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Path loss characterization for vehicular communications at 700 MHz and 5.9 GHz under LOS and NLOS conditions

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Abstract

In this letter we present a path loss characterization of the vehicular-to-vehicular (V2V) propagation channel. We have assumed a path loss model suitable for vehicular *ad hoc* networks (VANETs) simulators. We have investigated the value of the model parameters, categorizing in line-of-sight (LOS) and non-LOS (NLOS) paths. The model parameters have been derived from extensive narrowband channel measurements at 700 MHz and 5.9 GHz. The measurements have been collected in typical expected V2V communications scenarios, i.e., urban, suburban, rural and highway, for different road traffic densities, speeds and driven conditions. The results reported here can be used to simulate and design the future vehicular networks.

Index Terms

Vehicular communications, vehicular channels, channel measurements, path loss models.

I. INTRODUCTION

UNDER the intelligent transportation system (ITS) concept, new applications related to safety and efficient traffic management have been and are being proposed [1]. These applications promote the integration of information and communications technologies (wireless, computing and advanced sensor technologies) into both vehicles and infrastructure along the roadside [2], [3]. In this context, vehicular *ad hoc* networks (VANETs), as a special case of vehicular communications, can extend the communication distance among vehicles and provide information in real-time. The special features of the potential vehicular applications require to develop and implement new communications technologies, where one of the many challenges to be addressed is the characterization and modeling of the vehicular propagation channel [2], [4], [5].

Specific frequency bands have been allocated for the deployment for safety-related ITS applications. For instance, the Federal Communication Commission (FCC) assigned 75 MHz of licensed spectrum at the 5.9 GHz frequency band (from 5.850 to 5.925 GHz), as a part of ITS for dedicated short-range communications (DSRC) in the United States. In Europe, the European Telecommunications Standard Institute (ETSI) has adopted the DSRC band assigning 50 MHz (from 5.875 to 5.925 GHz) for ITS applications. In addition to the 5.9 GHz DSRC band, Japan has recently allocated 10 MHz at the 700 MHz band (from 755 to 765 MHz) for ITS applications [6].

The motion of terminals, the transmitter (Tx) and receiver (Rx), the use of low elevation antennas and the frequency bands operation make that vehicular-to-vehicular (V2V) systems differ from the traditional cellular or fixed-to-mobile (F2M) systems. Due to the particularities of the vehicular channel, propagation models developed for F2M are not suitable in the deployment of the future vehicular networks. Thus the knowledge of the vehicular channel properties and new channel models are essential in order to evaluate networking protocols taking into account more realistic propagation conditions. Several measurement campaigns have been conducted to investigate the propagation channel characteristics at the 5.9 GHz DSRC band, or adjacent bands, in different environments [7], [8], [9], [10], [11], [12], [13]. Nevertheless, with the exception of the work of Sevlian *et al.* [14], there have not been published measurement results at the opening 700 MHz frequency band.

In this letter, we present a path loss characterization and propose a simplified propagation model suitable for VANETs simulators to evaluate protocols and system architecture configurations. The parameters of the propagation model have been derived from channel measurements for typical environments expected in vehicular communications, with different road traffic densities and vehicle speeds. The measurements have been carried out at 700 MHz and 5.9 GHz simultaneously, facilitating comparisons between the two frequency bands, and under real driving conditions. Using the information recorded by a video camera, we have distinguished between LOS and NLOS conditions. The results show clear differences between LOS and NLOS conditions in the path loss model parameters, which are related to the propagation environment. It is worth noting that only few published works take into account LOS or NLOS in a comprehensive way. In this sense, this letter provides useful results of path loss characterization that can be used to simulate and design the future vehicular networks under more realistic propagation conditions.

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II. CHANNEL MEASUREMENTS

A. Measurement Setup

Narrowband propagation channel measurements were performed to characterize the path loss. At the Tx side (Tx vehicle), the HP8648C and HP83623A signal generators (SGs) were used to transmit an unmodulated continuous wave (CW) at 700 MHz and 5.9 GHz, respectively. High power amplifiers (HPAs) were used to achieve an equivalent isotropically radiated power (EIRP) equal to $+26.3$ dBm and $+23.8$ dBm at 700 MHz and 5.9 GHz, respectively. At the Rx side (Rx vehicle) we have used the HP8590L spectrum analyzer (SA) to measure the received power level at 700 MHz, whereas the ZVA24 vector network analyzer (VNA) of R&S was used to measure the received power level at 5.9 GHz.

