Review Article

Geometry-Based Channel Modelling for Vehicle-to-Vehicle Communication: A Review

Jalel Chebil ¹, Hanene Zormati ² and Jamel Belhadj Taher²

¹Department of Technology and Transport Engineering, University of Sousse, ISTLS, NOCCS Laboratory, Sousse 4023, Tunisia

²Department of Electrical Engineering, University of Sousse, ENISO, NOCCS Laboratory, Sousse 4023, Tunisia

Correspondence should be addressed to Hanene Zormati; zormati.hanen@hotmail.fr

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Vehicle-to-Vehicle (V2V) communication has received a lot of attention over recent years since it can improve the efficiency and safety of roads for drivers and travellers besides other numerous applications. However dynamic nature of this environment makes it difficult to come up with a suitable wireless communication channel model that can be used in the simulation of any V2V communication system. This paper reviews the recent techniques used for geometry-based stochastic channel modelling for V2V communication. It starts by presenting the various classes of wireless communication channel models available in the literature with more emphasis on the Geometry-Based Stochastic channel Models (GBSM). Then the paper discusses in more detail the state of the art of the regular-shaped and irregular-shaped GBSM for the two- and three-dimensional models. Finally, main challenges are identified and future research directions in this area are recommended.

1. Introduction

In recent years, Vehicle-to-Vehicle (V2V) communication has been the subject of many research studies due to the rapid growth of the fifth-generation (5G) technologies and its application in intelligent transportation systems [1, 2]. V2V communication is an automobile technology designed to allow vehicles to interact with each other. It attempts also to monitor traffic information which can be utilized to reduce road congestion. In addition, it helps to predict and avoid accidents, and it automates driving process by improving road safety and efficiency [3–5]. Most V2V studies use the 5.9 GHz spectrum which has been allocated by the United States and Europe for these types of communications [4, 6]. These studies addressed the lowest two layers of the Open Systems Interconnection (ISO) protocol stack: the data link layer and the physical layer. The former deals with the medium access control sublayer while the latter concentrates on wireless propagation channel modelling [7] which will be the focus of this paper. The characteristics of wireless propagation channels for V2V communication systems are different from

conventional Fixed-to-Mobile (F2M) cellular systems in many ways. For V2V communication system both transmitter (Tx) and receiver (Rx) are in motion and equipped with low elevation antennas whose heights are in the order of 1 to 2.5 m. On the other hand, in F2M cellular radio systems only one terminal moves while the other is fixed, and the heights of base station antennas are relatively much higher than those of the mobile antennas [8–10]. This leads to differences in the main propagation mechanisms [11]. For example, the dynamic nature of V2V systems makes it nonstationary [12] which may be the most important characteristic that differentiates the V2V channel from the F2M channel. Moreover, the main operating frequencies for cellular channels are between 700 MHz and 2100 MHz while the central carrier frequency dedicated to V2V communication systems is in the 5.9 GHz band [13]. Since the channel properties have large differences in comparison to traditional systems, the existing channel models designed for F2M communication cannot be directly applied to V2V systems [7, 14]. Therefore suitable channel models are essentially needed for successful design of V2V vehicular system.

The modelling of radio wave propagation channels is very important in the design and operation of wireless communication systems. That is why many channel models were proposed in the literature and they can be divided into two dominant classes: deterministic and stochastic models [11, 15]. The deterministic channel models are based on Maxwell's equations and ray tracing method which applies geometric optics and uniform theory of diffraction [16]. For example, Maurer et al. [17] proposed a Geometry-Based Deterministic Model (GBDM) based on the ray tracing technique to represent V2V communication channels. However, such types of models require detailed and precise information of the V2V communication environment such as the number of buildings, the number of scatterers along the roadsides, the number of moving vehicles and their speeds, the positions of the transmitter and receiver, etc. Although the obtained results reflect the reality, they are site specific and cannot be generalized to other scenarios with different environments [18]. Moreover, these deterministic models generally require high computational time [18–20]. Since V2V communication is characterized by high mobility of the transmitter and receiver with fast varying environment, then deterministic models were not favoured for such situations [4]. On the other hand, stochastic channel modelling approach is preferred in many applications since it is faster in generating a realistic channel with considerably fewer input parameters [21]. Stochastic channel models are based on channel statistics obtained from large numbers of measurements conducted at various communication environments. From these statistics, propagation path parameters are derived and used to describe the properties of stochastic channel models [11]. These types of models can be divided into Nongeometrical Stochastic channel Models (NGSMs) and Geometry-Based Stochastic channel Models (GBSMs) [7, 10]. For the NGSM, the physical parameters of a V2V channel are derived in a completely stochastic manner without assuming any type of geometry, while GBSM is determined from predefined stochastic distribution of effective scatterers and by using the fundamental laws of wave propagation [7]. In addition, the GBSM model can be easily adapted to different scenarios by altering the shape of the scattering region. So it can be simple for useful theoretical investigation of channels or can be rendered relatively complex for simulating real channels [22]. The flexibility provided by this model makes it important and popular among researchers. For this reason, this paper presents an overview of the geometry-based stochastic channel modelling techniques and discusses the recent trends in this research area.

