Project Work

Optimization of Antenna Placement for Car-to-Car Communications with Ray-Tracing

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**Declaration**

Hereby, I declare that I have prepared the following work by myself and without using any inadmissible aids.

Karlsruhe, 31.03.2009

Itsaso Eizmendi
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List of variables and abbreviations

List of variables

\( A_n(t_0) \)  
Attenuation of the n-path

\( a_S \)  
Short-term fading threshold

\( c_0 \)  
Speed of light

\( d_1 \)  
Direct distance between transmitter and receiver

\( d_2 \)  
Distance of the reflected path on the ground between transmitter and receiver

\( f_0 \)  
Carrier frequency

\( f_D \)  
Doppler frequency

\( f_S \)  
Sample frequency

\( F_{int} \)  
Interpolation factor

\( F_S \)  
Short-term fading

\( G_R \)  
_receiver gain

\( G_T \)  
Transmitter gain

\( h^{TP} \)  
Equivalent low-pass channel transfer function

\( H^{TP} \)  
Channel low pass frequency response

\( H^{TP}(v, t) \)  
Time-variant transfer function

\( k_0 \)  
Wave number

\( l(t) \)  
Long-term fading component

\( P(\tau, t) \)  
Power Delay Profile

\( P_R \)  
Received power

\( P_T \)  
Transmitted power

\( R_{p,s} \)  
Metallic surface

\( s(t) \)  
Short-term fading component

\( S_{HH}(f_D) \)  
Doppler spectrum

\( r_{HH}^t \)  
Time variant autocorrelation function

\( t \)  
Time

\( T_S \)  
Sample Time

\( T_O \)  
Observing Time

\( v_r \)  
Relative velocity

\( \lambda \)  
Wavelength

\( \lambda_0 \)  
Carrier wavelength

\( \alpha \)  
Angle of arrival

\( \sigma_{f_D} \)  
Doppler spread

\( \tau \)  
Time delay

\( \theta \)  
Reflection angle
Contents

εᵣ₂ Material permittivity
µᵣ₂ Material permeability

Abbreviations

B Bottom antenna position
BB Bumper back antenna position
BF Bumper front antenna position
C2C Car-to-Car
CDF Cumulative Distribution Function
CIR Channel Impulse Response
IEEE Institute of Electrical and Electronics Engineers
ISM Industrial Scientific Medical band
ITS Intelligent Transportation System
LOS Line Of Sight
MIMO Multiple Input Multiple Output
ML Mirror left antenna position
MR Mirror right antenna position
NLOS Non Line Of Sight
OFDM Orthogonal Frequency Division Multiplexing
PDP Power Delay Profile
R Roof antenna position
RSU Road Side Unit
SISO Single Input Single Output
UTD Uniform geometrical Theory of Diffraction
WAVE Wireless Access in the Vehicular Environment
1 Introduction

1.1 Abstract

Road traffic has been increasing over the last years, due to this fact the probability of accidents has been raised and this also causes more congestion. As a solution to this problem, specific information is provided to the driver. The given information are road and traffic conditions, as well as detailed information about the neighboring vehicles. So that C2C communications will be necessary to communicate and share data with other vehicles.

The development of C2C communications is increasing day by day, therefore several projects are and will be established. In Europe for example, there are a mount of projects working in different C2C communications applications. The aim is to reduce the number of traffic accidents with advanced preventive systems.

So the objective of this project work is to find out which is the best performing antenna position at the car for Car-to-Car Communications. To achieve this objective, Ray-Tracing is used to simulate the wave propagation in order to analyze the different radio channel parameters.

Due to the variety of traffic scenarios, like urban or motorway, several simulations are done in order to compare the different behavior of the channel for different antenna positions.

Six antenna positions at the car are chosen in order to evaluate the different performance of some significant communication parameters in C2C communications scenarios.

In the first chapter an introduction to C2C communications is done. Afterwards, in Simulation Tools and Optimization parameters, the antenna parameters and the antenna positions at the car are defined, as well as a description of the different tools, in order to obtain the simulations. The next chapter is the Channel Characteristics, where the studied parameters of the simulations are described. In Simulations Results, the obtained results are analyzed in detail. Finally, the Conclusions and the Future Analysis are summed up, where the best performing antenna combinations are commented and the possible future steps are explained.

1.2 Car-to-Car Communications

In order to reduce the number of traffic accidents and to make traffic more efficient, there are several projects working in different applications for C2C communications [13].

The first main area is the advanced driver assistance for road safety, reducing the number of accidents and also the impact of non-avoidable accidents.
One of the applications for road safety is the “Cooperative Forward Collision Warning”, which provides assistance to the driver to avoid rear-end collisions with other vehicles [1]. This application is based on the assumption, that the vehicles share relevant information, such as the position and the speed of vehicles. In order to predict an imminent rear-end collision the vehicle will warn the driver when there is a critical proximity between the vehicles. In that case, the driver will have time to avoid the accident.

Another road safety application is the “Pre-Crash Sensing/Warning” [1], to interact if there is an unavoidable crash. All vehicles periodically share information from neighboring vehicles to predict the collision. If a collision is no longer avoidable, the involved vehicles exchange more detailed information such as position and vehicles size. In that way, the involved vehicles can make a better use of the air bags, seat belts and extendable bumpers. This situation can be seen in figure 1.1.

![Figure 1.1: Car-to-Car Communications [13]](image)

Other areas that the Car-to-Car Communications can improve are applications which increase road safety efficiency and the local traffic flow. Providing information, not only to the drivers, but also to owners of the transportation network.

One of these traffic efficiency applications is the “Enhanced Route Guidance and Navigation” [1], where the network owner will collect the traffic information to offer the driver route guidance information. The expected traffic conditions will be sent to the vehicle, so that the driver will be informed about the expected delays and alternative routes.

The “Green Light Optimal Speed Advisory” [1], is one of the other traffic efficiency applications to avoid stopping. If a vehicle is approaching to a signalized intersection, the vehicle will receive information about the location of the intersection and the number of seconds to switch from red to green light. The vehicle has the possibility to calculate the optimal speed to reach the intersection once the traffic-light is green. This will have as a result less stop driving and a decrease of the use of fuel.

Furthermore communication and information services can be used for entertainment applications. In this area “Internet Access in Vehicle”[1] is the application which allows the connection to the Internet. A multi-hop route can be established to a RSU and an Ad-hoc network between the vehicles.

The “Point of Interest Notification” [1] is one of the other information applications for C2C communications. It allows local businesses to advertise their availability to the vehicles. For example, the driver could be shown the locations and prices for fueling
stations in the immediate area.

And there are several European projects working in those applications, and a lot of them are German research projects. Such as the CarTALK and the FleetNet, which were developed between 2001 and 2004, more recent projects for C2C communications are SIM-TD [14] and Network on Wheels [15]. All these projects are developing the Car-to-Car Communications, solving technical key questions on the communication protocols or working in the applications.

### 1.3 Technical Parameters

For C2C communications the working frequency is 5.9 GHz and the bandwidth in Europe 30 MHz [3]. In the USA for example some of the technical parameters are different, like the bandwidth that is 70 MHz. The system needs robust communication and a certain quality of service, minimum latency and maximum reliability, so that open bands like ISM can not be used.

The multiplexing modulation is Orthogonal Frequency Division Multiplexing (OFDM). The OFDM is a multi-carrier modulation method, where closely-spaced orthogonal subcarriers are used to carry data, as it is shown in the figure 1.2. For OFDM-systems it is very important to consider the huge importance of the Doppler spread and the delay spread, which will define our communication channel.

![OFDM modulation](image)

**Figure 1.2: OFDM modulation**

In the moment a new standard is being developed, the IEEE 802.11p standard. The aim of the 802.11p is to add Wireless Access in the Vehicular Environment (WAVE). It defines enhancements to 802.11 required to support Intelligent Transportation Systems (ITS) applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz).
2 Simulation Tools and Optimization Parameters

2.1 Antenna Position and Parameters

In order to know which is the best performing antenna, six positions are chosen for the simulations. In figure 2.1 those antenna positions are shown.

![Antenna positions](image)

Figure 2.1: Antenna positions

The chosen positions are at both bumpers, both side-mirrors, at the bottom of the car and at the top of the car. Both bumper positions were chosen to evaluate if it is possible to combine it with other communication systems, like sensor systems. Both side-mirrors, in order to see which are their technical parameters performances, as it is expected their behavior could be quite good. And the bottom antenna, because at the bottom of the car there is no design restrictions. The roof antenna position is chosen, because it is the common location for the communication antennas.

The antennas are simulated as omnidipol antennas with vertical polarization. And the antenna system is a SISO antenna system, which later can be extended to multiple antenna systems, MIMO.

2.2 Simulation tools

2.2.1 Roadcom

In order to create different C2C communications scenarios the “Roadcom” program is used. With this tool different scenarios are created by a stochastic model, the course of the road is created by a stochastic generation and the objects by stochastic positioning [4].

