Hybrid Environment-based Channel Model for Vehicular Communications

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***Abstract*—A novel hybrid environment-based approach for modeling the vehicular communication channel is developed in this study. It is a combination of a deterministic ray-launching algorithm (PIROPA) to model the Large-Scale parameters, and a stochastic model, to obtain the Small-Scale parameters. This hybrid channel model is site-dependent, i.e., the propagation parameters of the channel are obtained based on the particular scenario, giving a higher accuracy in modeling the channel than using an abstract representation of the scenario. The use of a stochastic approach also provides the model of a flexibility required for different scenario situations, specially in a dynamic environment like vehicular communications. The simulation results show the significance of the scenario and how the peculiarities of the vehicular communications, i.e., low antenna height and high mobility of the receivers and transmitters, impact on the communication channel. The proposed channel model can be used for different applications, such as anti-collision systems, autonomous driving or video applications.**

***Keywords*—vehicular communications, channel modeling, ray-launching, context awareness, urban outdoor propagation**

I. Introduction

Vehicular communications are characterized by the high mobility of the network elements and the impact of the environment geometry. These networks are composed of a large number of participants with a dynamic nature. Moreover, the low antenna height, compared to traditional mobile communications, makes the vehicular channel notably challenging to model. These peculiarities impede the possibility of applying the traditional well-known cellular channel models to obtain an accurate vehicular radio channel model.

In recent years, different approaches to model the vehicular channel have been developed. Some models using a pure ray-tracing algorithm, such as Maurer et al. [1]. This model uses a high detailed description of the scenario, and calculates the channel statistics analyzing the strongest paths obtained using the ray-tracing algorithm. Karedal et al. [2] proposed a different perspective; where the model parameters are extracted from several measurement campaigns done in highway and urban environments. Other models, as Mangel et al. [3], added information about the street architecture and intersections to the model. However, every approach has its own drawbacks, such as non site-dependent properties, because the parameters are obtained from different measurement campaigns, or the requirement of a highly detailed scenario information, which sometimes cannot be easily obtained. Moreover, using an abstract realization of the scenario, it is not possible to model the particularities of the environment, obtaining a less accurate channel model.

In order to overcome these difficulties, a novel hybrid radio channel model is proposed in this work. The most relevant characteristic of this channel model is the combination of a deterministic ray-launching algorithm (PIROPA) [4] [5] for Large-Scale parameters, along with a stochastic approach for Small-Scale propagation parameters. PIROPA is especially designed for urban scenarios, where it simulates the multipath components of a radio link. Since PIROPA uses geographical data as input, the resulting Large-Scale parameters are site-dependent, i.e., the obtained parameters are specific for a chosen scenario. This dependency of the scenario has a noteworthy drawback, which is the requirement of geographical information of the studied scenario. However, data acquired from open sources like OpenStreetMaps [6] have a sufficient level of detail.

Small-Scale parameters cannot be efficiently calculated using PIROPA, since it only uses the physics under the radiowave propagation and it does not use statistical distributions. Therefore, a stochastic approach to model the randomness of the Small-Scale parameters is used in this research. In urban scenarios, the number of scatters and surrounding object situated close to the network elements is large. Combined with the high mobility of the scenario elements, it makes modeling the Small-Scale parameters non trivial. First of all, the extensively exploited models for cellular systems are insufficient, due to the peculiarities of the vehicular communication channel. In addition, the higher frequency used for vehicular networks (5.9 GHz) is envisioned for short distances (10-1000 m), whereas in cellular systems the range of frequencies goes from 700-2100 MHz and the distances are larger, reaching a maximum of about 10 km. Hence, a novel stochastic approach is required in order to accurately model the Small-Scale parameters of the communication channel. Due to the fluctuating nature of the Small-Scale parameters, these values are yielded by statistical distributions. In this proposed model, these statistical distributions were calculated based on the surrounding scenario, making them site-dependent.

Since the implementation of vehicular communications is imminent, the accuracy of the radio channel model should be as high as possible, to be used in future applications. Because the channel model proposed is site-specific, a higher accuracy than in abstract random scenarios is expected. In addition, the scenario-based model is more flexible against the peculiarities of each scenario, due to the possibility of recreating them, giving a more realistic channel model.

