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Theoretical Polarimetric Channel Characterization of Road Tunnels in Presence of Vehicles at 5.9 GHz

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Abstract—**Vehicular communication is a hot topic for developing solutions for automatic guidance, safety-related problems, and end-user applications. The dedicated frequency band in Europe is around 5.9 GHz. Characterization of the communication channel is thus deeply studied especially for the urban and rural environments but most of the case studies are related to the prediction of path loss and fading distribution. In this paper, the special case of vehicular to infrastructure communication in a road tunnel is treated, owing to a ray tracing simulation tool. The influence of the direction of polarization of the field at the transmitter on channel characteristics is emphasized, assuming either an empty tunnel or the presence of a truck convoy. The contribution of the reflected waves on the trucks to the total field, the direction of departure and arrival of the rays, features of the polarization ellipse at the receiver, and cross-polarization discrimination are discussed.**

Keywords- tunnel; propagation; path loss; obstructed tunnel; elliptical polarization; channel modeling; vehicular communication

I. Introduction

There is a growing interest in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications to make vehicles more autonomous in a context of high security and also allow the development of many end-user applications. This implies implementing reliable and low latency connections with the environment and optimizing the transmission link, channel modeling is thus needed. This is particularly challenging due to the complex geometry of the environment and the low antenna heights on vehicles and roadside units. Related topics such as the realization of wideband triangular antennas and the optimization of the multi-depot vehicle routing problem are treated in [1] and [2], respectively.

The 5.9 GHz band has been designated by the European Administration for use by road Intelligent Transport Systems (ITS). For an urban environment, simulations to evaluate the communications issues that may occur are described in [3] and are based on COST 207 models [4]. A Non-Line of Sight (NLOS) path-loss and fading model, based on real-world measurements for characterizing V2V communications at intersections is proposed in [5]. A path loss model suitable for vehicular ad hoc network simulators and urban, rural, and highway scenarios is given in [6]. The model parameters are derived from extensive narrowband channel measurements at 700 MHz and 5.9 GHz, while in [7] a survey of various models and a classification based on the propagation mechanisms they employ and the complexity of their implementation is presented.

Among all possible environments, tunnels are quite specific since waves are guided by a 3-dimensional structure. In this paper, we will focus on such a configuration. For a straight rectangular or circular tunnel, propagation modeling can be made through either a modal or a ray tracing approach and various path loss models have been developed [8], [9]. The Vector Parabolic Equation method was used to study the propagation characteristics of tunnels of different geometries, as arched tunnels [10], while the influence of obstacles distributed in the tunnel is outlined in [11]. Path loss measurements have also been performed to extract the parameters of a 3-slope model [12]. Many other papers were also published in various frequency bands but, in most of them, results deal with path loss and short-range fading. Furthermore, a vertical polarization of the waves is usually assumed.

For vehicular communication, the physical layer is the same as that of 5G, and Multiple Input Multiple Output (MIMO) techniques can be applied. Therefore, to optimize and predict the performance of the link, understanding the role of other parameters, such as the direction of polarization and the Spatio-temporal channel characteristics, is needed [13].

In the following, to achieve this goal, simulations based on a ray tracing tool have been performed and the main contributions of this paper are: i) analysis of the influence of wave polarization on path loss assuming either an empty 2-lane tunnel or the presence of a truck convoy in one lane, ii) the characterization of the polarization at the receiver (Rx) which could be either nearly linear or elliptical, iii) the distribution of the angle of departure/arrival of the rays. The paper is organized as follows: The geometrical configuration of the tunnel with or without traffic is described in Section II, and the simulation tool is briefly presented. In Section III, a co-polarized configuration at the transmitter (Tx) and at Rx is assumed, the linear polarization at Tx being either vertical (V), horizontal (H), or inclined, making an angle of 45°referred to a horizontal axis. In presence of vehicles, the relative contribution of forward and backward waves due to reflection

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on the vehicles is outlined, the main features of the arrival angular profile, as well. Cross-polar configurations and polarization ellipse at Rx are then studied in Sections IV and V, respectively. This approach allows drawing a conclusion on the influence of the direction of wave polarization at the transmitter on the channel characteristics.

