Deterministic Propagation Prediction in Vehicular Environments

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Abstract: *Intelligent Transportation Systems (ITS) are currently under intense research and development for making transportation safer and more efficient. The development of such vehicular communication systems requires accurate models for the propagation channel. A key characteristic of these channels is their temporal variability and inherent non-stationarity, which has major impact on electromagnetic propagation prediction. This article investigates the channel properties of a wireless communication system within a vehicular communication environment with deterministic modeling. An analysis of the physical radio channel propagation of an ultra high frequency-radio frequency identification (UHF-RFID) system for a vehicle to infrastructure scattering environment is presented. A new module has been implemented in the proposed site-specific tool which takes into account the movement of the vehicles, leading to time and space-frequency models. The strong dependence with the environment due to multipath propagation is presented. These results can aid in the identification of the optimal location of the transceivers, in order to minimize power consumption and increase service performance, improving vehicular communications within ITS.*

Introduction

Intelligent Transportation Systems (ITS) consist of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) over wireless communications links, contributing to safety improvements and environmentally friendly driving. The ITS road infrastructure has the potential to enhance road safety by helping drivers to avoid collisions on basic maneuvers, changing lanes, merging on highways, and driving safely in blind turns. In the future, the main goal for vehicles is to gather sensor data and share information on traffic dynamics with each other and with the road infrastructure. For that purpose, deep understanding of wireless propagation channels is important to develop efficient and robust communication systems, which provide fast information access. Thus, accurate channel models, which reproduce the V2V or V2I behavior in a realistic manner, are required. The main challenge for vehicular communications is the rapidly changing radio propagation conditions. Both the transmitter and the receiver can be mobile, and the scattering environment can rapidly change. Hence, their detection from measurements, statistical characterization, and modeling is rather challenging, [1].

Different communications channel modeling approaches can be roughly split into four categories. One category comprehends the *empirical methods* that were traditionally used for initial coverage estimation (such as COST-231, Walfish-Bertoni, Okumura-Hata, etc.). Their advantage is that they give rapid results, but they require calibration based on measurements to give an adequate fit of the results based on initial regression methods. An empirical model is introduced in [2] for the slow channel variation, which leads to the understanding of the time variation of the in-vehicle channel. Karedal et al. presents in [3] the results of an empirical study of wireless propagation channels for V2V communications in street intersections, a scenario especially important for collision avoidance applications. A second category includes the *stochastic channel models* (narrowband or wideband), [4], which characterize the channel from a frequency selective perspective, by modeling power delay profiles, Doppler shift, Doppler spectrum and fadings. The third category has the *geometry-based stochastic* models, which are the most used for propagation prediction in mobile communication channels, e.g., the geometrical model proposed in [5], which predicts the Doppler spectrum and angle-of-arrival distribution associated with the diffuse component for various V2V scenarios. Reference [6] also presents a V2V geometrical channel model, but considering that the local scatterers move with random velocities in random directions. Walter et al. present in [7] a new geometric-stochastic channel modeling, in which the delay-dependent Doppler probability density functions (pdfs) are derived for general V2V propagation environments, to cope with the non-stationarity of these channels. In [8], a new geometry-based stochastic approach is presented for the development of three types of channel models, namely stationary, physically non-stationary, and statistically non-stationary channel models. For non-stationary processes, second order statistics are usually obtained, and in some cases a process is split into smaller regions where stationarity holds as shown in [9] where the length of such regions is determined. Ghazal et al. presents in [10] a novel non-stationary geometry-based stochastic model which characterize the non-stationarity of high-speed trains. Results achieve a good agreement with relevant measurement data. In [11], a new wideband multiple-input-multiple-output (MIMO) model for V2V channels based on extensive MIMO channel measurements is presented. A geometry-based stochastic channel model is described and verified directly from the measurements. In reference [12], Pätzold and Borhani present a non-stationary multipath fading channel model incorporating the effect of velocity variations of the mobile station. Reference [13] presents an adaptive reduced-rank estimation of non-stationary time-variant channels using subspace selection.

