

Antenna Evaluation for Vehicular Applications in Multipath Environment

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To Felicia & Stefan

*“La vida no se trata de como sobrevivir a una tempestad sino como
bailar bajo la lluvia.”*

– Unknown

Abstract

Antennas are essential components in any wireless communication system. To evaluate them is challenging, especially when new technologies are emerging.

Future intelligent transport systems, where vehicular communications play an important role will cover important aspects such as traffic safety and traffic efficiency. These applications will be covered by technologies such as IEEE 802.11p and LTE. For these emerging technologies, traditional methods for measuring the vehicular antennas such as anechoic chamber measurements or expensive and time-consuming field measurements may not be enough or suitable. Thus a new method for evaluating the antennas performance is desirable. A method that includes the multipath environment to give an idea of the antenna performance in the whole system and at the same time be able to be applied at early stages of product development. This thesis aims to provide such method.

The thesis is divided in two parts. The first part contains an overview and background of important concepts needed for development of methods for evaluation of vehicular antennas. In the second part, the papers that constitute the core of this work are appended.

In Paper A, we evaluate the vehicle's antenna performance using only simulations. We start by defining the multipath environment for vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communication. Then, the V2X environment is simulated using a multipath simulation tool to evaluate the vehicle's antennas radiation patterns placed at different positions on the vehicle. This will result in the received power cumulative distribution functions (CDFs) for the voltage samples at the receiving antennas port.

In Paper B, we present the design and evaluation of an antenna module for IEEE 802.11p and LTE technologies. The module is designed taking into consideration the available space and suitable placement on the vehicle. The proposed module is in accordance with the requirements for LTE and IEEE 802.11p technologies. This is validated with the analysis of the antenna efficiencies, S-parameters, radiation patterns, and diversity performance for the simulated and measured antenna module.

Finally, Paper C presents a method for the evaluation of V2V antennas in a simulated measurement-based multipath environment. Here, a measurement campaign is performed to obtain the parameters (i.e., the angular received power spectrum) that define a realistic V2V multipath environment. These parameters are then introduced in a multipath simulation tool where the antennas radiation patterns are evaluated. Results are expressed in terms of received power CDFs. This method is validated by comparing the simulated and measured received power for two roof-top vehicle antennas.

Keywords: Vehicular antenna evaluation, V2V measurements, V2V simulations, multipath environment, IEEE 802.11p, LTE.

List of Included Publications

The thesis is based on the following appended papers

- [A] E. Condo Neira, U. Carlberg, J. Carlsson, K. Karlsson, and E. G. Ström, "Evaluation of V2X Antenna Performance Using a Multipath Simulation Tool," *Antennas and Propagation (EuCAP) Proceedings of the 8th European Conference*, The Hague, The Netherlands, April 2014.
- [B] E. Condo Neira, J. Carlsson, K. Karlsson, and E. G. Ström, "Combined LTE and IEEE 802.11p Antenna for Vehicular Applications," *Antennas and Propagation (EuCAP) Proceedings of the 9th European Conference*, Lisbon, Portugal, April 2015.
- [C] E. Condo Neira, K. Karlsson, E. G. Ström, J. Carlsson, and A. Majidzadeh, "V2V Antenna Evaluation Method in a Simulated Measurement-Based Multipath Environment," submitted to *IEEE Transaction on Antennas and Propagation*, Dec. 2016.

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Edith Graciela Condo Neira

Gothenburg, March 2017

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Acronyms

AoA:	Angle-of-arrival
CDF:	Cumulative distribution function
CSI:	Channel state information
DSRC:	Dedicated short-range communication
ETSI:	European telecommunication standards institute
GPS:	Global positioning system
GUI:	Graphical user interface
ITS:	Intelligent transport system
LOS:	Line-of-sight
LTE:	Long term evolution
MIMO:	Multiple-input multiple-output
NLOS:	Non-line-of-sight
PIFA:	Planar inverted F-antenna
RIMP:	Rich isotropic multipath
RLOS:	Random-line-of-sight
SDARS:	Satellite digital audio radio service
V2I:	Vehicle-to-infrastructure
V2V:	Vehicle-to-vehicle
V2X:	Vehicle-to-vehicle and vehicle-to-infrastructure

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Part I

Overview

Chapter 1

1 Introduction

Wireless communication involves the transmission of information over a distance without using cables, wires or any other forms of electrical conductors. It is the oldest form of communication and it has experienced an enormous growth in the last few decades. Everything started with smoke signals, drums, semaphore flags, etc. followed by the telegraph and later by the telephone [1]. This technology took off with the discovery of electromagnetic waves. Thanks to physicists and scientists, we have the basis that is needed for the continuous growth of this technology which has several applications, e.g., cellular, satellite or vehicular communications. Cellular communications is one of the applications that have experienced an exponential growth. It has evolved from analog systems (i.e., 1G) to 2G, 3G, 4G, and beyond. These applications would not be possible without the use of antennas since they are one of the key components of any wireless communication system, enabling transmission and reception of propagating signals.

In cellular communications the evaluation of the antennas is well explored. For this application, the antenna may be measured in an anechoic chamber to find the line-of-sight (LOS) properties or in a reverberation chamber when non-line-of-sight (NLOS) or multipath components are expected. The latter may be caused by multipath phenomena such as reflection, scattering and diffraction. Unlike cellular communications, in vehicular communications there are still a lot to be explored when it comes to the evaluation of antennas, especially nowadays when new technologies are emerging and are intended to be implemented (e.g., IEEE 802.11p, LTE, 5G).

The application of these new technologies will contribute to Intelligent Transport Systems (ITS). ITS have the potential to increase traffic safety, traffic efficiency and infotainment through the communication between vehicles and/or vehicles to infrastructure. Communication types such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) together V2X communications are the basis for Cooperative-ITS (C-ITS). V2X can be supported by different technologies.

In Europe, V2V is standardized by European telecommunication standards institute (ETSI) as the ITS-G5 standard and in the United States is namely Dedicated Short-Range Communication (DSRC). Both ITS-G5 [2] and DSRC [3] are based on IEEE 802.11p and they operate in the 5.9 GHz band. For safety related applications, 802.11p is a suitable candidate due to low latency and communication range of several hundred meters [4]. In dense scenarios, where scalability problems may appear, a possible alternative for ITS may be Long Term Evolution (LTE) technology. The reliability of the application of

these technologies highly relies on the quality of the communication link, where antennas are one of the key components. Therefore finding an optimal antenna performance is important.

In vehicular communications, there are many factors that will be influencing the antenna performance, e.g., the placement of the antenna on the vehicle, the vehicle's large number of metallic objects, the frequency in which the antenna is operating together with the vehicle's shape, and the vehicle's mobility. These factors will have different impact depending on the technology that is used. Moreover the increasing number of antennas and the limited space on the vehicle due to aesthetic aspects requires the development and the use of multiband antennas integrated in a single module. These multiband antennas may be affected by effects such as mutual coupling or finite ground plane size. Considering the vehicles high mobility, the traditional methods for measuring the antennas may not be enough. Thus new methods need to be proposed.

For V2V communications, where the frequency is relatively high, i.e., 5.9 GHz, the radiation pattern of the antenna is more affected by the vehicle's shape than for other technologies operating at lower frequencies, e.g., LTE. Thus it is difficult to judge if the antenna performs well or not simply by looking at the radiation pattern. In addition, in V2V communications, the transmitting as well as the receiving antennas is placed on roughly the same height. Thus, scatters responsible for the multipath are located mostly in the horizontal plane. Therefore, the waves that are incident on the receiving antenna may come from arbitrary directions in azimuth but within a limited range of angles in elevation. Thus it is important to evaluate the antenna performance in realistic multipath environments as the incident waves' parameters such as Angle-of-Arrival (AoA), polarization, and power, depend on the multipath environment. A possible solution to this is to carry out field measurements [5]–[6]. However, they are expensive, time consuming and not even possible at early stages of product development. Then simulations become more attractive [7]–[8] since they are cost effective, less time consuming and they can be applied before any hardware is available. Then, when to use measurements or simulations? Is it good enough to rely on simulations?

