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Propagation Models in Vehicular Communications

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ABSTRACT In the advent of becoming reality, the era of autonomous vehicles is closer than ever, and with it, the need for faster and reliable wireless connections. The propagation channel determines the performance limits of wireless communications, and with the aid of empirical measurements, channel modeling is the best approach to predict and recreate how signal propagation conditions may perform. To this end, many different approaches and techniques have been implemented, from specific applications to general models, considering the characteristics of the environment (geometry-based or non-geometry-based) as well as seeking high performance algorithms in order to achieve good balance between accuracy and computational cost. This paper provides an updated overview of propagation channel models for vehicular communications, beginning with some specific propagation characteristics of these complex heterogeneous environments in terms of diverse communication scenarios, different combinations of link types, antenna placement/diversity, potentially high Doppler shifts, or non-stationarity, among others. The presented channel models are classified in four categories: empirical, non-geometry-based stochastic, geometry-based stochastic, and deterministic models, following the classical approach. The features and key concepts of the different vehicular communications channel models are presented, from sub 6 GHz to millimeter wave (mmWave) frequency bands. The advantages and disadvantages of the main works in the area are discussed and compared in a comprehensive way, outlining their contributions. Finally, future critical challenges and research directions for modeling reliable vehicular communications are introduced, such as the effects of vegetation, pedestrians, common scatterers, micro-mobility or spherical wavefront, which in the context of the near future are presented as research opportunities.

INDEX TERMS Vehicular communications, channel modeling, propagation, mmWave.

I. INTRODUCTION

According to data from the World Health Organization, annually 1.35 million people die in traffic-related accidents [1]. Although more and more sensors are incorporated into cars, and as a result, their safety and comfort are increased every moment, the solution will likely come from the hands of self-driving cars. Self-driving vehicles are becoming a closer reality and promise to be part of a society that is more organized, efficient, and safe than ever. The concept of fully connected vehicles, which can share sensor information with other vehicles or infrastructures in its surroundings, is an important support for future Intelligent Transportation Systems (ITS) designs. The strongest candidates for the future of vehicular communication are the Dedicated Short-Range Communication (DSRC) supported by the IEEE 802.11p standard and the use of the mobile network, also known as cellular vehicle-to-everything communication (C-V2X), as they offer greater coverage area, low latency, and a flexible organization [2]. Nevertheless, the future

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needs of autonomous vehicle applications require higher bandwidth and lower communication latencies than those that these technologies can offer. Highly data-rich applications such as automatic cloud management, large amounts of raw data from automotive sensors and cameras, high-speed streaming entertainment, and security-related applications with high latency restrictions (usually lower than 10 ms), have driven the new trends in vehicular communication technologies. In recent years, researchers suggest the adoption of millimeter-wave (mmWave) frequency bands to overcome these difficulties in bandwidth and latency. However, the description of the vehicular communication channel requires a careful analysis of signal propagation in the environment.

In the literature, several review articles have analyzed different aspects of vehicular communication technology. The work in [2] covers a wide number of research issues related to vehicular communication, such as information related to regulations, existing technologies, and important aspects of the MAC layer in vehicular communication. In [3], a holistic vision of vehicular technology is shown, delving into aspects such as the key requirements of this technology, the most referenced standards and their limitations. The works presented in [4]–[6] are more focused on the physical layer and channel modeling. These works present the specific considerations for vehicular wireless channels modeling for frequencies below 6 GHz. Although many articles focus mainly on the sub-6 GHz frequency bands, as a current trend, there is a large number of proposals for the adoption of mmWave frequencies in vehicular communications. Works such as [7], condenses extensive information on aspects such as the physical layer, access layer, and the future of mmWave bands in vehicular communications. In this regard, [8] presents a comprehensive survey dedicated to communications in mmWave frequency bands in general. Another important survey on measurements and channel modeling for 5G systems is summarized in [9], where important aspects of the physical layer and measurement campaigns available in the literature are presented. Furthermore, important aspects of the physical layer, and channel modeling in the mmWave frequency bands can be found in works such as [10]–[15], and specifically for vehicular environments in [16]–[18], with relevant information about channel modeling techniques and future challenges around mmWave frequency bands in vehicular communication. Table 1 presents a literature review comparison from the last ten years focused on surveys which include both, channel modeling and vehicular communications, specifying the vehicular use case communication (vehicle-to-vehicle, V2V, or vehicle-to-infrastructure, V2I) and the different frequency ranges (sub 6 GHz or mmWave). In this work, a comprehensive review of channel models focused on vehicular communications is presented, which complement the previous works. The major contributions are summarized as follows:

1) An update on recent trends in the considerations of the physical layer in vehicular communications, channel modeling, and measurement campaigns are introduced and compared in a comprehensive manner.
2) The different modeling approaches of vehicular wireless channels are summarized, taking into account the sub 6 GHz frequency bands and the mmWave frequency bands. The advantages and disadvantages of those models are discussed and compared in a comprehensive way.
3) Future research directions for modeling reliable vehicular communications, along with the main investigations and challenges around the different types of vehicular links are outlined.

The rest of this paper is organized as follows. In Section II, the special characteristics of the vehicle communication context, as well as the different considerations in vehicular communication systems design, are presented. Existing channel modeling approaches for various vehicular scenarios and different frequencies are presented in Section III. Future research directions and the main challenges in the area are summarized in Section IV. Finally, conclusions are drawn in Section V.