However, none of these methods consider all the elements of the environment, and because of that, they could fail in situations when the surroundings have a great impact on the electromagnetic propagation (i.e., vegetation, different type of scatterers, materials, etc.). Due to this fact, the fourth category corresponds to *deterministic methods*, which are widely used for propagation prediction given a specific environment. Their principle is mainly based on ray optics (advanced ray tracing techniques), or, more generally, on solving Maxwell's equations. These methods are precise but are time-consuming due to inherent computational complexity. Thus, methods based on geometrical optics (ray launching or ray tracing) for radio planning purposes, with strong diffractive elements, offer a reasonable trade-off between precision and required calculation time, [14]. In the ray launching technique, rays are launched from a transmitter and, at the locations where rays intersect an object; at least one new reflected, absorbed, diffracted, or scattered ray begins. On the other hand, in ray tracing approach, imaging techniques are usually employed leading to a number of possible paths that rays follow from the transmitter to receiver over the direct, reflected and diffracted rays. In the literature, for the author's knowledge, there are not a broad range of works which model vehicular channels with ray tracing or ray launching methods. Reference [15] shows a new inter-vehicle communication channel model which uses a ray-optical approach to model the wave propagation and the road traffic is generated stochastically.

In this work, an in-house developed three-dimensional (3D) ray launching (RL) tool has been used for the analysis of the behavior of an RFID system in a vehicular environment. The main contribution is that a new module has been added to the algorithm which copes with the non-stationarity of the channel. Hence, different velocities for the mobiles can be considered leading to Doppler Shift and Doppler Spread results, providing insight into the performance of the wireless communication system. We present the variations of received signal power within a vehicular scenario, and the power-delay-Doppler shift profile for an RFID system for vehicles. Real measurements were taken and compared to simulated values to show accuracy of the model. The statistical characterization of the Doppler shift of the received signal has been analyzed and it is shown that it follows a Rayleigh distribution. We also introduce the feasibility of the RFID system as a function of the tag's sensitivity when the received power and the angle with respect to the reader antenna vary. The objective of the analysis is to verify how the variability of the environment affect the electromagnetic propagation for the purpose of vehicular identification and traffic congestion control. RFID readers collect information of each vehicle on the road, and send it to a central base to manage traffic. RFID is optimal to guarantee the traceability of vehicles and allows not being concerned about the security and efficiency of the system, given by automatic interrogation of the tags when passing by on the road.

RFID is an emerging technology with low cost and power consumption. In the literature, there are several applications which make use of this technology for vehicular communications. In [16], RFID technology is used with the aim of reducing traffic accidents near intersections. The work reports an experimental system that senses the presence of pedestrians as well as their position and sends the data to an on-board device which alerts the driver. An extended version of the mentioned application for faster and co-operative message routing after an accident occurs, with the help of short-length warning codes, is presented in [17]. An RFID system for vehicle safety communication through cooperative routing for warning messages for post-accident scenarios is proposed in [18]. In [19], the channel modeling of an RFID system for vehicular identification in road and freeways is presented.

For vehicles to be identified with RFID systems, determination of successful read zones, particularly when speed and antenna directionality vary, are important for ITS from the technology integration point of view. The goal of this article is to help communication system designers to gain insight into the relevant channel characteristics in a V2I environment, specifically, the analysis of an UHF-RFID wireless communication system has been done. This paper is organized as follows. First, we introduce the channel modeling technique. Then, the simulation results in the considered scenario are presented and a comparison with real measurements is given. Finally, the last section provides the conclusions of the work.

Description of Channel Modeling

The channel modeling technique considered for the analysis of the vehicular radio channel is the base on which relevant channel propagation characteristics are obtained. Deterministic modeling allows considering all the elements within the environment. In general, the chosen environment contains obstacles and scatterers that cause the signals to propagate from the transmitter to the receiver via different paths, each of which can involve reflection, diffraction, scattering, etc. The different paths give rise to multiple attenuated, delayed and phase-shifted echoes of the transmitted signal arriving at the receiver. All these radio propagation effects have been taken into account in the development of our algorithm, leading to an efficient and robust technique, which has been used for different indoor and outdoor applications like interference analysis [20], electromagnetic dosimetry evaluation in wireless systems [21], or the analysis of wireless propagation in complex environments [22]. The 3D RL tool is based on geometrical optics (GO) and uniform theory of diffraction (UTD). The main principle of RL techniques is to identify a single point on the wave front of the radiated wave with a ray that propagates along the space following a combination of optic and electromagnetic theories. The spherical coordinate system is used to launch rays at an elevation angle θ and an azimuth angle Φ. Radiation patterns of the transceivers, as well as antenna parameters are taken into account. Parameters such as frequency of operation, number of multipath reflections, separation angle between rays, and cuboids dimension are introduced.