Selecting zero SPAN, the SA was continuously measuring the received power at 700 MHz. The received power was measured in traces of 401 power samples (the maximum trace size of the SA). The resolution bandwidth (RBW) of the intermediate frequency (IF) filter was 30 kHz, resulting in a sweep time per trace of about 15 ms. In the VNA, with zero SPAN selected, the received power at 5.9 GHz was continuously measured in traces of 5000 power samples. The received power was measured directly through the b_2 parameter (input power in the port 2, i.e., the last amplifier at the Rx was connected to the port 2 of the VNA). It is worth noting that modern VNAs have a direct receiver access option to connect external test setups, e.g., for antenna measurements. The RBW to the IF filter was 100 kHz, resulting in a sweep time per trace of about 220 ms.

The average of the power samples in each trace permits us to remove (filtering) the short-term fading fluctuations. This is equivalent to consider an integration period in each power measurement equal to the sweep time per trace, resulting in a sampling interval (duration of the averaged power samples) of about 225 ms at 700 MHz and 245 ms at 5.9 GHz. This time resolution takes into account the record time, which is higher in the SA. As a result, the fluctuations of the measured power are due to blocking (shadowing) effects of the interacting vehicles between the Tx and Rx. Two medium power amplifiers (MPAs) at the Rx and low-loss cables were also used to achieve a total gain system of about 60.45 dB at 700 MHz and 86.67 dB at 5.9 GHz. The total gain system refers to the sum of the Tx and Rx amplifier gain, antenna gain in the horizontal plane, and total losses of cables and connectors.

Two laptops were used to automate the measurement acquisition system and record the measured data, one connected to the SA and the other one to the VNA. Both Tx and Rx used the same antenna in each frequency band, which were omnidirectional monopoles roof-mounted in the center of the vehicles through a magnetic base and transmitting with vertical polarization. The height of the antennas was 1.41 m and 1.43 m above the ground for the Tx and Rx, respectively. The radiation pattern and the gain of the antennas were measured in an anechoic chamber, mounting the antennas over a 1 m by 1 m metallic plane emulating the roof of a car. The value of the antenna gain obtained in the horizontal plane (driving directions) was about -5.43 dB at 700 MHz and -2.56 dB at 5.9 GHz.

In addition to the radio frequency (RF) equipment, both Tx and Rx were equipped with GPS receivers, each one controlled by a laptop, to provide information about the acquisition time of measurements, as well as relative speed and separation distance between the Tx and Rx vehicles. The Rx vehicle was also equipped with a video camera. The information recorded by the video camera was used to separate (categorize) the paths in LOS and NLOS propagation conditions. To perform this classification was necessary to synchronize the video camera to the laptops through its timebase.

B. Measurement Environments

The measurements have been conducted in five different environments in and around the city of Valencia in Spain, i.e., urban with low traffic density (U-LD), urban with high traffic density (U-HD), suburban (SU), rural (R) and highway (H) environments. Urban measurements with low traffic densities were performed in urban areas with an average traffic density around 7500 vehicles/24 h and one or two lanes of one-way travel direction. The total length of the measured routes was about 31 km. Urban measurements with high traffic densities were performed in large avenues with up to five lanes, characterized by an average traffic density around 44200 vehicles/24 h. The total length of the measured routes was about 46 km. Suburban measurements were performed in streets and avenues just outside the center of the city, characterized by an average traffic density of about 71000 vehicles/24 h in two or three lanes in both directions. The total length of the measured routes was about 9 km. Rural measurements were taken on high roads with one lane in both directions outside the city. This is an open area with vegetation and very few houses nearby. During the measurements there was almost no traffic. The total length of the measured routes was about 14 km. Finally, highway measurements were performed on routes with two and three lanes in both directions, with medium and high traffic density. Both sides of the highway are open areas, and the total measured rotes was about 51 km. The measurements were collected with the vehicles driving in the same direction (convoy), with the Tx behind, and in real driving conditions in all environments. It is also worth noting that the measured environments have a fairly flat terrain.

III. RESULTS AND DISCUSSION

Different works related to experimental vehicular channel measurements have established a linear relationship between the path loss and the Tx-Rx separation distance [4], [11], [13]. This is a simplified path loss modeling but very accurate, which

TABLE I

MEAN PATH LOSS MODEL PARAMETERS FOR DIFFERENT ENVIRONMENTS: URBAN WITH HIGH HENSITY (U-HD), URBAN WITH LOW LENSITY (U-LD), SUBURBAN (SU), RURAL (R), AND HIGHWAY (H)

	700 MHz			5.9 GHz		
Scenario	PL_0 (dB)	γ	σ_S (dB)	PL_0 (dB)	γ	σ_S (dB)
U-HD	36.68	2.01	6.26	58.81	1.83	4.48
U-LD	38.33	1.82	6.85	59.37	1.75	5.45
SU	41.88	2.07	6.71	49.53	2.17	6.39
R	36.37	2.17	4.54	61.80	1.63	5.25
H	23.57	2.93	4.87	54.96	1.95	5.21