TABLE 1. Literature review comparison from the last 10 years focused in channel modeling and vehicular communications.

	Use Case		Frequency		Channel Model Analysis
Ref.	V2V	V2I	Sub 6GHz	mmWave/5G	
[4]	✓	✓	✓	-	✓
[7], [17], [18]	✓	✓	-	✓	-
[8], [13], [16]	✓	✓	-	✓	✓
[9]	✓	-	✓	✓	✓
[5]	✓	-	✓	-	✓
[10]–[12]	-	-	-	✓	✓
[14]	-	-	-	✓	-
[2], [15]	✓	✓	✓	✓	-
[3]	-	-	✓	✓	-
[19]	✓	-	-	✓	✓

-: There is no information in the related documents.

II. VEHICULAR CHANNEL REMARKS

The specific characteristics of vehicular systems result in a truly complex propagation environment with different properties than traditional wireless communications. Some of these specific features range from the diverse communication environments, different combinations of links types, potentially high Doppler shifts, non-stationarity, and shadowing by both mobile objects (surrounding vehicles) and static objects (e.g., buildings, foliage), which makes traditional channel propagation models unfit for V2X. Some considerations of these characteristics are presented below.

A. VEHICLE TYPES

Although analysis of vehicle blocking is found in numerous articles in the literature [20], [21], the study of different types of vehicles and their effects on the received signal has received less attention. The relationship between shadowing depth and duration with the obstacles dimensions is a matter of further investigation. Propagation models currently in use mostly do not take into account the losses associated with different types of vehicles, resulting in estimation errors that could constitute the link loss. Articles that have evidenced these errors place the losses associated with blocking, between 5 to 20 dB (some cases more than 20 dB) for vehicles ranging from personal small vehicles to large ones such as buses or trucks in the sub 6 GHz frequency bands [4].

B. LINK TYPES

V2X communication includes different types of links (vehicle to e.g. vehicle (V2V), infrastructure (V2I), pedestrian (V2P), grid (V2G)) that exhibit different propagation properties. V2V links are defined as the communication between two vehicles and are characterized by low-height antennas located on the metal body of the vehicles. V2I assumes communication linking a vehicle and an infrastructure or roadside unit. This infrastructure (i.e. access point) is characterized by being stationary and in many cases elevated above the relative level of vehicle height. V2P links are defined as the communication between a vehicle and pedestrians and can be affected by high levels of shadowing of objects such as trees, buildings or parked cars. V2G is presented in the context of electric vehicles (EVs), enabling the communication between EVs and the corresponding aggregator. The differences in mobility, shadowing, relative height of the antennas, as well as the different combinations of each of these factors, lead to different propagation characteristics in each link type.

C. NON-STATIONARITY

Communication models based on the Wide-Sense Stationary Uncorrelated Scattering (WSSUS) assumption have been widely accepted in recent decades for channel modeling in vehicular environments. This definition is made up of two assumptions, the first, Wide-Sense Stationary (WSS) means that the channel properties do not change over time. The second, Uncorrelated Scattering (US) means that multipath contributions at different delays are uncorrelated [22]. Despite this, results obtained through experimentation have shown that the WSS assumption is only valid for short periods of time due to fast changes of the scatterers in the surrounding environment and the movement of one or both transceivers. As a result, the transmission channel in a vehicular environment must be considered non-stationary (non-WSS) [23]. The interaction of different multipath components with the same object, once or several times, shows that the fading properties of multipath contributions at different delays can be correlated in amplitude and phase (non-US). As a result, the WSUSS assumption is not valid to describe the radio channel in vehicular environments, requiring the creation of non-WSUSS models [24].

D. ANTENNA PLACEMENT/DIVERSITY

Another factor to consider in vehicular communications is the location/placement of the vehicles' onboard antennas. This is a relatively recent issue in the literature but with a direct impact on the link quality. Aspects such as the radiation diagrams of each antenna also have an impact on the system performance. Other necessary studies may be devoted to analyzing the impact of the vehicle body on the antenna radiation pattern, and the use of antenna diversity as a means of increasing the signal-to-noise ratio at the receiver. The distance relationship between these antennas or its location and number, are aspects that need in-depth studies [25]–[28].

E. HIGH DOPPLER

The main challenges facing wireless communication in a vehicular environment are associated with the high mobility of the transmitters and receivers as well as the objects/scatterers around them. This particular environment is highly dynamic with multiple scatterers in a wide mobility range, directions and speeds, which leads to the deterioration of propagation factors such as the coherence bandwidth and/or the coherence time, among others. The Doppler effect associated with V2V communication, in the case of an Ad-Hoc system, may experience a relative mobility between 2 vehicles in opposite lanes that exceed 300 km/h resulting in frequencies shifts not considered in typical cellular applications. The correlation between frequency and Doppler effect results in an even more aggravated circumstance in the mmWave frequency bands, that in combination with the vehicular environment may be a critical challenge.