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II. Channel Model

A novel concept of radio channel for vehicular communications is described in this section. The proposed radio channel model is specially designed for urban scenarios, and requires geographical input data. The radio channel is created with the purpose of considering specific scenarios, obtaining a high accuracy as well as modeling the particularities of each scenario. In this proposed vehicular channel, the considered network elements are cars. Different canonical situations present the characteristics of the channel model in these scenarios.

The channel model implemented in this paper is based on the combination of two different approaches which are extensively developed in the following subsections.

A. Environment Scenarios

The characteristics of the vehicular radio propagation parameters are strongly related to the surrounding scenario. Moreover, since the proposed channel model encloses a deterministic ray-launching algorithm, the environment geometry plays a crucial role. In this paper, two relevant urban vehicular scenarios are studied.

1) Overtaking: This scenario displays a typical situation in urban road traffic, where safety can be conditioned by the context awareness of the driver and some efforts can be done using a video assisting method [7]. Two cars driving in the same direction, but with different speeds and in different lanes of the same road, as shown in Fig.1. The relevance in this scenario is the high mobility and different velocity of the network elements influencing the propagation parameters. In such a situation, the Doppler shift is of significance, since the spread in frequency affects the communication link and it appears when the elements of the network have a big difference in their speed. It is noteworthy, that the Doppler impact is a peculiarity of vehicular networks, since the Doppler shift is not high enough to affect the communication in classical cellular systems when only pedestrians are involved.

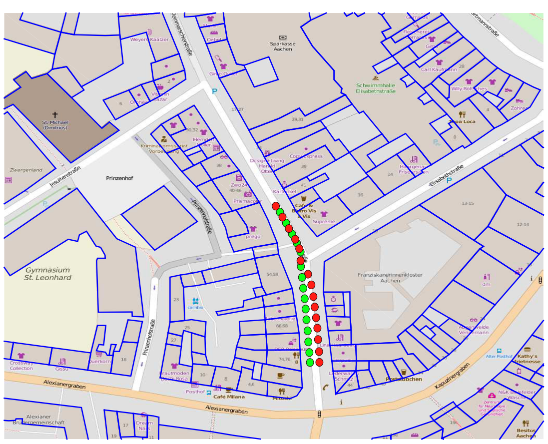

Fig. 1. Overtaking scenario

2) Cross: This scenario simulates a cross involving two cars, as displayed in Fig.2. The relevance of this scenario is to show the importance of the geographical information, regarding the propagation parameters. In a cross, the network elements suffer from different link situations, i.e., Line-of-Sight (LoS) or Non-Line-of-Sight (NLoS). Therefore, the knowledge of the surrounding scenario elements is essential. Particularly in this type of scenarios, it is expected to obtain a greater accuracy using the proposed model than applying abstract realizations of the scenario, due to the geographical input data. Moreover, this scenario is especially interesting in safety applications, since in such scenarios occur high numbers of collisions.

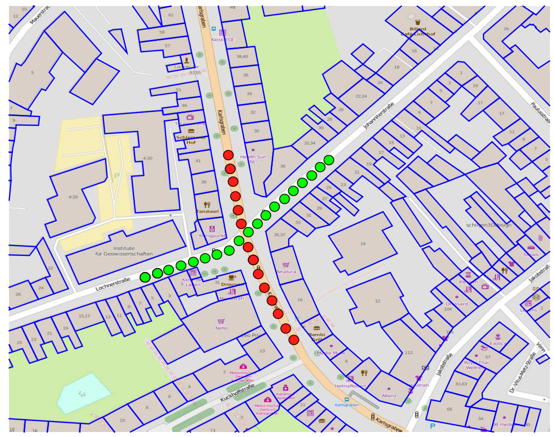

Fig. 2. Crossing scenario

B. Ray-launching algorithm

PIROPA (Parallel Implemented Ray Optical Propagation Algorithm) is a deterministic ray-launching algorithm. Due to its determinism, it could perfectly recreate the results, when given the same input information. It is specialized on urban scenarios operating on a geometric environment description. And to yield the desired performance for critical applications, as simulating vehicular communication channels, it is implemented in C++ and optimized towards runtime performance. The biggest drawback of this algorithm approach storage way is the requirement of detailed scenario information to generate the radio propagation parameters. However, sources are available, as for example, using OpensStreetMaps, this disadvantage is recessed. Therefore, having the complete input data, a scenario-based channel model can be obtained.

