Vehicular-to-Vehicular Channel Characterization and Measurement Results

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Abstract

Vehicular-to-Vehicular (V2V) communications are receiving considerable attention due to the introduction of the intelligent transportation system (ITS) concept. To design, evaluate and optimize ITS applications oriented to vehicular safety based on wireless systems, the knowledge of the propagation channel is vital, in particular the path loss. From a narrowband V2V channel measurements campaign carried out in a suburban area of the city of Valencia (Spain), this paper analyzes the path loss in terms of the transmitter (Tx) and receiver (Rx) separation distance. Based on a linear slope model, values for the path loss exponent and the standard deviation of shadowing are reported. Also, the Doppler Power Spectral Density (PSD) due to the time-selective behavior is examined.

Keywords: Vehicular channel modeling, vehicular communications, V2V channels, V2V path loss models, V2X.

1. Introduction

Traffic accidents have become an important health and social problem due to the high number of deaths and injuries, especially in dense traffic urban environments, highway and expressway areas. Although the total number of fatalities has been considerably reduced during the last decade due to the introduction of both traffic law enforcement and passive vehicle safety systems, the number of accidents has remained uniform as a consequence of the increasing number of vehicles and the total distance driven.

During the last years, the automobile industry, governments and academic institutions have increased economic resources and research efforts to develop systems to improve vehicular safety. Together with passive vehicles safety systems, such as airbags, anti-lock braking system (ABS) and electronic stability control (ESP), among others, active safety systems have been introduced. News proposals promote the integration of information systems, wireless communications and advanced sensor technologies into both vehicles and the infrastructure along the roadside. These proposals lead to the concept of intelligent transportation system (ITS). At present, different ITS applications have been introduced, such as navigation systems, variable message signs (VMS), parking radars, cameras and short-range emergency sensors systems in the vehicles. Nevertheless, there are some safety applications where large-range vehicular communications systems are required in both line-of-sight (LOS) and non-LOS (NLOS) conditions, e.g., blind corners and traffic crossing [1]. In this sense, the introduction of wireless cooperative systems on the road can extend the communication distance providing more information in real time to drivers. In a wireless cooperative system, vehicles and infrastructure exchange safety messages involving two capabilities: vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, also referred to in the literature as V2X communications. Vehicle communications systems are an emerging type of vehicular networks known as vehicular *ad hoc* network (VANETs), where vehicles, equipped with a radio transmitter on-board unit (OBU), and access points placed along the road, equipped with radio transmitter road-side units (RSUs), are the network nodes. Fig. 1 illustrates the concept of VANETs for V2V communications.

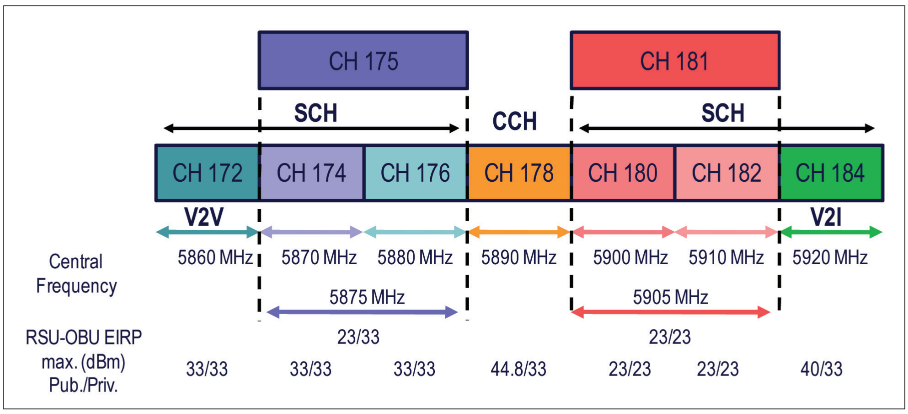
Government radio management organizations have allocated specific bands for the deployment of ITS applications throughout the world. For instance, the Federal Commu-