1.1 Objective

The aim of this work is to provide a suitable and efficient method for evaluation of antenna performance under realistic conditions by using the radiation pattern of possible antenna designs in realistic multipath environments. The method involves measurements and simulations and is intended to be used at any stage of product development and should be able to help the antenna designer to evaluate the antenna parameters, antenna placement, antenna types or number of antennas with respect to the system performance.

1.2 Thesis Outline

The structure of this thesis is organized as follows. Chapter 2 provides a brief introduction of wireless propagation environments as well as concepts such as Random Line-of-Sight (RLOS), Rich Isotropic Multipath (RIMP), weighted environment, and wireless propagation emulation are described. In Chapter 3, a brief overview of antenna theory used along this thesis as well as diversity concepts are given. Chapter 4 focuses on vehicular antennas for 802.11p and LTE technologies. In Chapter 5, a brief description of the proposed antenna evaluation method and a graphical user interface are presented. Finally, the contribution of this thesis as well as future work is summarized in Chapter 6.

Chapter 2

2 Wireless Propagation

In a wireless communication system, the medium in which electromagnetic waves propagate from the transmitter to the receiver is called propagation channel, and the behavior in which electromagnetic waves propagate is called wireless propagation. In a wireless propagation environment the electromagnetic waves may take only the direct path which is known as LOS or may take several propagation paths (multipath). In LOS the wave incident to the receiving antenna is coming from only one direction. In real V2X situations, we usually don't have LOS conditions since there are many objects in the surroundings that cause multipath phenomena such as reflection, scattering and diffraction. In addition to that, the received signal is often obstructed in a multipath environment.

In this chapter, we discuss three different wireless propagation environments for antenna evaluation. In Section 2.1 and 2.2, we discuss two extreme environments that are relevant for mobile communications and a starting point for vehicular communications. In Section 2.3, we discuss an environment that is relevant for vehicular communication which is the main focus of this thesis. We then describe how a multipath environment can be emulated.

2.1 Random Line-Of-Sight (RLOS)

A Random Line-Of-Sight (RLOS) environment is an environment that is characterized by one incident wave on the receiving antenna, and this incident wave has an arbitrary incident direction and polarization. This is shown in Fig. 2.1, where the antenna pattern is placed at the origin of the coordinate system and that a line from the center of the red square to the origin defines the AoA of the incident wave. The polarization of the wave is indicated by the black line that is on the red square.

In wireless mobile communications, a moving user is communicating with a fixed base station. The base station is normally elevated and the mobile device has an arbitrary orientation. Therefore, from the mobile perspective, RLOS environment is one extreme environment relevant for evaluating the antenna performance [9].

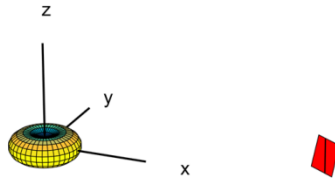


Figure 2.1. Visualization of a Random Line-Of-Sight (RLOS) environment in a specific time-instant.

2.2 Rich Isotropic Multipath (RIMP)

Unlike RLOS environment, RIMP environment is an environment which is characterized by many incident waves where the AoA of the waves are uniformly distributed over all directions in 3D space. In RIMP, the only antenna parameter that matters for a single antenna element is the total radiation efficiency. Fig. 2.2 shows the visualization of a RIMP environment where the waves are incident to the radiation pattern of an antenna that is placed at the origin of the coordinate system, e.g., a dipole antenna. As in Fig. 2.1, the incident waves are represented by the red squares and the polarization is indicated by the black lines on the red squares.

RIMP environment is another extreme environment to study the antenna performance for mobile communications [10], [11].

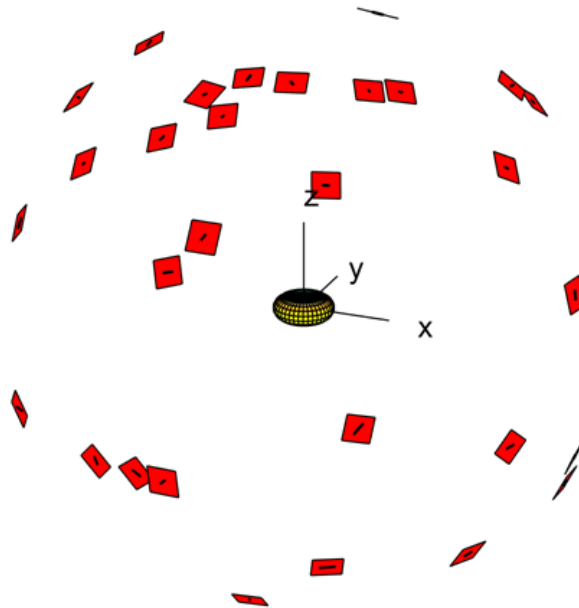


Figure 2.2. Visualization of a Rich Isotropic Multipath (RIMP) environment in a specific time-instant.

2.3 Weighted Environment for Vehicular Applications

As explained before, RLOS and RIMP environments are suitable environments for mobile communications but not for V2X applications since the vehicles are moving mostly in a horizontal plane and the antennas mounted on the vehicles are usually mounted at low heights. Then scatterers creating the multipath are located mostly in the horizontal plane. Thus, the environment for

vehicular applications is something in between RLOS and RIMP. Therefore, we define the environment for vehicular communications as a weighted environment [12] (Paper A).

In a weighted V2X environment, the waves that are incident on the receiving antenna will arrive from arbitrary directions in azimuth but within a limit range of angles in elevation. Each wave is vertically polarized. This assumption is described in [13] (Paper C).

In Fig. 2.3, the visualization of a weighted environment is given. This figure shows the incident waves in a specific time-instant which will be different in another time. In this example, we can see incident waves uniformly distributed in the whole horizontal plane with a limited angle of spread in elevation.

Unlike RIMP, the radiation pattern of the antenna is important in a weighted environment as it will be seen in the following chapter.

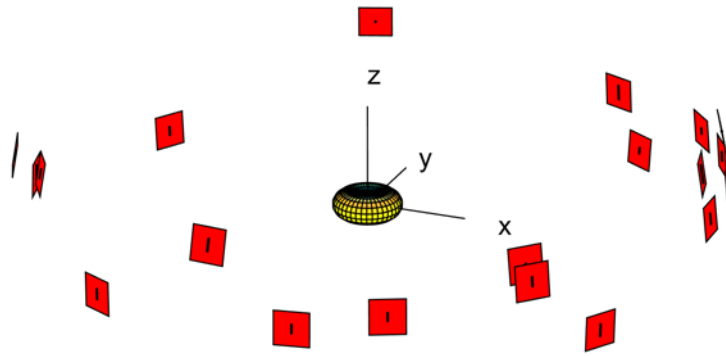


Figure 2.3. Visualization of a weighted environment in a specific time-instant.

2.4 Wireless Propagation Emulation

The discussed propagation environment may be emulated by anechoic chambers, reverberation chambers or by simulations. An anechoic chamber can be used to emulate a free space RLOS environment. This environment is a well-established reference environment for antennas mounted on roofs and masts with dominant LOS. However, modern antennas or terminals used for example in mobile communications cannot only be characterized in this environment since they need to be characterized in both extreme environments RLOS and RIMP [11].