The principle is that each ray propagates in the three-dimensional space as a single optic ray. Thus, electric field E created by an antenna with a radiated power P_{rad}, a directivity $D_t(\theta_t, \Phi_t)$ and polarization ratio ($X^{\perp}$, $X^{\parallel}$) at a distance r in free space is given by, [23],

$$E_i^{\perp} = \sqrt{\frac{P_{rad} D_t(\theta_t, \emptyset_t)\eta_0}{2\Pi}} \frac{e^{-j\beta_0 r}}{r} \mathrm{X}^{\perp} L^{\perp} \tag{1}$$

$$E_i^{\parallel} = \sqrt{\frac{P_{rad} D_t(\theta_t, \emptyset_t)\eta_0}{2\Pi}} \frac{e^{-j\beta_0 r}}{r} \mathrm{X}^{\parallel} L^{\parallel} \tag{2}$$

where $\beta_0 = 2\pi f_c \sqrt{\varepsilon_0 \mu_0}$, $\varepsilon_0 = 8.854 * 10^{-12}$ F/m is the vacuum permittivity, $\mu_0 = 4\pi * 10^{-7}$ H/m is the vacuum magnetic permeability and $\eta_0 = 120\pi$ ohms is the intrinsic impedance of free space. f_c is the transmission frequency and $L^{\perp\parallel}$ are the path loss coefficients for each polarization.

A finite sample of the possible direction of the propagation from the transmitter is chosen and a ray is launched for each such direction. If a ray hits an obstacle, then a reflecting ray and a refracting ray are generated. These rays have new angles provided by Snell's law. If a ray hits a wedge, then a family of diffracting rays is generated. It is important to emphasize that a full 3D scenario is created before simulation considering all the objects, walls, transmitters, receivers and the whole components of the environment. The material properties for all the elements within the scenario are taken into account, given the dielectric constant and permittivity at the frequency range of operation of the system under analysis.

A new module has been added to the in-house developed 3D RL tool to consider the frequency dispersive effects due to the movement of the vehicles in an ITS environment. Different velocities of the vehicles in the scenario can be considered and the Doppler shift at the receiver can be obtained by

$$f_d = \frac{v}{\lambda}\cos(\psi) \tag{3}$$

where ψ represents the angle between the direction of arrival of the specific examined propagation path and the receiver's movement, v is the speed of the vehicle and λ is the wavelength of the signal.

Simulation Results

As a starting step, several simulations of a typical road scenario have been developed considering different instants of time denoted as t_i, i=1, ..., 5, for the vehicle position as shown in Figure 1. The considered scenario has different scatterers (trees and streetlights) on both sides of the road and the vehicle is moving at a constant velocity of 22.22m/s (80 km/hr). The road is 100m in length, with a width of 37.52m and a height of 13m. All the elements within the scenario have been taken into account in the simulation. The material properties used in the simulation are defined in Table 1.

TABLE 1. *Material Properties in the Ray Launching Simulation*

Parameters	Permittivity (ε_r)	Conductivity [S/m]
Air	1	0
Glass	6.06	10^{-12}
Concrete	5.66	0.142
Metal	4.5	$4*10^7$
Rubber	2.61	0
Tree	4.48	0.02