■ **Figure 1.** *Graphical illustration of a VANET based on V2V communications.*

nication Commission (FCC) assigned 75 MHz of licensed spectrum at the 5.9 GHz frequency band in 1999, specifically from 5.850 GHz to 5.925 GHz, as part of ITS for dedicated short-range communications (DSRC) [2]. Fig. 2 shows the DSRC channel allocation in the 5.9 GHz band for ITS applications. Channel 178 is the control channel (CCH) used to broadcast communications related to safety applications. Service channels (SCHs) are dedicated to safety and non-safety applications. Channels 172 and 184 are especially used to V2V and V2I communications for safety applications in intersection environments, respectively. The maximum equivalent isotropically radiated power (EIRP) for DSRC devices, i.e., OBUs and RSUs, are also illustrated in Fig. 2, where we have distinguished between public (Pub.) and private (Priv.) applications. For a more complete description of DSRC channel allocation, the reader is referred to [2]. The protocol stack standardized for DSRC systems is known as wireless access in vehicular environment (WAVE) [3], where the physical layer (PHY) is based on the IEEE 802.11p standard, which is an adaptation of the IEEE 802.11.a standard.

Later on, in 2003 the European Telecommunication Standard Institute (ETSI) adopted the DSRC band for ITS applications in Europe [4]. However, other unlicensed bands can be also used for non-safety ITS applications, e.g., 2.4 GHz and 5.4 GHz bands. In 2005, the European vehicles manufacturers set up the Car-2-Car Consortium (C2CC) in order to establish an European open standard for V2X communications systems and to propose applications related to the ITS concept [5]. Within these applications are those concerning road safety, traffic management and business and information services, among others.

Due to the characteristic of low latency in the communications oriented to vehicular safety, a good knowledge of the propagation channel is vital to design, evaluate and optimize the future ITS applications. The vehicular propagation channel, where both the transmitter (Tx) and the receiver (Rx) can be in motion with low elevation antennas, presents important differences with regard to the traditional fixed-to-mobile (F2M) channel. These differences make that channel models developed for F2M communications cannot be applied to evaluate the performance of ITS applications based on vehicular communications systems. Also, the propagation mechanisms in the DSRC band are very different to those happening in the traditional cellular communications bands, i.e., from 1 to 2 GHz.



■ **Figure 2.** *DSRC channel allocation in the 5.9 GHz band for ITS applications.*

At present, the vehicular channel is a relatively novel research area in channel modeling. Based on the previous experience in cellular and ultra-wideband channel modeling, some researchers of the Electromagnetic Radiation Group (REG) at the Telecommunications and Multimedia Applications (iTEAM) Research Institute have decided to focus their research activities on vehicular channel modeling. In this number of the WAVES journal, which reports the main research activities at the iTEAM, the current paper shows preliminary results derived from an initial measurement campaign conducted in a suburban area. The paper analyzes the path loss in terms of the Tx/Rx separation distance. Values for the path loss exponent and the standard deviation of shadowing are reported. Also, the Doppler Power Spectral Density (PSD) due to the time-selective behavior is examined.

The paper is organized as follows. In Section 2, general aspects related to vehicular channel modeling and measurements campaigns are introduced. Section 3 describes the measurement setup and the suburban environment where the measurements were collected. Preliminary results of path loss and frequency dispersion are shown in Section 4. In Section 5, we compare the path loss exponent derived from the measurements with published results. Finally, the conclusions are given in Section 6.