RIMP can be emulated by reverberation chamber. Even though, anechoic chambers or reverberation chambers are very useful, there is still the need of simulation tools. Simulation tools are quite essential to try and test new ideas. They are repeatable, simple, fast and inexpensive.

In this thesis, we have used a wireless propagation simulation tool called ViRM-Lab (Visual Random Multi-path Environment Laboratory) [14]. ViRM-Lab is a computer code which generates a statistically fading environment by a number of statistically distributed incident waves. It uses antenna far-field

patterns and can simulate RLOS, RIMP and different kind of wireless propagation environments like a weighted environment.

In Fig. 2.4 and Fig. 2.5, the cumulative distribution functions (CDFs) as a function of the received power level are shown. Fig. 2.4 shows the comparison between RLOS and RIMP environments where three different antennas have been evaluated, i.e., a quarter-wave monopole centricly mounted on a $1 \times 1 \text{ m}^2$ ground plane, a probe-fed patch with a ground plane size of $20 \times 24 \text{ mm}$, and a half-wave dipole antenna. The antennas have been evaluated in free-space and the far-field patterns are obtained from simulations performed in CST Microwave Studio [15]. Details of the antennas can be found in [12] (Paper A).

When computing the CDFs, we have used 10^5 realizations. Each realization contains one wave for RLOS and twenty waves for RIMP. The incident waves are distributed over the whole sphere and they present random polarization. It should be pointed out that the number of realizations should be large enough to determine the CDFs accurately and the number of incident waves for RIMP should be large enough to assure that the waves are distributed over the 3D sphere.

The CDFs results shown in Fig. 2.5 have been performed in a weighted propagation environment with vertically polarized incident waves that are uniformly distributed over the whole horizontal plane and with an angular spread in elevation between -5° to 15° . The antennas that have been evaluated are a 5.9 GHz probe-fed patch antenna placed on the windscreen of a vehicle and a 5.9 GHz quarter-wave monopole antenna placed on the back of the vehicle's roof-top (shark-fin position). In this case, the monopole antenna performs better than the patch. This is because the monopole antenna presents an omnidirectional radiation pattern. As before, we have used 10^5 realizations and twenty incident waves.

As seen in Fig. 2.4 and Fig. 2.5, the directivity of the single port antenna is important in RLOS as well as in a weighted environment. In RIMP, the only antenna parameter that is important is the total radiation efficiency. The received power of RIMP will always follow the theoretical Rayleigh, see Fig. 2.4.

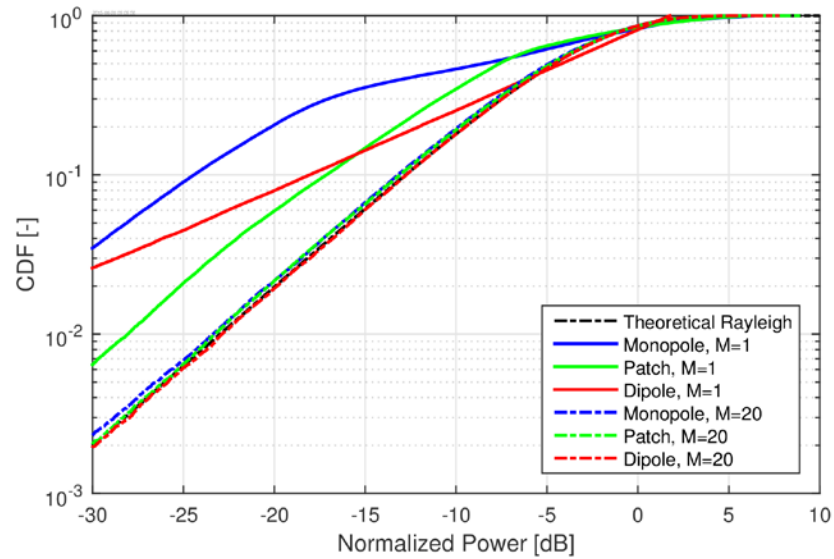


Figure 2.4. CDFs for linear polarized incident waves. Solid lines represent a RLOS environment ($M=1$) and dashed lines represent a RIMP environment ($M=20$).

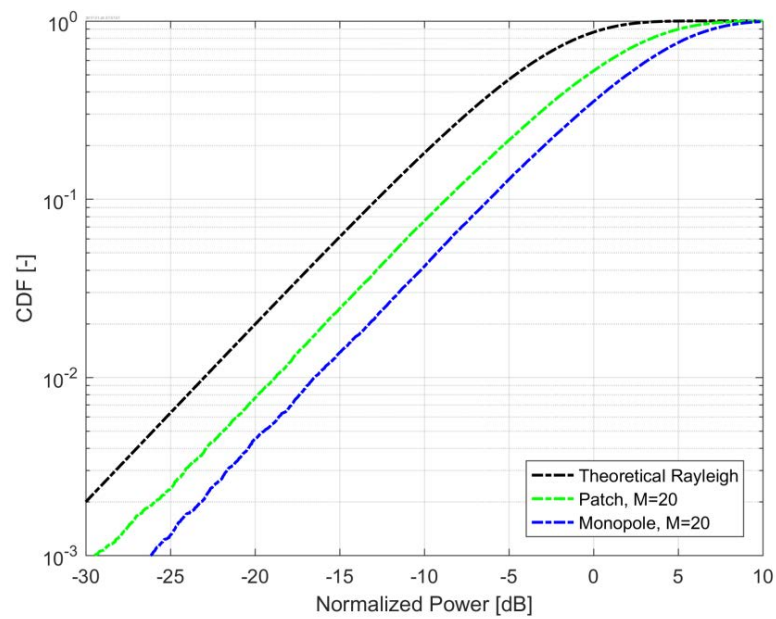


Figure 2.5. CDFs for vertically polarized incident waves in a weighted environment.

Chapter 3

3 Antenna Characteristics

Antennas are one of the most important components in any wireless communications system since they are responsible to transmit or receive electromagnetic waves through a wireless propagation channel.

An antenna is usually designed to operate in one or several specific frequency bands. There are different types of antennas and the selection of any specific design depends on many factors, e.g., the type of application, available space, cost, etc., and most of the time compromises need to be done. The size of the antenna is often expressed in terms of the wavelength at the frequency of operation. The wavelength is given by

$$\lambda = \frac{c}{f} \quad (3.1)$$

where $c = 3 \cdot 10^8$ m/s is the speed of light in free space and f is the frequency expressed in Hz.

Antennas can be classified in single-port antennas and multi-port antennas. Single-port antennas are antennas with one connector and they are the most common designs for automotive applications. Unlike single-port antennas, a multi-port antenna is an antenna with several radiating elements and several connectors. The main advantage of using multi-port antennas is that the signals from the several radiating elements can be combined in different ways, e.g., using diversity or multiple-input multiple-output (MIMO) schemes, and in this way the signal performance can be improved in comparison with a single-port antenna. An important parameter to be considered when designing a multi-port antenna is the distance between the antenna elements, which should be large enough in order to minimize mutual coupling. This can be quantified by measuring the antenna isolation (e.g., S21 in a two-port antenna).

Multi-port antennas are very useful in multipath environments since the waves that are incident to the antenna elements arrive from arbitrary directions, with arbitrary polarizations, phase and amplitudes. Application examples of multi-port antennas are in LTE and V2X communications. LTE requires the use of multi-port antennas in order to support MIMO schemes and V2X will benefit in using multi-port antennas since the complexity on the vehicle (i.e., the vehicle's shape) will have a great influence on the antenna radiation pattern.