A lot of different parameters can be chosen, first of all the simulation time and sample time are going to be chosen depending the scenario, and these two parameters will define
the number of snapshots. Also the diffraction order and the number of reflections are adjustable.

The different environment objects are important, depending on the kind of scenario that is going to be created, urban or motorway scenario [6]. For example, in a motorway environment the vegetation is one of the main environment objects, as well as the crash barriers. On the other hand, in the urban scenario, figure 2.2, mainly there are buildings and in a smaller proportion of vegetation. Other objects in the urban scenario are the parked vehicles and the traffic signs.

![Urban scenario](image)

**Figure 2.2: Urban scenario**

Buildings are modelled as large single rectangular boxes and the trees are described also by rectangular boxes [12], an example of such creation is shown in figure 2.2.

Some other scenario parameters, like the size and the material of the cars are also determined. The different material parameters also have to be defined. The road, glass, metal and vegetation permittivity and permeability, as well as their surface roughness. In table 2.1 the used value for the materials are defined.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\epsilon$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation</td>
<td>10-6j</td>
<td>1</td>
</tr>
<tr>
<td>Building</td>
<td>5-0.1j</td>
<td>1</td>
</tr>
<tr>
<td>Glass</td>
<td>6+0.01j</td>
<td>1</td>
</tr>
<tr>
<td>Road</td>
<td>5-0.1j</td>
<td>1</td>
</tr>
<tr>
<td>Metal</td>
<td>10-1000000j</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 2.1: Material parameters*
Furthermore some parameters for the transmitter and receiver have to be defined, as the working frequency, position and type of antenna. And if is needed, the number of vehicles between transmitter and receiver.

Finally, the stochastically generated traffic parameters are defined, as the number of cars and trucks for each lane, the velocity of each kind of vehicle, the direction of the vehicles and the position of each lane relative to the middle of the road.

2.2.2 Calipso Tool

The Roadcom locates the antenna in the default position, the roof. To locate the antenna in six different positions, the default antenna position has to be shifted to other antenna positions, so in order to get the new placements a C++ program has been created, called Calipso.

With the first version of Calipso it is possible to shift the antenna positions, relative to the middle-bottom of the car.

In the second version of Calipso is extended to choose different cars on the scenario to perform as transmitter or receiver.

2.2.3 Ray-Tracing

Once the scenario is ready, the next step is to simulate the propagation of the waves in the scenario. The ray optics are based on the assumption that the wavelength $\lambda$ is small compared to the dimension of objects in the simulation scenario [11]. For higher frequencies the solution is more accurate but the computational effort is also higher.

So if that is considered, there are different multi-path components due to the influence of the objects that are located in the scenario, as created by Roadcom, like buildings, vegetation, moving cars, parked vehicles and crash barriers, all these objects are going to cause some propagation phenomena like reflections, diffractions and scattering [8]. As it is shown in figure 2.3.

In the simulations multiple reflections, multiple diffractions and single scattering is considered. To model the reflections Fresnel reflection coefficients are used. The diffractions are modelled by the UTD and the scattering from the trees is incoherent calculated by distributed Lamberrian scattering sources [7]. The Ray-Tracing can work with a maximum of five reflections, more than five reflections do not make sense as the contribution to the receiving signal is negligible due to the high losses. The simulations are done with a reflection order of four and a diffraction order of two for each path, not to have such large simulation time.

These propagation phenomenas will influence in a multi-path propagation, which is the sum of attenuated, delayed and phase shifted replicas of the transmitted signal. As it is seen in figure 2.3.
Figure 2.3: Multi-path propagation


3 Channel Characteristics

The different channel parameters are described in this chapter.

3.1 Narrow-band Analysis

The narrow-band analysis is determined by the long-term and the short-term fading component of the received signal at a single frequency of 5.9 GHz. Also in the narrow-band the time variant behavior is analyzed.

3.1.1 Long-term Fading

The long-term fading component is the local mean value of the absolute value of the complex received signal, and it is calculated from the absolute complex transmission factor of channel transfer function by averaging over $40\lambda$.

The channel transfer function $H_{TP}(t)$ can be divided into a short-term and a long-term fading component:

$$|H_{TP}(t)| = l(t)s(t) \quad (3.1)$$

The long-term fading component $l(t)$ is the result of averaging $|H_{TP}|$ during the desired sample time $T_S$:

$$l(t) = \frac{1}{T_S} \int_{t-T_S/2}^{t+T_S/2} |H_{TP}(\varepsilon)|d\varepsilon \quad (3.2)$$

As it is shown in the figure 3.1, the long-term fading is the slow change of the signal strength during a large time interval.

If the amplitudes of the long-term fading are compared, high amplitudes mean high signal-to-noise ratios and this could conclude in wider ranges for a communication system, further distances or lower bit error rates.

The long-term fading is caused by multi-path short-term by the interference.

3.1.2 Short-term Fading

The short-term fading shows the fast changes in the signal strength during a short time interval [5], figure 3.2.

If there are fast signal drops, this could cause system outages, and this could bring data loss.

The short-term fading can be plotted by different forms, and in this case the “Cumulative Distribution Function” (CDF) is chosen, which provides the probability that the
signal strength is equal or less than a certain value and indicates the probability of the deviation from the local mean value of the signal, figure 3.3.

The CDF can be understood with the 3.3 formula. The $F_S(a_S)$ is the estimation of the short-term fading when the value of the short-term fading is smaller than a threshold $a_S$ during an observation time $T_O$.

$$F_S(a_S) = \frac{\Delta T_U(s(t) \leq a_S)}{T_O} \quad (3.3)$$
3.1.3 Doppler Shift and Doppler Spread

The time-variant behavior of the C2C communications channel is characterized by the Doppler spectrum. Not only the transmitter and the receiver influence the Doppler spectrum also the other moving vehicles and the objects of the environment. Due to these objects there is a huge influence of the Doppler effect in the channel behavior [9].

The Doppler shift is influenced by the relative velocity between the cars and the angle of arrival.

The celerity with which the low pass transfer function $H_{TP}(t)$ is changed causes the correspondent autocorrelation function, described by $r_{HH}^{t}(\Delta t)$ [2][10]. The calculation for $r_{HH}^{t}(\Delta t)$ during a sample time of $T_S$ is:

$$r_{HH}^{t}(\Delta t) = \int_{0}^{T_s} (H_{TP}(t)) * H_{TP}(t - \Delta t) dt \quad (3.4)$$

The Fourier transformation for the time variant autocorrelation function $r_{HH}^{t}(\Delta t)$ is the Doppler spectrum $S_{HH}(f_D)$:

$$r_{HH}^{t}(\Delta t) \circlearrowleft S_{HH}(f_D) = |H_{TP}^{D}(f_D)|^2 \quad (3.5)$$

$$H_{TP}^{D}(f_D) \circlearrowleft H_{TP}(t) \quad (3.6)$$

The measure of the Doppler spectrum $S_{HH}(f_D)$ in a determined moment $t = t_0$ is:
The Doppler spectrum is characterized by two different parameters, the mean Doppler $f_D$ and the Doppler spread $\sigma_{f_D}$.

The mean Doppler is the average value:

$$
\bar{f}_D = \frac{\int_{-\infty}^{\infty} f_D S_{HH}(f_D) df_D}{\int_{-\infty}^{\infty} S_{HH}(f_D) df_D} \quad (3.8)
$$

The Doppler spread is defined as two times the variation of the Doppler spectrum, if the Doppler spectrum is assumed as a probability density function.

$$
\sigma_{f_D} = 2 \sqrt{\frac{\int_{-\infty}^{\infty} f_D^2 S_{HH}(f_D) df_D}{\int_{-\infty}^{\infty} S_{HH}(f_D) df_D} - \overline{f}_D^2} \quad (3.9)
$$

The higher the value of the Doppler spread $\sigma_{f_D}$, the faster the changes in the channel and the more difficult would be to receive the transmitting signal correctly.

If the Doppler spread is smaller than the bandwidth of the transmitted signal, most of the transmitted power will be in the band.

### 3.2 Wide-band Analysis

In the wide-band behavior of the channel is analyzed by the frequency selectivity.