2. Vehicular channel modeling

The term channel modeling is used to describe the approaches, the models and the measurement campaigns conducted to understand how the propagation channel impairs and distorts the transmitted signal. The different propagation mechanisms that can occur in any wireless channel, e.g., free-space, diffraction, reflection and scattering, among others, require adopting certain simplifications of the propagation environment. Thus, a channel model is a simplified representation of the propagation channel centered in those aspects that affect the final performance of the wireless system [6]. In practice, the two most important parameters to characterize any wireless channel are the path loss and fading statistics. The path loss describes how the average received power varies with the distance between the Tx and Rx, whereas fading statistics describe how the instantaneous received power fluctuates over space, time and frequency. In this sense, accurate channel models are essential for a flexible and practical design of any wireless communications system under realistic propagation conditions.

2.1. Vehicular channel models

Wireless channel investigation has decades of history encompassing the early eighties with the deployment of mobile and personal communications systems. Nevertheless, vehicular channels, in which both the Tx and Rx can be in motion, is at present an important area in channel modeling [7], [8]. The interest in vehicular channel modeling is mainly motivated by the introduction of the ITS concept oriented to short-range communications in vehicular environments.

Due to the characteristic of low latency in vehicular safety communications, a good knowledge of the propagation channel is vital to design, evaluate and optimize the future ITS applications.

The motion of both terminals and the use of low elevation antennas make V2X systems differ from traditional F2M sys-tems. Nevertheless, it is necessary to distinguish between V2V and V2I channels. In V2V channels, the Tx and Rx can move with high velocities and there are relevant interacting objects (other vehicles) also moving. However, V2I channels can be similar to F2M only if the antenna height of the access point is elevated, otherwise the V2I channel could become like the V2V channel with the difference that the velocity of the terminals are not similar. The high mobility that can be observed in vehicular systems, due to the relative velocities between vehicular terminals and interacting objects, makes that the vehicular channel exhibits high temporal variability. On the other hand, in vehicular channels the probability of link obstruction increases due to movement of interacting objects and the use of low elevation antenna. The peculiarities of the vehicular channel and its differences from conventional F2M channels, together with the frequency band operation, make that channel models developed for cellular systems cannot be used in the deployment of future V2X communications systems.

The main features of vehicular environments which are necessary to take into account in channel modeling are the following [7]: (1) type of propagation link (V2V or V2I), (2) type of environment (urban, suburban, rural, expressway areas, etc.), (3) speed of terminals and interacting objects, (4) vehicular traffic density and (5) direction of motion of terminals. In real propagation conditions, these features are overlapped making difficult the development of deterministic models. For instance, traffic density is higher in urban areas and higher vehicles speeds are given in expressway environments. Therefore, the propagation characteristics in vehicular channels are mainly examined by means of simulation models or experimentally through measurement campaigns.

2.2. Vehicular channel measurement campaigns

In the context of vehicular communications, channel measurements are especially useful for understanding the propagation phenomenon due to the particular feature of the vehicular channel. The measurement setup used to measure the transfer function of any wireless channel is referred to as a channel sounder, and the measurements can be performed in the time or frequency domain. The configuration and implementation of the channel sounder depend on the channel parameters to be measured. Thus, a channel sounder can be considered as a narrowband or wideband. A narrowband channel sounder is used to perform a channel characterization through the path loss, frequency dispersion and both small- and large-scale fading statistics. When the chan-

Reference	Channel Sounder	Propagation Link	Scenario
[9]	WB	V2V-V2I	U, SU, E
[10]	NB	V2V	SU
[11]	WB	V2V	SU, R, H
[12]	WB	V2V-V2I	U, R, H
[13]	WB	V2V	U,R,H
[In this paper]	NB	V2V	SU

Table 1. *Vehicular channel measurements at 5.9 GHz: NB: Narrowband, WB: Wideband, U: Urban, SU: Suburban, R: Rural, E: Expressway, H: Highway.*

nel characterization is devoted to analyze the time-dispersion experienced by multipath propagation, a wideband channel sounder is necessary. To have a better understanding of measuring techniques and practical implementations of a channel sounder, the reader is referred to [7] and references contained therein.

