Vehicle-to-Vehicle Channel Modeling and Measurements: Recent Advances and Future Challenges

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ABSTRACT

Vehicle-to-vehicle communications have recently received much attention due to some new applications, such as wireless mobile ad hoc networks, relay-based cellular networks, and intelligent transportation systems for dedicated short range communications. The underlying V2V channels, as a foundation for the understanding and design of V2V communication systems, have not yet been sufficiently investigated. This article aims to review the state-of-the-art in V2V channel measurements and modeling. Some important V2V channel measurement campaigns and models are briefly described and classified. Finally, some challenges of V2V channel measurements and modeling are addressed for future studies.

INTRODUCTION

Frequent traffic accidents causing enormous number of deaths and injuries have become a serious health and social issue. To improve the vehicle safety, in addition to traditional passive safety technologies, e.g., seat belts and airbags, new vehicular communication technologies for active safety applications need to be developed. Some examples include cooperative forward collision warnings, e.g., emergency braking, and hazardous location vehicle-to-vehicle (V2V) notifications, e.g., ice on pavement [1, 2]. Besides safety applications, new vehicular communication technologies are also desirable to improve the efficiency of transportation systems, e.g., to avoid traffic congestion or construction sites, and to improve the comfort of drivers/passengers, e.g., Internet access in the vehicle. Initiatives to create safer and more efficient and comfortable driving conditions have therefore drawn strong support from both governments and car manufacturers. V2V communications, also known as inter-vehicular communications, play a central role in these efforts, enabling a variety of applications for safety, traffic efficiency, and infotainment.

An overall structure of V2V system components and functionalities is illustrated in Fig. 1. Non-safety applications normally require Internet access or use components that build on Internet technology and protocols. Therefore, the traditional protocol stack with transport control protocol (TCP) and Internet protocol (IP) is employed [2]. In order to support non-safety applications, e.g., the direct communication between the vehicle and Hot Spots, the V2V system needs to support at least one wireless local area network technology, e.g., IEEE 802.11a/b/g. In contrast to non-safety applications, safety applications are usually of broadcast nature. TCP/IP addressing mechanisms or Internet routing protocols are not suitable for such applications. Hence, safety applications are directly supported by specific V2V network and transport protocols, and are normally based on IEEE 802.11p [3]. The IEEE 802.11p radio technology is directly derived from IEEE 802.11a with some modifications to adapt to vehicular environments. It occupies 75 MHz of the licensed spectrum, from 5.85 to 5.925 GHz, as part of the intelligent transportation system for dedicated short range communications (DSRC) in the USA [3]. Note that some non-critical safety applications, e.g., hazardous location V2V notification, may transceive data through IEEE 802.11a/b/g or other wireless technologies.

To support various safety and non-safety applications with the desired quality of service, vehicles in the ad hoc network need to not only follow specific protocols, but also cooperate with each other. This indicates that different protocol layers are necessary to exchange information and interact, with the help of the so-called cross-layer information controller, in order to improve the overall performance of the designed V2V system and efficiently utilize resources.

Although V2V communication technologies are very promising, many research challenges have to be addressed before their wide deployment. This article will focus on one of the most important challenges: how to characterize V2V communication channels? Reliable knowledge of the propagation channel and a corresponding

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realistic channel model serve as the enabling foundation for flexible and practical design and testing of V2V systems. This underlines the importance of developing physically meaningful yet easy-to-use methods to mimic V2V channels. Therefore, much research attention has been attracted to V2V channel measurements, for understanding the underlying physical phenomenon in V2V propagation environments; and to V2V channel modeling, for facilitating the analysis and design of V2V communication systems.

The remainder of this article is outlined as follows. In the next section we give an overview of recent advances in V2V channel measurements. We then review the state-of-the-art in V2V channel models. We then address some future challenges of V2V channel measurements and modeling. Finally, conclusions are drawn in the final section.

Recent Advances in V2V Channel Measurements

Knowledge of the V2V propagation channel for different scenarios is of great importance for the design and performance evaluation of V2V systems. V2V systems, where both the transmitter (Tx) and receiver (Rx) are in motion with low elevation antennas, differ from conventional fixed-to-mobile (F2M) cellular radio systems, where only one terminal (mobile station) is moving while the other one (base station) is fixed. Channel knowledge obtained from conventional F2M cellular systems cannot be directly used for V2V systems. So far, some measurement campaigns have been conducted and others are ongoing to investigate the V2V propagation channels for different application scenarios. In this section, we will briefly review and classify some recent typical measurement campaigns according to carrier frequencies, frequency-selectivity, antennas, environments, Tx/Rx directions of motion, and channel statistics, as shown in Table 1.

