abstract: This paper proposes an antenna performance test method for vehicle-level to ensure the stable communication capability for vehicular networking technology and application. Firstly, considering the large size and heavy weight of characteristic for the vehicle, a spherical near-field test for the vehicle antenna test is then proposed in the paper. Secondly, the impact of the vehicle body on the antenna performance is analysed by comparing the different performance between different vertical angles and antennas. Finally, the experimental results verify the validity and correctness of this method.

1. Introduction

With the in-depth development of intelligent connected vehicles, wireless communication is the basic element of vehicle intelligence, vehicle connectedness and autonomous driving [1]. The performance of wireless communication greatly affects the realization of related functions of intelligent connected cars.

V2X (Vehicle to Everything), as a key technology of information interaction in intelligent connected vehicles, is mainly used to realize communication guarantee of information sharing and collaborative control [1]. The mainstream technologies used for V2X communication in the world include Dedicated Short Range Communication (DSRC) and C-V2X (Cellular Vehicle to Everything) which is based on cellular communication systems (including LTE-V2X and 5G NR-V2X) [2]. LTE-V2X is the V2X communication technology which currently adopted in China. As a comprehensive solution for vehicle-road collaboration, it can provide low-latency, high-reliability, high-speed, and secure communication capabilities in a high-speed mobile environment, and meet requirements of various applications. Furthermore, based on TD-LTE communication, it can maximize the use of resources such as TD-LTE deployed networks and terminal chip platforms, which can save network investment and reduce chip costs.

The network connection mode of LTE-V2X equipment can be divided into direct connection mode and network connection mode according to different communication methods. Direct connection mode is the communication mode without passing through the base station, which is called PC5 port communication mode. Network connection mode is the communication mode through the base station, which is called UU port communication mode [3].

The antenna is used as a medium for wireless communication such as LTE-V2X communication. The performance of the antenna plays a decisive role in the performance of wireless communication and even the performance of intelligent connected vehicles [4]. Therefore, the antenna performance test evaluation is a basic test for function evaluation of the intelligent connected vehicle.
The measurement of antenna is an important method for researching car antennas. It can be used to verify the simulation result of vehicle antenna, and to check the pass rate of vehicle antenna parameters in automobile mass production. Especially because of the large size and heavy weight of the vehicle, and the electromagnetic signal shielding effect of the metal structure of the car body will have a great impact on the performance of vehicle antenna, the vehicle-level antenna measurement technology has become an important way to solve the problem.

Antennas are usually tested using far-field test method in the field of mobile communication [5], but vehicles are bulky and heavy, and far-field test method cannot be directly applied to vehicle antenna test. Therefore, researchers proposed spherical near-field test method instead of far-field method. J. R. James introduced the principle, test method and error analysis of spherical near-field antenna test method in detail [6]. The IEEE standard 1720 released in 2012 introduced the actual test methods for antenna near-field test in cylindrical, planar and spherical coordinate systems [7]. M. E. Asghar et.al. rely on the Ilmenau University of Technology and the Antenna Technology Center (ATC) in Germany to compare the results of spherical near-field automotive antenna test methods in anechoic and semi-anechoic chamber [8]. This paper introduces an antenna performance test method of vehicle-level using spherical near-field method, designs the test system, and the experimental results are compared and analyzed.

2. Theoretical basis of near-field test

2.1. Minimum far-field distance

When vehicle antenna is tested, the minimum far-field measurement distance needs to be considered to determine whether the test data is a far-field result or a near-field result. The minimum far-field test distance \( R \) is defined as the distance from the center of rotation of the measured object to the phase center of the measurement antenna. Then the minimum far-field test distance of each frequency band is

\[
R = \max \left( \frac{2fD^2}{c}, 3D, \frac{3c}{f} \right)
\]

In equation (1), \( D \) is the maximum size of the measured object; \( f \) is the frequency of the electromagnetic wave; \( c \) is the speed of light, and its value is \( 3 \times 10^8 \text{m/s} \).