Several vehicular channel measurements have been conducted during the last five years. Table 1 summarizes the most representative measurement campaigns carried out in the DSRC band at 5.9 GHz, indicating the measuring technique (narrowband or wideband), the propagation link measured and the environment where the measurements were collected. The type of environment, i.e., urban, suburban, rural, expressway and highway, corresponds to a general classification in order to facilitate comparisons among empirical results. To know the specific features of the environment where the measurement campaigns were conducted, the reader is referred to the corresponding reference. All measurement campaigns in Table 1 have been performed using a single antenna at the Tx and Rx.

3. Channel measurements

This section describes our measurement setup and the environment where the measurement campaign was conducted.

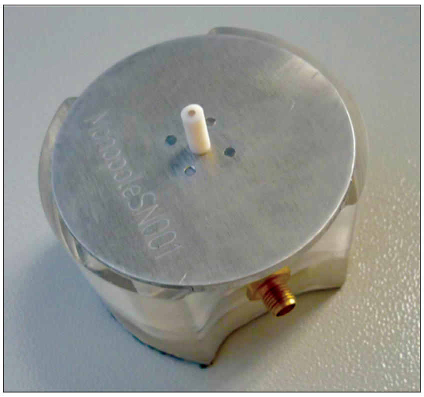
3.1. Measurement setup

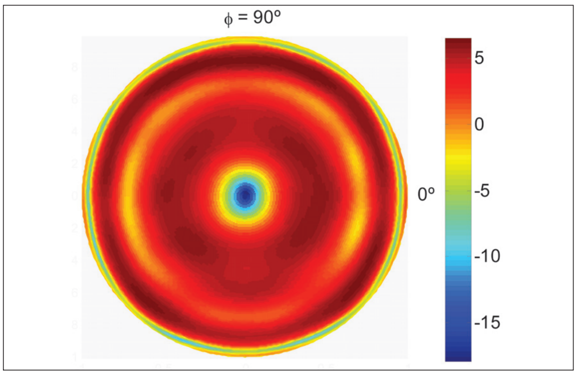
In order to characterize the V2V channel, we have performed a channel sounder at 5.9 GHz (DSRC band). It is a narrowband system designed to estimate the path loss, the Doppler PSD and fading statistics in vehicular communications. A HP83623A Signal Generator (SG) is used at the Tx transmitting a Continuous Wave (CW) at 5.9 GHz. A power amplifier allows us to transmit with 23.8 dBm of EIRP. Fig. 3(a) shows the measurement setup on board at the Tx vehicle. On the other hand, at the Rx a ZVA24 Rohde & Schwarz Vector Network Analyzer (VNA) is in charge of estimating the received power level. Note that our measurement setup uses a VNA as a power meter. A laptop manages the VNA to automate the measurements acquisition system and records the measured data. Furthermore, we use two amplifiers in series and low-loss cables (1.15 dBm/m at 5.9 GHz), to achieve a total gain margin of 68.12 dB. The devices that form the Rx vehicle as displayed in Fig. 3(b).

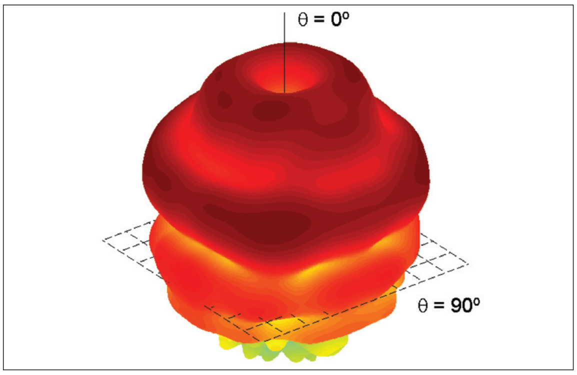
Figure 3. *On board system setup: (a) Tx vehicle and (b) Rx vehicle.*