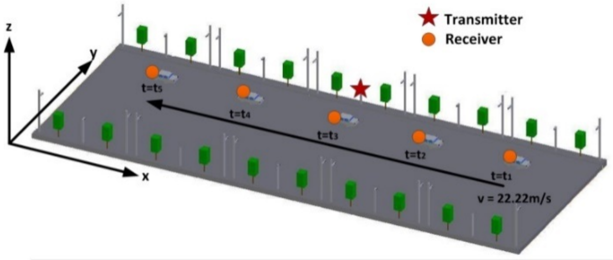


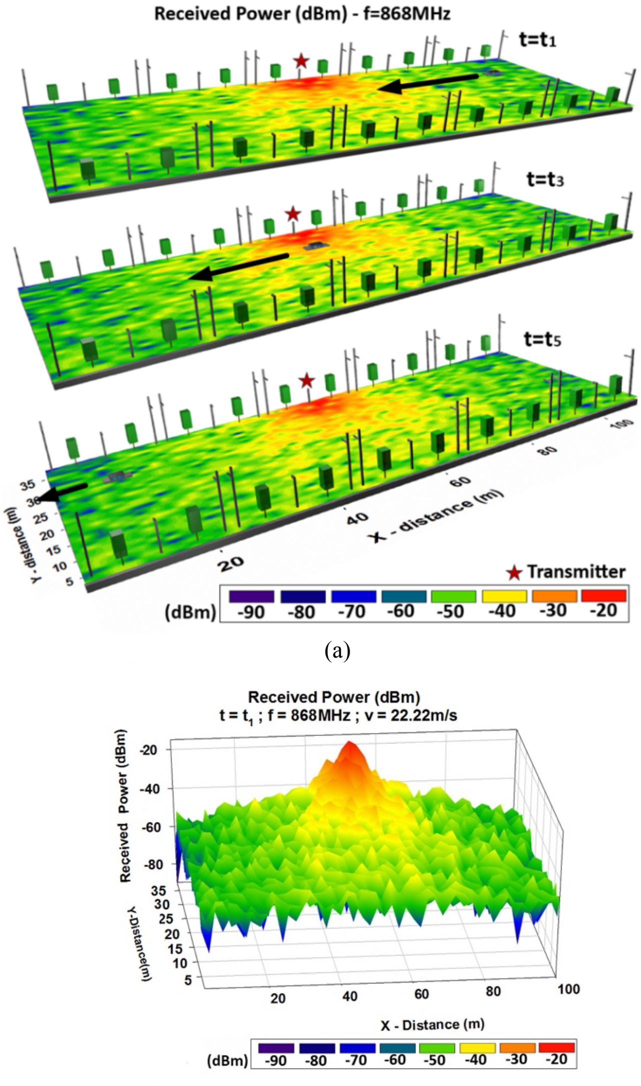
Figure 1. *Schematic view of the considered scenario.*

The main objective is to identify all the vehicles which go along the road with the RFID system. To achieve this goal, each vehicle is tracked using a commercial RFID tag. The transmitter antenna is placed on a streetlight on one side of the road, fixed at coordinates x=50m, y=36m, z=4m, corresponding to the red star depicted in Figure 1. The parameters used in the simulation are shown in Table 2. The frequency of operation is 868MHz (UHF-RFID Technology) with transmission rate of 106Kbps and power transmission of 10dBm. The transmitter antenna is directional with linear polarization with a gain of 7dBi and providing a 60º horizontal beam width for -3dB and 74º vertical beam width (model PATCH-A0026 from Poynting Antennas). For the receiver, an RFID generic tag is used, placed on the front part of the vehicle, with an omnidirectional radiation pattern.

TABLE 2. *Simulation Parameters*

Frequency	868MHz
Transmitter power	10dBm
Horizontal plane angle resolution ($\Delta\Phi$)	1º
Vertical plane angle resolution ($\Delta\theta$)	1º
Reflections	6
Cuboids resolution	0.5m x 0.5m x 0.5m

Firstly, the impact of the environment within the scenario has been assessed. It is a well-known fact that the impact of different scatterers in the radio wave propagation has a great influence in the decay of the signal. To asses this impact, simulations have been done with the considered scenario represented in Figure 1. It must be pointed out that scenarios of interest are presented in three-dimensional plane with local propagation parameters. In this case, the whole scenario is divided into a three-dimensional number of cuboids, in which the propagation parameters are stored during simulation. After that, with these parameters, the received power is calculated for each cuboid. With the obtained results, it can be represented the two-dimensional planes of received power for different heights, as it is represented in Figure 2a, which shows the XY-planes of received power for the same height as the tag is placed in the vehicle (at height of 1 meter) for different instants of time. To gain insight into the impact of the scatterers, Figure 2b represents the received power for the same height in the instant t_1 in a three-dimensional plane. It is shown that the impact of the scatterers along the road has considerable influence on signal propagation with significant multipath interference in the scatterers' zone. In addition, it is observed that the non-stationarity of the channel due to the movement of the vehicle produces more signal fading and changes the received power for different points in the considered environment. Because of that, this tool can be really useful in order to analyze these phenomena and aid in the optimal location of transceivers.



(a)

(b)

Figure 2. *Planes of received power (dBm) for 1m height (a) Two-dimensional planes for* t=t_1, t_3, t_5. *(b) Three-dimensional plane for* t=t_1.