The major contributions of this paper are as follows:

- (i) It presents an overview of V2V channel modelling.
- (ii) It discusses in detail the GBSM channel modelling techniques.
- (iii) It provides a review of the recent GBSM V2V channel models.
- (iv) It outlines future research directions for GBSM V2V channel modelling.

The rest of this paper is organized as follows: Section 2 presents an overview of GBSMs for V2V communication channel. Section 3 focuses on Regular-Shaped GBSMs (RS-GBSM) including Two-Dimensional (2D) and Three-Dimensional (3D) models, while Section 4 discusses the recent research trend for Irregular-Shaped GBSMs (IS-GBSM). Section 5 describes the main challenges in GBSM V2V channel modelling, and it also discusses future research trend in this area. Finally, conclusions are drawn in Section 6.

2. Geometry-Based Stochastic Channel Modelling for Vehicle-to-Vehicle Systems

Geometry-based stochastic modelling approach is a crucial and popular modelling method because of its flexibility and its ability to describe the time-evolution of the channel by moving transmitter, receiver, and scatterers [22]. This makes them very useful for nonstationary V2V channels [18]. The basic idea of GBSMs is to describe stochastically the location and properties of scatterers following some selected probability distributions [23]. Various scatterer distributions have been proposed in the literature such as Gaussian, Laplacian, Von Mises, and uniform distributions [24, 25]. The selection of the distribution depends on the nature of the considered environment. Then, the interaction of propagating waves with the scatterers can be modelled by a simplified ray tracing, and the multipath components are combined at the receiver. Hence the channel impulse response can be easily formulated and the statistical properties of its parameters can also be obtained from the knowledge of the stochastic distribution of scatterers [22]. It should be noted that the channel impulse response can be divided into a defined number of components including Line Of Sight (LOS) component, Single-Bounced (SB), Double-Bounced (DB), and Multibounced (MB) components produced by scatterers. Usually, multibounced rays are neglected and single bounce components are considered, because the latter affects more considerably the signal [11]. The channel impulse response model is used to derive many parameters such as Space Time Correlation Function (STCF), AutoCorrelation Function (ACF), Power Spectral Density (PSD), etc.

GBSM can be classified into two classes: RS-GBSM [8, 10, 24–34] and IS-GBSM which is also known as the parametric model [18, 35–43]. Both classes have the same model structure. However, the IS-GBSM is obtained from channel measurement, whereas RS-GBSM is based on the regular geometric shape [44]. Both types will be discussed further in the subsequent sections.

The geometry-based stochastic modelling approach can be summarized by the following four steps [11]:

- (1) Survey of the environment: Identification of the position and the velocity of the transmitter and the receiver are done along with the classification of essential scatterers whether moving or static.

- (2) Placement of scatterers: Setting a predefined scattering region is done based on the statistical distribution of scatterers. For example a regular shape is selected for RS-GBSM and random shapes for IS-GBSM.
- (3) Parameterization: There are two methods for the parameterization of scatterers. In the first method, a finite number of scatterers are considered and their fading properties are attributed based on measured data. In the second method, an infinite number of scatterers are assumed and the channel characteristics are determined by only using their probability density functions.
- (4) Determination of the channel impulse response: The contributions received from all the scatterers at the receiver are summed to obtain the channel impulse response.