Carrier Frequencies

Before the IEEE 802.11p standard was proposed, some measurement campaigns were conducted at carrier frequencies outside the 5.9 GHz DSRC band. In [4, 5], V2V measurements were carried out at 2.4 GHz, i.e., the IEEE 802.11b/g band. Some measurements were done around the IEEE 802.11a frequency band, e.g., at 5 GHz in [6] and at 5.2 GHz in [7]. Measurements at 5.9 GHz were presented in [8, 9] for narrowband and wideband V2V channels, respectively. The aforementioned measurements have shown that propagation phenomenon in similar environments with different frequencies can vary significantly. Therefore, more measurement campaigns are expected to be conducted at 5.9 GHz for the better design of safety applications for V2V systems following the IEEE 802.11p standard. On the other hand, for improved design of non-safety applications for V2V systems, measurement campaigns performed at other frequency bands, e.g., 2.4 GHz or 5.2 GHz, are still required.

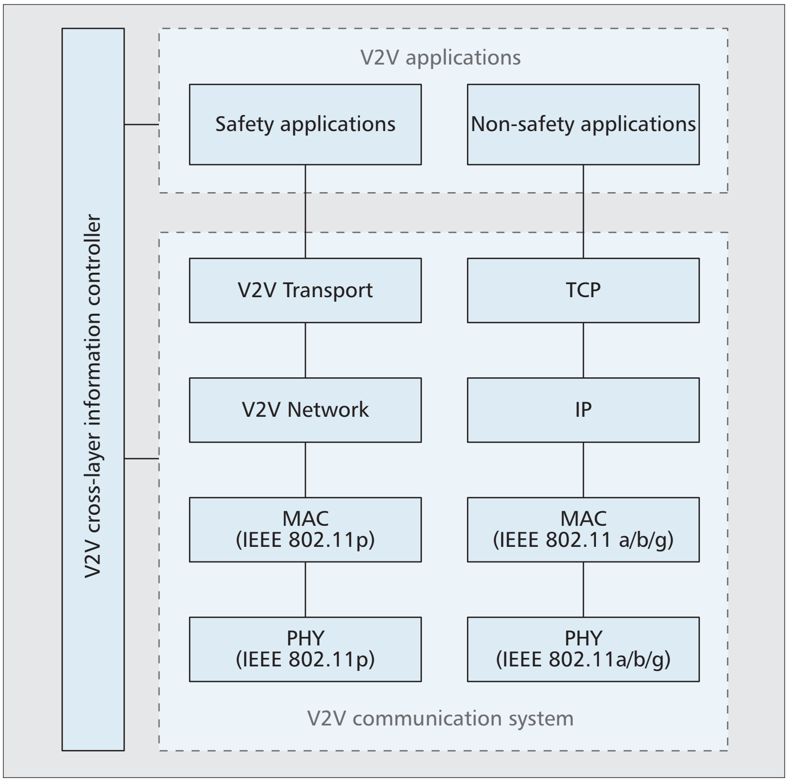

Figure 1. *V2V system components and functionality.*

Frequency-Selectivity and Antennas

In the USA, the Federal Communications Commission has allocated 75 MHz of licensed spectrum for DSRC, including seven channels, each with approximately 10 MHz instantaneous bandwidth. Such V2V channels are nearly always frequency-selective (or wideband) channels. Channel characterization based on narrowband measurement results [8] is not sufficient for such V2V DSRC applications. Wideband measurement campaigns [4–7, 9] are therefore essential for understanding the frequency-selectivity features of V2V channels and designing high-performance V2V systems.

Most V2V measurement campaigns so far have focused on single-antenna applications, resulting in single-input single-output (SISO) systems [4, 6, 8, 9]. Multiple-input multiple-output (MIMO) systems, with multiple antennas at both ends, are very promising candidates for future communication systems and are gaining more importance in IEEE 802.11 standards. Moreover, MIMO technology becomes more attractive for V2V systems since multiple antenna elements can be easily placed on large vehicle surfaces. However, until now only a few measurement campaigns [5, 7] were conducted for MIMO V2V channels. Hence, more MIMO V2V wideband measurement campaigns are needed for future V2V system developments.