F. ENVIRONMENTS

The descriptive characteristics of the wireless propagation channel are closely associated with the distributions and properties of the environment in which the communication takes place. In this regard, the vehicular environment is highly variable, where three typical scenarios have been usually distinguished in the literature: highway, urban, and rural [5]. Each of these scenarios presents specific differences in terms of the number of scatterers, probability of line-of-sight (LOS), traffic density, and landscape differences. Although these typical scenarios generally capture the main environments in which vehicular communications take place, there are other specific environments whose characterization has not been sufficiently addressed. Some of these scenarios encompass vehicular communication in tunnels [29], [30], roundabouts [31]–[33], parking lots [34], [35], or bridges [36].

III. CHANNEL MODEL APPROACH

The abstraction of the transmission channel distinctive parameters to propagation models is typically dependent on the carrier frequency, the bandwidth, the environment in which they propagate, and the system under consideration. As stated in the previous section, the scenario for vehicular wireless communication adds complexity to these considerations. Consequently, propagation channel characterization and analysis in vehicular environments requires a deep study and must not be underestimated as it is far from being a solved problem. In the later subsections, a literature review on the different approaches for the vehicular propagation channel modeling will be presented. The different vehicular channel models along with its main characteristics and channel metrics are provided in Table 2. Furthermore, a comprehensive comparison of the general standardized channel models is shown in Table 3. Firstly, a detailed classification of the vehicular channel model approaches is depicted in Figure 1.

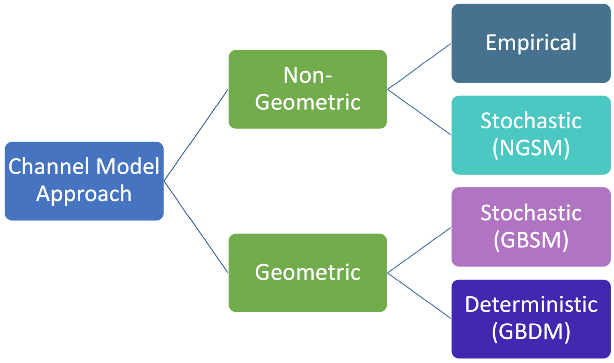

FIGURE 1. Vehicular channel model approaches classification.

A. EMPIRICAL MODELS

Empirical models use the collection of observations, usually obtained during measurement campaigns, in order to identify singular patterns of the environment that it is intended to represent. As a result, these models are very simple, with few parameters and thus, easy to use. Despite these advantages, its effectiveness is directly related to environments similar to those where measurements were performed. They are usually aimed at characterizing generic conditions such as urban, rural, or highway environments under many assumptions [37]. Traditionally they are used to estimate coverage in different areas, considering input parameters such as the distance between the transmitter and the receiver, among other general parameters. Since these models cannot determine situations of specific environment characteristics and have limited accuracy, their use in vehicular communication systems is very restricted. However, in the V2I communication case, the relationship is given by an elevated transceiver and a mobile receiver. This relationship resembles traditional cellular communications, so the use of models such as Cost 231-Hata can be used to calculate transmission losses in some scenarios [38].

The main advantage of empirical models is their ability to cover multiple urban, rural, or highway environments [39]. Many works present empirical studies for complex and/or typical common scenarios in vehicular communication, like the work in [40], which describes a campaign of measurements in a typical V2V scenario at 5 GHz frequency, to develop a statistical model. In [41], an empirical study for V2V communications at 5.9 GHz is presented in a suburban environment at Pittsburgh, Pennsylvania. The work concludes that the maximum Doppler spread set a limit for the spacing between carrier frequencies used in OFDM, and channel estimation depends on the values of the coherence time, suggesting that from their studies, 90% of the coherence time (defined as the time offsets for which the autocorrelation function drops to 90% of its peak value) is between 2 and 3 ms, implying that the packages should not be longer in time in suburban environments. The work conducted in [42] presents the results of empirical studies for V2V communication channels in 4 different urban intersection scenarios at 5.6 GHz. Power Delay Profile (PDP), Path Loss (PL), and delay spread are presented showing that the number of propagation paths increases dramatically when both cars are at the intersection. In [32], an empirical study at 5 GHz frequency band considering three types of intersections is presented. The packet delivery ratio (PDR) depending on the distance between the vehicle and the intersection center for different antenna locations is analyzed, presenting a generic model that can be integrated into simulations. In [20], a measurement campaign to evaluate signal propagation in V2X scenarios is presented. The effect of shadowing produced by large vehicles is analyzed at 5.8 GHz. Cumulative distribution functions (CDF) of the measured excess PL are presented for the different scenarios (V2I and V2V) at different transmitter antenna heights. As a result, the authors state that the impact is more significant in the V2V scenario with a maximum shadowing level of 27 dB. For the V2I scenario, the shadowing effect reaches a maximum of 23 and 21 dB considering the different antenna heights. In addition, a scalable shadowing model for simulation of V2X communication is also proposed in the research work [20]. Furthermore, reference [43] states that intersections in urban areas must be considered as more challenging scenarios for vehicular communications than in rural or highway environments. The work presents experimental measurements at 5.9 GHz with six different dimension vehicles, considering different heights for the transmitting and receiving antennas, obtaining a model for Vehicular Ad-Hoc Network (VANET) simulations. In [44], an empirical study at 5.8 GHz is presented for the PL characterization in V2V communication. Two vehicles of the same characteristics are considered with antennas located on their top roof, in three different scenarios: urban, suburban and highway. They conclude that PL parameters are strongly dependent on the type of environment, the vehicles physical characteristics and the antenna heights. These conclusions also demonstrate the specific characteristics of empirical studies, closely related to the environments in which they are performed. In general, many of these studies are the fundamental basis for obtaining stochastic models and for the validation of deterministic models.