3. Regular-Shaped Geometry-Based Stochastic Channel Model

In RS-GBSM, scatterers are considered to be stochastically distributed according to a particular regular geometric shape as shown in Figure 1. The regular shapes can be one-ring, two-ring, ellipse, and rectangle for 2D distributions of scatterers, and it can also be one-sphere, two-sphere, and elliptic-cylinder for 3D distributions of scatterers. In practice, the RS-GBSM might either use a combination of these basic shapes or add new geometric shapes [44]. This section presents the state-of-the-art 2D and 3D regular-shaped GBSM for V2V channels.

3.1. Two-Dimensional Regular-Shaped Geometry-Based Stochastic Channel Model. The authors in [45] proposed a 2D geometry-based narrowband nonstationary MIMO channel model for V2V communications using T-junction shape. This model considers only DB scattering rays obtained from fixed scatterers and also it makes use of the Choi-Williams distribution. In [46], Chelli et al. have proposed another 2D geometry-based narrowband channel model for straight road environments with the assumption of SB rays. Two types of scatterers were considered: fixed and mobile. Chelli et al. have demonstrated that the Doppler spread is larger for fixed scatterers if the moving scatterers and the communicating vehicles are moving in the same direction. Both studies in [45, 46] focused on narrowband channels; however, for V2V communications most of transmission schemes employ relatively wide bandwidths [10]. Furthermore, a GBSM of non-Wide-Sense Stationary Uncorrelated Scattering (non-WSSUS) Rayleigh Fading Channels has been proposed in [47] for machine-to-machine communications, where an arbitrary geometrical configuration of the propagation area has been employed. However, measurements needed for validation of the proposed channel model were missed. In addition, authors have considered that the transmitter and the receiver move at constant speeds and only static scatterers were taken into account. Ma et al. [48]

have developed a nonstationary GBSM nonstationary MIMO channel for V2V communication based on one-ring scattering geometry. They have also changed the assumption used by previous one-ring channel model by supposing that ring's radius is much smaller than the distance between transceivers. Nevertheless, only static scatterers were considered.

Since all mentioned geometric models cannot be used for complicated scattering environments, combination of regular-shape 2D GBSMs has been considered as a solution. In [49, 50], 2D two-ring GBSM and a 2D ellipse GBSM are combined to model V2V channels. The authors consider that the scattering of buildings along a street are represented by effective scatterers on an ellipse while the scattering of vehicles around the transmitter and receiver are represented by the effective scatterers on two rings. It has been shown in [49] that, for different directions of motion and shape of scattering region, SB rays lead up to a U-shaped PSD, while DB rays conduct to a "rounded"-shaped PSD. For [50], it has been found that a lower Vehicular Traffic Density (VTD) leads to smaller level crossing rate (LCR) and larger average fade duration (AFD). A 2D multiple-ring model was proposed in [51] for the purpose of cooperative MIMO channel modelling and effective scatterers were placed on circle. Results show that if the propagation of environment has low local scattering density (LSD), a high multilink spatial correlation takes place. In [52], the authors consider the implementation of Spatial Channel Model (SCM) for V2V communication; general expressions of statistical parameters such as impulse response, PSD, and Doppler shift were determined and simulated; authors have combined geometry with SCM in order to adapt to the V2V environment. However, measurements were missed. All mentioned models in this section are 2D and the angle parameters in the vertical plane are neglected.

From the previous discussion, it is observed that most 2D models adopt two-ring and ellipse geometries due to their simplicity. In addition, while two-ring model is used to model narrowband channels, ellipse model is employed for wideband channels. Moreover, many channel models were not verified by measurements; models complexity was relatively high and requires the determination of a large number of parameters. He et al. [53] used a two-ring geometry for V2V communication and results were derived from measurements carried out at 5.9 GHz. According to this work, it is found that the increase of the number of clusters contributes in reducing the time correlation function and according to mentioned paper this is also true for millimeter wave (mmWave) frequencies.