Environments and Tx/Rx Directions of Motion

Similar to conventional F2M cellular systems, V2V scenarios can be classified as large spatial scale (LSS), moderate spatial scale (MSS), and

Measurements	Carrier frequency	Antenna	Frequency-selectivity	Tx/Rx directions of motion	Environments	Channel statistics
Ref. [4]	2.4 GHz	SISO	wideband	Same	SS/EW (SSS), LVTD	PDP, DD power profile
Ref. [5]	2.4 GHz	MIMO	wideband	Same	UC/EW (SSS), LVTD	STF CF, LCR, SDF PSD
Ref. [6]	5 GHz	SISO	wideband	Same	UC/SS/EW (M(S)SS), H(L)VTD	Amplitude PDF, frequency CF, PDP
Ref. [7]	5.2 GHz	MIMO	wideband	Opposite	EW (SSS), LVTD	PL, PDP, DD power profile
Ref. [8]	5.9 GHz	SISO	narrow-band	Same	SS (M(S)SS), LVTD	PL, CT, amplitude CDF, Doppler PSD
Ref. [9]	5.9 GHz	SISO	wideband	Same + opposite	UC/SS/EW (M(S)SS), LVTD	Amplitude PDF, DD power profile

SS: suburban street; EW: expressway; UC: urban canyon; M(S)SS: moderate (small) spatial scale; H(L)VTD: high; (low) vehicular traffic density; PDP: power delay profile; DD: Doppler-delay; PSD: power spectrum density; STF: space-time-frequency; CF: correlation function; LCR: level crossing rate; SDF: space-Doppler-frequency; PDF: probability density function; PL: path loss; CDF: cumulative distribution function; CT: coherence time

Table 1. *Important V2V channel measurements.*

small spatial scale (SSS) according to the Tx-Rx distance. For LSS scenarios or MSS scenarios, where the Tx-Rx distance is normally larger than 1 km or ranges from 300 meters to 1 km, V2V systems are mainly used for broadcasting or geocasting, i.e., geographic broadcasting [2]. For SSS scenarios, where the Tx-Rx distance is usually smaller than 300 meters, V2V systems can be applied to broadcasting, geocasting, or unicasting. Since most V2V applications fall into MSS or SSS scenarios, these two scenarios are currently receiving more and more attention with several current measurement campaigns taking place [4–9]. However, there are still few applications that need communications between two vehicles separated by large distances, e.g., larger than 1 km. For such LSS V2V applications, one example is V2V decentralized environmental notification, which means that vehicles or drivers in a certain area share information with each other about observed events or roadway features. These applications have not gained much attention and thus no measurement results are available that explore V2V channels for LSS scenarios.

V2V scenarios can also be categorized as urban canyon, suburban street, and expressway in terms of roadside environments, i.e., buildings, bridges, trees, parked cars, etc., located on the roadside. Many measurement campaigns [4–6, 9] were conducted to study the channel statistics for various types of roadside environments. Due to the unique feature of V2V environments, the vehicular traffic density (VTD) also significantly affects the channel statistics, especially for MSS and SSS scenarios. In general, the smaller Tx-Rx distance, the larger impact of the VTD. Note that V2V channels usually exhibit non-isotropic scattering except in cases of high VTD. To the best of the authors' knowledge, only one measurement campaign [6] was carried out to study the impact of the VTD for expressway MSS and SSS scenarios.

Directions of motion of the Tx and Rx also affect channel statistics, e.g., Doppler effects. Many measurement campaigns [4–6, 8] have focused on studying channel characteristics when the Tx and Rx are moving in the same direction. Few V2V measurement campaigns [7, 9], have investigated channel characteristics when the Tx and Rx are moving in opposite directions.

In summary, it is desirable to conduct more measurement campaigns for MSS and SSS scenarios with various VTDs when the Tx and Rx move in opposite directions. In addition, measurement campaigns for LSS scenarios are indispensable for some V2V applications that need communications between two vehicles with a large distance.