TABLE II

TX-RX SEPARATION DISTANCE (IN METERS) IN URBAN WITH HIGH DENSITY (U-HD), URBAN WITH LOW DENSITY (U-LD), SUBURBAN (SU), RURAL (R), AND HIGHWAY (H)

	LOS		NLOS	
Scenario	d_{min}	d_{max}	d_{min}	d_{max}
U-HD	7.54	112.47	14.03	316.27
U-LD	7.97	106.8	29.66	216.01
SU	14.34	99.62	44.03	308.52
R	13.05	94.72	45.52	131.65
H	23.02	162.74	54.52	1259.10

is suitable and easily integrated into VANETs simulators. Adopting the classical log-distance power law, let the path loss be given by

$$PL(d) = PL_0\left(d_0\right) + 10\gamma \log_{10}(d/d_0) + S, \quad d \geq d_0, \tag{1}$$

where d is the Tx-Rx distance, PL_0 is the path loss at the reference distance d_0, and γ is the path loss exponent related to the propagation environment. S is a zero mean random variable with normal distribution and standard deviation σ_S, used to model the large-scale fading. Nevertheless, since the model parameters will be derived through linear regression from the measured data using the least-squares (LS) method, it is more convenient to write (1) in the form

$$PL(d) = PL_0 + 10\gamma \log_{10} d + S, \quad d_{min} \leq d \leq d_{max}. \tag{2}$$

Notice that now PL_0 in (2) is not the path loss at the reference distance d_0, and the validity of the model parameters derived is restricted to the range of the Tx-Rx distance for the measured data, i.e., $d_{min} \leq d \leq d_{max}$, where d_{min} and d_{max} refer to the minimum and maximum Tx-Rx separation distance, respectively.

Table I summarizes the values of the path loss model parameters given by (2) for each environment. The parameters have been derived in LS sense from all measured data without distinguishing between LOS and NLOS propagation conditions. Table II provides the range of the Tx-Rx distance for routes where the measurements have been conducted. In Table II d_{mean} refers to the mean Tx-Rx distance. The Tx-Rx distances measured range within typical values for each environment.

The path loss exponent ranges from 1.82 to 2.93 and from 1.63 to 2.17 at 700 MHz and 5.9 GHz, respectively. At 700 MHz, the higher path loss exponent occurs in the highway environment, whereas at 5.9 GHz higher values have been derived in suburban and highway environments. The tendency indicates that higher values of the path loss exponent are given at 700 MHz, whereas the values of PL_0 are lower, resulting in less path loss compared to 5.9 GHz, as expected. With regard to the large-scale fading modeled by σ_S, the received signal suffers larger variations in urban and suburban environments at 700 MHz, whereas at 5.9 GHz lower fluctuations occur in urban environments with high traffic density. At 5.9 GHz, our extracted values of the path loss exponent agree very well with previous works. In [8], [11] and [12] values of the path loss equal to 1.61, 1.68 and 1.83 have been measured in urban environments, respectively. In [7], [8] and [11] values of 2.1-2.5, 1.61 and 1.59 have been derived in suburban environments. In [8] a value of 1.70 was derived in rural areas, whereas values of 1.77, 1.85 and 2.21 were reported by [11], [8] and [12] in highway environments, respectively. It should be noticed that there are not available works related to path loss characterization at 700 MHz for vehicular communications in order to make a comparison with our results.

Using the information recorded by the video camera, the measured routes in each environment were categorized in paths with LOS and NLOS conditions. Table III summarizes the value of the path loss model parameters for all categorized LOS and NLOS paths. Maximum, mean and minimum values of the path loss model parameters are reported. The normalized percent root-mean-square deviation, denoted as $\%rms$, also appears in Table III as a dispersion measure of the parameters. $\%rms$,

TABLE III
PATH LOSS MODEL PARAMETERS USING THE VIDEO CAMERA.