In order to describe the characteristics of the antennas, definitions of various parameters are necessary. Therefore, in this chapter a brief overview of the antenna theory used in this thesis is given. In the first three sections of this

chapter, we describe the main antenna concepts and in the last section we briefly describe diversity.

3.1 S-parameters

Scattering parameters (S-parameters) describe the input-output relation between ports in an electrical system. The S-parameters can be calculated using network analysis techniques, more information can be found in [16]. Otherwise, they are often measured using a network analyzer.

Consider, a two-port network, shown in Fig. 3.1, where the incident voltage at port 1 and port 2 is denoted by V_1^+ , V_2^+ respectively, and the leaving voltage, i.e., the reflected voltage is denoted by V_1^- , V_2^- . The matrix elements S_{11} , S_{12} , S_{21} , and S_{22} are referred to as the S-parameters. The parameters S_{11} , S_{22} are the reflection coefficient (Γ) or return loss, and S_{12} , S_{21} are the transmission coefficient from port 2 to port 1, and port 1 to port 2 respectively.

In a multi-port antenna, it is important to present an acceptable impedance match over the frequency band of operation. The antenna impedance match is most commonly characterized by the return loss represented by the S-parameter S_{11} which is typically measured in dB, see Fig. 3.2. S_{11} is defined as the ratio of the reflected wave to the incident wave. It is a measure of how much power supplied to the antenna reflects back. Ideally, all of the power supplied to the antenna is radiated with no reflections.

While measuring the impedance match is important, it is also important to measure the mutual coupling between the antennas since it degrades the antenna efficiency, and it can also alter the radiation pattern of the antennas. Mutual coupling can be quantified by measuring the antenna isolation which is represented by S_{21} in a two-port antenna.

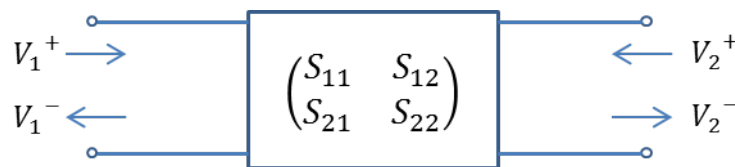


Figure 3.1. Transmitted and reflected waves in a two-port network.

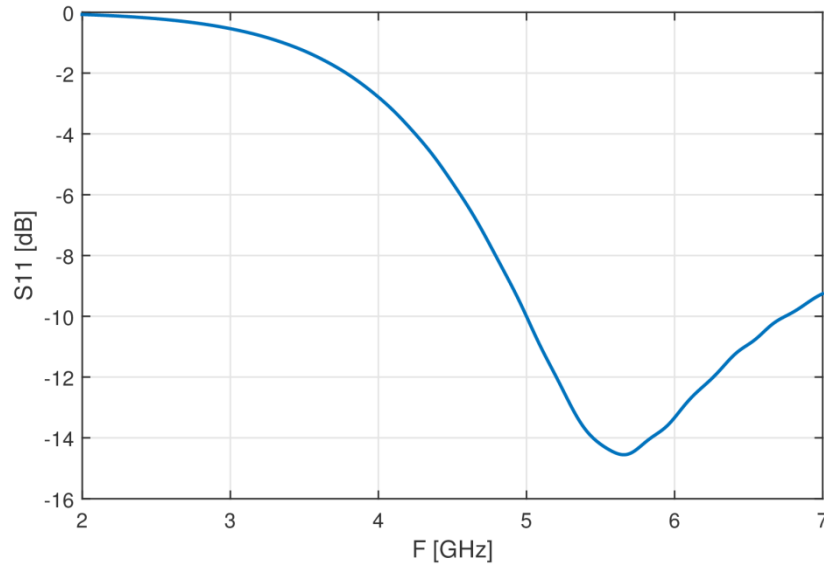


Figure 3.2. Reflection coefficient as a function of frequency for a monopole antenna designed for V2X communications. The antenna is mounted at the center of a finite size ground plane ($1 \times 1 \text{ m}^2$).

3.2 Total Radiation Efficiency and Radiation Efficiency

The total radiation efficiency is the ratio between the radiated power and the incident power on the antenna port and is given by

$$\varepsilon_T = \varepsilon_R \cdot M \quad (3.2)$$

where ε_R is the radiation efficiency (i.e., the ratio between the radiated power to the input power of the antenna), and M is the mismatch factor caused by a reflection coefficient at the antenna port. The mismatch factor is given by

$$M = 1 - |\Gamma|^2 \quad (3.1)$$

The total radiation efficiency is the same as the radiation efficiency if there is no loss due to impedance mismatch. However, this is only possible in theory. In real life, some of the power incident to the antenna port is always lost. For example, power losses can be caused due to the mismatch between the antenna and the feeding network. Thus, the total radiation efficiency is always below 100 % (0 dB).

It should be pointed out that the equations above are applicable for single-port antennas. In multi-port antennas, the total embedded element efficiency at every port is the ratio between the radiated power and the input power at the port of interest while the other ports are terminated.

3.3 Radiation Pattern

Radiation pattern is a graphical representation of the radiation properties of an antenna as a function of space coordinates [17]. It may be represented in a 3D plot, or in 2D polar plots as shown in Fig. 3.3, and Fig. 3.4 respectively. Radiation patterns are usually normalized to the isotropic radiation level [18]. A pattern is isotropic if the radiation pattern is the same in all directions. In real

life, antennas with isotropic radiation pattern don't exist. However, they are used as comparison with real antennas.

In practice, all the antennas present a directional dependence. Even an omnidirectional antenna will present a directional dependence, even though its radiation pattern is characterized by an isotropic radiation in a single plane. The radiation pattern of the antennas is affected by the frequency of operation. The highest the frequency, the most variation should be expected. This can be seen in Fig. 3.3 and Fig. 3.4 which show a 3D plot and 2D plots, respectively of a quarter-wave monopole antenna. The antenna is placed on the roof-top of a vehicle and it resonates at 5.9 GHz.

In multi-port antennas when the radiation pattern is measured, the measured port is excited while the other ports are terminated by 50 ohm. This measurement can be done in an anechoic chamber. Otherwise, the radiation pattern may be obtained using full-wave simulations.

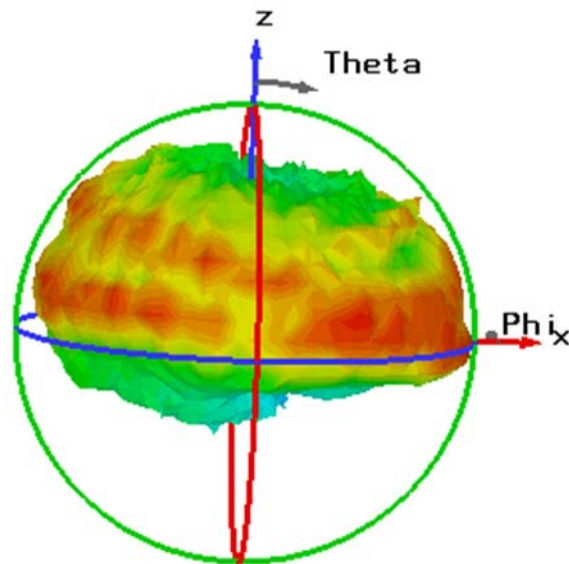


Figure 3.3. 3D radiation pattern of a quarter-wave monopole at 5.9 GHz. The antenna is mounted on the roof-top of a vehicle.