B. NON-GEOMETRY STOCHASTIC MODELS

Stochastic models are used to predict the modeled system values, considering the random elements occurrence within the system. They are designed to simulate uncertainty in different scenarios. These models can be relatively versatile to describe propagation channels in different environments.

One of the most widely used non-geometry-based stochastic model (NGSM) is the Tap Delay Line (TDL), which describes the impulse response of the propagation channel through a finite impulse response (FIR) filter with a discrete number of taps. Each tap can contain different propagation paths with statistics generally obtained from measurement campaigns. In these models, the average received power in each tap is represented with an exponential decrease. The fading is implemented by varying the amplitude of each tap over time, associated with a probabilistic fading characteristic. TDL can model channels with a strong line-of-sight (Rician fading) or non-line-of-sight (Rayleigh fading).

TDL was widely used by early models of wireless channels at indoor and outdoor environments, due to its relative simplicity and accuracy, in terms of low computational cost and easy implementation in both software and hardware. Indeed, the main objective of multiple measurement campaigns is to extract statistics for the implementation of TDL models [45]. In vehicular TDL channel modeling, one of the first models was developed by [46], where six scenarios (3 V2V and 3 V2I) are analyzed at 5.9 GHz in Atlanta, Georgia. The work concludes that the transmission channel related to V2V communication in the Expressway scenario has the highest Packet Error Rate (PER). These models have been adopted for the V2V channel model standard in IEEE 802.11p [47] which employs the 6- and 12-tap models, based on wide-sense stationary uncorrelated scattering (WSSUS) channels assuming that all multi-path channels at different delays are not correlated and the channel statistics are invariant for short periods of time. Based on the WSSUS assumption, classical TDL models do not consider the impact of non-stationarity of channel statistics [6]. Nevertheless, the high mobility associated with the vehicular environment makes the transmission channel statistics change over time. This comes associated with changes in the received power signal with distance between the transmitter, receiver and scatterers. Thus, multi-path fading may be propitiated by the interaction with the same object through different paths. Considering these characteristics, the application of WSSUS in vehicular environments may introduce erroneous values in the estimations. Therefore, to model the non-stationarity of the channel, parameters such as the received power and the time delay need to be modeled as time variables.

In [48], a V2V communication channel model is presented, where the TDL method is used in combination with stochastic geometric methods. This design allows the effective simulation of the contribution drift of scatters from one tap to another. It is concluded that the non-stationary characteristics of the vehicular environment must be considered. Classic versions of TDL based models assume no scatterers correlation, but this assumption is contradictory to vehicular channels characteristics. Studies such as that carried out in [49] present a method to generate correlated taps in V2V communications, where the propagation model can generate V2V channels correlated in both amplitude and phase. It is concluded that the inclusion of non-WSSUS properties increases the ability to represent the vehicle communications channel. In [50], a TDL model is proposed, based on a measurement campaign at 5.3 GHz in Helsinki, Finland. Through theoretical experiments, three types of spectrum Doppler are identified of regular occurrence. The non-stationary characteristics in vehicular communications lead to adjustments to classic TDL models. The work presented in [24] proposes a propagation model based on TDL that takes into account the non-WSSUS for V2V communications at 5.9 GHz. The work considers that different taps are correlated both in amplitude and in phase, so the correlated taps represent the interaction with the same object. To simulate the non-WSS property, a first-order two-state Markov chain is used.

C. GEOMETRY BASED STOCHASTIC MODELS

Geometry-based stochastic models (GBSM) use a simplified distribution of scatterers around the transceivers to identify and emulate the real environment statistics. According to the simplified way in which these scatterers are distributed, GBSM can be subdivided into regular and irregular shaped.

Regular-shaped geometry-based stochastic models (RS GBSM) use the distribution of scatterers around the transmitter and receiver with the shape of one or more regular figures (circular, elliptical or other shapes). In [51], a 2D RS GBSM propagation model based on the 2-ring model is presented. The work includes a mobile-to-mobile scenario communication system at mmWave bands and the use of MIMO systems. The model adopts a cluster-based structure, fine-tuning the clusters parameters (number, center position, intra-cluster non-isotropic scattering degree) and can be adjusted to a variety of scenarios, reflecting more precisely the shadowing effect. As a conclusion it is found that, when a directional antenna is used, a high channel correlation is obtained (compared to an omnidirectional antenna), reducing the degree of non-stationarity for mobile-to-mobile channels which could simplify the system evaluation. Reference [52] presents a RS GBSM for mobile-to-mobile communications in MIMO systems, with the combination of the 2-ring model in conjunction with the ellipse-based model. As a result, the traffic density effect on channel modeling is also represented. Although the use of regular shapes can reduce the scenario complexity as well as represent the different scenarios in simpler sets, irregular models can represent communication environments in a more realistic way. In these irregular models, the scatterers distribution is usually performed stochastically following an irregular shape. The work presented in [53] describes an irregular-shape geometry-based stochastic model (IS GBSM) for V2V communication based on 5.2 GHz measurement campaigns conducted in Helsinki, Finland. The model is for single input single output (SISO) systems and it is validated with the measured data. Another work presented in [54] shows an IS GBSM for V2V communications, implemented for MIMO systems based on 5.2 GHz measurement campaigns in Lund, Sweden. It is argued that the received energy from scatterers such as cars, buildings, and traffic signs can make an important contribution to the received signal. Authors conclude that the vehicle communication channel has not-WSSUS behavior. Although these

TABLE 2. Comparison of main characteristics of different approaches of vehicular channel models.

