Design and Simulation of vehicle antenna in different frequency band

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Abstract. In order to meet the needs of a variety of automotive communication services, vehicle antennas working in multiple frequency bands are emerging. It promotes the development of antenna in the direction of multifrequency and miniaturization. Based on the above research background, this paper designs a vehicle antenna for the requirements of mobile communication frequency band. The antenna consists of a half-t monopole and a half cone monopole, which are vertically placed on a metal floor. T-shaped branches mainly work at low frequency, while cone-shaped branches mainly work at high frequency. The tapered branch is used to improve the impedance matching, increase the bandwidth of the antenna, and the antenna miniaturization is realized by using half reduction technology. The antenna is processed and measured, and the working frequency bands are 720MHz-960MHz and 1.6GHz-4GHz, covering amps, GSM, LTE and 5G.

1. Background and significance

1.1. Background
Nowadays, people's requirements for cars are not satisfied with simple and fast driving, but pursuit of higher-level entertainment services, such as communication services, navigation services [1]. These entertainment services can improve the driver's driving experience and increase the driver's enjoyment. By integrating antennas of different frequency bands on the car, different types of entertainment services can be provided to meet people's spiritual pursuit. The antenna module on the car is usually composed of antennas for mobile communication, navigation system and radio service. In order to provide multiple services, there are more than ten antennas on a common vehicle. Generally, the vehicle antenna of the wireless mobile communication system is installed at the back of the vehicle top, such as shark fin antenna [2]. The roof antenna module is centered on the roof and is located at the rear of the roof. In addition to the roof position, there are many hidden positions where this kind of mobile communication service antenna can be installed, such as: car console, bumper, baffle, etc. This kind of antenna is limited in a limited space because of the environmental needs, so the miniaturization performance of the vehicle antenna is very high.
1.2. Significance
In order to achieve a variety of wireless mobile communication systems, it is necessary to install multiple vehicle antennas on the vehicle, and each antenna is best to achieve multifrequency. At the same time, in order to better integrate in the vehicle, the vehicle antenna needs to achieve miniaturization. After 2020, with the extension of 4G, 5g system will be put into commercial use, which puts forward new requirements for antenna frequency band [3]. It is not only necessary to add a new frequency band on the basis of the original car antenna, but also to maintain the high performance of the car antenna. Therefore, while maintaining the excellent performance of the vehicle antenna, it does not affect the aesthetics of the vehicle, which puts forward high requirements for the miniaturization design and multifrequency design of the antenna.

2. Basic performance parameters of antenna
The function of the antenna is energy conversion. It can transform the current into the radio wave propagating in the medium or the radio wave propagating in the medium into the high frequency current. In order to effectively feed the energy from the transmitter to the antenna, there are three points to be noted: first, the antenna is connected with the transmission line, which needs to be matched to effectively convert the energy and improve the radiation efficiency; second, the antenna is a radiation device and a receiving device, which needs to be able to radiate the radio electromagnetic wave in a specific direction (or omni-directional); third, the polarization of the antenna is divided into linear polarization and elliptical polarization, the antennas at both ends of the transmitter and receiver need to have the same polarization, or polarization mismatch. Generally, the electrical characteristics of the antenna are represented by input impedance, gain coefficient, working frequency band, efficiency and other parameters. The antenna has reciprocity, and the electric characteristic value of the same antenna at the receiving and transmitting end is the same.

2.1. Antenna input impedance
The input impedance of the antenna refers to the equivalent impedance value at the feeding point of the antenna when looking from the feeding end to the antenna. The input impedance can be used to measure the matching of antenna and transceiver. The calculation formula is as follows:

\[ Z_{in} = \frac{U_{in}}{I_{in}} = R_{in} + jX_{in} \]

Among them, \( U_{in} \) is the input voltage, \( I_{in} \) is the input current, \( R_{in} \) is the input resistance, \( X_{in} \) is the input reactance. When the antenna is connected to the transceiver through the transmission line, it is equivalent to connecting a load to the transceiver through the transmission line, and the load value is \( Z_{in} \).

At present, the characteristic impedance of transmission line is 50 ohm. In order to reduce the reflected wave and ensure that the guided wave can be converted into radiation wave better, it is necessary to match the input impedance of antenna with the characteristic impedance of transmission line. That is to say, the antenna should be close to 50 ohm and close to 0 under the ideal matching condition. Compared with the input impedance, reflection coefficient (\( \Gamma \)), return loss (RL) and VSWR (voltage standing wave ratio) of the antenna, these parameters can more intuitively display the matching degree of the antenna and the transmitter (receiver). The reflection coefficient is the ratio of the amplitude of the reflection wave and the incident wave. The closer the reflection coefficient is to 0, the better the antenna matching is. The more the incident power is converted into the radiation power, which can be calculated by the load impedance and the characteristic impedance of the transmission line.