Channel Statistics

Knowledge of channel statistics is essential for the analysis and design of a communication system. As shown in Table 1, many different V2V channel statistics have been studied in recent measurement campaigns [4–9]. Here, we only concentrate on two important statistics, amplitude distribution and Doppler power spectral density (PSD). Analysis of amplitude distributions has been reported in [6, 8, 9]. In [9], the authors modeled the amplitude probability density function (PDF) of the received signal as either Rayleigh or Ricean. In [8], it was observed that the received amplitude distribution in a dedicated V2V system with a carrier frequency of 5.9 GHz gradually transits from near-Ricean to Rayleigh as the vehicle separation increases. When the line-of-sight (LoS) component is intermittently lost at large distances, the channel fading can become more severe than Rayleigh. A similar conclusion has been drawn in [6], where the amplitude PDF is modeled as Weibull distribution and this *worse than Rayleigh* fading is called severe fading. The reason behind the severe fading is the rapid

Channel models	Antenna and FS	Stationarity	Impact of VTD	Per-tap CS	Scatterer region/ distribution	Scattering assumptions	Applicable scenarios
Ref. [10] GBDM	MIMO wideband	Non-stationary	yes	no	3D non-isotropic (deterministic)	SB+MB	Site-specific
Ref. [9] NGSM	SISO wideband	Stationary	no	yes	2D non-isotropic (N/A)	N/A	M(S)SS
Ref. [6] NGSM	SISO wideband	Non-stationary	yes	yes	2D non-isotropic (N/A)	N/A	M(S)SS
Ref. [11] RS-GBSM	SISO narrowband	Stationary	no	no	2D isotropic (two-ring)	DB	LSS
Ref. [12] RS-GBSM	MIMO narrowband	Stationary	no	no	2D non-isotropic (two-ring)	SD+DB	L(M)SS
Ref. [5] RS-GBSM	MIMO wideband	Stationary	no	no	3D non-isotropic (two concentric-cylinder)	SB+DB	L(M)SS
Ref. [13] RS-GBSM	MIMO narrowband	Stationary	yes	no	2D non-isotropic (two-ring+ellipse)	SB+DB	L(M/S)SS
Ref. [14] RS-GBSM	MIMO wideband	Stationary	yes	yes	2D non-isotropic (two-ring+multiple confocal ellipses)	SB+DB	L(M/S)SS
Ref. [15] IS-GBSM	MIMO wideband	Non-stationary	yes	no	2D non-isotropic (randomly)	SB	M(S)SS

FS: frequency selectivity; CS: channel statistics; SB: single-bounced; MB: multiple-bounced; DB: double-bounced; N/A: not-applicable

Table 2. *Important V2V channel models.*

transitions of multipath components induced by high speed and low height of the Tx/Rx and fast moving scatterers.

The Doppler PSD has been investigated in [4, 5, 7–9]. Joint Doppler-delay PSD measurements for wideband V2V channels at 2.4 GHz, 5.2 GHz, and 5.9 GHz were reported in [4, 7, 9], respectively. It was demonstrated that Doppler PSDs can vary significantly with different time delays in a wideband V2V channel. In [8], the authors analyzed the Doppler spread and coherence time of narrowband V2V channels and presented their dependence on both velocity and vehicle separation. Recently, the space-Doppler PSD, which is the Fourier transform of the space-time correlation function in terms of time, was investigated in [5, 7]. It is worth noting that the Doppler PSD for V2V channels can be significantly different from the traditional U-shaped Doppler PSD for F2M channels.

Recent Advances in V2V Channel Modeling

In this section, we will give a brief overview of recent advances of V2V channel models. Table 2 lists some recent important V2V channel models. In terms of the modeling approach, these models can be categorized as geometry-based deterministic models (GBDMs) [10] and stochastic models, while the latter can be further classified as non-geometrical stochastic models (NGSMs) [6, 9] and geometry-based stochastic models (GBSMs) [5, 11–15]. In the following, we will first present a general expression of the impulse response for V2V channels and then analyze each category of V2V models in more detail.

With the assumption of ideal omni-directional antennas, the double-directional time-variant complex impulse response of a V2V channel can be modeled as the superposition of L resolvable paths or taps

$$h(t,\tau,\Omega_T,\Omega_R)=\sum_{l=1}^{L} h_l(t)\delta(\tau-\tau_l(t))\delta\left(\Omega_T-\Omega_{T,l}(t)\right)\delta\left(\Omega_R-\Omega_{R,l}(t)\right) \quad (1)$$

where $\tau_l(t)$, $\Omega_{T,l}(t)$, and $\Omega_{R,l}(t)$ represent the excess delay, direction of departure (DoD), and direction of arrival (DoA) of the lth ($l = 1,\ldots,L$) resolvable path at time t, respectively, $\delta(\cdot)$ denotes Dirac delta function, and $h_l(t)$ denotes the complex fading envelope of the lth resolvable path and can be expressed as

$$h_l(t)=\sum_{n=1}^{N} a_{l,n}(t)e^{\{j2\pi f_{D,l,n}(t)t\}}e^{j\vec{k}\left(\theta_{T,l,n}(t)\right)\vec{d}_T}e^{j\vec{k}\left(\theta_{R,l,n}(t)\right)\vec{d}_R} \quad (2)$$