We have taken into account when setting up the channel sounder that the thermal noise level at Rx and the spatial resolution that the VNA is capable of providing, also known as acquisition measurement time, are substantially related to the value of the Bandwidth of the VNA's Intermediate Frequency Filter (B_{IF}). Thereby, for lower values of B_{IF} a lower noise level is obtained and therefore, a greater Tx/Rx separation distance. Whereas a high value of B_{IF} allows us to analyze with higher resolution the short-term fading behavior. For that purpose, we have measured the noise level and the spatial resolution in the laboratory. The results show that using 10 KHz of B_{IF} leads a noise level equal to -80 dBm and an acquisition measurement time of 135 μs. However, with 100 KHz of B_{IF}, the noise level reaches -70 dBm and 45 μs of acquisition time.

Both Tx and Rx use the same antenna, a $\lambda/4$ magnetic monopole with a maximum gain in the horizontal plane







■ **Figure 4.** *(a) Magnetic monopole antenna. (b) 2D antenna gain pattern and (c) 3D antenna gain pattern, both expressed in dB. 2D and 3D gain patterns have been measured with the antenna mounted over a finite metallic plane with 1 m by 1 m dimensions.*

The interest in vehicular channel modeling is mainly motivated by the introduction of the ITS concept oriented to short-range communications in vehicular environments.

of about -2.56 dB and a scattering parameter S_{11} lower than -21 dB at 5.9 GHz. The gain and the radiation patter were measured in an anechoic chamber, mounting the antenna over a 1 m by 1 m metallic plane emulating the root of a car. Fig. 4(a) shows the magnetic monopole antenna. The 2D antenna gain patter is shown in Fig. 4(b), whereas a view of the 3D antenna gain patter is shown in Fig. 4(c).

In addition, the Tx and Rx systems are equipped with a GPS (Global Positioning System), each one controlled by a laptop, to provide constant information about the acquisition measurement time, as well as relative speed and separation distance between the Tx and Rx vehicles. The laptops have been synchronized over time to relate the data from the different GPSs and the measurement from the VNA.

Since the measurement system equipment is to be installed in vehicles, a power feeding system is needed. The power is achieved from a 75 Ah battery. It supplies 12 V-DC and then, by using an inverter, a 220 V-AC is obtained, to provide around 90 minutes of autonomy, enough time to carry out the measurement campaign.

3.2. Measurement environment

The preliminary campaign has taken place in a suburban scenario. Specifically in a 67 m wide and 1.7 km long avenue in the North-East of Valencia (Spain). The avenue has 4 lanes of road traffic for each direction separated by a 2-way Metro. There are cars parked nose to the kerb on both sides of the avenue. Other scenario characteristics consist of big open areas with low rise buildings, between 20 and 30 m high, many trees along the sidewalk and a medium traffic density. Fig 5(a) shows the measurement scenario and the way followed by Tx

■ **Figure 5.** *(a) 3D view of the measurement environment. Red solid line shows the routes followed by the Tx and Rx vehicles. (b) On board view from the Tx vehicle of the measurement scenario.*

Channel measurements are especially useful for understanding the propagation phenomenon due to the particular features of the vehicular channel.

and Rx with red solid line. It is a 3.4 km long path. Fig 5(b) shows a view of the traffic conditions during the measurement campaign, with LOS conditions between the Tx and Rx.

The measurements were taken between 11.00 a.m. and 1.00 p.m., with the Rx and the Tx vehicless in the same direction and medium traffic density, according to the statistics from the City hall of Valencia 2022 vehicles/hour. Most of the time, we have found LOS conditions, although, depending on the traffic, there were time instants where NLOS conditions were also present, due to the interposition of vehicles between the Tx and Rx, especially when trying to increase the Tx/Rx separation distance.

The vehicles used in the measurement campaign were a Renault Clio as Tx and a Peugeot 406 as Rx. The antennas were placed on the roof of the cars. The height of the antennas was 1.41 m and 1.43 m for the Tx and Rx, respectively.