PIROPA yields a variety of simulation results such as, pathloss, delay, Angle of Arrival (AoA), Angle of Departure (AoD) and number of rays per cluster. These Large-Scale parameters are mostly influenced by the geometry and they have no stochastic behavior. The Large-Scale parameters are based on electromagnetic wave propagation prediction and physical properties.

The impulse response obtained by applying PIROPA is based on the Double-Directional radio channel [8], where

$$h(t,\tau,\theta,\varphi) = \sum_{n=1}^{N} A_n \delta(\tau-\tau_n)\delta(\theta-\theta_n)\delta(\varphi-\varphi_n) \quad (1)$$

being A_n the complex amplitude of the received ray, τ the delay of each single path, θ the Angle of Arrival and φ the Angle of Departure for each cluster. Using Eq.1 the received power is calculated as

$$P(t, \tau, \theta, \varphi) = \int_0^\infty |h(t, \tau, \theta, \varphi)|^2 \, \mathrm{d}t. \tag{2}$$

As shown in Eq.2, all the parameters involved in the calculation of the received power are generated by the ray-launching algorithm, i.e., they are deterministic. This assumption is valid because θ, φ and A_n of each cluster do not change rapidly. However, the phase of the inter-cluster rays fluctuates fast and need to be determined stochastically. Moreover, the fast-fading phenomenon and the Doppler shift will be calculated using statistical distributions.

C. Stochastic Approach

The Small-Scale stochastic parameters are used to finely adjust the channel model to its random nature. Parameters too fine grained for modeling in the deterministic step, e.g., pedestrians or traffic signs, are considered by adding a stochastic component including such elements in the overall performance of the radio channel model.

1) Doppler Shift: The Doppler spectrum gives the statistical power of the channel at a given frequency. This spectrum is given by the motion of the surrounding objects and by the movement of the transmitter and receiver. Therefore, the bigger the relative speed between both ends of the communication channel and the higher the mobility of the environment elements, the higher the Doppler spread will be. The Doppler spectrum is given by the following expression:

$$DoppS = \frac{F_c}{c}((v_1 - v_2)\cos(\theta) + (v_2 - v_1)\cos(\varphi)) \tag{3}$$

$$= \frac{F_c}{c}(v_{rel}\cos(\theta) - v_{rel}\cos(\varphi)). \tag{4}$$

being F_c the central frequency used in the radio channel, c the speed of light, θ the Angle of Arrival, φ the Angle of Departure and v_1,v_2 the speeds of the transmitter and receiver given in $m \cdot s^{-1}$, respectively.

2) Inter-cluster Phases: Using the deterministic ray-launching algorithm, the angle of arrival of each cluster is calculated. However, due to the deterministic nature of the algorithm, the motion of the surrounding network elements is not considered. As it is known, the movement of these elements produces a change in the incident phase of the rays. Therefore, a stochastic model is required, since the movement of the network elements cannot be completely predicted. The shift in the phase is created as a function of the surrounding elements motion, as follows:

$$InterClustPh' = K \cdot InterClustPh + X \tag{5}$$

being X uniformly distributed values in the range $[0, 2\pi]$, K a value which fluctuates between [-1,1], due to constructive or destructive interference, in function of the number of reflections the rays suffer and $InterClustPh$ the phase obtained using PIROPA.