From Eq. 2, it is clear that each resolvable path $h_l(t)$ also consists of multiple unresolvable subpaths with complex amplitudes represented by $a_{l,n}(t)$ ($n = 1,\ldots,N$). Here, $f_{D,l,n}(t) = v(t)f_c \cos\beta_{l,n}(t)/c$ is the Doppler frequency of the nth

A GBSM is derived from a predefined stochastic distribution of effective scatterers by applying the fundamental laws of wave propagation. Such models can be easily adapted to different scenarios by changing the shape of the scattering region.

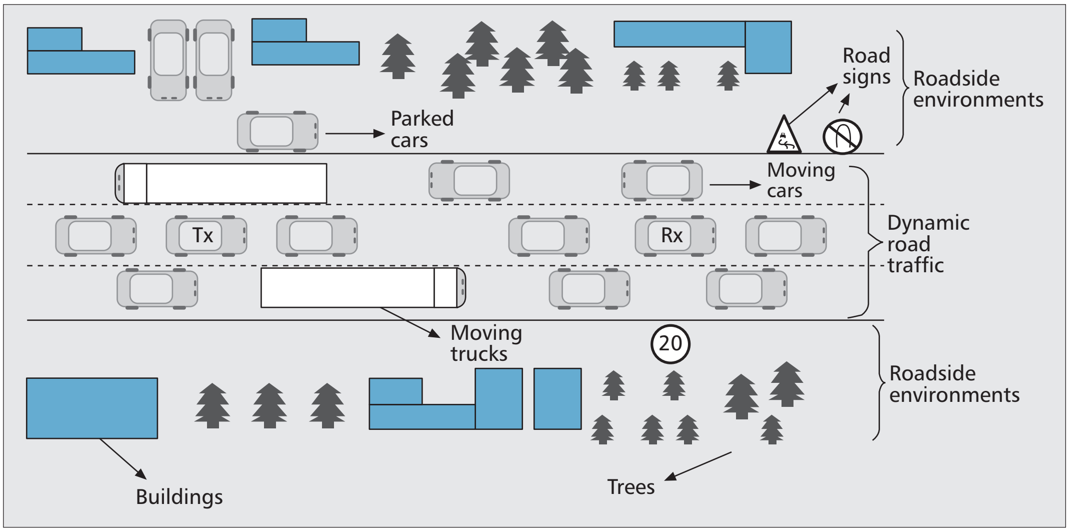

Figure 2. *A typical V2V environment and the corresponding geometrical description of the GBDM in [10].*

unresolvable subpath within the lth resolvable path at time t induced by the motion of both the Tx and Rx, $v(t)$ denotes the relative velocity, f_c is the carrier frequency, $\beta_{l,n}(t)$ is the aggregate phase angle of the nth subpath, and c is the speed of light. The terms $e^{j\vec{k}(\theta_{T,l,n}(t))\vec{d}_T}$ and $e^{j\vec{k}(\theta_{R,l,n}(t))\vec{d}_R}$ are the corresponding distance-induced phase shifts, where $\theta_{T,l,n}(t)$ and $\theta_{R,l,n}(t)$ denote the DoD and DoA of the nth subpath within the lth path, respectively, $\vec{d}_T$ and $\vec{d}_R$ are the vectors of the chosen element position measured from an arbitrary but fixed reference points on the corresponding arrays, and $\vec{k}$ is the wave vector so that

$$\vec{k}\left(\theta_{T(R),l,n}(t)\right)\vec{d}_{T(R)} = \frac{2\pi}{\lambda}\begin{pmatrix} x\cos\upsilon_{T(R)}(t)\cos\phi_{T(R)}(t) \\ +y\cos\upsilon_{T(R)}(t)\sin\phi_{T(R)}(t) \\ +z\sin\upsilon_{T(R)}(t) \end{pmatrix}$$

where $\upsilon_{T(R)}$ and $\phi_{T(R)}$ denote elevation and azimuth angles, respectively.