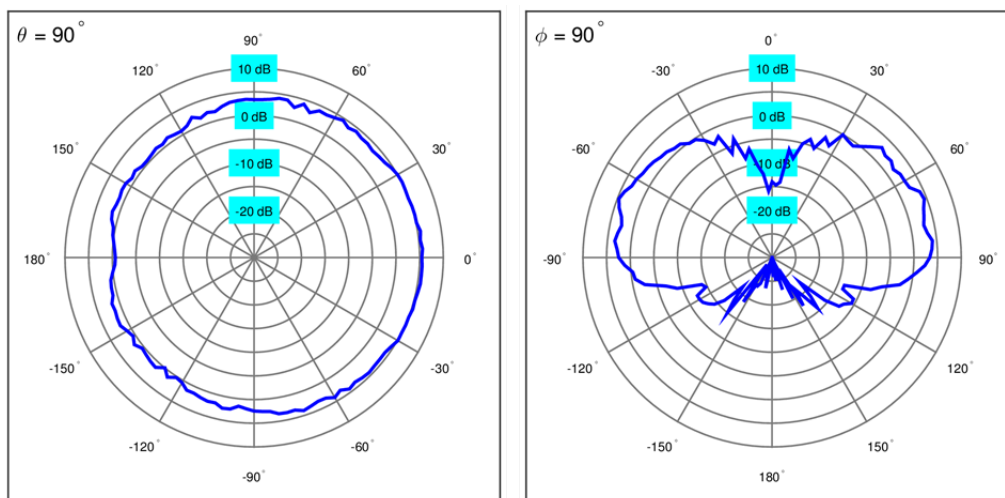


Figure 3.4. 2D polar radiation plot of a quarter-wave monopole at 5.9 GHz. The antenna is mounted on the roof-top of a vehicle. Left figure shows the radiation pattern in the horizontal plane and the right figure shows the elevation plane.

3.4 Diversity

Wireless communication systems may experience reflections from multiple scatterers, creating multipath channels, which are modeled as fading channels. If not properly designed, fading degrades the performance of a wireless system. One of the techniques to mitigate the effects of fading and improve system performance is MIMO.

MIMO is a technology that uses multiple antennas and it can be used to improve performance through diversity or to increase data rates through multiplexing [1]. Multiplexing consists in having multiple antennas at the transmitter as well as at the receiver. Thus the multiplexing gain is obtained from the fact that the MIMO channel can be separated into a number of parallel channels, more information can be found in [1]. Unlike multiplexing, diversity is also possible with a single antenna element at both ends. This is the case for time diversity and frequency diversity. For antenna diversity, which is another type of diversity technique, requires multiple antennas at the transmitter and/or at the receiver.

The idea of diversity is to send or receive the same information over independent fading channels. Reception over independent fading channels can be realized by spatial antenna diversity which is one of the most used diversity techniques [19]. For example, consider a case with two antennas at the receiving side. If the antennas are located far enough from each other (space diversity), it is unlikely that both antennas experience fading dips at the same time. Therefore, it is important to combine the signals properly. There are different diversity schemes to do this. In this thesis, we have used the selection combining scheme. Here, the receiver always selects the antenna with the strongest signal, detailed information about this and different diversity schemes can be found in [1].

Diversity performance is measured by diversity gain, and it is usually expressed in dB. Here, we won't go into details about different types of diversity gain, rather we refer to [18].

Fig. 3.5 shows how much a signal can be improved by applying diversity selection combining when two antennas are used. The antennas are designed for LTE communications to operate at three different frequency bands [20]. They are spatially separated by approximately $\lambda/2$ at 2590 MHz. From the figure, it can be seen that the signal is improved by 5 dB when four or more incident waves are applied on the radiation patterns of the multi-port antennas.

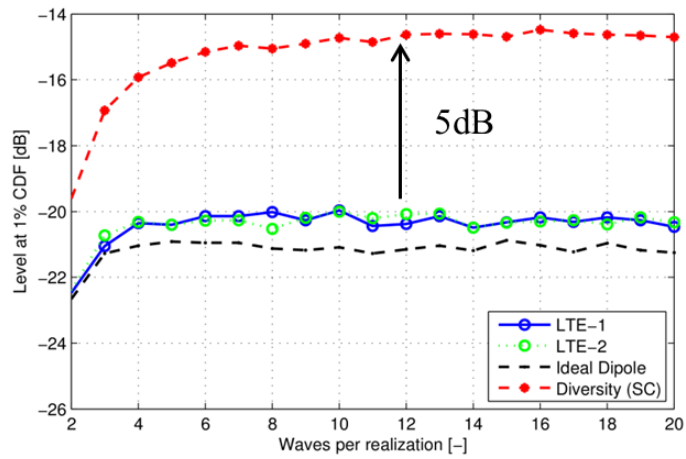


Figure 3.5. Received power level at 1% CDF level as a function of linearly polarized incident plane waves. The graph shows the diversity combined results when using a multi-port antenna for LTE.

Chapter 4

4 Antennas for Vehicular Applications

Modern vehicles may contain multiple antennas for different wireless applications such as AM/FM radio, remote keyless entry, satellite navigation, satellite digital audio radio services, electronic toll collection, and others. All these applications are allocated at different frequency bands, covering frequencies from 0.5 MHz (AM radio) up to 77 GHz (Radar Collision System) [21]. In addition to the existing applications, modern vehicles are proposed to include IEEE 802.11p and LTE technologies. Both of them can contribute to ITS communications [4]. ITS communications aim to provide traffic safety, traffic efficiency and infotainment. For V2V communications, the leading technology is IEEE 802.11p due to its low latency, while LTE is currently restricted to V2X communications that is relatively latency-tolerant.

Even though vehicles are many wavelengths bigger than mobile phones at high frequencies, there are very limited available space and locations for placing an antenna. This is due to the design and aesthetic of the vehicles is very important. Therefore, traditional antennas are out of the scope when it comes to design. Thus, antenna engineers have to come up with new solutions like the development of multiband and multiport antennas integrated in a single module.

Aspects that should be considered when designing an antenna are the frequency of operation as well as the available location for placing the antenna on the vehicle. These two factors will affect the performance of the antenna considerably.

This chapter focuses on 802.11p and LTE technologies as well as the design and implementation of a combined antenna module including V2V and LTE antennas.

4.1 802.11p Antennas

For V2X communication, a suitable antenna candidate may be an omnidirectional antenna which radiates electromagnetic waves uniformly in all directions in the horizontal plane with the radiated power decreasing in elevation. This is taking into account that vehicles move mostly in the horizontal plane. Thus, communication between them occurs mostly in the horizontal plane. In the case of communication between vehicles and road infrastructure a certain degree in elevation should be considered.

Other types of antennas that may be considered are rectangular patch antennas, which are low profile antennas. These antennas are usually constructed on a dielectric surface. They may be a possible solution for V2X communications since they are cheap to manufacture and their gain is higher than an omnidirectional antenna. However, these antennas are directive and they radiate in a specific direction [17], [18]. Thus, they do not cover the whole horizontal plane. A solution to this could be placing the antennas at different positions on the vehicle, e.g., on the windscreen and rear window of the vehicle, as was done in [12] (Paper A). In this way, the horizontal plane can be covered.

Most of the measurement campaigns that have been carried out for V2X communications have used omnidirectional antennas [5], [6], [22-24]. The authors of [6] and [22] have used a short-circuited circular patch antenna. Antennas elements of this kind present omnidirectional pattern, for more information refer to [25]. The antenna was designed for a roof-top mounting position.

In this thesis, we have design a quarter-wave monopole antenna centrally mounted on a ground plane with size $30 \times 30 \text{ mm}^2$, and a probe-fed patch antenna, both of them resonating at 5.9 GHz and they are vertically polarized. The patch antenna has a length of 11 mm, width of 15 mm and a ground plane size of $20 \times 24 \text{ mm}$. The substrate is FR4 with a thickness of 1.6 mm, see Fig. 4.1.