3) Fast-fading: The last stochastic parameter calculated is the fast-fading characteristic of the radio wave propagation channel. It is defined as the fluctuation suffered by the transmitted signal due to the multipath components. As a result of the different replicas reaching at the receiver side, the resulting addition at the end could be constructive or destructive, being influenced by the phase of the receiving rays. In the proposed stochastic approach, the fast-fading is calculated in function of the surrounding objects, using as reference [3]. In this study, it has been proved how the geometry of the surrounding roads affects the profile of the propagation loss, giving different pathloss models depending on the geometry. Moreover, the type of scenario is studied, e.g., rural, urban or quasi-urban and the NLOS/LOS situation is determined using the deterministic algorithm. The fast-fading is modeled as Rician fading and the scaling factor of the distribution is biased by the environment. Therefore, in a LoS situation, the fast-fading will have a smaller impact on the communication channel than in a NLoS situation where the multipath propagation will have a bigger influence.

III. Results

In the simulation of both scenarios, the transmitter and receiver antennas are situated 1.5 m above ground level, emulating the height of a car. Since the height of the antennas is much smaller than the surrounding buildings, the roof refraction is neglected, and only the diffractions and reflections on the walls off the buildings are considered. The transmitted power used is 1W, to obtain a clear value of the pathloss.

A. Overtaking Scenario

1) Power Delay Profile: In Fig. 3, the PDP of the overtaking scenario shows a typical profile dependent of the distance between transmitter and receiver, since the network elements are in a LoS situation. The received power is inversely proportional to the square of the distance in the directly received rays and only the multipath components suffer a higher delay and lower power.

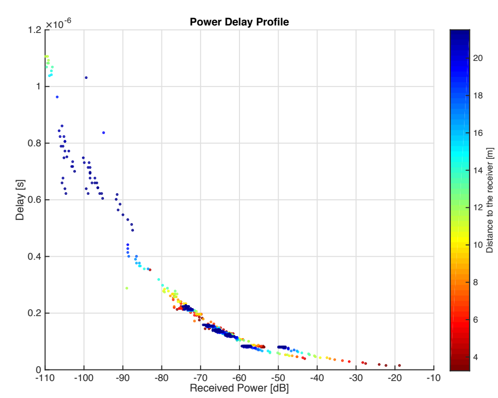

Fig. 3. Power Delay Profile in an overtaking scenario

2) Doppler Shift: The Doppler Shift in an overtaking scenario behaves as can be expected, as shown in Fig. 4. In the first 20 measurement points, the receiver and transmitter have the same speed, giving an almost null Doppler shift.

Nevertheless, the Doppler shift rises once the relative speed between both increases.

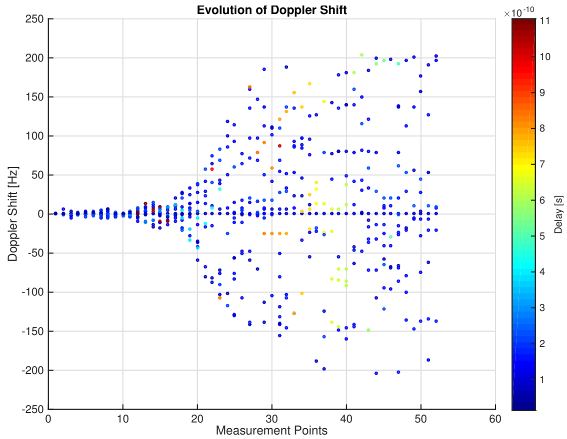

Fig. 4. Doppler Shift in an overtaking scenario

B. Cross Scenario

1) Power Delay Profile: In Fig. 5, the PDP of a crossing scenario shows different behavior when compared with the overtaking scenario. While having a main part of the graph which follows the same negative exponential behavior as the overtaking scene, and since this part of the channel is in a LoS situation, the two other paths suffer from a different phenomenon. These two paths are created due to the NLoS of the channel and, both have a lower received power, due to the higher number of bouncing-off suffered until they reach the other part of the communication link.