2.2. Antenna bandwidth
Because the performance parameters of the antenna have a great relationship with the frequency, the antenna has a specific working frequency band. In the working frequency range, the electrical
parameters of the antenna are all in the index range, and the antenna meets the performance requirements we need. However, outside the working frequency band, the electrical parameters of the antenna will exceed the index range, resulting in a series of performance deterioration, such as impedance mismatch, direction coefficient reduction, polarization characteristics deterioration, gain reduction, etc. Generally, the frequency of antenna design will be set to the central working frequency $f_0$:

$$f_0 = \frac{f_{\text{max}} + f_{\text{min}}}{2}$$

Where, $f_{\text{max}}$ is the maximum working frequency of the antenna, and $f_{\text{min}}$ is the minimum working frequency of the antenna.

2.3. Antenna radiation direction
The radiation field of the line is mainly divided into radiation near field and radiation far field. In the near field, the field pattern and space are related to the distance between antennas; in the far field, the field pattern and space are not related to the distance between antennas. The radiation pattern of the antenna refers to the performance of the far-field radiation area that does not change with distance. Generally, the radiation pattern of the antenna is drawn by polar coordinates.

The pattern of the antenna is also called the pattern of lobes. The main lobe is the one with the strongest electric field intensity, the back lobe is the one at the opposite position of the strongest electric field intensity, and the other direction is the side lobe. The main lobe width represents the degree of radiation power concentration. There are two main types: Zero Power lobe width and half power lobe width.

2.4. Antenna polarization
At the highest radiation power, the track of electromagnetic wave vector pointing with time in free space is called antenna polarization. Because the electric field and the magnetic field have a constant relationship, the electric field vector E is generally used to represent the electromagnetic wave vector in polarization. The polarization of antenna can be divided into three types:

(1) Linear polarization, that is, the direction of electric field E in free space is a straight line. According to the relationship between the direction of electric field E and the direction of the ground, it can be divided into horizontal polarization and vertical polarization.

(2) Circular polarization, that is, the curve of electric field vector pointing with time in free space is a circle, which can be divided into left circular polarization and right circular polarization according to the right-hand rule.

Elliptical polarization, that is, the trajectory is an ellipse. The circular polarization with the same amplitude and opposite electric field rotation direction can form the linear polarization. Two perpendicular linear polarizations can form circular (elliptical) polarization. When the excitation current amplitude of two vertically placed current elements is the same and the phase difference is $90^\circ$, a circularly polarized antenna can be formed. When the excitation current amplitude is different and the phase difference is not $90^\circ$, an elliptical polarization antenna can be formed, so most of the antennas are elliptical polarization.

3. Vehicle antenna design
3.1. Design principle
Today, the mobile communication band mainly includes three bands: 824MHz-954MHz, 1710MHz-2635MHz and 3.4GHz-3.6GHz. Because of its small size, light weight, easy integration and low profile, microstrip antenna is the best choice for multi frequency miniaturization. Traditional monopole antenna cannot be easily integrated into the vehicle due to its volume and other reasons, while printed monopole antenna overcomes the volume defects and bandwidth defects of traditional monopole antenna by
printing the traditional monopole antenna on the dielectric substrate, and has the similar structural
characteristics and performance advantages with microstrip antenna, so it is widely used in mobile
communication band antenna.

As we all know, both traditional monopole antenna and printed monopole antenna have only one
resonance frequency point, and the resonance length is one quarter of the wavelength. Therefore,
increasing the frequency band, broadening the bandwidth and reducing the size of the antenna become
the main research direction of the printed monopole antenna. The traditional monopole antenna is a
metal column with a length of about a quarter of a wavelength, which is placed vertically on the ground.
Using the mirror theory, a mirror monopole below the ground is used to replace the surface current effect
of the ground. Therefore, when analyzing the surface current distribution of monopole, the surface
current distribution of the upper half of the equivalent dipole can be used instead. It should be noted that
dipole antenna can radiate in the whole space, while monopole antenna only radiates above the ground.
When the ground is infinite, according to the theory of symmetric oscillator in free space, the radiation
area of the upper half of monopole antenna can be directly equivalent to the far-field radiation field of
monopole antenna:

\[
F_\theta = \frac{\cos(\beta L/2)\cos\theta - \cos(\beta L/2)}{\sin\theta}
\]

When \(\theta=90^\circ\), \(F_\theta\) is a fixed value. That is to say, the horizontal pattern of the antenna is a circle,
and the monopole antenna is directionless. As an improvement of traditional monopole, printed
monopole has similar characteristics. The traditional monopole antenna cannot be integrated into the
limited space because of the limitation of volume and profile. Therefore, the monopole antenna is usually
printed on the dielectric substrate to achieve integration. At the same time, the printed monopole is a
planar antenna with wider bandwidth than the traditional monopole. Therefore, compared with the
traditional monopole, the printed monopole antenna also has a wide band, as shown in the figure below.
It has many advantages, such as small size, easy processing and integration, low price and so on.