It is highly important in these types of environments, which include non-stationarity elements, to consider the effects due to the movement of the vehicles. Because of that, the Doppler shift has been calculated with a constant vehicle velocity of 22.22m/s. Besides, multipath propagation has a great impact on this scenario due to the scatterers placed at both sides of the road. Figure 3 shows the variations of the received power for each multipath component with its Doppler shift associated for different instants of time during the movement of the vehicle. The path components shown are different at different instants of time due to the changing environment as the vehicle moves along the road, capturing different rays coming from the transmission antenna and from different scatterers. It can be seen that there is substantial variability in the received power for each component. These results can aid in the design of the antenna receivers to obtain optimal performance of the system.

To get an insight of the impact of Doppler shift in the considered scenario, the Doppler Spread has been calculated for all the spatial samples of the scenario. The Doppler Spread has been defined for each spatial sample as the difference of the maximum and the minimum frequency shifts. Figure 4 shows the Doppler Spread for a constant velocity of 22.22m/s for the first instant of time, t_1, and the third instant of time, t_3. It is observed in Figure 4a that Doppler Spread is higher in values in the areas farthest of the transmitter antenna and it is lower in the closest zone. This is because of the great influence of distance between transceivers and scatterers along the road, in radio wave propagation behavior. These results change in different time slots, as it is observed in Figure 4b, since the topology of the scenario changes with time due to the movement of the vehicle, and this has a great impact in frequency dispersion of the signal. The knowledge of the Doppler Spread at different instants of time are a great aid in the design of antenna receivers as well as for radio planning purposes before the deployment of a wireless communication system.

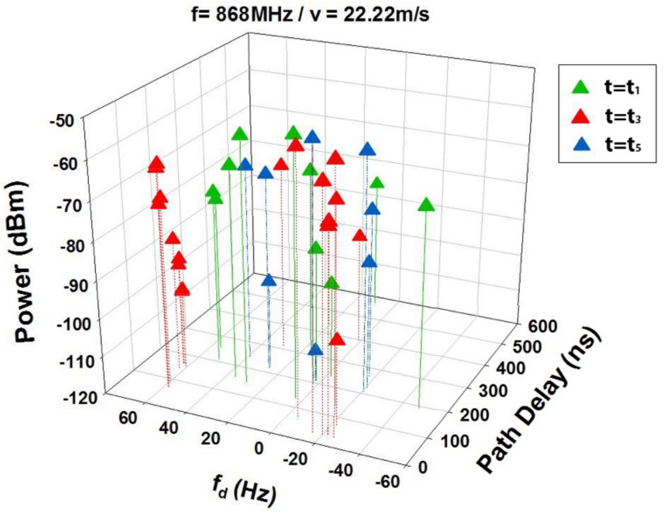
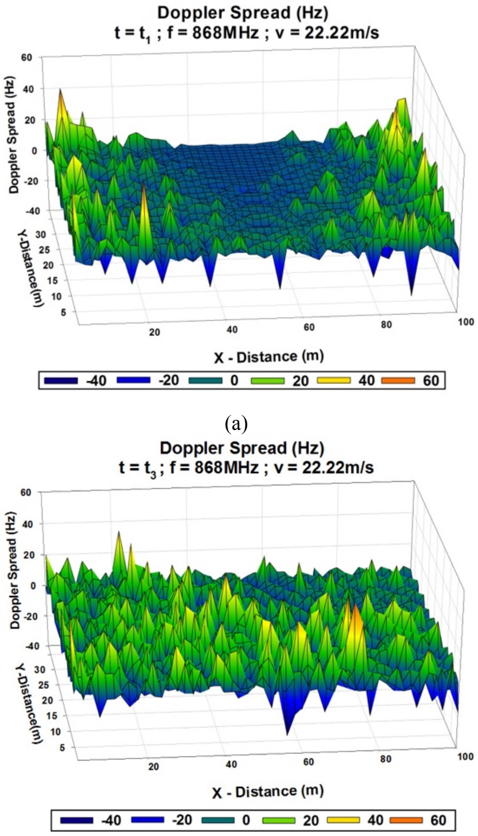


***Figure 3**. Power-Delay-Doppler Shift Profile for different instants of time during the movement of the vehicle.*



(a)

(b)

***Figure 4**. Three-dimensional plane of Doppler Spread (Hz) for 1m height (a) t=t$_1$ (b)t=t$_3$.*

Statistical Analysis

In order to get a sound understanding of the radio channel, the statistical distribution of the powers associated with the Doppler shifts of the received signal has been analyzed. Figure 5 presents the Cumulative Distribution Function (CDF) for the powers associated with the Doppler shift shown in Figure 3 for different instants of time, and its matching with the Rayleigh distribution. It can be seen that powers associated with the Doppler shifts follow a Rayleigh distribution with different values of standard deviation depending on the considered instant of time.