II. Geometrical Configuration and Simulation Tool

All simulations have been carried out assuming a straight rectangular tunnel, 10 m wide and 6 m high, these dimensions being those of a highway tunnel where measurements will be carried out in a near future. The omnidirectional Tx source is situated at a height of 2.2 m and a distance of 0.5 m from one of the vertical walls. The transmitting frequency is 5.9 GHz. The receiving point moves in the middle of one lane, free of cars, at a height of 2.7 m, as shown in Fig. 1. In the following, the case of either an empty tunnel or the presence of a 20-truck convoy along a lane is envisaged, the other lane being free of vehicles. In this configuration, the trucks are in a static position, the first truck being at 50 m from Tx. For the simulation, each truck is assumed to be a perfectly conducting parallelepiped, 2 m wide, 4 m high, and 12 m long. The distance between 2 successive trucks is 40 m corresponding to the safety distance for a speed of 100 km/h.

Simulations have been done with Opal, a ray-tracing propagation simulator based on Graphics Processing Units (GPU). It uses the shooting and bouncing (SBR) method, electromagnetic waves being simulated by rays launched from Tx. This tool currently implements n-order reflections for flat, curved, or combined flat-curved scenario elements, and single-order diffraction. It works with both static and moving 3D scene objects, represented as triangle meshes. Objects, transmitters and receivers can be dynamically added and removed from the scene and subsequent ray launches take those changes into account. It must be emphasized that a full description of the wave polarization is obtained. The simulations are deterministic and no confidence interval is needed. Possible errors are related to the high frequency approximation assumed in the ray tracing approach, and the size of the reception sphere introduced in ray bouncing methods. In our simulations, we have used the ray density normalization approach, which reduces the errors due to the size of the reception sphere. This tool, whose main features and performances are described in [14], has already been applied for the simulation of the propagation of 1.3 GHz waves in a tunnel [15]. Since the shape of the trucks introduced in this tool is rather rough, diffraction phenomena on the edges of the parallelepiped are not taken into account. The conductivity and relative permittivity of the tunnel walls are 10^{-2} S/m and 5, respectively.

III. Co-Polarization Configurations

In this section, the influence of vehicles on path loss is emphasized, and the contribution of forward and backward propagating waves on the received field is then studied. Lastly, delay spread and spatial characteristics of the channel in terms of angles of arrival/departure, are given.

A. *Path Loss*

Curves in Fig. 2 show the variation of the field amplitude, referred to an arbitrary value, versus distance either for an empty tunnel or in presence of 20 trucks, the spatial step being 1 m. The polarization of the waves at Tx is vertical (V) and at Rx, only the co-polarized component has been considered, such a link being noted VV.

In the empty tunnel, the decrease of the field amplitude along the first 500 m is about 3.3 dB/100 m, but beyond this distance, the mean attenuation becomes much smaller, less than 1 dB/100 m. Such a 2-slope behavior is well known because near Tx, a large number of propagating modes is excited, but high order modes are rapidly attenuated.

Therefore, at large distance, low order modes become dominant and propagate with a low attenuation constant. If a ray tracing approach is used, high order modes correspond to rays propagating with a large angle of incidence on the tunnel walls [16]. In presence of trucks, the global shape of the curves remains the same but the break point of the 2 slopes occurs at a larger distance.

Other simulations have shown that the polarization at Tx does not play an important role in the field attenuation since for this frequency of 5.9 GHz, the transverse dimensions of the tunnel (10 m x 6 m) are much larger than the wavelength (5.1 cm).