There is no metal patch under the dielectric substrate corresponding to the radiation patch of the
printed monopole antenna, while there is a metal plate under the radiation patch of the microstrip antenna,
forming a resonant cavity with the radiation patch. Although both microstrip patch antenna and printed
monopole antenna belong to plane antenna, they have similar structure characteristics, but their
performance is different. Compared with microstrip patch antenna, the bandwidth of printed monopole
is relatively wide. In addition, the dielectric plate of printed monopole antenna is generally very thin,
and the dielectric loss is small, so it is not easy to be affected by the material of the dielectric plate.

The printed monopole consists of a metal floor, a dielectric substrate and a radiation patch. It is
mainly fed by microstrip line (the microstrip feeder is directly connected with the radiation patch) and
coplanar waveguide (the microstrip feeder, the floor and the radiation patch are in the same plane).
According to the different shapes of metal patches, printing monopoles can be divided into circular patch
monopoles, rectangular patch monopoles, triangular patch monopoles, etc. As we all know, microstrip
antenna is also composed of metal floor, dielectric substrate and radiation patch.

Generally, the radiation length of printed monopole antenna is one quarter of the wavelength. In order
to achieve the required performance in practical application, the printed monopole antenna needs to be
deformed, that is, to change the radiation patch, there are two main deformation measures: cutting and
loading. For example, when the antenna size needs to be reduced, the simulation software can be used
to display the current distribution of the antenna, so as to obtain the resonance path of the antenna,
analyze the main radiation area, and then cut the non-main radiation area properly to achieve the purpose
of antenna miniaturization. Or we can cut the gap in the reasonable position of the radiation patch,
change the current distribution of the patch, increase the effective current path of the antenna, and reduce
the resonance frequency of the antenna.

When the antenna frequency band needs to be increased, the parasitic unit or other branches can be
loaded to increase the resonator of the antenna so as to obtain different resonance frequencies. When the
different resonance frequencies are close, the antenna bandwidth can also be increased. The multi
frequency antenna can also be realized by cutting the floor to form a defective structure, and the impedance matching can be improved at the same time.

3.2. Simulation analysis

In this paper, the current of antenna radiation patch is simulated by HFSS and analyzed. Fig. 1 shows the surface current distribution before and after the antenna is halved at 0.9GHz, 2.0GHz and 3.5GHz. It can be seen from Fig. 1 that the current distribution on the surface of the antenna after halving is similar to that on the right half of the antenna before halving. Because the structure of the antenna before halving is symmetrical and the excitation of the feed to the antenna of symmetrical structure is even, the left half of the antenna before halving will not have a great influence on the current distribution on the right half (miniaturized structure). The current of antenna radiation patch is different with different antenna frequency. When the frequency is 0.9GHz, the surface current of monopole patch mainly flows in the -Z direction on the T-shaped structure, and a small amount of current in the cone-shaped part also flows in the -Z direction. If 2.0G is mainly contributed by the lower part of the T-shaped structure and the lower part of the conical structure, and the current flows along the -Z direction. At the high frequency of 3.5G, the antenna current is concentrated in the conical part, and the current flows along the +Z direction, which is opposite to the direction of the medium and low frequency current. The above current distribution shows that the low frequency of the antenna is mainly produced by T-type monopole, the medium frequency by tapered and T-type monopole, and the high frequency by tapered.

Figure 1. Influence of halving and miniaturization on current distribution on antenna surface at different frequencies

These current distributions are basically consistent with the design process of the antenna, which proves that the design idea is correct from the side. It should be noted that the current of the antenna before half reduction is mutually offset in X direction, while the antenna after half reduction is not. The
bandwidth of the antenna before and after half reduction is 0.75GHz-1GHz and 1.7GHz-3.95GHz, and the bandwidth of the antenna after half reduction is 0.77GHz-1GHz and 1.7GHz-3.78GHz. Before and after half reduction, although the antenna bandwidth is reduced, it still covers amps, GSM900, GSM1800, TD-LTE and 5g mobile communication frequency bands. Therefore, after the antenna is halved, the current distribution of the antenna is basically unchanged, and supports the mobile communication frequency band.

4. Conclusion
In this paper, a vertical polarization, horizontal omnidirectional vehicle antenna is designed. The antenna can support amps, GSM900, GSM1800, TD-LTE and 5g multiple mobile communication bands, and the height must be less than 70mm, the length less than 140mm, and the width less than 70mm. Firstly, the principle of printed monopole is introduced, including the comparison with traditional monopole antenna and microstrip antenna. Then an antenna supporting mobile communication frequency band is designed in the form of printed monopole antenna, and the antenna miniaturization is realized by using half reduction technology.

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