These antennas have been mounted at different positions on the vehicle and they have been evaluated in different road traffic environments. The evaluation, placement and comparison between the antennas are explained in [12] (Paper A).

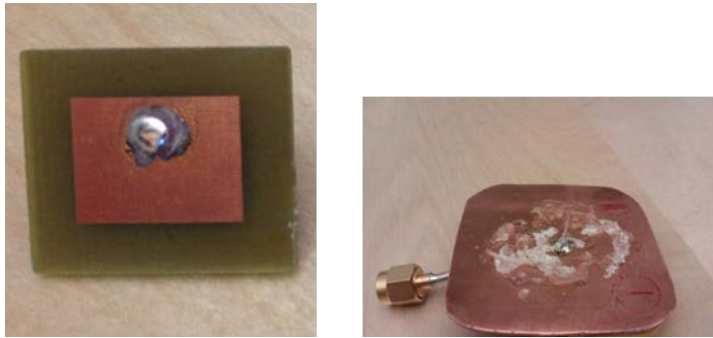


Figure 4.1. Antennas for V2X communication. Probe-fed patch antenna (left) and a quarter-wave monopole antenna (right).

4.2 LTE Antennas

In recent years, there is a considerable interest into LTE technology by the automotive industry. This is due to LTE is a possible alternative for ITS communications [4]. LTE presents high data rates for applications such as internet connectivity.

A considerable number of LTE antenna designs have been published in the literature. Most of them are for laptops [26], or for mobile devices [27-29]. These antennas are required to perform well at many frequency bands and to support multi-antenna techniques such as MIMO.

For vehicular applications, a few designs have been published [30], [31], [32]. These antennas are based on a monopole concept. In [30], they present a design which is intended to be mounted on the roof of large vehicles for public transportation. The authors of [31] and [32] present a roof-top LTE antenna design. The antenna is designed to be integrated in the shark-fin module on the roof-top on a vehicle.

Unlike previous research, our LTE antenna design is intended to be integrated into the rear-spoiler on a vehicle. The antenna prototype is based on a Planar Inverted F-Antenna (PIFA) [33]. The antenna has an omnidirectional behavior. It is vertically polarized, and it's designed to cover three frequency bands, see Table I.

Table I. Frequency Bands for LTE

LTE Frequency Bands	
<i>Uplink</i>	<i>Downlink</i>
698 - 716 MHz	925 - 960 MHz
1710 - 1785 MHz	2110 - 2170 MHz
2500 - 2570 MHz	2620 - 2690 MHz

For the design, we have focused on achieving the highest antenna matching, lowest mutual coupling and an omnidirectional radiation pattern performance. The antenna is shown in Fig. 4.2. The design parameters and results are presented in [20].

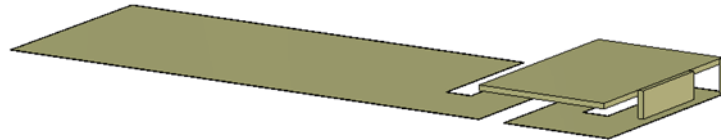


Figure 4.2. PIFA antenna for LTE communications.

4.3 Combined Antenna Module

As mentioned before, it is important to develop multiband antennas integrated in a single module to maintain the aesthetic of the vehicle. For example [34] has designed an antenna that covers both terrestrial services and satellite services. While [6], presents an antenna module including V2V, Global Positioning System (GPS) and LTE antennas. This module is placed on the roof-top on a vehicle.

In [20] (Paper B), we present an antenna module suitable to be integrated inside the rear-spoiler on a vehicle. The module consists of two identical LTE antennas and two identical V2X antennas. As mentioned before, the LTE antennas are based on a PIFA design. These antennas are printed on FR4 substrate with permittivity of 4.3, loss tangent of 0.025 and thickness of 1.6

mm. The antennas have individual ground planes, which are spatially separated by 50 mm, see Fig. 4.3. For V2X, we have used quarter-wave length monopole antennas. The antennas are placed on the ground plane of each LTE antenna as shown in Fig. 4.3 and they are spatially separated by 90 mm. The separation between the antennas is to achieve a good isolation as well as to have enough available space for future GPS, Satellite Digital Audio Radio Service (SDARS) antenna integration.

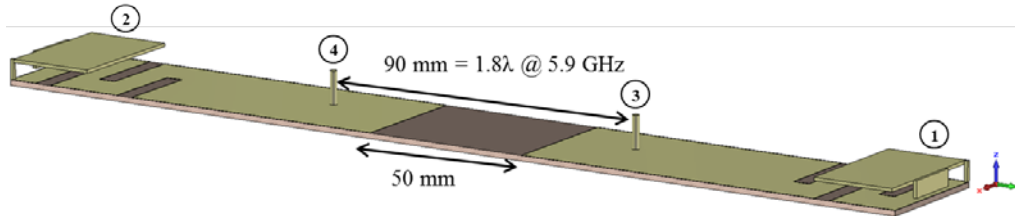


Figure 4.3. Antenna module for LTE and V2X communications.

The manufactured antenna module prototype is shown in Fig. 4.4. The dimensions of the module are 290 x 40 x 7.6 mm³. These dimensions are within the specification requirements which are given by the available space inside the rear-spoiler on a vehicle, e.g., crossover vehicle. Simulations and measurement results can be found in [20] (Paper B).



Figure 4.4. Manufactured prototype of the antenna module

Chapter 5

5 Novel Vehicular Antenna Evaluation Method

The increasing number of antennas in the vehicles due to the desire of implementing new wireless technologies especially for making a more safe and efficient vehicle requires accurate and efficient methods for evaluating the antenna performance. These antennas must be evaluated in different multipath environments. A possible solution to this is to carry out measurement campaigns. However, they are expensive and time consuming. Therefore, simulations are more attractive. They are less time consuming, repeatable and they can be applied at any stage of product development.

In this chapter a general overview of the antenna evaluation method presented in [13] (Paper C) is discussed in Section 5.1 and Section 5.2. In Section 5.3 a graphical user interface is presented together with a brief description.

5.1 Propagation Model

A multipath environment can be simulated by using ray tracing approach as in [7]–[8], but could also be simulated by performing measurement campaigns since they can provide the information that is needed to emulate a multipath environment.

From a measurement campaign, we can obtain the angular power spectrum which can be used to simulate a multipath environment. We start by writing a general equation for the average received power at the antenna port due to an incident plane wave

$$\overline{P}_a = E \left[|\mathbf{G}(\theta, \varphi) \cdot \mathbf{E}(\theta, \varphi)|^2 \right], \quad (5.1)$$

where E is the expectation operator, $\mathbf{G}(\theta, \varphi)$ is the radiation field, $\mathbf{E}(\theta, \varphi)$ is the incident complex electrical field, θ is the polar angle, and φ is the azimuth angle of the incident field. Then some assumptions are made

- 1) The incident field consist of a number of vertically polarized, plane waves with statistically independent zero-mean complex Gaussian amplitudes.
- 2) The incident plane waves arrive in the horizontal plane and their angle of arrivals are uniformly distributed.
- 3) The angular power spectrum is constant in each of the four equal-sized sectors around the vehicle.

After the two first assumptions, we can express the average received power at the antenna port as

$$\overline{P}_a = E \left[\left| \sum_{m=1}^M E_m^{(i)} W(\varphi_m) G(\varphi_m) \right|^2 \right] \quad (5.2)$$

Finally, considering the last assumption, the above equation is simplified as

$$\overline{P}_a = \sigma^2 \left(W_F^2 |G_F|^2 + W_L^2 |G_L|^2 + W_B^2 |G_B|^2 + W_R^2 |G_R|^2 \right), \quad (5.3)$$

where W_x^2 is piece-wise constant in the forward, left, back and right sectors, and $|G_x|^2$ is proportional to the average power gain in the sector $X \in \{F, L, B, R\}$. The full derivation of these equations can be found in the attached Paper C.