	700 MHz						5.9 GHz					
	LOS			NLOS			LOS			NLOS		
Scenario	PL_0 (dB)	γ	σ_S (dB)	PL_0 (dB)	γ	σ_S (dB)	PL_0 (dB)	γ	σ_S (dB)	PL_0 (dB)	γ	σ_S (dB)
URBAN - High density												
Max	43.52	3.11	9.28	52.04	3.53	5.94	66.60	2.59	7.99	66.42	3.55	6.47
Mean	**33.26**	**1.65**	**4.57**	**30.15**	**2.21**	**4.39**	**53.57**	**1.77**	**3.36**	**48.90**	**2.18**	**3.65**
Min	16.14	1.06	2.35	7.69	1.22	3.14	41.18	1.09	1.17	20.50	1.24	1.86
$\%rms$	19.02	25.91	36.65	39.72	30.73	17.92	11.23	21.58	32.94	24.05	27.89	31.60
URBAN - Low density												
Max	40.88	2.19	9.68	44.35	2.85	9.23	63.40	2.92	6.75	66.33	3.59	6.81
Mean	**34.55**	**1.54**	**4.71**	**28.95**	**2.25**	**5.99**	**54.82**	**1.67**	**4.05**	**54.55**	**1.90**	**4.74**
Min	23.45	1.05	2.86	17.80	1.28	4.12	35.24	1.20	1.69	38.44	1.16	2.70
$\%rms$	11.93	21.78	33.76	30.35	24.41	24.87	10.81	26.21	25.63	14.76	31.93	24.04
SUBURBAN												
Max	42.40	2.31	6.42	44.82	2.89	6.23	52.12	2.01	4.29	62.84	3.42	8.06
Mean	**37.38**	**1.80**	**5.19**	**33.55**	**2.39**	**4.93**	**47.53**	**1.76**	**3.44**	**46.69**	**2.25**	**5.20**
Min	30.06	1.36	3.42	19.47	2.01	3.29	42.87	1.41	2.68	21.92	1.52	3.48
$\%rms$	17.34	26.61	30.22	31.28	15.53	21.80	8.80	13.81	18.76	30.88	29.16	30.69
RURAL												
Max	34.87	2.25	3.94	29.24	2.71	3.04	62.46	2.10	5.49	66.02	2.31	5.23
Mean	**29.83**	**2.04**	**2.48**	**26.39**	**2.34**	**2.19**	**57.46**	**1.61**	**5.49**	**55.20**	**1.81**	**4.63**
Min	25.10	1.80	1.84	19.25	2.21	1.59	50.45	1.39	3.56	46.35	1.29	3.11
$\%rms$	11.91	10.15	36.36	18.13	10.55	28.83	5.91	13.27	14.86	14.17	24.05	19.44
HIGHWAY												
Max	42.40	2.09	5.22	26.77	3.23	4.31	60.00	2.02	4.43	52.48	2.96	8.61
Mean	**37.92**	**1.64**	**4.46**	**17.33**	**2.98**	**3.63**	**54.02**	**1.66**	**3.68**	**39.39**	**2.53**	**5.94**
Min	30.41	1.37	3.78	12.36	2.59	2.85	50.19	1.35	2.77	32.32	2.01	4.32
$\%rms$	13.85	19.31	13.69	31.81	7.88	19.90	7.59	15.34	18.65	18.95	13.39	28.79

also known as coefficient of variation, is defined as $\%rms \triangleq 100 \times (\sigma_x/\overline{x})$, where σ_x and $\overline{x}$ are the standard deviation and mean of the x variable, respectively. It is worth noting that the value of the path loss exponents of Table I are between the mean values of Table III in all environments, and these differences suggest taking into account the propagation conditions, i.e., LOS and NLOS, for a better description of the path loss behavior. Notice that the path loss exponent has a key impact on both the coverage area and the interference characteristics in the deployment of wireless systems. In both frequency bands, the values of the path loss exponent are higher in NLOS conditions, with higher $\%rms$ in urban and suburban environments.

At 700 MHz the mean path loss exponent value ranges from 1.54 to 2.04 in LOS, and from 2.21 to 2.98 in NLOS. At 5.9 GHz the mean path loss exponent value ranges from 1.61 to 1.77 in LOS and from 1.81 to 2.53 in NLOS. The path loss exponent suffers a larger dispersion in urban and suburban environments. The PL_0 parameter is also influenced by the propagation conditions, showing higher variations at 700 MHz in NLOS conditions according to the $\%rms$ values. The large differences between LOS and NLOS of the PL_0 parameters occurs in the highway environment, about 21 and 15 dB at 700 MHz and 5.9 GHz, respectively. It is likely due to the presence of vans and larger trucks in this environment.

It is worth noting that a high path loss exponent corresponds to a low PL_0. Thus high path loss exponents result in low values of PL_0. This relationship between PL_0 and the path loss exponent was also observed in [12], [13]. There are two possible explanations for this relationship. The first one is that from (1) and (2) the term PL_0 is influenced by the term $10\gamma\log_{10} d_0$, and the second one is that the model parameters have been derived through linear regression in LS sense.

IV. CONCLUSION

A path loss characterization and modeling is presented in this letter based on extensive channel measurements at 700 MHz and 5.9 GHz. The measurements have been collected in typical vehicular environments. Values of the path loss model parameters in LOS and NLOS have been derived from the measurements in a LS sense. The differences observed between LOS and NLOS suggest considering the propagation conditions to improve the characterization of the path loss. In this sense, this letter contributes to a better understanding of the propagation path loss in vehicular environments. Therefore the values of the propagation path loss model reported here can be incorporated into VANETs simulators to evaluate protocols and system architectures for the future vehicular networks taking into account more realistic propagation conditions.

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