The 2D RS-GBSM channel models consider that waves travel only in horizontal plane; therefore, they neglected signal variation in the vertical plane. In real scenarios, scatterers disperse in the horizontal and vertical planes and the effect of elevation angles must be taken into account. Thus, 2D models may not fully represent the channel characteristics and 3D RS-GBSMs are needed for V2V communication channels.

FIGURE 1: Classical regular-shape GBSMs, (a) one-ring, (b) two-ring, (c) ellipse, (d) rectangle, (e) one-sphere, (f) elliptical cylinder, (g) semiellipsoid, and (h) two-cylinder.

3.2. Three-Dimensional Regular-Shaped Geometry-Based Stochastic Channel Models. Many studies proposed several three-dimensional RS-GBSMs for V2V communications using different geometries. For many cases, it has been observed that a single geometry is not adequate enough to describe 3D environment for complicated V2V communication scenarios [11]. Consequently, propagation characteristics are normally described by the combination of several geometric shapes. For example, Yuan et al. proposed 3D-GBSMs that combine two-sphere and elliptic-cylinder shapes for both narrowband and wideband V2V communication channels in [8, 10]. They also showed that low VTD always led up to better channel performance in comparison to high VTD case. However, this model considers uniform linear array configuration and only constant vehicle speeds with two special movement directions. In [25], another geometry represented by two-cylinder shape was utilized to characterize moving vehicles around transmitter and receiver. Authors in [54] proposed a channel model for multireflecting propagation paths in dense urban street environment using a multiple confocal ellipsoid geometry; nevertheless, the impacts of moving vehicles around transceivers on channel characteristics were not studied. Furthermore, a 3D model for V2V communication combining two-cylinder and multiple confocal semiellipsoid shapes was adopted by Jiang et al. [26] for tunnel scenarios. The channel characteristics were determined and it was demonstrated that PSD behaviour deviates over time due to motion of Tx and Rx. However, the disadvantage is that this model is complex and employs a large number of parameters. Wang et al. [27] proposed a 3D MIMO-GBSM for V2V communication systems which uses two-ring and semiellipsoid shape. This model considers both LOS and NLOS components emanating from static and moving scatterers. Wang et al. studied also the impacts of key factors on

FIGURE 2: Received spatial CCF vs. normalized antenna spacing where V_s refers to the velocity of scatterers [27].

absolute spatial cross-correlation function (CCF). They found that the received spatial CCF decreases when antenna spacing increases or when scatterers move with higher velocity as illustrated in Figure 2.

Different scenarios were also investigated in [28] where the authors suggested a MIMO channel model for congested curved-street environment for V2V communication; the model is the combination of both SB and DB components. The proposed model was compared with the measured data to validate the utility of the model.

Figure 3 presents the distribution of temporal ACF with respect to the variations time interval for some studied GBSM models for MIMO-V2V communication. It is clearly

FIGURE 3: Comparison between the temporal ACFs that are produced by 5 GBSM models.

observed that the ACFs decrease rapidly, almost within a short delay, and then decline in a fading trend. Ideally, the ACF values should decay rapidly to zero when time delay increases. The Tang model shows lowest values for time delay lower than 6.5 ms, but its values increase afterward. On the other hand, the temporal ACF for the Zhao model has low values that decrease steadily to zero. So the Zhao model can be favoured in terms of temporal ACF.

Multiple RS-GBSMs were also suggested for massive MIMO V2V communication. In [24] Jiang et al. proposed a 3D model for massive MIMO V2V communication; the model employed semiellipsoid geometry to locate scatterers. Another 3D model was proposed in [31] for nonstationary massive MIMO V2V communication in crossroads environments. The model is the superposition of both two-ring and four-quarter cylinder shape and it considers the influence of VTD on the model. This study has shown that faster movements of vehicles lead to stronger nonstationary behaviour.