#### 3.2.1 Mean Delay and Delay Spread

The origin of the characterization of the frequency selective channels is the frequency autocorrelation function $r_{HH}^{f}(\Delta, t)$ of the time-variant transfer function $H^{TP}(\nu, t)$ which is defined as [2]:

$$
H^{TP}(\nu, t) = \sum_{n=1}^{N(t)} A_n(t) e^{-j2\pi(f_0+\nu)\tau_n(t)} \quad (3.10)
$$

$$
r_{HH}^{f}(\Delta f, t) = \int_{-\infty}^{\infty} (H^{TP}(\nu, t)) * H^{TP}(\nu + \Delta f, t) d\nu \quad (3.11)
$$

$$
r_{HH}^{f}(\Delta f, t) \circ \bullet P(\tau, t) = |h^{TP}(\tau, t)|^2 \quad (3.12)
$$

The Power Delay Profile (PDP) is the relative received power as a function of the delay time. In the PDP can be recognize the power and the arrival time of each multi-path component:
\[ P(\tau, t) = \sum_{n=1}^{N(t)} |A_n(t)|^2 \delta(\tau - \tau_n(t)) \] (3.13)

The delay spread is the variation of the time impulse response and gives a measure for the time-dispersive and frequency-selective behavior of the channel.

\[ \sigma_{\tau}(t) = \sqrt{\frac{\int_{-\infty}^{\infty} \tau^2 P(\tau, t)d\tau}{\int_{-\infty}^{\infty} P(\tau, t)d\tau}} - \left( \frac{\int_{-\infty}^{\infty} \tau P(\tau, t)d\tau}{\int_{-\infty}^{\infty} P(\tau, t)d\tau} \right)^2 \] (3.14)

Similar to the Doppler spread is the delay spread, if the symbol time is smaller than the delay spread there will be frequency selective fading, therefore a very complicated system will be needed to rebuild the transmitted signal in the receiver.
4 Simulation Results

In this chapter the analysis of the simulated scenarios is done. Four different scenarios are evaluated, three of them in motorway and one in urban environment. In the motorway a LOS case, a NLOS case and a passing scenario. In the urban scenario only a passing scenario is analyzed.

Before explaining the obtained results from the simulations, some other important parameters for the simulations are mentioned.

4.1 Sample Time and Interpolation Factor

In order to reduce the duration of the simulation time, as the simulations for C2C communications can take very long, interpolation is used [7].

With the Roadcom it is possible to define different number of snapshots for each simulation. The number of snapshot is the result of dividing the total simulation time by the sample time.

The superposition of the paths originates interference, and that is why there are fast changes in the signal strength, called short-term fading, chapter 3.1.2. In order to detect all these fast changes the receiving signal must be sampled with $T_s$.

The sample time $T_s$ is calculated by the maximum Doppler frequency $f_{D,max}$.

$$T_s = \frac{1}{f_s} \leq \frac{1}{2f_{D,max}} \quad (4.1)$$

To find out the maximum Doppler frequency the maximum velocity of the cars $v_{max}$ has to be taken into account, the transmitting frequency $f_0$, the velocity of the light $c_0$ and also the $m$ factor. The $m$ factor is different depending the scenario, $m = 4$ for urban scenarios and $m = 2$ for motorway scenarios.

$$f_{D,max} = mv_{max}\frac{f_0}{c_0} \quad (4.2)$$

If the sample time $T_s$ is too low for a simulation, a lot of snapshots will be obtained, so that the sample time $T_s$ should be reduced. To achieve this objective an interpolation factor is defined $F_{int}$. A higher value for the sample time is defined by $T'_s$.

$$F_{int} = \frac{T'_s}{T_s} \quad (4.3)$$

The interpolation factor $F_{int}$ value is different for each scenario and visibility case, if there is LOS or NLOS. In table 4.1 these values are shown.
It is important to have knowledge of these maximum interpolation factor values before starting with the simulations.

The total time of the simulations is defined as 10 s, which is the real driving time.
4.2 Motorway LOS Scenario

In the first scenario the LOS case in the motorway environment is analyzed. In this scenario both cars, transmitter and receiver, are driving in the same direction and also in the same lane. In order to get LOS there are no vehicles between transmitter and receiver.

In the scenario are other vehicles driving in both directions. The environment at both sides of the road is vegetation. Also crash barriers are modelled in the left side, right side and middle of the motorway, figure 4.1.

Figure 4.1: Motorway LOS scenario

The velocity of the transmitting car is around 170 km/h for the whole simulation. For the receiving car in the beginning of the simulation its velocity is 190 km/h and after 10 s is decreased until 180 km/h. So that the relative velocity is established to 20 km/h, so that the mean Doppler is around 120 Hz, as there is LOS there is not much influence of other vehicles in the main paths.

The distance between both cars is 125 m in the first snapshot and around 80 m in the end of the simulation, so that the distance is decreasing over time.

In this scenario an interpolation factor $F_{int}$ of 45 is used in order to get a sample time $T_S$ of 23 ms. With this sample time would be possible to recognize Doppler frequencies of 2200 Hz.
4.2.1 Long-term Fading and Short-term Fading

The first results for the motorway scenario are the long-term and short-term fading, both parameters are shown and analyzed in this section. The different antenna combinations are compared with each other.

The first graphic is the long-term fading plot for the case where the transmitter antenna is at the roof of the car and the different receiving antenna positions are shown by different colors, figure 4.2.

![Figure 4.2: Motorway LOS long-term fading transmitter at the roof](image)

Different analysis can be made by comparing the performance of the different receiving antenna positions. The first perception is that the back bumper antenna position at the receiver is behaving worst during the whole simulation, its pathloss is constant and always around 108 dB, that is due to its NLOS configuration in this scenario, as the transmitting car is always in front of the receiving car. About the best antenna combination in this particular case it has to be mentioned that both side-mirrors are the best performing ones during the 10 s simulation with a pathloss of 85 dB and lower, figure 4.2.

In addition, most of the antenna combinations are increasing their received power during the simulation, that is caused by the decrease of the distance between the transmitter and receiver over time.

Furthermore the roof-roof antenna combination is decreasing its received power. This can be explained by the “Two-Ray Theory”, see chapter 4.2.2. The “Two-Ray Theory” shows the influence of the first two main paths in the received power. This influence can be bad for the behavior of the long-term fading and as a result of the destructive
interference between the first two paths. In this case a clear influence of the destructive interference can be seen in the plot after the fifth second, where the pathloss is increasing until the end of the simulation.

Moreover there is also another distinctive change in the performance of the long-term fading. Until the sixth second mainly all the antenna combinations have a irregular behavior, as they have a lot of peaks. After this time their behavior is quite more smooth. The reason for this change is that in the last four seconds, there is a lack of cars in the other side of the road, so that the reflections in the first seconds due to the vehicles in the other side mainly disappeare in the end. This effect can be appreciated in the figure 4.3.

Figure 4.3: Motorway LOS general view

In order to finish with the analysis of the long-term fading in the motorway LOS scenario, where the transmitter is at the roof, therefore is to mention that the big peaks during the whole simulations are interactions with other vehicles. In figure 4.4 that effect can be seen by the truck between transmitter and receiver. In a certain moment, when the truck is more or less in the middle of both vehicles, a lot of paths are reflected at the truck, as the reflection points on the truck show.

Figure 4.4: Reflection points on the truck

For the short-term fading analysis for the same antenna combinations the figure 4.5 is shown:

In the CDF graph the fast changes of the signal strength are shown. So the most straight the lines are, the better the behavior of the antenna combination. In this case a bigger change in the short-term fading values is seen for the receiving antenna at the back of the car, so again this is the worst antenna combination. The other antenna combinations are more similar and most of them are very close to 0 dB for low probabilities.
To sum up about the short-term fading (CDF) values it is important to mention that in most of the cases the behavior of the different antenna combinations in the short-term fading is equal to the good and bad performing antenna combinations in the long-term fading.

In table 4.2 the values for all the antenna combinations for the long-term fading are shown.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>116</td>
<td>93</td>
<td>89</td>
<td>88</td>
<td>95</td>
<td>85</td>
</tr>
<tr>
<td>B. Back</td>
<td>127</td>
<td>109</td>
<td>105</td>
<td>105</td>
<td>112</td>
<td>108</td>
</tr>
<tr>
<td>M. Left</td>
<td>108</td>
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<td>85</td>
<td>84</td>
<td>93</td>
<td>82</td>
</tr>
<tr>
<td>M. Right</td>
<td>108</td>
<td>89</td>
<td>84</td>
<td>84</td>
<td>94</td>
<td>82</td>
</tr>
<tr>
<td>Bottom</td>
<td>104</td>
<td>95</td>
<td>93</td>
<td>92</td>
<td>100</td>
<td>88</td>
</tr>
<tr>
<td>Roof</td>
<td>116</td>
<td>85</td>
<td>83</td>
<td>83</td>
<td>86</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 4.2: Motorway LOS pathloss in dB

After analyzing the values for the different antenna combinations, the next conclusions can be done. Both side-mirror antennas are performing very well as transmitter and receiver, so these combinations are good ones. In addition, there are also some other
good combinations when the transmitting antenna is placed at the roof of the car and the receiver at both side-mirror antenna positions. The other way around, when the transmitter is at both side-mirror antennas and the receiver at the roof antenna position, the behavior is also very good.