Ref.	Model Approach	Type	Carrier Frequency	Environment	Simulation	Measurements*	Dual mobility	Non-stationarity	Blockage	Channel metrics
[41]	Empirical	V2V	5.9 GHz	Suburban	-	✓	✓	-	-	PL, Doppler Spectrum, Coherence Time
[42]	Empirical	V2V	5.6 GHz	Intersection	-	✓	✓	-	-	PDP, PL, and Delay Spread, MIMO
[32]	Empirical	V2V	5 GHz	Intersection	-	✓	×	-	-	Packet Delivery Ratio
[44]	Empirical	V2V	5.8 GHz	Urban/ Highway/ Suburban	-	✓	✓	-	-	PL
[43]	Empirical	V2V	5.9 GHz	Intersection	-	✓	✓	-	✓	PL, Packet Success Ratio
[20]	Empirical	V2X	5.8 GHz	Urban	✓	✓	×	-	✓	PL
[40]	Empirical/NGSM	V2V	5.12 GHz	Urban/ Highway	-	✓	✓	✓	✓	PDP, RMS Delay Spread
[75]	Empirical/ NGSM	V2V	2.4 GHz	-	-	-	-	-	-	Doppler Spread
[46]	NGSM	V2X	5.9 GHz	Urban	-	✓	-	-	-	Packet Error Rate
[48]	NGSM	V2V	5.9 GHz	Urban/ Highway/ Suburban	✓	✓	-	-	-	Impulse response, PDP, Delay Spread
[49]	NGSM	V2V	5 GHz	Urban	✓	-	-	✓	-	Doppler power spectral density
[24]	NGSM	V2V	-	Urban	✓	✓	-	✓	-	PDP
[51]	2D-RS GBSM	D2D	60 GHz	-	✓	✓	✓	-	✓	Time-Frequency correlation, PDP, Doppler Power Spectrum, MIMO
[52]	2D-RS GBSM	D2D	5.9 GHz	Urban	✓	-	-	✓	-	PDP, Doppler Power Spectrum, MIMO
[53]	2D-IS GBSM	V2V	5.2 GHz	Urban/ Highway/ Suburban	✓	✓	✓	✓	×	RMS Delay Spread, Channel Gain, SISO
[54]	2D-IS GBSM	V2V	5.2 GHz	Urban/ Highway	✓	✓	✓	✓	×	Time delay domain, Doppler delay, MIMO/SISO
[55]	3D-RS GBSM	V2V	5.2 GHz	-	✓	✓	✓	✓	-	PDP, Space-Time Correlation function, Frequency Correlation function, MIMO
[23]	3D-RS GBSM	V2V	2.4 GHz	-	✓	✓	✓	✓	-	Space-Time Correlation function, Temporal correlation function, Spatial correlation function, MIMO
[61]	GBDM	V2V	5.2 GHz	Urban	✓	✓	✓	✓	✓	PDP
[62]	GBDM	V2V	5.6 GHz	Intersection	✓	✓	✓	-	✓	PDP, Channel Gain, SISO
[64]	GBDM	V2I	28 GHz	Urban	✓	✓	×	✓	✓	Doppler Spread, Coherence Time, K-Factor, RMS Delay Spread, PDP, Angular Spread, PL
[65]	GBDM	V2X	28 GHz	Urban	✓	✓	×	-	✓	RMS Delay Spread, PL exponent, Shadowing Factor
[67]	GBDM	HST	25.25 GHz	Rural/ Urban/ Tunnel	✓	✓	×	✓	✓	Wideband directional PL parameters, RMS Delay Spread, Rician K-factor, Coherence Bandwidth
[66]	GBDM	V2I	28 GHz	Urban	✓	×	×	✓	×	PDP

NGSM: non-geometry-based stochastic model; GBSM: geometry-based stochastic models; GBDM: geometry-based deterministic models; RS GBSM: regular-shaped geometry-based stochastic models; IS GBSM: irregular-shape geometry-based stochastic models; HST: high speed trains; PL: path loss; PDP: power delay profile; RMS: root-mean-square; MIMO: multiple-input-multiple-output; SISO: single-input-single-output; V2V; vehicle-to-vehicle; V2I: vehicle-to-infrastructure; V2X: vehicle-to-everything; D2D: device-to-device; -: There is no information in the related documents. *: Measurements campaigns have been conducted before channel modeling.

simplified 2D models have high versatility and low computational load, they assume that the scatterers location are in the horizontal plane. Due to this simplification, these models cannot simulate the effects on the elevation plane, which may considerably decrease the scenario realism. Therefore, GBSM with a three-dimensional (3D) representation are usually used to increase the system accuracy. The work presented in [55] presents a 3D RS GBSM for V2V communication environments considering the LOS components, the 2-sphere model components, and the multiple elliptical cylinder model components. The work concludes that vehicular density has a significant impact on the statistical channel properties. In reference [23], a 3D RS-GBSM is also proposed for V2V communication systems using a 3D Von Mises Fisher representation of the scatterers' environment. In general, 3D GBSM are considered more general and capable of emulating a wider range of scenarios, with the disadvantage of higher computational load and complexity, when compared with 2D models.