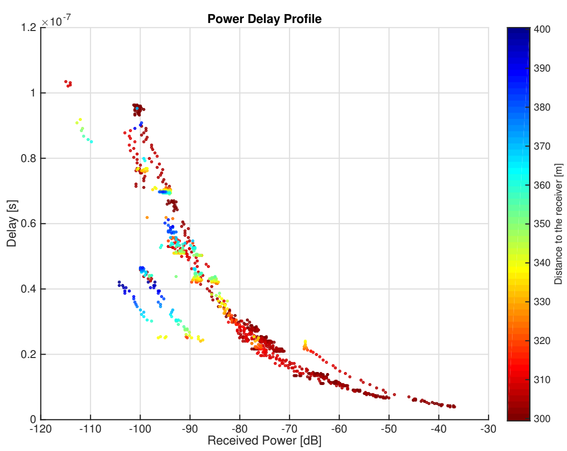

Fig. 5. Power Delay Profile in a crossing scenario

2) Doppler Shift: Fig. 6 displays the results for the Doppler shift. Due to the NLoS situation in most of the simulated scenario, the Doppler shift is higher than in the overtaking scenario. This is caused by the higher number of reflections in the surrounding scenario scatters. In this case, the maximum value obtained by the Doppler shift is between [-600, 600 Hz], having a low impact on the communication link, but it cannot be neglected. In the first 40 measurement points of Fig. 6, the Doppler shift is increasing almost constantly, due to the constant acceleration of the cars, increasing the relative speed between the cars. Nevertheless, once the speed is stable, the Doppler shift is constant around $\pm$ 550 Hz.

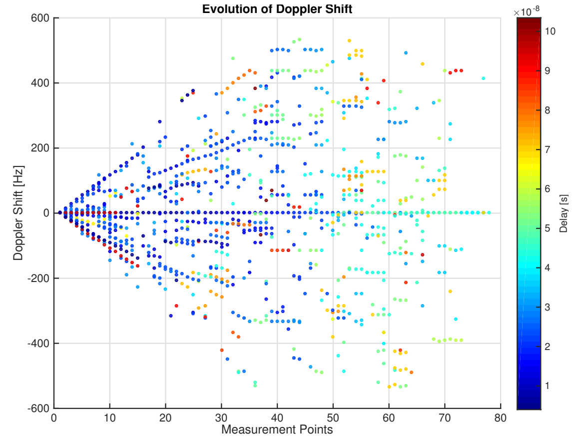

Fig. 6. Doppler Shift in a crossing scenario

IV. Applicability

In this section different examples of the possible applications for the vehicular channel model are introduced. These applications are focused to exploit the context awareness of the channel model, and are directed towards creating a feasible vehicular network. The cumulative distribution function for the received power is illustrated in Fig. 7. Using this parameter, it is possible to observe the connectivity level between two cars, i.e., we select a power threshold where an application will work, and using this parameter, the percentage of availability can be detected. Moreover, using this attribute, it is possible to modify the transmitted power in different scenarios, consequently conserving the energy.

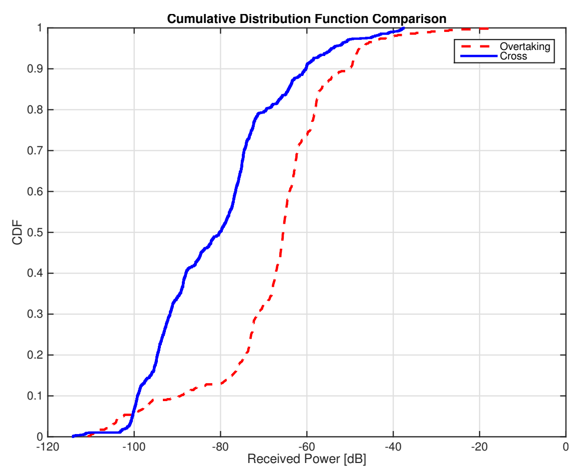

Fig. 7. Received Power CDF Comparison

In Fig. 7, we can see the differences in the performance of the received power depending on the scenario. In the overtaking scenario, since the network elements are in a LoS situation, the received power is approximately 20 dB higher than in the crossing scenario.

The context aware channel model is specially suitable for the planning and deployment of RSU (Road Side Unit), since the parameters of the channel are site-dependent, and the changeable characteristics of the environment are taken into account. For the purpose of deployment a vehicular network, the same concepts as in the classical mobile communications can be used, because the RSU is elevated over the buildings and static.