Considering that the body length of a conventional car is close to 5m, if the whole vehicle is regarded as the object to be measured, the minimum far-field test distance of specified frequency is shown in Table 1.

| Frequency (MHz) | \( \frac{2fD^2}{c} \) (m) | 3D (m) | \( \frac{3c}{f} \) (m) | Far-field distance (m) |
|----------------|------------------------|--------|----------------------|------------------------|
| 100            | 17                     | 15     | 9                    | 17                     |
| 1000           | 167                    | 15     | 0.9                  | 167                    |
| 2000           | 333                    | 15     | 0.45                 | 333                    |
| 3000           | 500                    | 15     | 0.3                  | 500                    |
| 4000           | 667                    | 15     | 0.225                | 667                    |
| 5000           | 833                    | 15     | 0.18                 | 833                    |
| 6000           | 1000                   | 15     | 0.15                 | 1000                   |

According to Table 1, when the antenna is a radio antenna and its frequency is about 100 MHz, the far-field measurement distance is about 17 meters. However, when the antenna frequency exceeds 1GHz, the far-field distance is more than 100m. This means that if the far-field test method is still used, the test distance is far, and it is difficult to choose a test site that meets the test requirements. In addition, the test signal is also attenuated and disappeared at a longer distance, and the result cannot be measured accurately. Considering the size of the vehicle and the validity of the test method, it is recommended that the minimum near-field measurement distance from the measurement antenna to the vehicle antenna is about 1.5 meters.

2.2. Spherical near-field test
2.2.1. Spherical wave expansion theory

Electromagnetic waves propagate energy outward in the form of spherical waves. When transmitted to far field, the electromagnetic energy received by a point is from relatively single source and can be equivalently regarded as a uniform plane wave, so a specific electromagnetic wave can be decomposed into countless plane electromagnetic waves transmitted radially outward by the source. Based on this theory, if the theoretical expression of each plane electromagnetic wave is required, and the spherical wave expression of the electromagnetic wave can be obtained by mathematical accumulation. This method of solving the plane wave expansion of each mode of the spherical wave is called the spherical wave expansion theory.

The spherical wave expansion (SWE) of the electric field radiated by the antenna into free space can be defined as the weighted sum of the spherical vector wave function.

\[
\tilde{E}(r, \theta, \phi) = \frac{k}{\sqrt{\eta}} \sum_{s=1}^{\Delta} \sum_{n=1}^{N_r} \sum_{m=n}^{N_r} Q_{s,n} \tilde{F}_{s,n}(r, \theta, \phi)
\]

In equation (2), \(Q_{s,n}\) are the complex expansion coefficients, \(k\) is the wave number, \(k = \frac{2\pi}{\lambda}\), \(\lambda\) being the wavelength, \(\eta\) is the free-space admittance, \((r, \theta, \phi)\) is the usual spherical coordinates.

In equation (2), the triple summation is understood as

\[
\sum_{s=1}^{\Delta} \sum_{n=1}^{N_r} \sum_{m=n}^{N_r} = \sum_{s=1}^{2} \sum_{n=1}^{N_r} \sum_{m=n}^{N_r} = \sum_{s=1}^{2} \sum_{n=1}^{N_r} \sum_{m=n}^{N_r} \sum_{n=1}^{N_r} \sum_{m=n}^{N_r} \sum_{n=1}^{N_r}
\]

The maximum summation index \(N\) of the expansion coefficient of the spherical wave mode is customarily given by the empirical rule

\[
N = [kr]_{+} + n_1
\]

In equation (4), \(r\) is the size of the effective spherical radius that can completely cover the target antenna, \([kr]\) represents the integer closest to \(kr\), and \(n_1\) is an integer which depends on the positions of the sources within the minimum sphere, the distance from the minimum sphere at which the field is evaluated, as well as on the accuracy needs. If the evaluation distance is more than a few wavelengths from the minimum sphere, early numerical studies have shown that a value of \(n_1=10\) would be adequate for most practical purposes.