In appendix A.1 all the long-term fading figures for the motorway LOS scenario can be found.
4.2.2 Two-Ray Theory

The “Two-Ray Theory” as mentioned before, is the influence of the direct path and the path reflected on the ground in the received power [2]. The influence of the second main path, which is the one reflected on the ground, compared to the main path can have as a result a non-desired consequence, a destructive interference, as it is shown in figure 4.6.

\[
P_R = \left(\frac{\lambda_0}{4\pi}\right)^2 P_T G_T G_R \left| \frac{e^{-jk_0d_1}}{d_1} + R_{p,s}(\theta, \varepsilon_r, \mu_r) \frac{e^{-jk_0d_2}}{d_2} \right|^2
\]

(4.4)

Figure 4.6: Two-Ray Theory

The sum of the phases of the main path and the reflected path on the floor can have as a result the worst of the cases, a destructive interference, that is why is important to analyze the influence of this effect in the scenario. The “Two-Ray Theory” analyzes the dependence between the distance between the cars, the height of the receiving antenna and the transmitting antenna position.

In figure 4.7 the influence of transmitting from the roof antenna position by a transmitter height of 1.4 m is shown. The behavior for different distances between the cars(x-axis) and the height of the receiving antenna position(y-axis) is shown:

Figure 4.7: Two-Ray Theory transmitter roof height
In figure 4.7 the influence of the long-term fading decrease for the roof-roof antenna combination can be also seen, and verify that the decrease in the received power is due to the “Two-Ray Theory”. As the transmitting antenna position for this plot is at the roof and checked for the receiving height at the same position, 1.4 m, the influence from 80 m to 100 m can be seen, where the pathloss is increasing for those distances until 100 dB. Those are more or less the same values which can be seen for the long-term fading plot for the roof-roof antenna combination in the previous section, figure 4.2. Although in the long-term fading there is the influence of the other four reflections for each path, it can be seen that the influence of the destructive interference is crucial.

In figure 4.8, the theoretical plot for the “Two-Ray Theory” is shown in the case where the transmitting position is at 0.8 m, where the side-mirrors are located.

![Two-Ray Theory plot](image)

Figure 4.8: Two-Ray Theory transmitter mirror height

If the receiving height is considered at the same position of the transmitting antenna position a better performance of the pathloss values are shown. For the same distances between the cars, 80-100 m, the values of the pathloss are lower, around 85 dB.

To make a final conclusion for the “Two-Ray Theory” a better performance for the antennas located in both side-mirror antenna positions is shown for this scenario, so that this is the optimum height to locate the antennas.
4.2.3 Doppler Effect

The Doppler effect is the consequence of the influence of the moving cars in frequency.

In figure 4.9 the Doppler effect can be explained for the theoretical case where there is only the influence of a moving transmitter or receiver. When the receiver is getting closer to the transmitter the Doppler frequency is positive and when it is driving away the value for the Doppler frequency is negative. The shown formula 4.5 is only for this theoretical case.

\[ f_D = \frac{v_r}{c_0} f_0 \cos(\alpha) \]  

(4.5)

If the Doppler shift \( f_D \) and the angle of arrival \( \alpha \) are plotted in the same graph, for the theoretical previous case a cosines plot is the result, figure 4.10. When the angle of arrival, which is the angle between the direction of the receiver and the direction of each path arriving to the receiver, is 0°, for example, the maximum Doppler frequency will be achieved, and on the contrary if the angle of arrival is 180° or -180° the negative value for the maximum Doppler frequency will be the result. When the transmitter and the receiver are passing by each other, in other words when the angle of arrival between them is 90°, the Doppler frequency is zero Hz.

On the other hand if the same graph is plotted for the motorway LOS scenario, figure 4.11, differences with reference to the previous theoretical case will be seen. A big
influence have other driving cars in the environment and the movement of receiver and transmitter can be appreciated. In graph 4.11 the Doppler shift is plotted versus the angle of arrival. Here several differences can be seen with reference to the previous theoretical case.

Figure 4.11: Doppler shift in motorway scenario

In order to explain the behavior of the Doppler shift in this case, the figure 4.12 is added. The figure shows the different kind of paths that can influence the different Doppler shift values.

Figure 4.12: Doppler shift paths

In the motorway LOS scenario is possible to have doubled this Doppler frequency. A path can be reflected in a vehicle in the other driving direction, so that the relative velocity is doubled, as a result the Doppler frequency value is also doubled.

In figure 4.11 also some negative values for the Doppler frequency can be appreciated. The negative values are in this case due to the scattering on the trees or reflections in other cars that are coming from the back of the receiver. For near 180° the lowest values for the Doppler frequency can be seen, in this case the reflections are coming from the side of the road where the cars are driving in the other direction. On the other hand, in the negative values of the angle of arrival there are not so high negative Doppler frequencies, on this side the cars are driving in the same direction, so that the relative velocities are not so high.

In the motorway LOS scenario the zero Hz value for the Doppler frequency is not got with 90° angle of arrival, but with 35° - 40°. This can be explained by the compensation
of the Doppler frequency at this position, figure 4.12. In a point between the transmitter and the receiver, the path coming from the transmitter has a negative Doppler frequency, as the transmitter is driving away, but the receiver is getting closer to this point, so positive Doppler frequency. Both Doppler frequencies get compensated and the result is a zero Hz Doppler frequency.
4.2 Motorway LOS Scenario

4.2.4 Doppler Spectrum

As it was mentioned before in the motorway scenarios the Doppler effect is one of the most important considerations. In this case, in motorway LOS scenario is also important and in the next paragraphs different plots for different antenna combinations will be analyzed.

The first Doppler spectrum figure 4.13 is for the back-back antenna combination.

![Doppler Spectrum Back Bumper-Back Bumper](image)

Figure 4.13: Motorway LOS Doppler spectrum back bumper-back bumper

First of all, the most remarkable issue in this Doppler spectrum plot is, that there are a lot of paths for the Doppler shift during the 10 s simulation, due to the NLOS case for this antenna combination. There are two main paths around 100 Hz and -100 Hz, one is the result of the path between both cars and the other the consequence of a strong reflection from the back of the receiver, as one has a positive and the other a negative Doppler frequency.

Otherwise, the Doppler spectrum is full of curved paths, which are the result of the scattering at the trees. There are positive and negative with different Doppler frequency values, that is because the vegetation is everywhere in the scenario.

In the next case, figure 4.14, the left-mirror/left-mirror antenna combination is analyzed.

In this case there is LOS between the antenna position at the transmitter and the antenna position at the receiver, as both of them are in the left-mirror position. Due to these locations there is a main Doppler shift path in the Doppler spectrum, the value of this main path is the result of the relative velocity between both cars.
Figure 4.14: Motorway LOS Doppler spectrum left-mirror/left-mirror

The effect of the scattering at the trees is also visible, but there are not so strong paths as in the back bumper - back bumper antenna combination, where there is NLOS. The last example for the Doppler spectrum of the motorway LOS scenario is the roof-roof antenna combination, figure 4.15.
In the Doppler spectrum of the roof-roof antenna combination a change in the behavior of the antenna combination can be seen, as it was mentioned in the long-term fading plot. After the sixth second a decrease in the received power was seen, cause that in the Doppler spectrum the effect of the scattering on the trees is bigger than in the first seconds, where the main path is stronger and its influence more important.

Figure 4.15: Motorway LOS Doppler spectrum roof-roof
4.2.5 Doppler and Delay Spread

The Doppler spread and the delay spread are both very important parameters for the design of an OFDM-system, so their values have to be as low as possible, as they are critical for the transmission.

For the Doppler spread calculation the short-term fading parameter is used, and a dynamic range of 40 dB is taken into account in order not to consider noise values. In table 4.3 the values for the Doppler spread are summarize.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>1035</td>
<td>151</td>
<td>20</td>
<td>56</td>
<td>85</td>
<td>34</td>
</tr>
<tr>
<td>B. Back</td>
<td>188</td>
<td>789</td>
<td>627</td>
<td>657</td>
<td>674</td>
<td>822</td>
</tr>
<tr>
<td>M. Left</td>
<td>735</td>
<td>42</td>
<td>11</td>
<td>30</td>
<td>103</td>
<td>11</td>
</tr>
<tr>
<td>M. Right</td>
<td>764</td>
<td>74</td>
<td>16</td>
<td>26</td>
<td>147</td>
<td>14</td>
</tr>
<tr>
<td>Bottom</td>
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<td>173</td>
<td>150</td>
<td>197</td>
<td>166</td>
<td>99</td>
</tr>
<tr>
<td>Roof</td>
<td>1037</td>
<td>20</td>
<td>15</td>
<td>13</td>
<td>53</td>
<td>155</td>
</tr>
</tbody>
</table>

Table 4.3: Motorway LOS Doppler spread in Hz

To make a final conclusion for the Doppler spread in this scenario, it has to be mentioned that the best values are for the transmitter at the left-mirror antenna and receiving from the front bumper, both side-mirror antenna positions or roof. Moreover the receiving antenna at the roof is also performing very well due to its low values in the Doppler spread when the transmitter are the back bumper and both side-mirror antennas.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>0.54</td>
<td>0.001</td>
<td>0.01</td>
<td>0.01</td>
<td>0.001</td>
<td>0.02</td>
</tr>
<tr>
<td>B. Back</td>
<td>0.33</td>
<td>0.15</td>
<td>0.13</td>
<td>0.15</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>M. Left</td>
<td>0.38</td>
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<td>0.06</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>M. Right</td>
<td>0.55</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.51</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Roof</td>
<td>0.79</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 4.4: Motorway LOS delay spread in µs

The delay spread values, table 4.4, are quite similar, and there are a lot of low values. It is more interesting to mention the bad values of the delay spread, which are all the receivers which are transmitting from the front bumper and all the transmitting positions that are receiving at the back bumper, so all the NLOS combinations. In appendix A.5 all the delay spread figures for the motorway LOS scenario can be found.
4.3 Motorway NLOS Scenario

The second scenario is also in the motorway environment but with NLOS between transmitter and receiver. Both cars are driving in the same direction and lane, but there are some vehicles between transmitter and receiver, that cause the NLOS case.