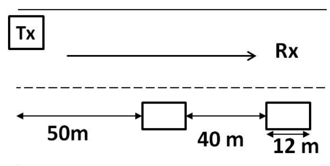


Fig. 1. Plane view of the tunnel and position of the truck convoy

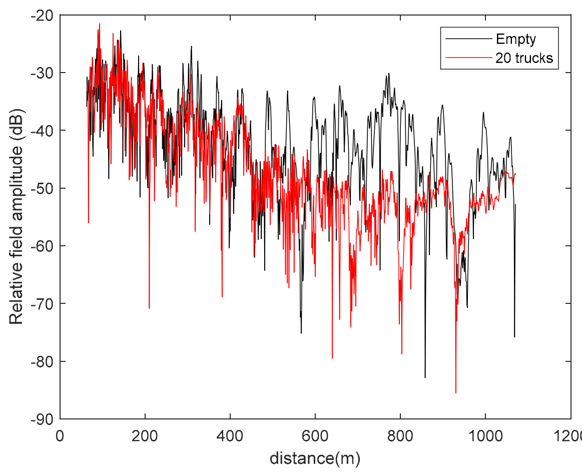


Fig. 2. Variation of the relative field amplitude versus distance in an empty tunnel and in presence of trucks for a VV polarization

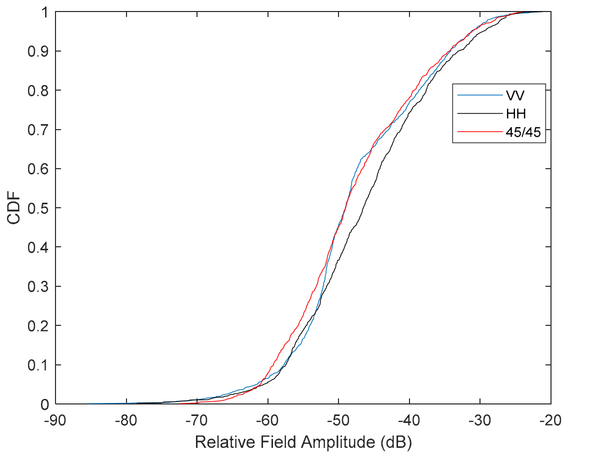


Fig. 3. Cdf of the relative field amplitude for the 3 co-polar configurations in presence of 20 trucks

TABLE I. ADDITIONAL ATTENUATION DUE TO THE PRSENCE OFTRUCKS

Polarization	VV	HH	45°/45°
Percentile 50%	3.9 dB	2.7 dB	4.1 dB
Percentile 90%	17 dB	15 dB	15 dB

This also clearly appears in Fig. 3 giving the complementary distribution function (cdf) of the field amplitude along all the tunnel, for 3 co-polar configurations (VV, HH, 45°/45°) in presence of trucks. It must be mentioned that, at lower frequencies, the attenuation would minimum if the polarization of the waves is parallel to the largest side of the tunnel.

The additional attenuation due to a truck convoy, the reference being the case of an empty tunnel, was determined for the 3 polarizations, VV, HH, and 45°/45°. The median value of this additional attenuation and that calculated for a percentile of 90%, deduced from the cdf of this function taking all receiving points along the tunnel into account, are given in Table I.

The median value is on the order of 3 to 4 dB, whatever the polarization. For a percentile of 90%, this attenuation can reach 17 dB. Indeed, the calculation is based on the ratio, at the same Rx point, between the field in an empty tunnel and that in presence of trucks. Since the environment is quite different for these 2 configurations, a deep fading may occur at a given point in an empty tunnel but elsewhere in presence of vehicles. Therefore, at this point, the ratio between the amplitudes of the field can be high.

B. *Amplitude of Forward and BackwardWaves*

The presence of trucks all along the tunnel gives rise to multiple reflections on their sides and it is thus interesting to quantify the contribution of the waves reflected on the trucks and propagating back to Tx, i.e. appearing at Rx as waves coming from the end of the tunnel and noted backward waves.