In test sampling, due to the symmetry, the range of values in the \(\theta\) direction is generally \(0 \leq \theta < \pi\), the sampling interval in the \(\theta\) direction is \(\Delta \theta = \frac{\pi}{N} \), number of sampling points is \(N+1\), including the zero point, the range of values in the \(\phi\) direction is generally \(0 \leq \phi < 2\pi\), the sampling interval in the \(\phi\) direction is \(\Delta \phi = \frac{2\pi}{N} \), number of sampling points is \(2N+1\), including the zero point.

Then, the spherical vector wave functions \(\tilde{F}_{s,n}(r, \theta, \phi)\) are defined as follows:

\[
\tilde{F}_{s,1}(r, \theta, \phi) = \left\{ \frac{m}{|m|} \right\} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{n(n+1)}} \left( \frac{h_{n}^{(1)}(kr)}{\sin \theta} \right) \frac{im\tilde{P}_{1}^{(1)}(cos \theta)}{\sin \theta} e^{i\omega \phi}
\]

\[
\tilde{F}_{s,2}(r, \theta, \phi) = \left\{ \frac{m}{|m|} \right\} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{n(n+1)}} \left( \frac{n(n+1)}{kr} \tilde{h}_{n}^{(1)}(kr) \tilde{h}_{n}^{(1)}(kr) \tilde{P}_{2}^{(1)}(cos \theta) e^{i\omega \phi}
\]

\[
\tilde{F}_{s,3}(r, \theta, \phi) = \frac{1}{kr} \frac{1}{\tilde{h}_{n}^{(1)}(kr)} \left\{ \frac{im\tilde{P}_{1}^{(1)}(cos \theta)}{\sin \theta} \right\} e^{i\omega \phi}
\]

where we have assume—and suppressed—a time dependence of \(e^{-i\omega t}\). In equation (5) and (6), \(h_{n}^{(1)}(kr)\) is the spherical Hankel function of the first kind, corresponding to outward wave propagation, while \(\tilde{P}_{n}^{(1)}(cos \theta)\) is the normalized associated Legendre function. In this notation any single radiated spherical wave with unit amplitude will radiate a power of 0.5 watt. Therefore the expansion above is denoted a power-normalized spherical wave expansion, where the wave functions \(\tilde{F}_{s,n}(r, \theta, \phi)\) are dimensionless, and the dimension of the expansion coefficients \(Q_{s,n}\) becomes \([\text{watt}]^{0.5}\). The total power radiated from the test antenna then becomes
\[ P_{rad} = \frac{1}{2} \sum_{s,m,n} |Q_{s,m,n}|^2 \text{ watt.} \]  

2.2.2. Vehicle antenna test of spherical near-field method

The spherical near-field test system is an effective method with wide applicability in near-field measurement. Compared with the planar near-field test system and the cylindrical near-field test system, the spherical near-field test system has a better and wider support for the antenna under test (AUT).

The coordinate system and polarization relationship of the spherical near-field test are shown in Figure 1(a). This coordinate system is expressed using a spherical coordinate system, which is used to represent the test angle, the test antenna at each angle can be divided into two cross polarization: theta polarization and phi polarization.

For 3D scanning method, select the conic cut method. Among them, the DUT (Device Under Test) is placed on a turntable and rotates 360 degrees in the horizontal direction. The antenna bracket drives the test antenna to rotate in the vertical direction, and measures the antenna performance at multiple positions from top to bottom, as shown in Figure 1(b).

Figure 1. (a) Diagram of spherical coordinate system; (b) Diagram of conical positioning system

Considering the use of vehicles, antenna performance test is necessary in the range of theta from 0 to 90°, which tests above the ground of the turntable. The range meets the minimum requirement of the upper hemisphere test. Moreover, the origin of the test system (center of the ball) must be above the turntable. The distribution of sampling points is shown in Figure 2.