As in the previous scenario in this scenario there are also located other vehicles in both driving directions, vegetation in both sides of the road, as well as crash barriers in the left side, right side and middle of the road, figure 4.16.

![Figure 4.16: Motorway NLOS scenario](image)

The velocity of the transmitting car is around 140 km/h and for the receiving car 80 km/h. The receiver is driving behind a truck, which is the NLOS obstacle.

The distance between both cars is 220 m at the beginning of the simulation and 365 m in the end of the simulation, so that the distances between them is increasing.

An interpolation factor $F_{int}$ of 45 is used in order to get a sample time $T_S$ of 23 ms, as in the previous scenario. This sample time will give the possibility to have a Doppler frequencies of 2200 Hz.
4.3.1 Long-term Fading and Short-term Fading

In the next paragraphs the long-term fading is analyzed for the motorway NLOS scenario. In the figure 4.17, the long-term fading for the transmitter at the front of the car is shown.

![Figure 4.17: Motorway NLOS long-term fading transmitter at the front bumper](image)

The front bumper antenna position as a transmitter, as it will be shown later, is one of the worst transmitters in this scenario. The average value of the pathloss for the different receivers are the highest ones in the motorway NLOS scenario, all of them are above 110 dB, as it can be appreciated in figure 4.17, where the best performing receive antenna is at the bottom.

The next case is for the transmitter at the right-mirror antenna, figure 4.18.

In the right-mirror transmitting antenna, figure 4.18, it can be seen that in general the mean values for the pathloss are lower than in the previous case, due to that the right-mirror antenna position as a transmitter antenna is one of the best performing ones for this scenario. It can also be appreciated a big increase in the pathloss values before the second second. A vehicle, is intercepting the receiving paths during a short time interval in the right side of the transmitter and receiver. In this case the bottom antenna position is also the best performing receiving antenna position.

In the figure 4.19 the long-term fading plot can be seen when transmitting from the right-mirror antenna.

The main difference of the bottom transmitting antenna position in comparison with the previous transmitting antenna positions is that more peaks can be appreciate in the plot. Due to the receiving antenna positions are receiving the paths after more
4.3 Motorway NLOS Scenario

Figure 4.18: Motorway NLOS long-term fading transmitter at the right-mirror

Figure 4.19: Motorway NLOS long-term fading transmitter at the bottom

reflections, in this case the receiving antenna positions are behaving quite equal and their mean value for the pathloss is around 100-110 dB for all of them.

After analyzing the long-term fading for some of the transmitters in the motorway NLOS scenario, now the short-term fading values are going to be analyzed in the next pages. The first plot is for the transmitter at the front bumper, figure 4.20.

Looking to the CDF figure 4.20 of the front bumper transmitter, it is shown that the
values are not very good, as the lines are not very vertical, and if the 10% probability values are analyzed, as a comparing reference, it can be seen that all the receiving antenna positions values are between \(-5\) and \(-10\) dB fading amplitude. So that this bad 10% probability values also match with the bad behavior of the same transmitter for the long-term fading values, as mentioned before.

The CDF graph for the short-term fading when the transmitting antenna is in the
right-mirror antenna, 4.21, shows in general a better behavior of the receiving antennas. It must be mentioned that the back bumper antenna position is the worst performing one, as the other receivers have acceptable values for 10% probability. All of them are between -5 and 0 dB. In conclusion the performance of the right-mirror antenna is better than the transmitter in the front bumper for example, the one analyzed previously.

The last short-term fading plot is for the transmitter at the bottom antenna, figure 4.22.

![Short-term fading plot](image)

**Figure 4.22: Motorway NLOS short-term fading transmitter at the bottom**

As seen for the long-term fading values, the transmitter at the bottom of the car did not have so low values, and that can be reflected also in the short-term fading plot, by analyzing the fading amplitude values for the probability of the 10%. The values for the different receivers are around -7 and -2 dB, which show quite a bad performance compared to other combinations for the short-term fading.

In table 4.5 all long-term fading values for the motorway NLOS scenario are summed up.
### Table 4.5: Motorway NLOS pathloss in dB

Analyzing the table above the best performing antenna combinations can be chosen for the motorway scenario: transmitting from both side-mirror antennas and receiving from the bottom of the car. But there are also good combinations when the receiving antenna is at the bottom and transmitting from the back bumper or roof of the car. Finally it must be commented the both side-mirror antennas as transmitter and receiver also have good behavior for this scenario.

In appendix A.2 all the long-term fading figures for the motorway NLOS scenario can be found.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
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<td>98</td>
<td>99</td>
<td>104</td>
<td>105</td>
</tr>
<tr>
<td>B. Back</td>
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<td>117</td>
<td>116</td>
<td>117</td>
<td>113</td>
<td>117</td>
</tr>
<tr>
<td>M. Left</td>
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<td>104</td>
<td>98</td>
<td>98</td>
<td>101</td>
<td>105</td>
</tr>
<tr>
<td>M. Right</td>
<td>117</td>
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<td>98</td>
<td>98</td>
<td>100</td>
<td>105</td>
</tr>
<tr>
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<td>94</td>
<td>89</td>
<td>88</td>
<td>102</td>
<td>99</td>
</tr>
<tr>
<td>Roof</td>
<td>126</td>
<td>103</td>
<td>103</td>
<td>105</td>
<td>107</td>
<td>103</td>
</tr>
</tbody>
</table>
4.3.2 Doppler Spectrum

In order to see the influence of the Doppler shift in the motorway NLOS scenario, some of the Doppler spectrums will be analyzed in the next paragraphs. The first one is the left-mirror/left-mirror antenna combination, figure 4.23.

In the first view several paths of Doppler shift can be seen, the strongest path is a negative Doppler frequency path, which is a reflection at a car behind the receiver. Some of the other main paths have a positive value which are reflections at objects, which are getting closer to the receiver. There is also another important path in the Doppler spectrum which has a high positive Doppler frequency of 900 Hz in the beginning. This path becomes after the fourth second to negative values, about -1000 Hz. The reason of this behavior is a reflection in a car which is driving in the opposite direction. First the values are positive because the car, where the strong reflection is happening, is getting closer to the receiver from the other direction, but once it is passed by, the receiver is getting the paths from the back of the car. Now the cars are driving away from each other. The influence of the scattering on the trees can be appreciated in the curved lines which are plotted with a smoother color, due to the lower received power of those paths.

The next Doppler spectrum is the right-mirror/right-mirror antenna combination, figure 4.24.

In this case there is quite a big difference to the previous Doppler spectrum. In this plot the influence of the right side traffic can be seen and in the previous plot mainly the influence of the left side traffic was appreciated. The main path is quite similar, but then there is another quite strong curved line. As mentioned before this is the influence of a car that is reaching the receiver in the beginning and then are passing by. The
influence of the scattering at the trees is not so important in this case, cause of the high relative power of the plotted Doppler path.

The last Doppler spectrum plot for the motorway NLOS scenario is the bottom-bottom antenna combination, figure 4.25.
In this combination the result is completely different to the other ones. As the Doppler spectrum has several straight paths. The negative straight paths are due to strong reflections in the neighboring cars and received at the back of the receiver. As it was mentioned in the previous parameters, long and short-term fading, this antenna combination has a lot of reflections in other cars, and that is what it is also verify in this picture.
4.3.3 Doppler and Delay Spread

With the aim of analyzing the values of the Doppler spread and the delay spread, the next tables, table 4.6 and table 4.7 are shown.

The first, table 4.6, is for the Doppler spread, the values are calculated from the short-term fading values.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
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<td>43</td>
<td>47</td>
<td>123</td>
<td>111</td>
<td>336</td>
</tr>
<tr>
<td>B. Back</td>
<td>201</td>
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<td>440</td>
<td>377</td>
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<td>462</td>
</tr>
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<td>M. Left</td>
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<td>202</td>
<td>225</td>
<td>118</td>
<td>206</td>
<td>274</td>
</tr>
<tr>
<td>M. Right</td>
<td>461</td>
<td>97</td>
<td>103</td>
<td>166</td>
<td>125</td>
<td>288</td>
</tr>
<tr>
<td>Bottom</td>
<td>559</td>
<td>27</td>
<td>70</td>
<td>166</td>
<td>139</td>
<td>222</td>
</tr>
<tr>
<td>Roof</td>
<td>680</td>
<td>139</td>
<td>212</td>
<td>280</td>
<td>202</td>
<td>259</td>
</tr>
</tbody>
</table>

Table 4.6: Motorway NLOS Doppler spread in Hz

Having the lowest Doppler spread value is the important fact in this case, so in this case the next antenna combinations are the admissible ones. When the transmitter is at the back bumper or left-mirror and the receiver antenna positions are at the front bumper or bottom of the car.