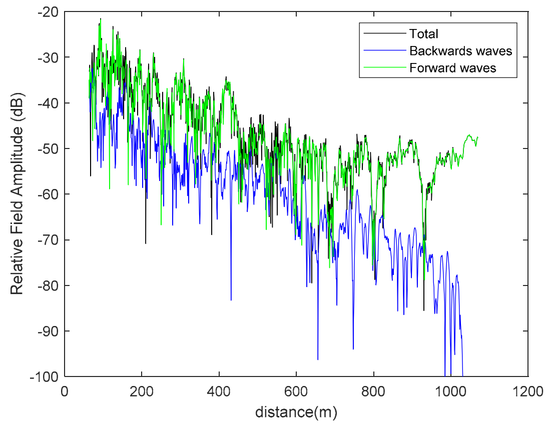


Fig. 4. Contribution to the total field of the forward and backward rays

The other contribution to the total field is that of forward waves, propagating from the tunnel entrance, where Tx is situated, towards the end of the tunnel. This last case includes multiple reflections on the trucks, between Tx and Rx. Curves in Fig. 4 show the field amplitude versus distance only due either to backward rays, or to forward rays, for a VV polarization. The total field variation is also plotted. The number of trucks situated beyond Rx and which can reflect the waves, of course, decreases with distance. Therefore beyond 800 m, the contribution of the forward ray becomes much smaller than that in the middle of the tunnel.

To give quantitative results, one can introduce the ratio between the amplitude of the field associated with the backward waves to that of the forward rays. Values of this ratio, for a percentile of 50% (median value) and for 90% are given in Table II. The median value is on the order of -15 dB and thus the average contribution of the backward waves to the total field is nearly negligible. Of course, if a fast fading occurs at a given Rx point for the forward waves and not for the backward waves, this would lead to an opposite conclusion. This situation rarely occurs but is implicitly included in the results for a percentile of 90%.

C. *Angular Characteristics and Delay Spread*

The knowledge of the angular characteristics of the propagation channel is interesting to appreciate the richness of the channel in terms of multipath propagation and to optimize receiving and transmitting arrays, as well as the signal processing technique. An empty tunnel and the presence of trucks will be successively envisaged.

TABLE II. RATIO (DB) BETWEEN THE AMPLITUDE OF THE BACKWARD WAVES, FROM THE END OF THE TUNNEL, ("REAR REFLECTIONS"), AND THAT OF THE FORWARD WAVES, CALCULATED ONLY ON THE FIRST 800 M.

Polarization	VV	HH	45°/45°
Median value	-13 dB	-17 dB	-17 dB
Percentile 90%	-2 dB	-7 dB	-6 dB

- Angles of departure/arrival in an empty tunnel

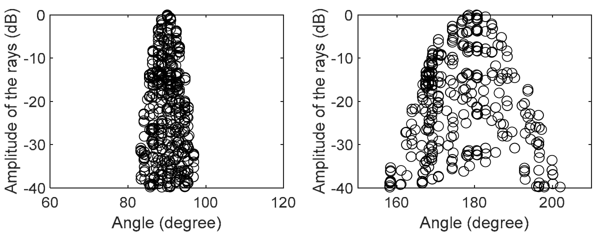
The arrival angular profile is defined as the relative amplitude of the rays versus their arrival angle, the amplitude of the most powerful ray being normalized to 0 dB. Examples of profiles in elevation and azimuth are given in Fig. 5a and 5b, respectively, Rx being situated at 300 m from Tx. In elevation and in azimuth, values are centered around 90° and 180°, respectively, corresponding to the direction of the tunnel axis. By considering a range of 40 dB for the amplitudes of the rays, Fig. 5 shows that the rays are more spread in azimuth than in elevation, since the tunnel width is about 2 times greater than its height. In elevation, rays are thus much concentrated around the tunnel axis. However, the root mean square (RMS) angular spread is about 5° both in elevation and in azimuth, each ray being weighted by its power. The same results were obtained at Tx and clearly show the guiding effect of the tunnel. However, at a short distance, less than 50 m, the contribution of rays having a wide angle of incidence on the tunnel walls can play a non negligible role.

- Angles of departure/arrival in presence of vehicles

The elevation angular profile has the same shape as that in an empty tunnel (Fig. 5a). However, all rays appearing on the azimuth angular profile, Fig. 6, can be divided into 2 groups related to waves propagating either "forward" or backward" and centered around 180° and around 0°, respectively. The angular spread remains on the order of 5° for the elevation and the azimuth but, in this last case, by separately calculating the angular spread of the forward rays and that of the backward rays.