5.2 Measurement Campaign

In order to estimate the parameters that describe the multipath environment a measurement campaign was performed.

Fig 5.1 shows a block diagram of the steps to follow to obtain the parameters that were needed to simulate a multipath environment.

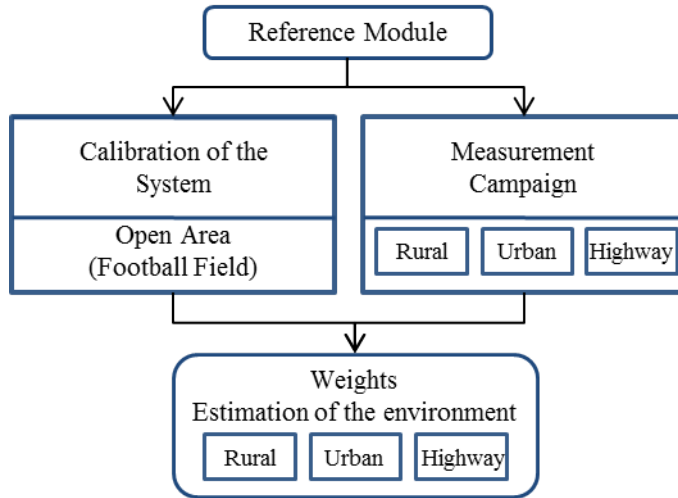


Figure 5.1. Block diagram to obtain the weights.

We started by designing a reference module which consists in four identical 5.9 GHz probe-fed patch antennas oriented outwards and placed far from each other, see Fig. 5.2.



Figure 5.2. Reference module mounted on the vehicle. The red circles show the placement of the antennas.

The reference module was used for the calibration of the system and for the measurement campaign. The calibration of the system was performed in an open area to obtain the reference antenna gain, and the measurement campaign was performed to obtain the average received power in three different road traffic environments (rural, urban, and highway). In both cases, two vehicles were used. On the transmitter side a 5.9 GHz quarter-wave monopole antenna was used. The antenna was mounted on the roof-top of the vehicle, and on the receiver side the reference module was used, see Fig. 5.2.

Once the reference antenna gain as well as the average received power for the four antennas used in the reference module are obtained, then the parameters that describe the multipath environment (W_L , W_B , W_R) can be calculated. This is done by solving (5.3), where W_F is normalized to 0 dB.

5.3 Antenna Evaluation Method and a GUI

For the evaluation of the described method a graphical user interface (GUI) has been designed as shown in Fig. 5.3.

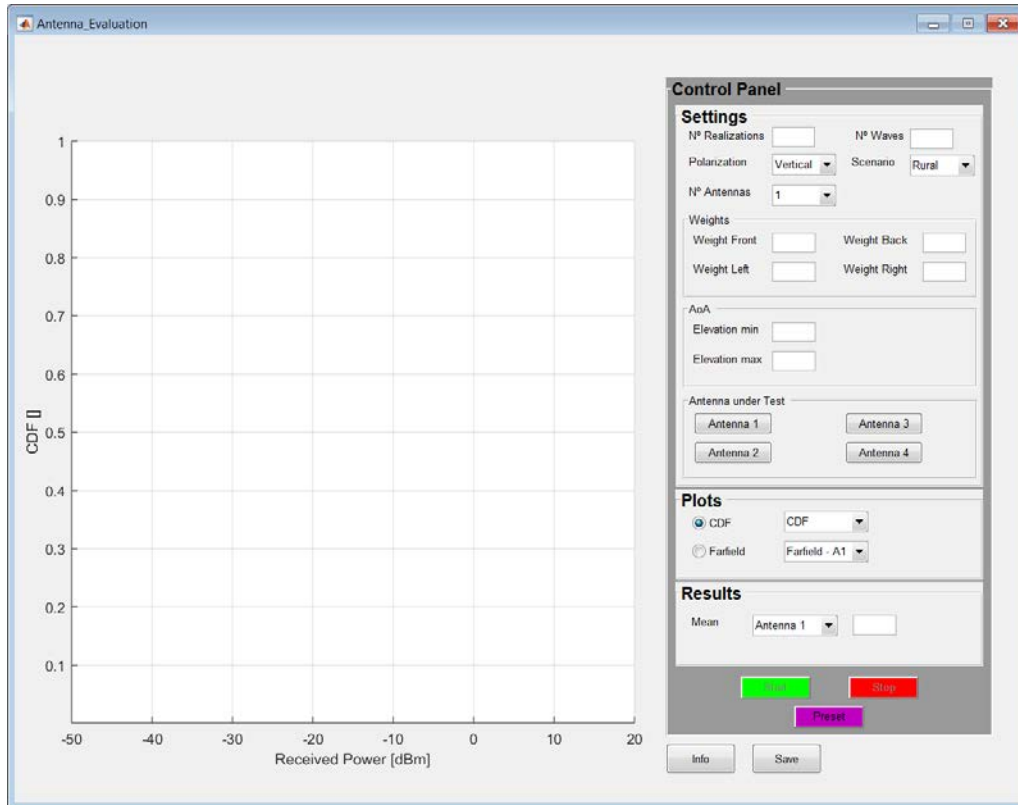


Figure 5.3. GUI for the evaluation of the antennas.

The GUI consists in a control panel divided in settings which are defined by the user, plots which show the graphical results according to the settings, and results which show a numerical value obtained from the plots.

5.3.1 Settings

The user defines the settings as follow

- **N° Realizations:** In order to simulate a changing environment as it is in reality a large number of realizations should be chosen. An appropriate number could be 10^4 or 10^5 . The larger the number of realization the better accuracy for low CDF values. However, the simulation time is longer.
- **N° Waves:** The number of incident waves should be chosen to assure that each sector get at least one incident wave. An appropriate number is twenty waves.
- **Polarization:** The user can choose between vertical, horizontal, and random (i.e., vertical, and horizontal) polarization.
- **Scenario:** The user can choose between rural, urban, and highway environment where each environment has its own weights.
- **Number of Antennas:** The user can choose between one to four antennas. The number of antennas chosen here are the number that should be uploaded in antennas under test.

- **Weights:** The weights are the parameters calculated in [13] (Paper C). These are set automatically when the scenario is selected. User defined weights can be entered manually.
- **Angle-of-Arrival (AoA):** The minimum and maximum AoA of the incident plane waves with respect to the elevation angle (θ) should be written here. The range of the elevation minimum value is between 0° to 90° and for the elevation maximum value the range is between 90° to 180° .
- **Antenna under Test:** The far-field pattern imported as ASCII.txt file from CST should be uploaded here.

5.3.2 Plots

- **CDF:** The user can choose between CDF, CDF and theoretical Rayleigh, and 1% CDF level.
- **Farfield:** The user can choose between Farfield and Farfield & Waves.

5.3.3 Results

- **Mean:** It shows the average received power of the antennas under test.

5.4 GUI example

Fig. 5.4 shows an example of the GUI where two probe-fed patch antennas have been evaluated. The antennas have been designed to operate at 5.9 GHz and they are placed on the roof-top of the vehicle as shown in Fig. 5.5.