Some standardized 5G models that fall under this category are the following: QuaDRiGa channel model [56], Millimeter-Wave Based Mobile Radio Access Network for 5G Integrated Communications (mmMAGIC) [57], 5GCMSIG [58] channel model and COST 2100 channel

TABLE 3. Comparison of main features of standardized general vehicular channel models.

Ref.	Model Approach	Type	Carrier Frequency	Environment	Simulation	Measurements*	Dual mobility	Non-stationarity	Blockage	Model features / Novelty
[56]	GBSM - QuaDRiGa	Mobile-V2X, D2D	0.45-100 GHz	Urban / rural / indoor	✓	✓	✓	✓	×	Correlated large-scale parameters, smooth time evolution, variable speeds
[57]	GBSM - mmMAGIC	Mobile-V2I	6-100 GHz	Urban / indoor	✓	✓	×	✓	✓	3GPP 3D methodology, ground reflection, spatial consistency, blockage modeling
[58]	GBSM – 5GCMSIG	Mobile-V2I	Up to 100 GHz	Urban micro / urban macro / indoor	✓	✓	×	✓	✓	Extended 3GPP 3D model, spatially consistent, smooth time evolution
[59]	GBSM – COST 2100	Mobile-V2I	Up to 6 GHz	Urban / rural / indoor	✓	✓	×	✓	×	Cluster-level structure, MIMO systems, visibility regions
[70]	Q-D – IEEE 802.11ay	Mobile-V2X, D2D	57-68 GHz	Indoor / outdoor open area	✓	✓	✓	✓	✓	Q-D methodology, human blockage model, MIMO systems extension
[71]	Q-D – MiWEBA	Mobile-V2X, D2D	57-66 GHz	Open area / urban / indoor	✓	✓	✓	✓	✓	Q-D methodology, blockage modeling
[72]	Hybrid – METIS (GBSM, Map-Based)	Mobile-V2V, D2D	Up to 100 GHz	Urban micro / urban macro / rural / indoor / highway / stadiums	✓	✓	✓	✓	✓	Sum of sinusoids spatially consistent large-scale parameters, map-based, stochastic and hybrid model approach
[73]	Hybrid – 3GPP TR.38.901 (GBSM, Map-Based)	Mobile-V2I	0.5-100 GHz	Urban micro / urban macro / rural macro / indoor	✓	✓	×	✓	✓	Stochastic and map-based hybrid model approach, oxygen absorption, spatial consistency, blockage modelling
[74]	Hybrid – IMT-2020 (GBSM, Map-Based)	Mobile-V2I	0.5-100 GHz	Urban micro / urban macro / rural macro / indoor	✓	✓	×	✓	✓	Stochastic and map-based hybrid extension, vegetation effects, oxygen absorption, spatial consistency

Q-D: Quasi-Deterministic;

model [59]. The latter uses the concept of visibility regions to simulate the channel non-stationarity conditions and at the same time achieve spatial consistency. This model is designed for frequencies below 6 GHz and dual mobility is not supported, although it may be used in some V2I links, its utility in V2V environments is very poor. In the case of mmMAGIC channel model, mmWave frequency bands are considered with frequencies spanning up to 100 GHz. This model considers blocking effects although it does not support dual mobility. The 5GMSIG is a model that supports also a wide frequency range from 0.5 to 100 GHz based on extensive campaign of measurements and ray tracing simulations. This model supports a smooth temporal and spatial evolution, blocking effects and a wide variety of scenarios. Despite these advantages, dual mobility is not supported either. However, the latest recently released version of the QuaDRiGa channel model supports dual mobility considering a wide range of frequencies (0.45-100 GHz), buy the dynamic blockage is not yet implemented. Nevertheless, in general, the no dual mobility and/or blockage modeling capabilities of these models make them unsuitable for V2V communication, although the V2I link types can find useful insights on these channel models.

D. GEOMETRY BASED DETERMINISTIC MODELS

Geometry based deterministic propagation models (GBDM) characterize the channel communication using detailed scenario information. They are site-specific methods and are generally highly expensive at the computational level. Deterministic models whose application consists of the solution of Maxwell's equations, as the Method-of-Moments (MoM) and Finite Differences Time Domain (FDTD), are generally used in small areas where high precision is needed. These methods are full-wave techniques and are mainly used in radiation diagram antenna patterns. Due to the high computational load in their implementation, they are not related to large areas such as vehicular communications. The alternative is the use of deterministic geometric methods such as Ray Tracing (RT), rebuilding the virtual propagation environment with the assistance of Geometrical Optics (GO) and Geometrical Theory of Diffraction (UTD). The accuracy of this approaches depends on a strict description of the propagation environment and all the components/scatterers that may affect the wave propagation (i.e., buildings, trees, etc.). In Fig. 2, an example of the received signal strength (RSS) in a bi-dimensional plane for a certain height using a RT algorithm is presented. A I2V link in a real urban environment has been simulated considering all the presented scatterers within the scenario such as different shapes of buildings, trees and vehicles on the road. The received power at the vehicle's roof height is represented, showing that the morphology and topology of the scenario have a great impact in radio wave propagation. The main difference of the RT-based methods, compared to the empirical and theoretical ones, is that these methods do not offer simple formulas for the path loss calculation. RT methods use exhaustive simulations with the assistance of numerical methods, in order to solve approximations of Maxwell's equations [60].