- Delay spread

The RMS delay spread is deduced from the amplitude of the successive rays arriving at Rx. In an empty tunnel, the RMS delay spread at 300 m from Tx is very small, equal to about 6 ns, and does not vary appreciably with distance. In presence of trucks, the situation is quite different due to multiple reflections between trucks and between the tunnel walls and the trucks, leading to backward waves, as shown in Fig. 6. If both forward and backward waves are taken into account, the delay spread varies between 350 and 600 ns, depending on the position of Rx, values to be compared to the 6 ns in an empty tunnel.



(a) (b)

Fig. 5. Arrival angular profile, for an empty tunnel, at a distance of 300 m; a) in elevation, b) in azimuth

IV. Cross-Polarization Configurations

The cross-polar discrimination factor, XPD, is defined as the ratio of the field received for co-polarized and cross-polarized configurations, respectively. The mean value of XPD along the tunnel and its value for a percentile of 90%. are given in Table 3, for a V or +45° polarization at Tx, the field component calculated at Rx being thus H (noted VH) or -45° (noted +45°/-45°), respectively. Results for an empty tunnel or in presence of trucks are given.

Results are quite different depending on the polarization at Tx. For V polarization the mean value of XPD is on the order of 50 dB, the same result is obtained for H polarization, while for a 45° polarization, it is only 5 dB. To explain this result, for a 45° polarization, the field radiated at Tx is put as the vector sum of 2 equal orthogonal in-phase components, horizontal (E_{HTx}) and vertical (E_{VTx}). Since the reflection coefficient on each wall of the tunnel differs according to the polarization of the incident field, it results that, at any Rx point, the 2 field components, noted E_{HRx} and E_{VRx} respectively, differ both in amplitude and phase [15]. However, along the tunnel, the mean values of E_{HRx} and E_{VRx} do not differ appreciably from one another, since the direction of polarization at Tx has nearly no influence on path loss as it was shown in Fig. 3. It results that the median values of co-polar and X-polar configurations only differ from 5 dB. To give a deeper insight into the field characteristics at Rx, the main features of the polarization must be determined.

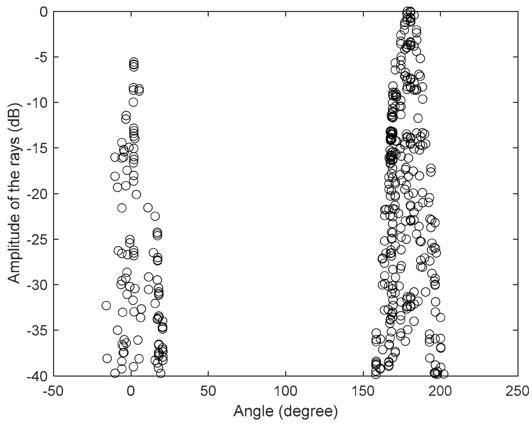


Fig. 6. Arrival angular profile in azimuth, in presence of trucks

TABLE III. XPD (dB) for a Vertical (V) and 45° Polarization at Tx in an Empty Tunnel and in Presence of Trucks

Configuration	V H empty	V H trucks	+45 /-45° empty	45°/-45° trucks
median value	44 dB	51 dB	6 dB	4 dB
90 %	56 dB	65 dB	16 dB	13 dB

V. POLARIZATION ELLIPSE

If E_{HRx} and E_{VRx} are not in phase, the field at Rx is elliptically polarized. This ellipse is characterized by 2 parameters, the tilt angle defined as the angle between the major axis of the ellipse and the horizontal direction, and the axial ratio between the major and minor axes.