In actual engineering, the entire spherical near-field test system is divided into the following subsystems: mechanical system, radio frequency system, data acquisition and control system, and data processing system. The measurement system completes the near field data sampling and data conversion processing through the cooperation of different subsystems.
3. Vehicle antenna test method

The test methods of automotive antenna performance test in the environment of the whole vehicle and the single antenna are generally similar, but the test layout is slightly different. The following describes the test equipment and test method in detail.

3.1. Test environment

Since the purpose of the vehicle antenna performance test is to obtain the direct transmission performance of the vehicle antenna under the entire vehicle operating conditions, the vehicle needs to be placed in an environment without electromagnetic wave reflection. It is recommended to use anechoic chamber. If there is no anechoic chamber, the metal floor of the semi-anechoic chamber should be covered with absorbers.

3.2. Test equipment

Since the vehicle antenna performance test needs to obtain a three-dimensional pattern, a turntable needs to be installed in the anechoic chamber to achieve horizontal rotation, and the turntable accuracy should reach 0.1°. The vertical rotation is achieved by the antenna positioning system.

The radiation and reception of test signals are completed by the network analyzer. Since the antenna performance tested is passive, the radiation and reception are reciprocal. In this test, the vehicle antenna is required to transmit signals and the test antenna receives signals. The cross-polarized antenna is used as the test antenna, which can shorten the test time.

3.3. Calibration method

Calibration before antenna performance test is divided into two steps: cable calibration and space attenuation calibration.

Because the cable L3 under the turntable which is connected to outside the chamber cannot be directly connected to both ports of the network analyzer, another coaxial cable L0 is required as a reference. The attenuation of the L0 cable is first measured as normalization data. Next, L3 and L0 are connected together, and then calibrate the cable L3 under the turntable. The process is as shown in Figure 3.

![Figure 3. The diagram of cable calibration process](image)

![Figure 4. The diagram of space attenuation calibration process](image)
A horn antenna with standard gain is used as the reference antenna in space attenuation calibration. Place the reference antenna on a wooden table of 1.5 m height. Adjust the phase center of the standard gain antenna to the center of the turntable with the cross laser as the reference, and make sure the distance between the reference antenna and the test antenna is 1.5m.

After connecting L₁ or L₂ and L₃ as an overall attenuation, connect the two ends of the cable to both ports of the network analyzer, and record the total attenuation of the two cables with vertical and horizontal polarization, respectively, as normalization data. Then connect cable L₃ to the reference antenna as the radiation, and connect L₁ and L₂ to the test antenna respectively as the reception, record the space attenuation under vertical polarization and horizontal polarization. The diagram of space attenuation calibration is as shown in Figure 4.

3.4. Test Setup
When testing vehicle-level antenna performance, first align the center of the vehicle with the center of the turntable, adjust the antenna bracket and make the angles between the test antenna and the vertical axis are 50° and 60°, and adjust the distance between the test antenna and the vehicle antenna to 1.5m, finally the center of the test antenna is aligned with the center of the vehicle antenna.

3.5. Test Procedure
The diagram of the vehicle-level antenna test is as shown in Figure 5. The DUT is defined as a complete vehicle.

![Diagram of vehicle-level antenna test](image)

Figure 5 The diagram of vehicle-level antenna test

1) Place the DUT in the center of the turntable so that the center of the DUT coincides with the center of the turntable. Use the car head direction and the turntable reference 0° as the horizontal reference starting point, \( \varphi_n = 0 \), as shown in Figure 6.

![Diagram of horizontal movement](image)

Figure 6. The diagram of horizontal movement
2) Place the test antenna on the vertical reference angle of $\theta_n = 50^\circ$, as shown in Figure 7.

3) Disconnect the vehicle antenna from the vehicle OBU, connect the antenna under test to port 1 of the network analyzer as a radiation. The horizontal polarization port of the test antenna is connected to port 2 of the network analyzer.

4) Keep the vertical angle of the antenna probe unchanged and rotate the turntable horizontally. During the test, the turntable was rotated 360° counterclockwise in the horizontal direction, and the angle value and the corresponding gain were recorded to obtain the horizontal polarization gain. The rotation step angle of the turntable is 5 degree in this test.