GBDMs

GBDMs characterize V2V physical channel parameters in a completely deterministic manner. A GBDM based on the ray-tracing method for V2V channels was proposed in [10]. It aims at reproducing the actual physical radio propagation process for a given environment. Figure 2 illustrates a typical V2V environment including the dynamic road traffic, e.g., moving cars, vans, and trucks, and the roadside environment, e.g., buildings, packed cars, road signs, and trees. In [10], a 3-dimensional (3D) ray-tracing approach was used in a wave propagation model, where the aforementioned typical V2V environment is simulated by generating possible paths or rays from the Tx to the Rx according to geometric considerations and the rules of geometrical optics. The resulting complex impulse response incorporates the complete channel information, e.g., the non-stationarity of the channel, the impact of the VTD on channel statistics, and the impact of the elevation angle on channel statistics, and thus agrees very well with measurement results. However, GBDMs require a detailed and time-consuming description of site-specific propagation environments and consequently cannot be easily generalized to a wide class of scenarios.

NGSMs

A NGSM determines physical parameters of a V2V channel in a completely stochastic manner without presuming any underlying geometry. The SISO NGSM proposed in [9] is the origin of the V2V channel model standardized by IEEE 802.11p. The complex impulse response of the SISO V2V channels in [9] can be modeled from Eqs. 1 and 2 by removing the terms $\delta(\Omega_T - \Omega_{T,l}(t))$, $\delta(\Omega_R - \Omega_{R,l}(t))$ and the corresponding distance-induced phase $e^{j\vec{k}(\theta_{T,l,n}(t))\vec{d}_T}$ and $e^{j\vec{k}(\theta_{R,l,n}(t))\vec{d}_R}$ while the aggregate phase angle $\beta_{l,n}(t)$ is 2D, i.e., has zero elevation. Based on the tapped delay line (TDL) structure, this model consists of L taps, with the tap amplitude PDF being either Ricean or Rayleigh, and thus has the ability to study per-tap channel statistics. Furthermore, each tap contains N unresolvable subpaths that have different types of Doppler spectra, e.g., flat shape, round shape, classic 3 dB shape, and classic 6 dB shape [9]. This allows one to synthesize almost arbitrary Doppler spectra for each tap. However, this NGSM is still based on the wide-sense stationary uncorrelated scattering (WSSUS) assumption and has not investigated the impact of the VTD on channel statistics.

Recently, a SISO NGSM was proposed in [6] which has the ability to consider the impact of the VTD on channel statistics. Also, the NGSM in [6] takes into account the non-stationarity of the channel by modeling multipath component persistence via Markov chains. The complex impulse response of the SISO V2V channel model in [6] can be obtained from the complex impulse response in [9] by adding an additional term, named as the birth/death or

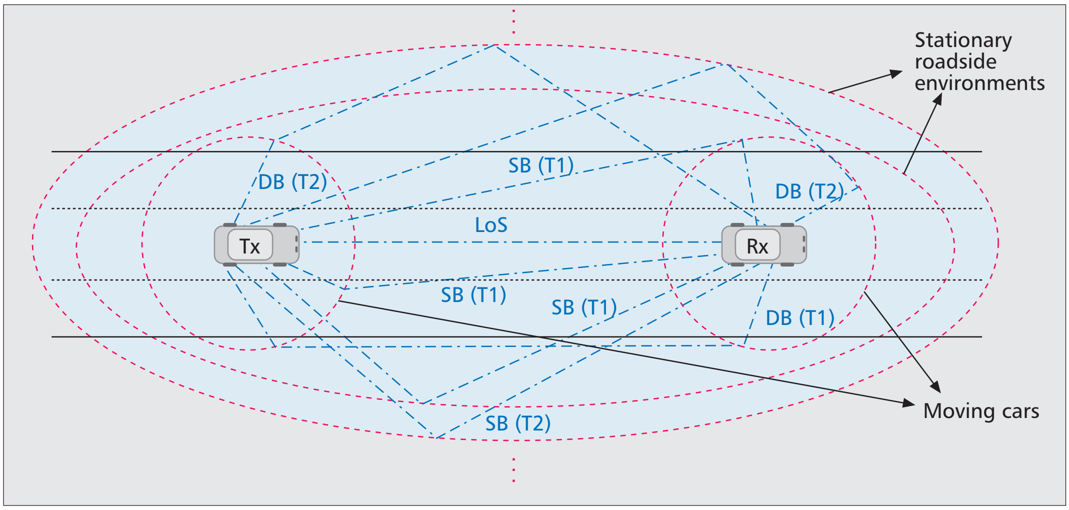

Figure 3. *The geometrical description of the RS-GBSM in [14] according to the typical V2V environment in Fig. 2. SB: single-bounced; DB: double-bounced; T1: Tap 1; T2: Tap 2.*