4. Preliminary results

Fig. 6(a) shows the evolution of the separation distance between the Tx and Rx over time, in a record of 120 s. From Fig. 6(b), it can be seen that there are some moments where velocities of both vehicles are zero, corresponding to a stopped situation due to a traffic light. Fig. 6(c) depicts the received power level using an integration time of the order of 30 ms. The measured parameters allow us to analyze the path loss and the frequency-dispersion effect.

4.1. Path loss

According to [7], given a Tx/Rx separation distance, d, the path loss in logarithmic units (dB), denoted by $PL(\mathrm{d})$, can be described in identical manner as F2M traditional channels by the general formula:

$$PL(d)=\overline{PL_0}+10n\log\left(\frac{d}{d_0}\right)+S,\quad d\geq d_0 \qquad [1]$$

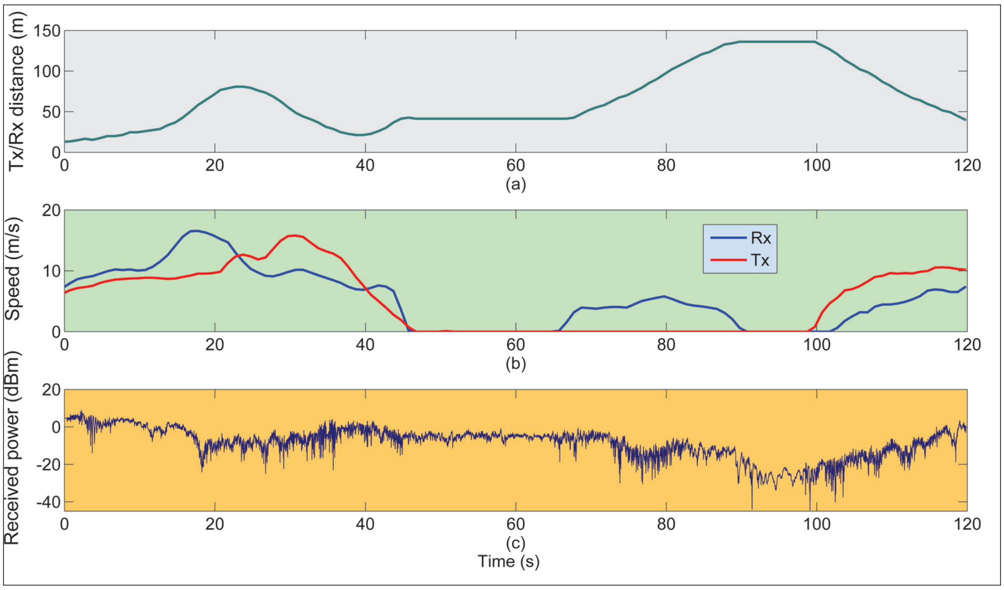
where $\overline{PL_0}$ is the mean path loss at the reference distance d_0 = 1 m; the term $10n\log(\mathrm{d}/\mathrm{d}_0)$ denotes the mean path loss referenced to 1 m; n is the path loss exponent related to the propagation environment; S is a zero-mean random variable with Gaussian distribution and standard deviation σ_S, used to model the large-scale fading.

Fig. 7 shows the scatter plot of the path as a function of the Tx/Rx separation distance. The solid blue line in Fig. 7 is the result of a linear regression analysis of the measured data. According to (1), we have obtained $\overline{PL_0}$ = 49.27 dB, n = 2.64 and σ_S = 4.51 dB. The solid red line corresponds to free space path loss (n= 2).

From the whole data set obtained in the measurement campaign, the path loss exponent is ranged from 1.83 and 3.27, with a mean value of 2.58. It is important to note that the greater values of the path loss exponent correspond to those paths where LOS was obstructed by an interacting vehicle. The standard deviation σ_S is ranged from 2.57 dB and 4.55 dB, with a mean value of 3.74 dB.