The next, table 4.7, is for the delay spread.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>B. Back</td>
<td>0.23</td>
<td>0.21</td>
<td>0.3</td>
<td>0.31</td>
<td>0.21</td>
<td>0.28</td>
</tr>
<tr>
<td>M. Left</td>
<td>0.14</td>
<td>0.06</td>
<td>0.09</td>
<td>0.04</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>M. Right</td>
<td>0.14</td>
<td>0.06</td>
<td>0.05</td>
<td>0.07</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.52</td>
<td>0.04</td>
<td>0.11</td>
<td>0.13</td>
<td>0.17</td>
<td>0.11</td>
</tr>
<tr>
<td>Roof</td>
<td>0.16</td>
<td>0.09</td>
<td>0.08</td>
<td>0.12</td>
<td>0.09</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 4.7: Motorway NLOS delay spread in µs

For the delay spread values in the motorway NLOS scenario there are a lot of low values that can be taken as good values. Indeed, there are only a few values that are superior. The ones obtained receiving from all the receiving positions when the transmitter is at the front bumper and for some of the receivers when the transmitter is at the roof antenna position.

In appendix A.6 all the delay spread figures for the motorway NLOS scenario can be found.
4.4 Motorway Passing Scenario

The third simulated scenario is the passing scenario in the motorway. In this case the transmitter is driving in one direction and the receiver in the opposite. In the beginning they are getting closer to each other, then there is a moment where they are passing by and afterwards they are driving away from each other. The distance between both cars in the beginning is 100 m, then they decrease the distance between them until they are in the same position and then the distance is again increasing until 600 m. In the scenario there are other vehicles in both driving directions and also vegetation in both sides of the road. As well as crash barriers in the left side, right side and middle of the road, figure 4.26.

![Diagram of Motorway Passing Scenario](image)

Figure 4.26: Motorway passing scenario

The velocity of the transmitting car is around 200 km/h in the beginning of the simulation. For the receiving car the velocity is around 100 km/h. So that the relative velocity is established to 300 km/h.

In this scenario in the beginning the interpolation factor $F_{int}$ was established to 45, so that the sample time $T_S$ was of 23 ms and the maximum Doppler frequency of 2200 Hz. Otherwise, later it was seen that the sample time was not enough to recognize all the Doppler frequencies so that the interpolation factor $F_{int}$ was increased to 90, so that Doppler frequencies of 4400 Hz were also recognize.
4.4.1 Long-term Fading and Short-term Fading

The first graph of the long-term fading, figure 4.27, in the motorway passing scenario is transmitting from the left-mirror antenna position and receiving from all the other antenna positions.

![Motorway passing long-term fading transmitter at the left-mirror](image)

Figure 4.27: Motorway passing long-term fading transmitter at the left-mirror

As it is seen in this first picture of the long-term fading, an increase in the received power can be appreciated, in that moment the transmitter and receiver are passing by, so that is the moment where they are at closest one to each other. The distance between them is decreasing until that moment, so that the pathloss is also decreasing. After they have passed by and they start driving away the distance between them is increasing again until 600 m, so the pathloss is again increasing.

In addition, some other analysis can also be made by this graph about the behavior of the antenna combinations. First of all, in the moment they are passing by a change between the behavior of the back bumper and the front bumper can be clearly seen, as before the moment they are close to each other, the back bumper has the worst performance, as there is no LOS probability, and in the moment they are driving away this same performance is for the front bumper antenna position. Another interesting comment in this plot is the same performance of both side-mirror antennas around 100 m, after a decrease in the received power both of them have an increase. Both side-mirror antennas have the same performance and that is caused of the “Two-Ray
Here the dependence of the height of the antennas and the distance between the cars have as a result different pathloss values, and in this case both antennas have the same height and the same distance between the receiver and transmitter.

In the second graph the transmitting antenna position is at the right-mirror, figure 4.28.

Figure 4.28: Motorway passing long-term fading transmitter at the right-mirror

In this case the performance of the right-mirror antenna as a transmitter is shown. In a first view, comparing with the previous long-term fading plot, a bad behavior of this transmitter can be seen, as it is not seen so clearly the moment were both cars, transmitter and receiver, are passing by. As in the previous plot, figure 4.27, also in this one the change between the back bumper and front bumper can be appreciated. In the moment where the distance between the cars is 180 m a decrease in the pathloss can be observed, in the Doppler spectrum section this behavior will be explained more in detail. The cause is that before this moment there is NLOS between transmitter and receiver, but after that moment there is almost for all the receiving antenna positions LOS. That is why there is an increasing in the received power.

Some of the short-term fading figures for the motorway passing scenario will be analyzed in the next page. The first, figure 4.29, will be for the transmitter in the left-mirror.

The short-term fading values are quite similar for the different receiving antenna positions, and all of them have good values for the CDF, as it can be seen for the 10 %
probability the values are all around -2 dB.

In order to compare the difference of both side-mirror antenna positions as transmitters, the right-mirror antenna as a transmitter for the short-term fading plot is shown next, 4.30.

Comparing both graphs, in this last one a clear difference is shown. The lines are more curved, which means that for 10% probability the values are quite worst, around -7 dB. The difference in the performance of these both transmitters can be explain by seen that if the transmitter is in the right-mirror antenna position and the receiver is passing by from the left side of the transmitter. The LOS probability is much more difficult that if the transmitter is in the left side-mirror.

Summing up all long-term fading values the results are shown in table 4.8.
Table 4.8: Motorway passing pathloss in dB

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>94</td>
<td>110</td>
<td>96</td>
<td>112</td>
<td>95</td>
<td>107</td>
</tr>
<tr>
<td>B. Back</td>
<td>110</td>
<td>91</td>
<td>92</td>
<td>106</td>
<td>92</td>
<td>102</td>
</tr>
<tr>
<td>M. Left</td>
<td>94</td>
<td>91</td>
<td>85</td>
<td>104</td>
<td>86</td>
<td>89</td>
</tr>
<tr>
<td>M. Right</td>
<td>99</td>
<td>93</td>
<td>90</td>
<td>107</td>
<td>90</td>
<td>93</td>
</tr>
<tr>
<td>Bottom</td>
<td>95</td>
<td>93</td>
<td>85</td>
<td>103</td>
<td>94</td>
<td>91</td>
</tr>
<tr>
<td>Roof</td>
<td>102</td>
<td>97</td>
<td>92</td>
<td>102</td>
<td>90</td>
<td>89</td>
</tr>
</tbody>
</table>

For the motorway passing scenario the best antenna combination are, if the pathloss is taken into account, receiving at the left-mirror or bottom of the car when the transmitter is at the left-mirror position. Also good combinations are both side-mirror antennas when transmitting from the bottom of the car. And the last good combinations are transmitting from the roof antenna position and receiving at the left-mirror or roof antenna positions. In appendix A.3 all the long-term fading figures for the motorway passing scenario can be found.
4.4.2 Doppler Spectrum

The Doppler effect can be clearly seen in the next Doppler spectrums for two different antenna combinations. The first is the left-mirror/left-mirror antenna combination, figure 4.31.

![Doppler Spectrum](image)

Figure 4.31: Motorway passing Doppler spectrum left-mirror/left-mirror

The main Doppler shift path that is appreciated in figure 4.31, is the result of the direct path between the transmitter and receiver. In the beginning the Doppler frequency is positive because the receiver is getting closer to the transmitter. After the moment they are passing by, the Doppler frequency is negative, as they are driving away from each other. The scattering at the trees is also visible by the yellow curved lines. There is also the influence of another Doppler frequency path, with negative values, due to a strong reflection in a car behind the receiver which is driving with high velocity, that is why the Doppler frequency values are very low, due to the relative velocity between them.

The next Doppler spectrum, figure 4.32, is for the transmitter in the right-mirror antenna position and receiving from the left-mirror antenna.

In this Doppler spectrum plot the path between the transmitter and receiver can also be seen, but no so clearly than in the previous case. In this graph the influence of the scattering on the trees is quite bigger, due to the curved red lines in the first moments of the simulation. Then, there is a lack of paths during a time interval and then again
4.4 Motorway Passing Scenario

Figure 4.32: Motorway passing Doppler spectrum right-mirror/right-mirror

more paths are seen. Having a look to the next pictures, which are the snapshots before the fourth second and after the fourth second, the Doppler effect shown in the plot can be better understood, figure 4.33.