In presence of trucks, variation of the tilt angle is given in Fig. 7, the polarization at Tx being either vertical (V), horizontal (H), or inclined at 45°. For V and H polarizations at Tx, the tilt angle at Rx is nearly the same as that at Tx and there is thus no change in the direction of polarization. On the contrary, for an inclined polarization of 45° at Tx, the variation of the tilt angle at Rx is quite large and varies very rapidly with distance. This is due, as previously mentioned, to the differences in phase and in amplitude between E_{HRx} and E_{VRx} which depend on the position of Rx. Another way of emphasizing the spread of the tilt angle when Rx moves in the tunnel is to plot its histogram for a 45° polarization at Tx. Such a histogram is shown in Fig. 8. We note that, in presence of trucks, there is a slight change in the average direction of

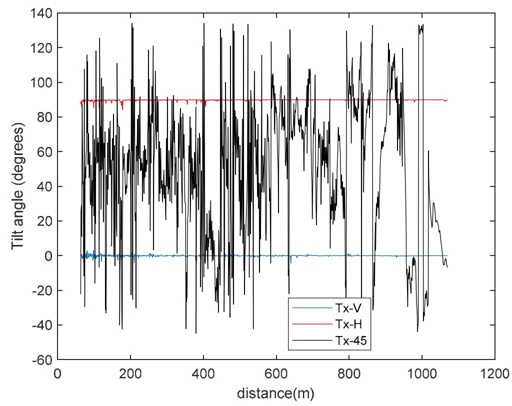


Fig. 7. Tilt angle at Rx for 3 polarizations at Tx: vertical (V), horizontal (H) or inclined (45°)

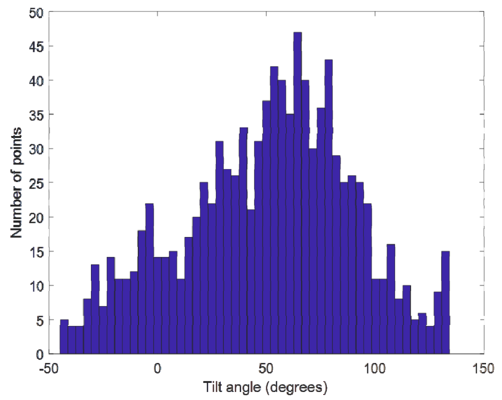


Fig. 8. Histogram of the tilt angle for a 45° polarization at Tx and in presence of trucks in the tunnel

polarization, but the tilt angle is mainly spread between 30° and 80°. The shape of the ellipse can be described in terms of its axial ratio. Numerical simulations show that, for a V polarization at Tx, its median value is about 50 dB for an empty tunnel or in presence of trucks. Such a high value means that the field remains linearly polarized and thus there is no depolarization. On the contrary, for a 45° polarization at Tx, the axial ratio is around 12 dB, i.e. a ratio of 4 between the lengths of the 2 axes of the ellipse.

VI. CONCLUSION

It was shown that path loss in the tunnel at a frequency of 5.9 GHz does not depend on the direction of polarization at Tx, whether V, H, or inclined at 45°. The same conclusion also applies to the median value of the additional attenuation due to the presence of a truck convoy, equal to 3 to 4 dB. On the contrary, the amplitude of cross-polarized field components strongly depends on this polarization since the average XPD is around 5 dB for a 45° polarization instead of 50 dB for V or H polarization. It was also outlined that this direction of polarization also plays an important role in the characteristics of the polarization ellipse at the receiver. Lastly, the guiding effect of the tunnel was highlighted, owing to the determination of the arrival angular profile, in the presence or not of a truck convoy.

The next step in the simulation will be the introduction of dynamic conditions, i.e. displacement of Rx together with other vehicles in the same lane, a truck convoy being still present in the other lane. Lastly, measurement campaigns based on a massive MIMO channel sounder will take place in such a tunnel within the next few months, allowing a comparison to predicted results. The measured channel characteristics will also be used to evaluate the performance of the MIMO link in terms of the sum-rate capacity, and depending on the number of users in the tunnel.