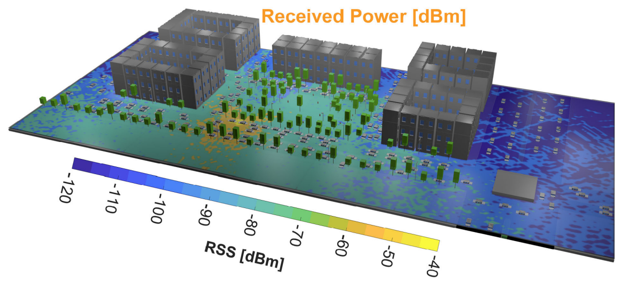

FIGURE 2. GBDM approach results in an urban environment.

One of the pioneers in the use of RT in vehicular communications is the work presented in [61], which uses this method to determine the propagation characteristics in a scenario with different types of vehicles. Simulation results were compared with a 5.2 GHz measurement campaign conducted in Karlsruhe, Germany showing good agreement between them. In addition, the work presented in [62] shows a comparative study between a measurement campaign and a RT propagation model at 5.6 GHz for V2V communication, specifically in an intersection scenario. Authors state that diffuse scattering is not considered in the proposed model and they conclude that power contributions of high-order diffuse scattering cannot always be ignored. In more recent studies, the use of mmWave systems has applied RT techniques to determine channel propagation characteristics. An example is the work presented in [63], which performs an experimental analysis at 28 GHz with a channel sounder, which is compared with a RT simulation software. Due to the high diffraction and penetration losses in the mmWave bands, multiple diffraction of more than 2 penetrations are not considered in this study. It is also noted that for model simplicity, obstacles such as cars, people, or street objects are not considered as well, and buildings are moderated as flat surfaces. Another work presented in [64] uses the RT technique to characterize the channel communication in a V2I environment, showing results of PDP, PL, Root-Mean-Square (RMS) delay spread, and K-factor. Different types of vehicles are used in the simulation and the virtual reconstruction of the stage is carried out with the assistance of Open Street Map software. Modeling the blocking effects on propagation channels is one of the most complex tasks to perform. Works such as reference [65] use the RT technique to derive propagation models in vehicular communications. This specific study focused on the mmWave frequency band and the blocking effects by other objects. The work proposed in [66] aims to accelerate simulations based on RT with the implementation of quasi-stationary regions. This work is carried out for the analysis of V2I communications in the mmWave band (28 GHz). Authors conclude that the use of new intervals (quasi-stationary regions) for the acceleration of RT allows obtaining similar parameters to the performed simulations in medium wavelength intervals. RT modeling techniques has also been used for the communications channel for high-speed trains (HST). The works presented in [67] uses a RT software to explore the different characteristics of the propagation medium for HST. It is conducted at 25.25 GHz frequency and is validated for urban, rural and tunnel communication environments. Other works in mmWave bands that use RT can be found in [68], [69]. The RT technique is one of the deterministic electromagnetic modeling tools that achieves a good performance/tradeoff between accuracy and computational cost. The development of positioning technologies, joint with the access to the geographic and topological database of cities and vehicular environments will lead to the integration of RT techniques in many of the modern software for the analysis of electromagnetic propagation channels.

Some standardized models that use the GBDM in combination with GBSM modeling for the 60 GHz frequency band are the following: IEEE 802.11ay channel model [70] and MiWEBA channel model [71]. These approaches are also called quasi-deterministic models (Q-D). The MiWEBA channel impulse response (CIR) uses the composition of deterministically modeled rays and rays generated from random arrangements of clusters following a certain distribution. The IEEE 802.11ay follows the MiWEBA design with the addition of rays related to moving objects such as vehicles. These rays are stochastically modeled like their counterpart in MiWEBA but with a short existence duration. Both models support dual mobility, although due to their design in the 60 GHz band and the high mobility of the vehicular environment, they may not be suitable for its use in V2X. In addition, following this hybridization between deterministic and stochastic methods, Mobile and wireless communications Enablers for the Twenty–twenty Information Society (METIS) [72], 3GPP TR.38.901 [73], and IMT-2020 channel model [74] propose hybrid alternatives between map-based approach and the already well-established stochastic models. In this configuration, these models support a wide spectrum of frequency bands (e.g. 0.5-100 GHz), massive MIMO and spatial consistency. Nevertheless, dual mobility is not yet supported in 3GPP TR.38.901 and IMT 2020 channel models and is limited in the hybrid METIS model.