Figure 4.33: Motorway passing scenario snapshots

As it shown in the first snapshot, which makes reference to the first moments of the simulation, where there is a big influence of the scattering at the trees, a lot of paths scattered at the trees can be seen. In the second picture, for example, there are only a few paths, and that is due to the LOS probability in that certain moment of the simulation, because of their geometrical positions, that is why a direct path between both cars can be seen. After a few seconds they are losing again LOS, as a car behind the transmitter is intercepting the direct path between the transmitter and the receiver.
4.4.3 Doppler and Delay Spread

In the next section the Doppler spread and the delay spread values are going to be analyzed.

First of all, the table 4.9 with the Doppler spread values for the motorway passing scenario is shown.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>352</td>
<td>784</td>
<td>710</td>
<td>878</td>
<td>1020</td>
<td>773</td>
</tr>
<tr>
<td>B. Back</td>
<td>833</td>
<td>145</td>
<td>153</td>
<td>422</td>
<td>315</td>
<td>586</td>
</tr>
<tr>
<td>M. Left</td>
<td>828</td>
<td>496</td>
<td>335</td>
<td>663</td>
<td>656</td>
<td>591</td>
</tr>
<tr>
<td>M. Right</td>
<td>830</td>
<td>605</td>
<td>296</td>
<td>650</td>
<td>965</td>
<td>412</td>
</tr>
<tr>
<td>Bottom</td>
<td>724</td>
<td>807</td>
<td>750</td>
<td>679</td>
<td>760</td>
<td>655</td>
</tr>
<tr>
<td>Roof</td>
<td>774</td>
<td>486</td>
<td>460</td>
<td>647</td>
<td>456</td>
<td>525</td>
</tr>
</tbody>
</table>

Table 4.9: Motorway passing Doppler spread in Hz

In this table the lowest values for the Doppler spread are for the transmitting antennas in the back bumper or left-mirror when transmitting from the back bumper.

If the delay spread values are analyzed, table 4.10 shows the results.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>0.14</td>
<td>0.12</td>
<td>0.14</td>
<td>0.27</td>
<td>0.11</td>
<td>0.24</td>
</tr>
<tr>
<td>B. Back</td>
<td>0.40</td>
<td>0.02</td>
<td>0.05</td>
<td>0.2</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>M. Left</td>
<td>0.42</td>
<td>0.14</td>
<td>0.08</td>
<td>0.23</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>M. Right</td>
<td>0.49</td>
<td>0.15</td>
<td>0.08</td>
<td>0.17</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.20</td>
<td>0.07</td>
<td>0.1</td>
<td>0.2</td>
<td>0.06</td>
<td>0.17</td>
</tr>
<tr>
<td>Roof</td>
<td>0.39</td>
<td>0.11</td>
<td>0.1</td>
<td>0.17</td>
<td>0.12</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 4.10: Motorway passing delay spread in µs

The values for the transmitting antenna at the bottom of the car has very low values for all the receiving positions, and also when transmitting from the left-mirror and back bumper antennas the delay spread values are good.

In appendix A.7 all the delay spread figures for the motorway passing scenario can be seen.
4.5 Urban Passing Scenario

Until now all the simulated and analyzed scenarios are in the motorway scenario, and now a new kind of scenario will be analyzed, the urban scenario. In this scenario there are many changes with regard to the motorway scenario. In the urban scenario environment a lot of buildings, some trees and a lot of parked vehicles are modelled, figure 4.34. In the urban scenario the density of the vehicles is higher, so there is much more influence of the traffic than in the motorway scenario.

The vehicles in the urban scenario are driving with a maximum velocity of 50 km/h, and so are also driving transmitter and receiver. The transmitter and receiver are driving in different directions so the relative velocity is around 100 km/h between them. The interpolation factor $F_{int}$ is 30, and the maximum Doppler frequencies that can be recognize is 1100 Hz.

The urban scenario is also a passing scenario, where between the transmitter and the receiver in the beginning there is a distance of 230 m, then they are getting closer until they pass by each other and then they are driving away until the end of the simulation where the distance between them is 40 m.
4.5.1 Long-term Fading and Short-term Fading

The first long-term fading plot for the urban scenario is for the transmitter at the bottom of the car and all the receiving antenna positions will be plotted, figure 4.35.

In the long-term fading plot a remarkable increase of the received power is seen. The highest peak is for the moment where the transmitter and the receiver are passing by. After that moment the pathloss again increases as the distance between them is increasing. Interesting in this graph is, that comparing with other transmitters, transmitting from the bottom of the car is performing very well. Because the pathloss values are the lowest ones and the fading has not a lot of peaks during the simulation. The best receiving position is for the bottom antenna, where it is receiving with LOS probability, that is why the values for the received power are higher than for the other antenna positions. The change between the front and back bumper can be also appreciated in this scenario, where there is a bad performance for the back bumper until they are close and then the front bumper is the one with the bad behavior, due to the increasing of the distance.

The next long-term fading plot is for the transmitter at the roof antenna, figure 4.36. The main difference in this case is that the mean values of the pathloss are much higher, and that there are quite more peaks during the whole simulation. The cause of
this effect is, that mainly there is NLOS probability for most of the receiving positions, so that the performance of the roof antenna as a transmitter is not so adequate in this scenario. As it has been mentioning in the other passing scenario, also in this case the change of the behavior between the front bumper and the back bumper can be appreciated. In the moment where the transmitter and receiver are passing by the best performing antenna combination in this case is the roof - roof antenna combination.

Summarizing all the long-term fading values in a table, table 4.11 is achieved.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
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<td>99</td>
<td>80</td>
<td>87</td>
<td>82</td>
<td>86</td>
</tr>
<tr>
<td>B. Back</td>
<td>97</td>
<td>84</td>
<td>81</td>
<td>88</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td>M. Left</td>
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<td>81</td>
<td>73</td>
<td>81</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>M. Right</td>
<td>84</td>
<td>88</td>
<td>77</td>
<td>84</td>
<td>78</td>
<td>85</td>
</tr>
<tr>
<td>Bottom</td>
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<td>84</td>
<td>76</td>
<td>80</td>
<td>74</td>
<td>81</td>
</tr>
<tr>
<td>Roof</td>
<td>85</td>
<td>88</td>
<td>80</td>
<td>84</td>
<td>81</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 4.11: Urban pathloss in dB
Trying to find out which are the best antenna combinations for the long-term fading in the urban scenario, the transmitting antenna at the left-mirror and the receiver at both side-mirror or bottom antenna positions are good performing. But there are also good performing antenna combinations when transmitting from the bottom of the car and receiving from both side-mirror antennas or bottom of the car. It must be mentioned also the good behavior of the roof - roof antenna combination.

In appendix A.4 all the long-term fading figures for the urban scenario can be found.
4.5.2 Doppler Spectrum

In the urban scenario the values for the Doppler frequency are lower as the relative velocity between the cars is also lower, compared to the previous scenarios, but the Doppler effect is also important to analyze.

In the first Doppler spectrum the bottom-bottom antenna combination is plotted, figure 4.37.

Figure 4.37: Urban Doppler spectrum bottom-bottom

As it was mentioned in the previous section the bottom-bottom antenna combination was one of the best performing ones for its good fading values. The main Doppler shift path is the direct path between the transmitter and receiver, where at the beginning the Doppler frequency is positive, as the receiver is reaching the transmitter, then the Doppler frequency is going to be 0 Hz, when they are one in front of each other, and finally when they are driving away the Doppler frequency is becoming negative.

There is an interesting point in this plot, the two paths around zero Hz during the whole simulation, both paths are the consequence of a strong reflection in parked vehicles or in a building far away from the transmitter and receiver. In this point there is a compensation of the Doppler frequency as the transmitter is approaching this point, so that the Doppler frequency is positive, and the receiver is driving away from this point, so that the Doppler frequency is negative, and because of the position of this point and that the velocity of the cars are similar, the result is zero Hz.
Another interesting observation in this plot is the performance of the paths around zero Hz, as three different parallel and curved lines can be seen. This effect is due to some strong reflections in the buildings, once the cars are passing by each other. In figure 4.38 that can be appreciated.

![Urban scenario snapshot](image)

Figure 4.38: Urban scenario snapshot

The next Doppler spectrum, figure 4.39, is for the transmitting antenna at the roof of the car and the receiver at the back bumper.