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REFERENCES

[1] J. M. Sanchez-Vite, M. Reyes-Ayala, E. A. Andrade-Gonzalez, S. Chavez-Sanchez, H. Terres-Pena, and R. Rodriguez-Rivera, "ETMSA and ITMSA Antenna for Wideband Wireless Radiocommunication Systems," WSEAS Trans. on Communications, vol. 21, pp. 86-91, 2022

[2] G. S. Sahar, K. Okba, L. Abdelkader, Y. M. Amine, R. Euler, A. Bounceur, and M. Hammoudeh, "An Optimized Scalable Multi-ant Colony System for Multi-depot Vehicle Routing Problems Using a Reactive Multi-agent System," WSEAS Transactions on Systems, vol. 20, pp. 249-259, 2021

[3] M. C. Surugiu, I. Petrescu, and R. A. Gheorghiu, "Analysis of Signal Propagation in Vehicular Communications", Procedia Manufacturing, vol. 46, pp. 754-759, 2020.

[4] COST 207, "Digital Land Mobile Radiocommunication", European Commission Pub. office, 1990

[5] T. Mangel, O. Klemp, and H.Hartenstein, "5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight path-loss and fading model". J. Wireless Com Network, paper 182, 2011

[6] H. Fernández, L. Rubio, V. M. Rodrigo-Peñarrocha, and J. Reig, "Path Loss Characterization for Vehicular Communications at 700 MHz and 5.9 GHz Under LOS and NLOS Conditions," IEEE Antennas and Wireless Propag. Letters, vol. 13, pp. 931-934, 2014

[7] W. Viriyasitavat, M. Boban, H. Tsai and A. Vasilakos, "Vehicular Communications: Survey and Challenges of Channel and Propagation Models," IEEE Vehicular Technology Mag., vol. 10, no. 2, pp. 55-66, June 2015

[8] A. Hrovat, G. Kandus, and T. Javornik, “A survey of radio propagation modeling for tunnels,” IEEE Communications Surveys & Tutorials, vol. 16, no. 2, pp. 658-669, 2014

[9] H. Jin, C. Li, and W. Wu, "Path Loss Analysis for VANET in Tunnel Environment", Int. Conf. on Information and Commun. Techno. Convergence (ICTC), pp. 241-244, 2021

[10] Z. Huang, X. Zhang, and C. D. Sarris, "Vector Parabolic Equation Modeling of sub-6 GHz 5G Propagation in Tunnels", IEEE Int. Conf. on Antennas and Propag. and URSI Symp., pp. 647-648, Dec. 2021

[11] M. Gan, G. Steinbock, Z. Xu , T. Pedersen, and T. Zemen, "A Hybrid Ray and Graph Model for Simulating Vehicle-to-Vehicle Channels in Tunnels", IEEE Trans. on Vehicular Techno., vol. 67, no 9, pp. 7955-7968, 2018

[12] A. Santos, L. Matos, P. Castellanos, and V. Mota, "Channel Characterization in V2I System inside a Tunnel in 5.8 GHz", SBMO/IEEE MTT-S Int. Microwave and Optoelectronics Conf. 2021.

[13] A. Saleem, H. Cui, Y. He, and A. Boag, "Channel Propagation Characteristics for Massive Multiple-Input/Multiple-Output Systems in a tunnel Environment," IEEE Antennas and Propag. Mag., pp. 126-142, June 2022

[14] E. Egea-Lopez, J. M. Molina-Garcia-Pardo, M. Lienard, and P. Degauque, "Opal: An open source ray-tracing propagation simulator for electromagnetic characterization". PLoS ONE 16(11): e0260060, 2021, https://doi.org/10.1371/journal.pone.0260060.

[15] E. Egea-Lopez, J. M. Molina-Garcia-Pardo, M. Lienard and P. Degauque, "Deterministic Polarimetric Propagation Analysis in Road Tunnels", to be presented at the Int. Wireless Commun. and Mobile Computing Conf., Dubrovnik, May 30 - June 2, 2022.

[16] J.-M. Molina-Garcia-Pardo, M. Liénard, P. Degauque, D. Dudley, and L. Juan Llácer, “Interpretation of MIMO channel characteristics in rectangular tunnels from modal theory,” IEEE Trans. Veh. Technol., vol. 57, no. 3, pp. 1974–1979, May 2008