In [32], a 3D wideband GBSM is developed for 5G massive MIMO V2V communications in urban-merging environments. The model used superposition of semicircle and semiellipsoid shapes, and it is claimed to be the first GBSM that models the blocking effect of sound barrier. The study showed that the model can describe the characteristics of the V2V communication channels in a merging area. Nevertheless, to the best of our knowledge, only few GBSM for V2V communication modelling the effect of sound barriers have been proposed. A 3D GBSM channel model for massive MIMO V2V wireless communication has been suggested in [33]. The model is simulated in different environments including expressway, urban road, and tunnel scenarios. A dual-sphere model is employed to characterize road traffic scatterers, and an ellipsoid model is used to characterize road environmental scatterers. However, measurements were missed and moving vehicles were not taken into account. Table 1 summarizes the main characteristics of the 3D RS-GBSM channel models discussed so

far. According to this study, many models are not verified by measurements which are needed to prove effectiveness of these models. Furthermore, few models have studied the combination of different technologies together such as massive MIMO and mmWave. Thus, this leads the path for similar models to be investigated in the future. In addition, many scenarios have not been treated for V2V channel modelling such as V2V communication on bridges, airports, near shopping malls, etc. Thus new scenarios should be investigated.

Another case of V2V system which has attracted many researchers is Unmanned Aerial Vehicles (UAV) communication. In [34], a wideband GBSM for low-altitude UAV channels based on WSS assumption was developed. However, mobile UAV channels present nonstationary behaviour and WSS assumption is only valid for short time periods. Thus, nonstationary aspects of those channels must be considered. For this reason, Chang et al. proposed a nonstationary wideband GBSM for low-altitude UAV to ground. They have considered four components: LOS, ground reflection, SB, and DB. They have also employed birth death process and smooth transition region to model cluster evolution [35]. The study found that the stationary interval for LOS scenario is larger than that of the NLOS scenario and the latter includes more fluctuations than the former. Nevertheless, models in [34, 35] are not applicable for mmWave band. To the best of our knowledge, few papers studied UAV communication for mmWave band and even for frequencies below 6 GHz. Hence, much research efforts are needed to explore UAV channel measurements and modelling.

4. Irregular-Shaped Geometry-Based Stochastic Channel Models

In IS-GBSM, scatterers are assumed to be stochastically distributed without being located on a regular shape and the model is built from the analysis of measured data in order to determine path parameters [44]. The IS-GBSM model takes into consideration the LOS components, discrete components reflected from moving or fixed scatterers, and diffuse components emanating from weak static scatterers placed on the roadside. It was found that these types of models show good agreement with the measured data and attain a better compromise between accuracy and complexity in comparison with the RS-GBSMs [36]. In order to determine the channel parameters, IS-GBSM modelling can be divided into three steps as illustrated in Figure 4 [44]. A brief description of these steps is provided below:

- (1) Preparation and measurements: First, the expression for the generic channel model is specified along with the parameters to be measured. Then, the experimental setup for the collection of required measured data is prepared. Finally, measurements are conducted and the collected data are stored.
- (2) Postprocessing of measured data: Different methods can be applied on the measured data to extract the required parameters such as impulse responses, path

TABLE 1: Summary of the main characteristics of 3D RS-GBSM channel models.

References	Category	Environment	Used geometry	Considered components	Measurements	Channel statistics
[8]	MIMO V2V	Urban	Two-sphere model and an elliptic-cylinder	LOS, SB, DB	No	STCF, LCR, PSD, AFD
[10]	MIMO V2V	Highway and urban	Two-sphere model and an elliptic-cylinder	LOS, SB, DB	No	STCF, FCF*, PDP**
[25]	MIMO V2V	—	Two-cylinder	LOS, SB, DB	No	STCF, PSD
[54]	MIMO V2V	Dense urban street	Multiple confocal ellipsoid	MB	No	PDF of AoD and AoA, Doppler frequency
[26]	MIMO V2V	Tunnel	Two-cylinder and semiellipsoid	SB + DB	No	STCF, ACF, PSD
[27]	MIMO V2V	Street	Two-ring + semiellipsoid	LOS + NLOS	No	STCF, ACF,
[28]	MIMO V2V	Curved-street	—	SB + DB	Yes	STCF
[24]	Massive MIMO V2V	—	Semiellipsoid	—	No	PDF of AoD and AoA, STCF, PSD
[31]	Massive MIMO V2V	Crossroad	Two-ring + four-quarter cylinder	SB + DB	No	STCF, ACF,
[32]	Massive MIMO V2V	Urban	Semicircle and semiellipsoid	LOS, SB, DB	No	STCF, ACF
[33]	Massive MIMO V2V	Highway, urban, and tunnel scenarios	Dual-sphere confocal ellipsoid	LOS, SB, DB	No	ACF, spatial CCF***
[34]	MIMO UAV	—	Ellipse + elliptical cylinder	LOS + ground reflection + scattering	Yes	STCF, ACF, PSD
[35]	MIMO UAV	Open + residential scenarios	Cylinder + multiple confocal ellipsoid models	LOS + SB + DB + ground reflection	Yes	STCF, ACF, PSD

*FCF: frequency correlation function, **PDP: power delay profile, ***CCF: cross-correlation function.