4.2. Frequency dispersion

Fig. 8 shows the PSD versus the normalized frequency. The Fast Fourier Transform was applied over a period time equal to 966 ms. In this particular case, the mean velocity of the Tx, υ_{Tx}, was 0.42 m/s and the one of the Rx,, was



■ **Figure 6.** *(a) Tx/Rx separation distance, (b) vehicles speed and (c) received power level over time.*

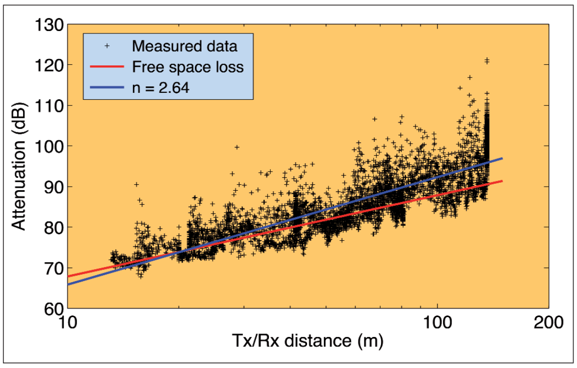


Figure 7. *Scatter plot of the path loss as a function of the Tx/Rx separation distance.*

2.45 m/s. The maximum frequency dispersion, ν_{max}, is approximately 98 Hz, a much higher value than the one estimated by $\hat{\nu}_{max} = (\upsilon_{Tx} + \upsilon_{Rx})/\lambda$ = 56 Hz, corresponding to a situation in which scatterers remain static. Results exhibited in Fig. 8 (b) were obtained from a measurement

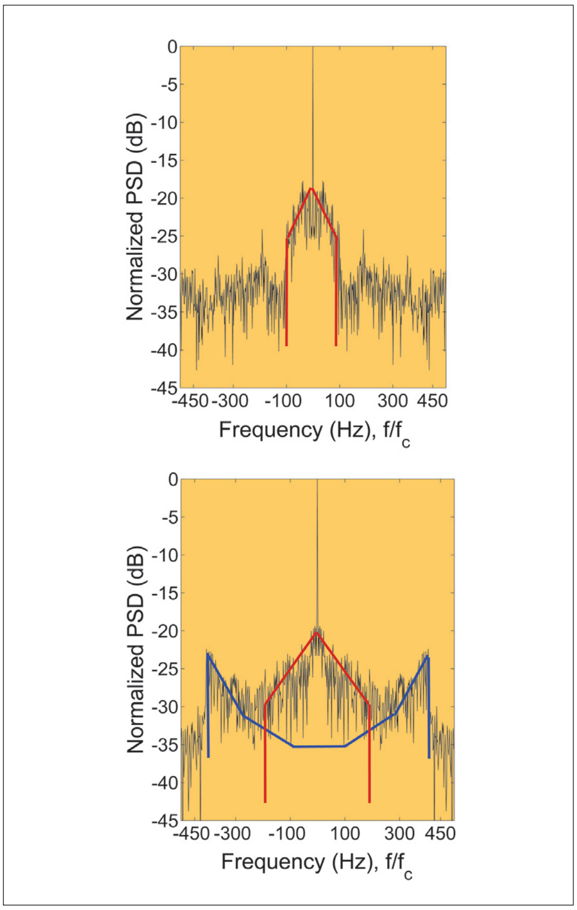


Figure 8. *Normalized power spectral density (PDS).*

data set where υ_{Tx} =2.51m/s and υ_{Rx} = 12.87 km/h, with ν_{max} = 408 Hz and ν_{max} = 431 Hz.

In Fig. 8(a), the solid red line is an approach that would describe the PSD trend. That PSD trend can also be seen in Fig. 8(b), where the overlapped blue solid line represents the classic U-Shaped or Jakes spectrum, as a result of an increase of the Tx and Rx terminals speed. The trend shown in Fig. 8(b) allows us to assume isotropic scattering conditions for the considered scenario. According to Fig. 8, the normalized PSD presents around 20 dB less of amplitude in the multipath components (MPCs) which have suffered frequency dispersion effect.