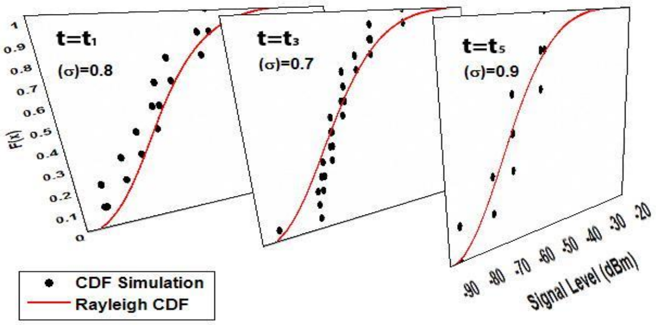


***Figure 5**. Cumulative Distribution Function (CDF) for the powers associated with the Doppler Shifts in different instants of time.*

Impact of the RFID system

In order to validate previous predictions, measurements in a real vehicular environment have been performed. A real scenario with similar characteristics to that of Figure 1 has been reproduced. A signal generator, a spectrum analyzer, and a set of antennas (used as a transmitter and a receiver) in the 900MHz frequency band have been used. The transmitter antenna has been located at coordinates *x*=50m, *y*=36m, *z*=4m, corresponding to the red star depicted in Figure 1, with a transmission power level of 10dBm. It has been placed in a streetlight in the middle of the considered scenario. The signal generator is a network analyzer Agilent N1996A configured with a minimum sweep frequency to obtain a single-frequency pulse at the output. The spectrum analyzer is an Agilent N9912 FieldFox. The transmitter antenna PATCH-A-0026 has been used, and the receiving antenna is a monopole (model FLEXI-SMA90-868) of small dimensions to show minimal interference with the scenario. The group of measurements has been done with a typical car (Mazda 3) moving along the road with a constant velocity of 22.22m/s.

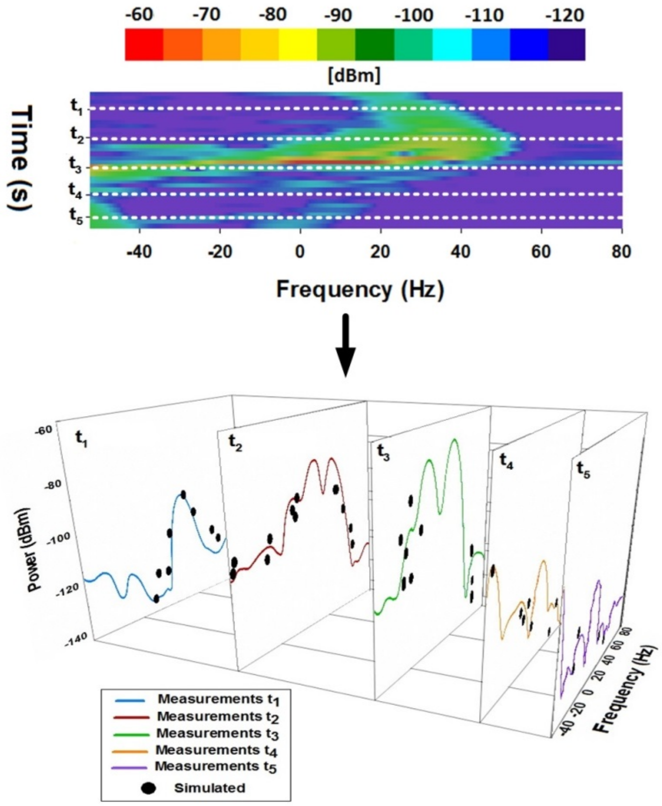


Figure 6. *Spectrogram in 868MHz when the vehicle with the receiver antenna is in movement and the transmitter is fixed in the streetlight.*