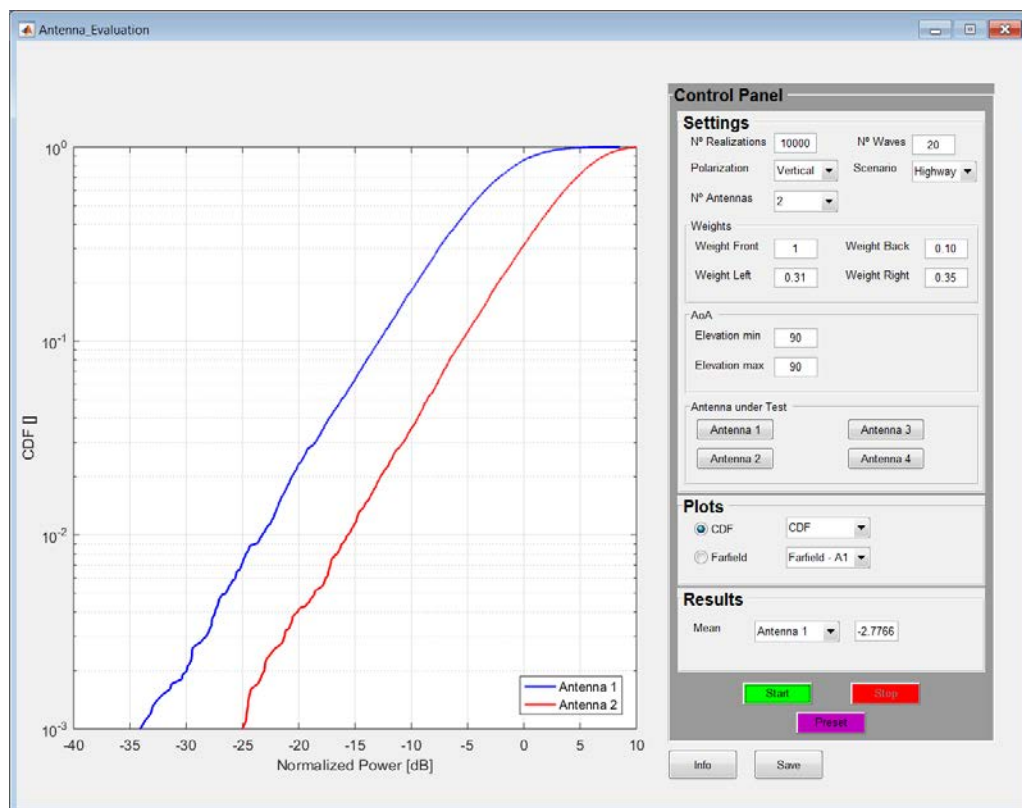


Figure 5.4. An example using the GUI.

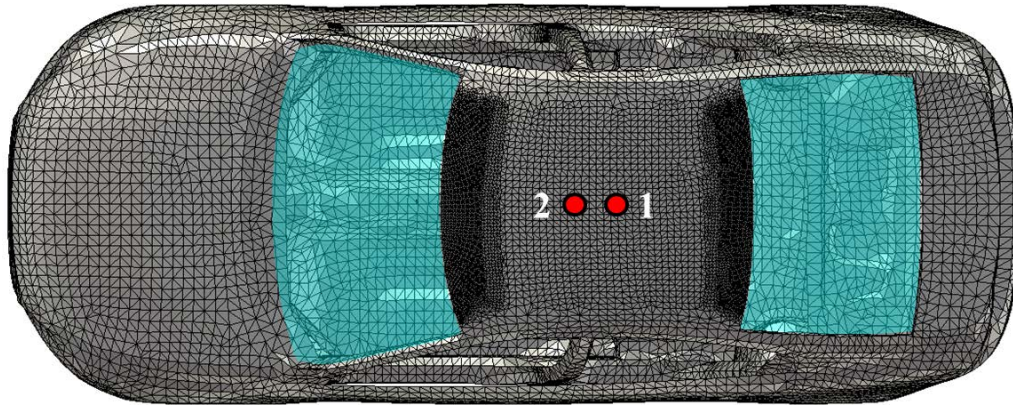


Figure 5.5. Placement of the antennas that are used in a GUI.

Chapter 6

6 Conclusions and Future Work

This chapter summarizes the main contributions of this thesis to the research field. In Section 6.1, we summarize each of the three appended papers. In Section 6.2, conclusions are given and in the last section some ideas on future work are presented.

6.1 Contributions

6.1.1 Paper A: Evaluation of V2X Antenna Performance Using a Multipath Simulation Tool

In this paper, we present a method for evaluating the V2X antennas performance. The method is based on simulations. First we start by defining a multipath environment for V2X communications, i.e., weighted environment. In a weighted environment, the waves that are incident on the receiving antenna will come from arbitrary directions in azimuth, but within a certain range of angles in elevation. Then, this environment is simulated in a multipath simulation tool and applied to the antennas radiation patterns and the evaluated results are presented in terms of the received power CDFs.

This simulated method has been applied to two different V2X antennas placed at different positions on the vehicle. Results show that the method is efficient, fast, and it can be applied to evaluate different antenna types, and positions. The importance of having antennas with radiation patterns covering the whole azimuth plane is also emphasized.

6.1.2 Paper B: Combined LTE and IEEE 802.11p Antenna for Vehicular Applications

Nowadays, the increasing number of antennas and the restricted space due to aesthetic aspects on the vehicle emphasizes the importance to have multiband antennas integrated in a single module. In this paper, we design a compact antenna module for LTE and IEEE 802.11p technologies that could be easily integrated inside the rear spoiler on a vehicle. The module consists of two identical quarter-wave monopoles for V2X applications and two identical printed inverted F-antennas for LTE communications. In both cases the antennas radiation patterns cover the whole azimuth plane. The module has been evaluated by analyzing the antenna efficiencies, S-parameters, radiation patterns, and by calculating diversity performance. Results of our proposed module are in accordance with LTE and IEEE 802.11p requirements.

6.1.3 Paper C: V2V Antenna Evaluation Method in a Simulated Measurement-Based Multipath Environment

In this paper, a method for evaluating V2V antenna performance under realistic conditions is presented. As was done in Paper A, first we start by defining the V2V environment. Then, we use the antenna radiation pattern (obtained from full-wave simulation software) in combination with a multipath simulation tool which generates a realistic multipath environment. In order to obtain the parameters that define the realistic multipath environment a measurement campaign was performed in three different road traffic environments. Then, these parameters are used in the multipath simulation tool to generate a realistic multipath environment. The accuracy of the method is validated by comparing the simulated and measured received power for two roof-top vehicle antennas.

Results show that the method is fast and efficient and it can be applied at early stages of product development.

6.2 Conclusions

Through this thesis we have developed a method for evaluating the vehicular antenna performance for ITS applications with emphasis on V2V communications. We have seen that in order to evaluate the antenna performance it is important to consider the multipath environment. This environment may be simulated as in Paper A, and Paper B or may be estimated based on field measurements as in Paper C.

Then, when to use simulations or measurements? Simulations are usually fast in comparison with measurements. They are repeatable and can be applied at early stages of product development. However, to give a meaningful evaluation of the antenna performance for ITS vehicular applications it is important to consider a realistic multipath environment. Such environments can only be obtained by performing field measurements, as has been done in Paper C. Therefore, instead of using only simulations, we propose a method that uses simulations to evaluate the antenna performance in a measurement-based multipath environment. Results, presented in a GUI, show that the method is fast, accurate, and it can be applied as an alternative to field measurements. Moreover, the method can be used at early stages of product development, and it can become a helpful tool for antenna designers.

6.3 Future work

The increasing number of antennas on vehicles due to the development of new technologies requires methods that are repeatable, fast and accurate. These methods should include the multipath environment.

A further extension of this work may be to generate a multipath environment for LTE communications, or 5G, and apply our proposed method.

Another interesting area may be to study another traffic scenario than a convoy scenario.

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