![Urban Doppler spectrum roof-front bumper](image)

Figure 4.39: Urban Doppler spectrum roof-front bumper
The plot is quite similar to the previous Doppler spectrum, but the difference is that due to the high number of reflections in this case, some other extra curved paths can be seen during the simulation. As it was mentioned before, in this antenna combination there is NLOS so that more reflections are needed to reach the receiver.
4.5.3 Doppler and Delay Spread

The Doppler spread values for the urban scenario are summarized in table 4.12.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
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<tbody>
<tr>
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<td>204</td>
<td>112</td>
<td>136</td>
<td>149</td>
</tr>
<tr>
<td>B. Back</td>
<td>326</td>
<td>338</td>
<td>341</td>
<td>336</td>
<td>328</td>
<td>344</td>
</tr>
<tr>
<td>M. Left</td>
<td>223</td>
<td>401</td>
<td>280</td>
<td>237</td>
<td>261</td>
<td>253</td>
</tr>
<tr>
<td>M. Right</td>
<td>130</td>
<td>385</td>
<td>280</td>
<td>202</td>
<td>173</td>
<td>271</td>
</tr>
<tr>
<td>Bottom</td>
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<td>299</td>
<td>217</td>
<td>129</td>
<td>163</td>
<td>188</td>
</tr>
<tr>
<td>Roof</td>
<td>164</td>
<td>372</td>
<td>199</td>
<td>180</td>
<td>210</td>
<td>230</td>
</tr>
</tbody>
</table>

Table 4.12: Urban Doppler spread in Hz

For the Doppler spread values there are low values for the receiving antenna in the front bumper when transmitting from the front bumper, right-mirror, bottom or roof of the car. Some other good performing antenna combinations can be find when transmitting from the front bumper and receiving from the right-mirror or bottom of the car.

The delay spread values, that are important to be as low as possible, are defined in table 4.13.

<table>
<thead>
<tr>
<th>Rx / Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Front</td>
<td>0.04</td>
<td>0.1</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>B. Back</td>
<td>0.09</td>
<td>0.16</td>
<td>0.11</td>
<td>0.19</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>M. Left</td>
<td>0.04</td>
<td>0.28</td>
<td>0.1</td>
<td>0.08</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>M. Right</td>
<td>0.03</td>
<td>0.2</td>
<td>0.08</td>
<td>0.07</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.04</td>
<td>0.19</td>
<td>0.05</td>
<td>0.05</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Roof</td>
<td>0.03</td>
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<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 4.13: Urban delay spread in µs

For the delay spread in general there are good values for almost all antenna combinations. Important to know is, that the back bumper is behaving badly as a transmitter for all receiving positions, and as a receiver also for all transmitting positions.

In appendix A.8 all the delay spread figures for the urban scenario can be found.
5 Conclusions

In order to make a final conclusion about the best performing antenna position for Car-to-Car communications, several aspects have to be taken into account, like the design considerations. Also a summary of each analyzed parameter will be done.

Design considerations have to be taken into consideration also, as this will be very important in the implementation of the antenna. As there are some positions at the car, which are not so easy to locate an antenna, a comparison between the different antenna positions is done.

<table>
<thead>
<tr>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
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<tr>
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<td>√</td>
<td>√</td>
<td>√</td>
<td>✓</td>
<td>✓✓</td>
</tr>
</tbody>
</table>

Table 5.1: Design criteria

Analyzing which are the best options from our six possible antenna positions, the conclusion is, that the best option for design considerations is at the bottom of the car. At the bottom of the car, there are no design restrictions and the designers will not have so many problems to locate a communication system device here. Otherwise, as it was seen in the previous chapters the technical parameters for some scenarios for the bottom antenna position are not the best ones, so that an agreement has to be done.

On the other hand, the roof, is not the best option, as the roof of the car is already quite crowded with other communication system devices. Also designers do not want to place there so many devices because of the huge importance of the aerodynamic considerations in a car. So, although the technical considerations are not bad in this position, it must be taken into consideration what the designers would decide about it.

Both side-mirrors and both bumpers are not so bad positions to place the antennas for the designers. In addition, the results of both side-mirror antennas in most of the analyzed parameters were the best performing antenna combinations.

In the following pages the final conclusions for each analyzed parameter, as well as a final conclusion for all the parameters for all the scenarios will be made. Each simulated scenarios will be represented by a symbol, table 5.2.

For the long-term and short-term fading criteria table 5.3 is define for the different simulated scenarios.

As it can be appreciated in table 5.3, the combination of the left-mirror antenna as a transmitter and as receiver is after representing all the scenarios the best option for the long-term and short-term fading values. Also is remarkable the very good performance of the left-mirror antenna position as a transmitter and receiving at the bottom of the car.
CHAPTER 5 CONCLUSIONS

Motorway LOS ⋆
Motorway NLOS ⋄
Motorway passing ⋄
Urban ⋆

Table 5.2: Scenario symbols

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
<th>M. Right</th>
<th>Bottom</th>
<th>Roof</th>
</tr>
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<td>⋆ ⋆ ⋆ ⋆</td>
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<td>⋆ ⋆ ⋆ ⋆</td>
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<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
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<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
<td>⋆ ⋆ ⋆ ⋆</td>
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</tr>
<tr>
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Table 5.3: Long-term and short-term fading summarization

If only both passing scenarios, motorway and urban, are analyzed, the best performing antenna combinations are transmitting from the bottom of the car and receiving from the left-mirror or right-mirror antenna position. Moreover the roof - roof antenna combination has also a very good behavior for this case.

In table 5.4 the Doppler spread is the analyzed parameter.

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
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<td>Roof</td>
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Table 5.4: Doppler spread summarization

For the Doppler spread analysis there is no antenna combination that behaves good in all the scenarios, but there are some antenna combinations that perform better than others like transmitting from the left-mirror antenna position and receiving from both side-mirror antennas. Also a good behaving antenna combination is the one transmitting and receiving from the front bumper. This good result for this antenna combination is
due to that the front bumper is only receiving from the front of the car, so only with $180^\circ$ of coverage.

In table 5.5 the delay spread is analyzed, also a critical parameter for an OFDM-system.

<table>
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<tr>
<th>Rx/Tx</th>
<th>B. Front</th>
<th>B. Back</th>
<th>M. Left</th>
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<td>Bottom</td>
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Table 5.5: Delay spread summarization

In the delay spread there is a best performing antenna combination for all the scenarios and that is the one transmitting from the bottom of the car and receiving at the front bumper. But there are also some other good performing combinations, like most of the receiving antenna positions when transmitting from the bottom or left-mirror antenna. The combination when transmitting from the back bumper and receiving from the front bumper has also good behavior for most of the simulated scenarios.

If a final conclusion wants to be done, summarizing all the analyzed parameters and all the simulated scenarios, table 5.6 summarizes the results.

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<tr>
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<th>B. Front</th>
<th>B. Back</th>
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<tr>
<td>B. Back</td>
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<td>√</td>
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<tr>
<td>M. Left</td>
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</table>

Table 5.6: Final conclusion

After having analyzed in four different Car-to-Car communications scenarios, wideband and narrow-band parameters, it is concluded the best performing antenna combination for the different scenarios is the left-mirror/left-mirror antenna combination.

There are also some other antenna combinations which perform well like receiving from the right-mirror or bottom antenna positions when transmitting from the left-mirror antenna. Good performing antenna combinations are also when transmitting
from the bottom of the car and receiving at the front bumper or left-mirror or right-mirror antenna positions.

In addition, it is important to remind the influence of the “Two Ray Theory”, where the height of both side-mirror antennas was the optimum height, and it performs better than higher heights like the roof antenna position or lowers like both bumpers. These considerations were made for distances between transmitter and receiver between 80 m and 200 m.
6 Future Analysis

In this project work four scenarios were simulated and analyzed, and for each scenario different wide-band and narrow-band analysis were done. After the analysis of the different parameters some conclusions were made relative to the obtained results. So that it will be very interesting to have the results and conclusions of other scenarios. That is why the analysis of other scenarios will be very useful, to see if the performance of the good antenna combinations analyzed in this project work are the same for other scenarios. In the urban scenario only one scenario was simulated and analyzed, so that some other different scenarios in the urban scenario can be analyzed. Moreover, it is always interesting to analyze for the urban and motorway scenarios different distances between the cars and also different relative velocities, to see the influence of these parameters in the results.

In this project work the analysis is done for the SISO antenna system, so another interesting improvement will be to analyze the optimization of the antenna placement for MIMO systems. As the performance of the antenna positions could be improved.

Finally, it will be very important also to analyze diversity-systems. In order to combine different antenna positions as transmitters and/or receivers. The results will be better, as if a antenna position is not performing so well in a certain moment, if there is another antenna located in another position at the car, this will improve the behavior of the whole system.
References


A Appendix

A.1 Long-term Fading Motorway LOS Scenario

Figure A.1: Motorway LOS long-term fading transmitters
A.2 Long-term fading Motorway NLOS Scenario

Figure A.2: Motorway NLOS long-term fading transmitters
A.3 Long-term Fading Motorway Passing Scenario

Figure A.3: Motorway passing long-term fading transmitters
A.4 Long-term Fading Urban Scenario

![Graphs of urban delay spread transmitters for different locations: front bumper, back bumper, left-mirror, right-mirror, bottom, and roof.](image)

Figure A.4: Urban delay spread transmitters
A.5 Delay Spread Motorway LOS Scenario

Figure A.5: Motorway LOS delay spread transmitters
A.6 Delay Spread Motorway NLOS Scenario

Figure A.6: Motorway NLOS delay spread transmitters
A.7 Delay Spread Motorway Passing Scenario

Figure A.7: Motorway passing delay spread transmitters
A.8 Delay Spread Urban Scenario

Figure A.8: Urban delay spread transmitters
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