Figure 6 represents the measured and simulated spectrogram when the car with the receiver antenna moves along the road. The frequency 0Hz corresponds with 868MHz. The top figure represents the measured spectrogram with five dashed white lines which corresponds with the received power measured for the different five slots of time. These white dashed lines of measured received power has been compared with the simulated received power for the same different instants of time and the comparison is shown in the bottom figure. It can be seen the effects of Doppler shift due to movement, and the good trend of the simulation technique to obtain accurate results of Doppler effects. The differences between the simulated and measured results are due mainly to the differences between the real and schematic scenario. In addition, the single-frequency pulse at the output of the signal generator had some small variations around the center frequency, due to local oscillator instability, which can produce slight mismatches between simulation and measurement results. Figure 7 shows the comparison between simulation and measurements for the received power in the car for different time instants, exhibiting good agreement, with a mean error of 0.776dB and standard deviation of 0.782dB.

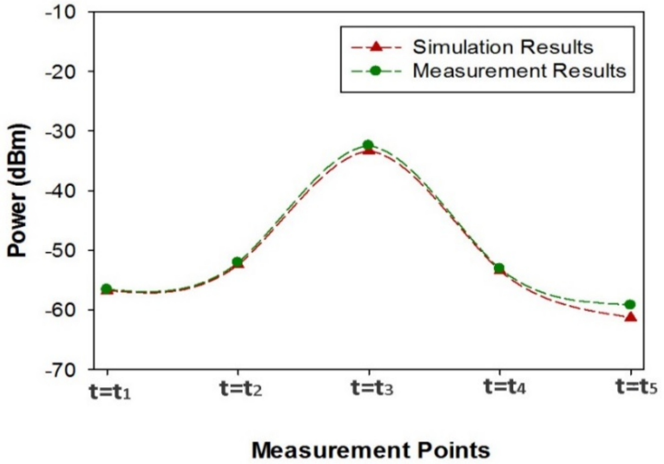


Figure 7. *Comparison simulation versus measurements for 868MHz frequency in the considered scenario.*

The next step is to consider the impact of the Doppler shift in a conventional UHF-RFID system. For that purpose, the geometry model shown in Figure 8 has been considered. For every instant of time, the Doppler shift worst case has been considered, and with this value the angle Φ shown has been calculated using (3). The most common RFID systems use passive tags. Figure 9 shows the range of the estimated read and non-read passive tags for the UHF-RFID system considering the worst case of Doppler shift for a constant velocity of 22.22m/s. The horizontal beam width has been also represented and it is observed that in this specific environment, at instants t_1 and t_5, the tags will not be read, and the more read tags will be at instant t_3.

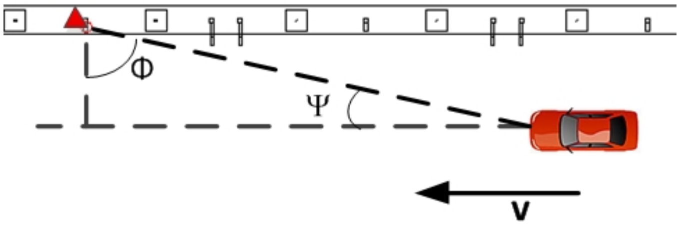


Figure 8. *Geometry model considered for the calculation of the Doppler shift impact in the UHF-RFID system.*

In a passive UHF-RFID system, a tag receives radiation from the reader and modulates its reflection coefficient in order to communicate. The read range is the parameter that defines the maximum distance at which a tag can be read. A successful read is achieved when two conditions are satisfied. One is that the received power by the tag is above the power-up threshold. The second condition is that the sensitivity of the reader is sufficient to detect the signal from the tag. With the 3D RL tool, propagation losses can be calculated and become an input to a radio link budget for RFID to obtain effective read range. Thus, the power received at the reader in the backscatter communication radio link budget has been calculated as a function of the differential reflection coefficient of the tag (ρ'=ρ$_1$-ρ$_2$), where ρ$_1$ and ρ$_2$ are the 0 and 1 states of the chip reflection coefficient, respectively, which depend on the chip load [24].