FIGURE 4: Basic steps for IS-GBSM.

loss, Angle of Arrival (AoA), Angle of Departure (AoD), etc. Typical methods include Expectation-Maximization (EM), Space-Alternating Generalized EM (SAGE), and RIMAX. Statistical analysis can also be applied to obtain the PDFs of the statistical parameters.

- (3) Model Generation: Combine the generated parameters with antenna information to get the transmission matrix. Then, generate the CIR.

Several IS-GBSM models have been proposed in the literature. Liang et al. developed a 3D V2V channel model considering motion of local scatterers with random velocities and directions [37]. Both single-bounced reflection and diffuse scattering were included in the channel model. However, models in [37] focus only on Single Input Single Output (SISO) channels and their temporal correlation

properties. A 3D irregular-shaped geometry-based stochastic model for V2V radio propagation environments has been proposed by Jiang et al. [38]. The impacts of moving directions and delay time on the channel statistical properties are studied. However mobility of scatterers is not taken into account by the model. Another model based on extensive measurements conducted at the frequency band 5.2–6.2 GHz was suggested by Gustafson et al. in [39] for intersections scenario in Berlin, Germany. First, second- and third-order interactions were taken into account, and the gamma process is found to be the best model for power fading of single multipath components with an exponential autocorrelation behaviour. In addition, path coherence distance is found to be in the order of 0 to 2 meters. Nevertheless, the model in [39] considered only SB reflections which might not hold when applied to measurements data in [40]. That is why the paper proposed a 3D MIMO-GBSM model for V2V communication based on extensive measurements performed in different street canyon environments [40]. The model is composed of five components including LOS, discrete components resulting from interactions with static and mobile scatterers, and component resulting from MB reflections and diffuse scattering. This

TABLE 2: IS-GBSM channel models.

References	Category	Environment	Considered components	Measurements	Channel statistics
[18]	MIMO V2V	Rural + highway	LOS, DC_M , DC_s , DS	Yes	Channel transfer function
[37]	MMO V2V	—	NOS + NLOS	Yes	PDF space CFs
[38]	MIMO V2V	—	LOS, SB, DB	Yes	ACF, PSD
[39]	MIMO V2V	Intersections	SB, DB and TB	Yes	Doppler spread, delay spread
[40]	MIMO V2V	Street canyon	LOS, MB reflections and diffuse scattering	Yes	RMS delay spread and angular spreads
[41]	MIMO V2V	Urban and highway	LOS, NLOS	Yes	ACF, CCF, PSD
[42]	MIMO V2V	Urban	MB	No	SCF, TCF
[43]	MIMO V2V	—	(LoS), SB, DB, MB	Yes	PDFs, ACFs, and DPSDs. Straight-right turn, left-straight turn, and left-right turn in the opposite direction
[55]	MIMO V2V	Airport	SB	Yes	Impulse response, Doppler frequency
[56]	M2M	Dense urban areas	DB	No	ACF, Doppler spread
[57]	M2M	—	LOS + NLOS	No	PSD
[58]	MIMO V2V	—	—	Yes	PSD, Spatial Correlation Function

study found that positions of the buildings affect the angular spread, and the velocities of transmitter and receiver along with the separating distance between them significantly influence the delay spread. However, this model does not consider the change in speed and directions for transceivers. Authors in [41] developed a three-dimensional nonstationary multimobility V2V channel model, which considers the changes in speeds and moving directions of transceivers and scatterers and its impact on statistical properties. Another nonstationary IS-GBSM V2V channel model was suggested in [42], but the proposed models are complicated and it is not practical to derive the closed form expressions of its statistical parameters. A nonstationary IS-GBSM has also been presented for V2V applications in [43]. It considers the 3D scattering environments and allows 3D velocity variations. In this model four different trajectories of transceivers were considered: the same direction, straight-right turn, left-straight turn, and left-right turn in the opposite direction. Nevertheless, static scatterers located in both sides of the street have not been taken into consideration in this model. Table 2 summarizes some of the 3D IS-GBSMs.