5. Comparison with other published results

Reference [7] reviews the most significant measurement campaigns carried out and published until March 2011. Table 2 summarizes the different path loss exponent obtained in rural, urban, suburban and highway scenarios.

In a highway scenario, the mean values obtained for the path loss exponent in [10], [13] and [14] are 1.9, 1.85 and 1.77, respectively. It is worth noting that values lower than 2 indicate better propagation than free space conditions due to the constructive interference of MPCs. In rural scenarios, the path loss exponent values are 2.3 in [10] and 1.74 in [13]. For urban scenarios, the measured path loss exponent values are 1.68 in [8] and 1.61 in [13]. Whereas for suburban scenarios, in [10] the path loss exponent values derived were 2.32 and 2.75, and a value equal to 1.59 was reported in [14]. The published results show that the path loss exponent is closely related to the propagation environment, as well as the measurement technique used in the channel sounder, the physical characteristics of the vehicles and the height of the antennas.

In view of the results obtained from our measured data, the minimum value of the path loss exponent, n = 1.83, is slightly higher than the results given in [14], where the measurement campaign was carried out in a suburban scenario in Lund (Sweden). However, the mean value, n = 2.57, is similar to data available in [10], where the suburban scenario belongs to the city of Pittsburgh, Pennsylvania (USA). Regarding the large-scale fading due to the topography of the area and the obstruction effect caused by vehicles, in [7] σ_S = 2.1 dB was derived, whereas in [10] values of 2.1 dB and 7.1 dB were reported.

Reference	Parameter	Urban	Suburban	Highway	Rural
[10]	n/σ_S (dB)	---	2.32/7.1 2.75/5.5	1.9/2.5	2.3/3.2
[13]	n/σ_S (dB)	---	---	1.85/3.2	1.79/3.3
[14]	n/σ_S(dB)	1.68/1.7	1.59/2.1	1.77/3.2	---
[In this paper]	n/σ_S (dB)	---	2.57/3.74	---	---

Table 2. *Path loss model parameters for different environments.*

Comparing PSD results with those obtained in [7] and [15], the Doppler spectrum has a similar trend, where frequency dispersion increases with the relative speed of the terminals Tx and Rx, given a classic spectrum from an isotropic scenario.

6. Summary and conclusions

The ITS concept for DSRC systems, together with new applications related to driving safety and VANETs, have triggered great interest in vehicular channel modeling during the last years. In this context, this paper introduces some concepts related to vehicular channel characterization and describes the principal features of V2X channels, highlighting those that make a clear difference with traditional F2M channels.

A narrowband channel sounder to characterize the vehicular channel sounder has been presented. From a narrowband channel measurement campaign in the DSRC band at 5.9 GHz, the relationship between the path loss and the Tx/Rx separation distance has been analyzed. Measurements have been carried out in a suburban area in the city of Valencia (Spain), with a mean road traffic density of 2022 vehicles/hour.

The path loss exponent derived from all measured data ranges from 1.83 and 3, with a mean value of 2.57. Channel temporal selectivity due to the frequency-dispersion has also been examined, showing that the Doppler PSD has a similar trend to the classic spectrum as Tx/Rx relative speed increase.

Despite the published studies on V2V channel, the number of measurement campaigns in the DSRC band is too small to make a characterization of the vehicular propagation channel in statistical terms. Thus, and considering the different morphological characteristics of the cities, rural environments and highways within the same country, as well as from one country to another, it is needed to perform a greater number of measurements data in order to provide knowledge about the propagation mechanisms that allow us to develop more accurate propagation models.

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Biographies

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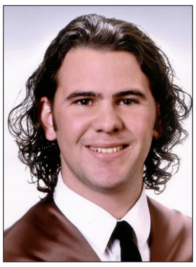

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