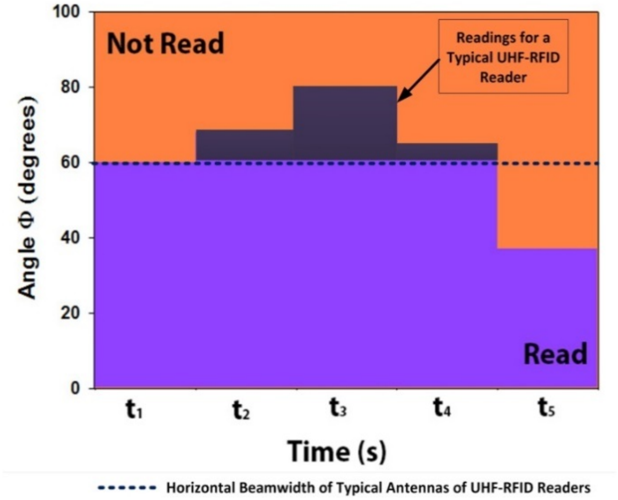


Figure 9. *Horizontal beam width of the transmitter antenna for a typical UHF-RFID system versus different instants of time in the considered scenario.*

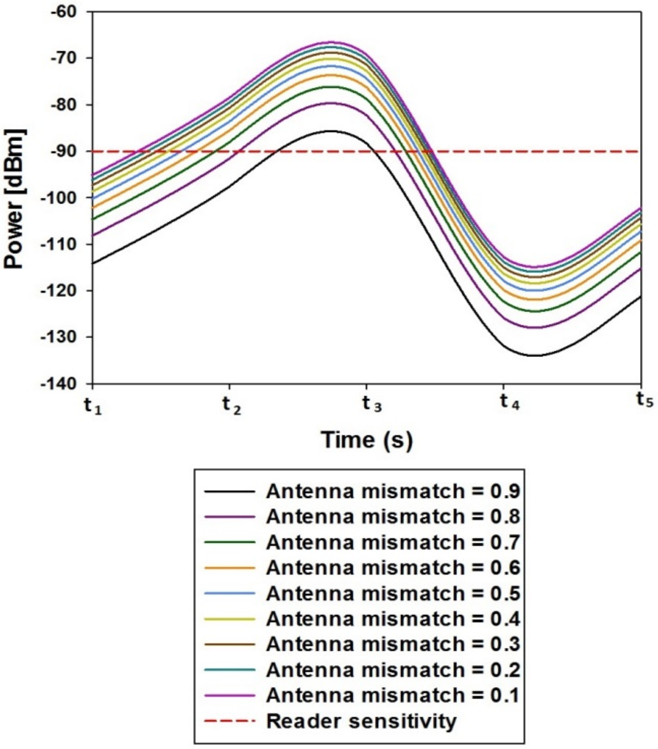


Figure 10. *Received power in the reader in the backscatter communication radio link for different values of antenna mismatch.*

Figure 10 represents the receiver sensitivity of a typical UHF-RFID reader. It is observed that for instants t_1, t_4 and t_5, the received power is very low and the tags could not be read. At instant t_3, for all values of the tag antenna mismatch (due to usual impedance difference in the on/off states of the tag), the power received is greater than the reader sensitivity (-90dBm), so the link budget is positive and the reader could read the information from the tag. At instant t_2, for values of antenna mismatch larger than 0.7, the reader could not read the tag due to the lack in power strength. In all cases, the right position of the reader and the tag play a key role in the capability of reading the tag. From Figure 10, it is observed that the received power in the instant t_5 is bigger than in the instant t_4, when in t_5 the distance between the transmitter and the vehicle increases. This is because the received power is not only distance dependent, but also depends on the morphology and topology of the considered scenario, as well as the movement of the surrounding environment, which affect greatly to multipath propagation.

Conclusions

In this paper, an alternative approach for propagation prediction in vehicular environments has been presented. The new technique is based on a 3D Ray Launching technique which can take into account the movement of different vehicles in the considered scenario, leading to V2V or V2I environments, which are not an easy task to analyze due to channel impairments. Specifically, this work presents the assessment of an UHF-RFID system for vehicular applications. The novel technique gives Doppler shift and Doppler spread results, which can be useful to analyze the impact of the system on this complex specific environment. Simulation as well as measurement results have been presented, showing good agreement, with application to a link budget analysis of an RFID system. Results show that by considering radio planning tasks in the vehicular applications, the overall system performance can be strongly optimized, reducing power consumption as well as non-desired interference levels.

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