5. Challenges for Vehicle-to-Vehicle Channel Modelling

Many research studies have been carried out on V2V communication channel modelling. However, there are still many areas that should be investigated in the future. Some research directions are drawn in this section including working with other modelling methods, covering high frequency bands, and studying new scenarios.

Vehicular environment can encounter complicated scenarios which can appear simultaneously in the same area

such as bridges, blocks, tunnels, etc. However existent channel models do not consider such issues and new studies should characterize these mixed scenarios in order to be supported by new channel models. In addition, there are many scenarios where measurements are lacking such as V2V communication in airports, near shopping malls, etc. Therefore more measurement campaigns should be performed in the future for V2V channel modelling. Subsequently, the volume of measured data for V2V communication can be very large, especially when using large number of transceivers in the presence of moving and static scatterers. The generation of large volume of data will certainly necessitate the use of big data and machine learning in channel modelling. Another point to be raised is the nonstationary statistical behaviour of V2V communication channel; many papers have addressed this problem but more studies are still required.

Besides moving scatterers around transceivers in the road, V2V communication systems can be affected by obstacles in the air like drones, so the impact of elevation angles should be considered. It is also important to consider the time varying path and angular parameters which require the characterization of multidimensional channels in time, frequency, and spatial domain. Furthermore, it is necessary to reduce model complexity by investigating other approaches such as IS-GBSM and nongeometry-based channel models.

Another issue that can be investigated is the development of a model that can consider the time varying velocities in arbitrary directions of the transmitter and receiver. Also, the effects of antenna array rotations and the influence of obstructions on V2V channel have not been examined sufficiently in the literature. Obstructions are generally

caused by different dimensions of scatterers present between transceivers which may include trucks, buildings, and vegetations. Another matter of concern is the operating frequency of V2V communication systems. Most V2V channel models are projected for frequency bands below 6 GHz; however, the congestion of these frequency bands has led to proposing models at millimeter wave frequencies. At this frequency band, researches focus mainly on path loss whereas other parameters should also be investigated. This is considered as a limitation for channel modelling and more study is required for these frequency bands. In addition, it is suggested to investigate the combination of the massive MIMO and mmWave in the future V2V communications systems. Finally, 3D channel models are characterized by their complexity which can be a challenge for the computation of channel statistics. Hence, it is recommended to explore new techniques that can optimize and simplify V2V channel models representation.

6. Conclusions

This paper has provided an overview of the latest techniques used for geometry-based stochastic V2V channel modelling. After highlighting the importance of modelling radio wave propagation channels in the design and operation of V2V communication systems under 5G, the paper discusses the different classes of V2V channel models and then focuses mainly on the regular-shaped and irregular-shaped GBSM models. The first part of this study presents a review on recent 2D channel models that use RS-GBSM. It was noted that 2D models may not fully represent the channel characteristics in real scenario. That is why more recent papers have focused on 3D models for RS-GBSM. Many regular geometric shapes were applied to 3D RS-GBSM for different scenarios and environments such as expressway, urban road, dense urban street, tunnel, congested curved-street, UAV to ground, etc. It has also been applied to MIMO and massive MIMO V2V communications. For many cases, it has been observed that a single geometry is not adequate enough to describe 3D environment for complicated V2V communication scenarios. Therefore, propagation characteristics can be better described by combining several geometric shapes. However, many of the published 3D RS-GBSM were not validated with real measured data. The next part of the paper presents basic concepts about IS-GBSM and discusses the recent proposed 3D models for different scenario and environment. Fewer models addressed the issue of nonstationary statistical behaviour of the V2V channel. Despite the fact that GBSMs are able to model channel characteristics in a more accurate manner, they usually involve higher computational complexity. Finally, main challenges are discussed and future research directions in this area are suggested.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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