5) Connect the vertical polarization interface of the test antenna to port 2 of the network analyzer, and perform step 4 again to obtain the vertical polarization gain.

6) Place the test antenna on the vertical reference angle of $\theta_n = 60^\circ$, as shown in Figure 7. Repeat step 3 to step 5 to obtain the horizontal polarization gain and vertical polarization gain.

7) Process the data, and calculate the total gain of $\theta_n = 50^\circ$ and $\theta_n = 60^\circ$.

4. Test results and comparative analysis

In this test, the vehicle antenna is of a V2X OBU, the test frequency range is 5860MHz ~ 5960MHz, and the frequency step is 5MHz. The test angle of vertical direction is $\theta_n = 50^\circ$ and $\theta_n = 60^\circ$. There are two V2X communication antennas in the V2X OBU, which antenna 1 transmits and receives signal and antenna 2 only receives signal.

The test includes the situation of the two antennas at vertical angles of $\theta_n = 50^\circ$ and $\theta_n = 60^\circ$, and the antenna location includes the roof shark fin and a wooden table. So the test result can divided into 8 groups in total. The comparison of the 8 near-field total gain patterns around the vehicle is shown in Figure 8 to Figure 10, and the arrow upwards refers to the direction of vehicle front, and the direction of vehicle rotation is clockwise.
In addition, other parameters such as maximum gain, average gain, half-power beam width, and gain flatness were selected to compare the antenna performance of different situations. The half-power beam width is the angle between two points where the power of maximum radiation direction become half. Gain flatness refers to the value of the gain “dramatic increase” and “rapid decrease” within the given bandwidth.

| Parameter Types | Maximum Gain/dB | Average Gain/dB | Half-power beam width/° | Gain flatness/dB |
|-----------------|-----------------|-----------------|-------------------------|-----------------|
| 50°              | -1.31           | -8.41           | 15                      | 15.75           |
| 60°              | 1.67            | -3.91           | 20                      | 11.55           |

The comparison of the parameters is listed in Table 2, and the corresponding vertical angle is $\theta_n = 50^\circ$ and $\theta_n = 60^\circ$, and the test antenna is antenna 1. Affected by the shape of the vehicle roof, the reflection is unavoidable. The number and amplitude of glitch in the pattern of $\theta_n = 50^\circ$ is more than that of $\theta_n = 60^\circ$. The operation characteristic of V2X antenna and the shadowing effect of the vehicle might be the reason. Furthermore, the maximum gain of the $\theta_n = 50^\circ$ is about 3dB smaller than that of $\theta_n = 60^\circ$, the average gain is about 4.5dB smaller than that of $\theta_n = 60^\circ$, and the gain flatness is about 4dB larger than that of $\theta_n = 60^\circ$. But the half-power beam width is similar in the comparison because of the glitches in the pattern.

Due to the characteristic of V2X antenna, the communication quality of the front and rear of the vehicle is more valued in actual road conditions. Therefore, the area around the vehicle is divided into...
four parts, as shown in Figure 11. The average gain of the vehicle-level is calculated by region, and the results are shown in Table 3. As can be seen from the results in Table 3, since the V2X antenna is installed at the rear of the roof, the body reflection in the rear area is smaller, and the average gain in the rear area is larger.

![Figure 11. Diagram of area division](image)

### Table 3. The data chart of area average gain

| Area   | Front | Back | Left | Right |
|--------|-------|------|------|-------|
| Area average gain/dB | -7.81 | -8.14 | -8.68 | -11.78 |

### 5. Conclusion

According to the existing antenna performance test methods in the mobile communications industry, and considering the characteristic of vehicle antennas, this paper proposes a calibration and performance test method for vehicle antennas. A V2X antenna was actually tested in the anechoic chamber. In the next step, the results of more vertical angles and the improvement of the calibration accuracy before the antenna performance test will be studied.

### Data Availability

The input data used to support the results of this research are included within the article.

### Conflicts of Interest

The authors declare no conflicts of interest.

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