Another important aspect to determine the applicability of the channel model is to obtain the maximum delay and angle spread value. Both parameters are second order statistics obtained using the ray-tracing algorithm. Delay spread is an important parameter for the receiving end of the communication link, since a really high delay will negatively affect the performance of the decoder. Therefore, knowing the upper bound of the delay spread will help to design the receiving system. In addition, the angle spread has been also analyzed. This parameter is important in the receiver side whether a directional beam is used. The angle spread has been calculated for both studied scenarios, using the following expression:

$$\sigma_A = \sqrt{\int (\theta - \theta_0)^2 \cdot Power(\theta) \, \mathrm{d}\theta} \tag{6}$$

where θ is the Angle of Arrival, θ_0 is the mean value of the Angle of Arrival and $Power(\theta)$ is the received power in function of the angle for each ray.

Likewise, the Doppler spread has been calculated using the following equation:

$$\sigma_D = \sqrt{\int (\tau - \tau_0)^2 \cdot Power(\tau) \, \mathrm{d}\tau} \tag{7}$$

where τ is the delay, τ_0 is the mean delay value and $Power(\tau)$ is the received power in function of the delay for each ray. Using these expressions, the obtained values are displayed in Table I:

TABLE I. DELAY AND ANGULAR SPREAD

Scenario	Delay Spread [s]	Angular Spread [degrees]
Overtaking	2.9355×10^{-10}	100.8281
Crossing	2.3844×10^{-8}	106.5911

Observing the Table I, we can see the delay spread is higher, as expected, in the crossing scenario where the multipath is a predominant phenomenon. However, the Angle spread is comparable in both situations. For this reason, the Angle of Arrival was also analyzed using the angular distribution for both scenarios.

The Angle of Arrival distribution is displayed in Fig. 8. The AoA for a cross scenario is concentrated in the range of [90, 270 degrees], with peaks around 270 degrees, when the overtaking maneuver is being done and 45 degrees due to the reflections created by the buildings surrounding the vehicles. Moreover, there is also a great concentration of paths around 0 degrees, which are created when However, in the cross scenario the AoA is distributed uniformly, having only a higher concentration of received rays around 0 degrees when the overtaking maneuver is completed. This result is consistent with the higher impact of the multipath in a crossing scenario. Using this result, the directional beam of the receiver antenna can be designed to take advantage of this knowledge. Having the receiver antennas pointing to the most likely arrival

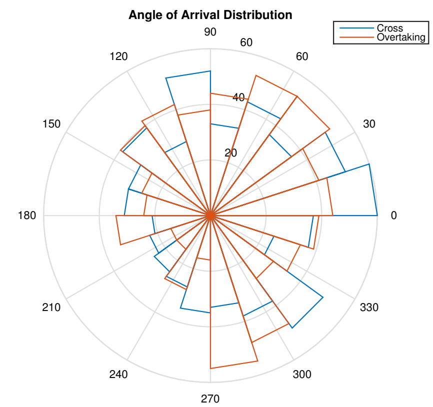

Fig. 8. Angle of Arrival Distribution

directions will give a better performance of the vehicular radio channel, since the gain will be higher.

V. Conclusion

In this paper, a novel vehicular radio channel model is introduced and analyzed. The channel model was created using a combination of a deterministic ray-tracing algorithm and stochastic methods to model the randomness of a variable scenario. The radio channel model was used in the simulation of two canonical scenarios for vehicular communications, i.e., an overtaking and a crossing scenario involving two vehicles. The results obtained show the characteristics of the vehicular radio channel and the challenges faced to model it perfectly. Moreover, using the characteristics of the channel model, different applications were introduced and analyzed.

The main goal of this proposed radio channel model is to develop a context aware model to exploit the knowledge of the scenario to model the vehicular channel with increased accuracy. In the near future, vehicular communications will be a reality and therefore, the precise knowledge of the surrounding scenario will help to create different applications for safety and/or entertainment.

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