IV. FUTURE CHALLENGES

A. ANTENNA PLACEMENT/DIVERSITY

The optimal location of antennas in vehicular environments has been studied on several occasions, despite this, it is an area that needs further in-depth studies. Although some research indicates the location on the roof of the vehicle as the optimal location, this aspect may not be the best for the visual or aesthetic aspects of the vehicle considering its streamlined shape. In this sense, further analysis results are needed in terms of location placement alternatives in order to increase the onboard antennas' capabilities. In addition, the use of multiple antennas on the body of the vehicle and its efficient location is also an area that needs more research, as multiple antennas can assist in improving aspects of signal quality. In the case of V2I communication, aspects related to the location, height, and density of the roadside units are still an open area of investigation. Analysis dedicated to the optimization of these infrastructures, which takes into account aspects of the vehicular environment and their optimal coverage, is still under debate. As there is no openly commercial infrastructure in the vehicular environment, the refinement of all these aspects is still a relatively new area, and future works in this line will contribute to this domain.

B. ALL-IN MODELS

The vehicular environment is characterized by high mobility in non-stationary conditions with relatively low height antennas. Models which are capable of capturing all these characteristics while reducing computational complexity is still an area of constant study. In order to meet the expectations placed on vehicular communication, models that support features such as smooth space-time evolution, a non-stationary channel, and micro-mobility are necessary for the development and testing of future vehicular communication systems. MIMO systems are very likely to be tied to vehicular communication in the near future as it can be seen from the fifth-generation arrival. Therefore, precise spatial information will be pivotal for a proper channel characterization. In this aspect, geometric or hybrid models are preferred over stochastic models. The development of vehicular communication models that optimally takes all these effects into account is still a field of open research.

C. VEHICULAR DENSITY, PEDESTRIANS, OBJECTS ACCOUNTABILITY

Although simple models have the ability to scale up at the system level more easily, effects such as traffic density, common objects on the sidewalk, and vegetation have been identified as parameters that can significantly influence the wireless link. This is especially true at high frequencies, where the promise that mmWave frequency bands will allow high throughput, and low communication latencies can be compromised by models approaches that do not take these into account. Although different investigations in the literature have studied these issues, the empirical analysis of the influence of any of these effects on communication parameters is still of research interest. The inclusion of these propagation effects optimally into the different propagation models is a domain open to debate.

D. SYSTEM LEVEL SIMULATION MODELS

Although the introduction of more features of the communications medium would shed more light on how wireless communications behave on the vehicular link, system-level simulations may not be as practical with this excess in complexity. Balancing between which aspects are important to characterize and which are not is a task to describe taking into account the specific characteristics of the vehicular environment. Vehicle communications encompass various types of links and capturing all these links massively and simultaneously (multiple V2V, V2P, V2I) is a complex task far from being a problem solved. Propagation models that can scale up to massive simulations at the system level and maintain a relatively low computational complexity while accounting for characteristic aspects of the vehicular communication channel is still a project under development.

E. POOR WEATHER CONDITIONS MEASUREMENTS AND MODELS

Several measurement campaigns have been organized to obtain information from the vehicular wireless communication channel, together with multiple models which have been proposed, but most of these models, as well as the measurement campaigns, are presented or obtained in optimal weather conditions. More measurement campaigns, specifically focused on the vehicular environment under poor weather conditions such as fog, light/moderate/heavy rain are needed. This is a more delicate matter for communications under the conditions of mmWave frequencies, as impact of these conditions in these frequencies needs deeper analysis. The synthesis of these effects and their abstraction to current propagation models is a matter of interest in the future of vehicular communications.

F. BEAM TRACKING ANALYSIS

Beamforming is expected to be a key aspect of upcoming communication technologies, with many advantages in energy/spatial efficiency. Owing to beamforming technology, beam tracking algorithms are going to be summited to heavy conditions under the V2X links. Mobility is closely tied to the performance of beam tracking algorithms, and models that can account for realistic deployment and mobility are needed [76]. For V2V communications the temporal constraints for beam tracking are more strict and further analysis on this aspect is a matter of interest.

V. CONCLUSION

In this paper, a comprehensive review of vehicular communication technologies is presented, focused mainly on recent channel models approaches and measurements campaign in vehicular related environments. Although extensive research has been performed in the area, there are still several important obstacles that need to be addressed before V2X communication becomes a widespread technology. Vehicular propagation models that take into account the effects of vegetation, pedestrians, common objects, micro-mobility, massive MIMO systems, spherical wavefront, and non-stationarity of the channel are still under development. At the system level simulation, the reduction in complexity of these models, while considering these features, will allow deeper and more precise insights of the vehicular communication link as well as the accurate evaluation of beam tracking. Although multiple measurement campaigns have been carried out, more data is still needed to derive information from the vehicular wireless communication channel. This is especially true for communication in mmWave frequency bands where the scarcity of vehicular measurement campaigns is higher. Although vehicular communication in the context of ITS and smart cities promise to achieve high standards in organization, optimization and reduction of risks and accidents, it is still a relatively premature technology. This paper presents some of the recent directions taken by researchers in the area towards modeling the vehicular communications channel and summarizes some of the critical challenges to be solved in the field, which in the context of the near future are presented as research opportunities.

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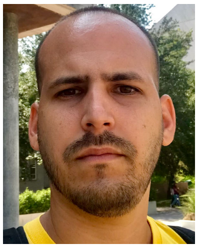

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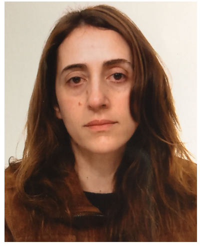

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