Unlike RS-GBSMs, IS-GBSMs intend to reproduce the physical reality and thus need to modify the location and properties of the effective scatterers of RS-GBSMs. IS-GBSMs place the effective scatterers with specified properties at random locations with certain statistical distributions.

persistence process, $z_l(t)$, which accounts for the finite lifetime of the lth resolvalbe path. The NGSM in [6] can easily capture the effect of a sudden disappearance of strong multipaths, mainly caused by rapid blockage or obstruction from another vehicle or other obstacles. However, the model did not consider the drift of scatterers into different delay bins (resolvable paths) and therefore the transitional probabilities of the Markov model for the persistence processes may not be accurate. This may reduce the ability of the NGSM [6] to accurately capture the non-stationarity of real V2V channels and thus deserves more investigations.

GBSMs

A GBSM is derived from a predefined stochastic distribution of effective scatterers by applying the fundamental laws of wave propagation. Such models can be easily adapted to different scenarios by changing the shape of the scattering region. GBSMs can be further classified as regular-shaped GBSMs (RS-GBSMs) and irregular-shaped GBSMs (IS-GBSMs) depending on whether effective scatterers are placed on regular shapes, e.g., one-ring, two-ring, and ellipses, or irregular shapes.

In general, RS-GBSMs are used for theoretical analysis of channel statistics and theoretical performance evaluation of V2V communication systems. To preserve the mathematical tractability, RS-GBSMs assume that all the effective scatterers are located on regular shapes. Akki and Haber [11] were the first to propose a 2D two-ring RS-GBSM with only double-bounced rays for narrowband isotropic scattering SISO V2V Rayleigh fading channels in LSS scenarios. In [12], the authors proposed a general 2D two-ring RS-GBSM with both single- and double-bounced rays for narrowband non-isotropic scattering MIMO V2V Ricean channels in both LSS and MSS scenarios. The 2D narrowband two-ring RS-GBSM in [12] was further extended to a 3D wideband two-concentric-cylinder RS-GBSM in [5]. However, all the aforementioned RS-GBSMs in [5, 11, 12] cannot study the impact of the VTD on channel statistics. Also, the wideband RS-GBSM in [12] has no ability to investigate per-tap channel statistics.

To fill the above gaps, in [14] we have proposed a new 2D non-isotropic scattering wideband MIMO V2V RS-GBSM, which is an extension of our narrowband model in [13] with respect to the frequency-selectivity. This wideband RS-GBSM is based on the TDL structure and thus can investigate the per-tap channel statistics. Based on the typical V2V environment described in Fig. 2, Fig. 3 shows the geometrical description of our wideband model that combines a two-ring model and a multiple confocal ellipses model consisting of LoS, single-, and double-bounced rays. The complex impulse response can be easily obtained from Eqs. 1 and 2 by assuming the elevation angle $\upsilon_{T(R)} = 0$. To take into account the impact of the VTD on channel statistics for every tap in our wideband model, we distinguish between the moving cars around the Tx and Rx and the stationary roadside environments, which are described by a two-ring model and a multiple confocal ellipses model, respectively. In agreement with the typical V2V environment in Fig. 2, we divide the impulse response for the first tap into three parts:

- The LoS component
- The single-bounced rays generated from the effective scatterers located on either of the two rings or the first ellipse
- The double-bounced rays produced from the effective scatterers located on both rings

Whereas for other taps, the impulse response contains two parts:

- The single-bounced rays generated from the effective scatterers located on the corresponding ellipse
- The double-bounced rays caused by the effective scatterers from the combined one ring (either of the two rings) and the corresponding ellipse

However, our model does not have the ability to study the non-stationarity due to the static nature of the geometry in RS-GBSMs.

3D channel measurements and models are necessary, especially for urban canyon scenarios and some expressways with high walls or sound blockers on both edges. We need to investigate the impact of the elevation angle on various channel statistics in different V2V scenarios.

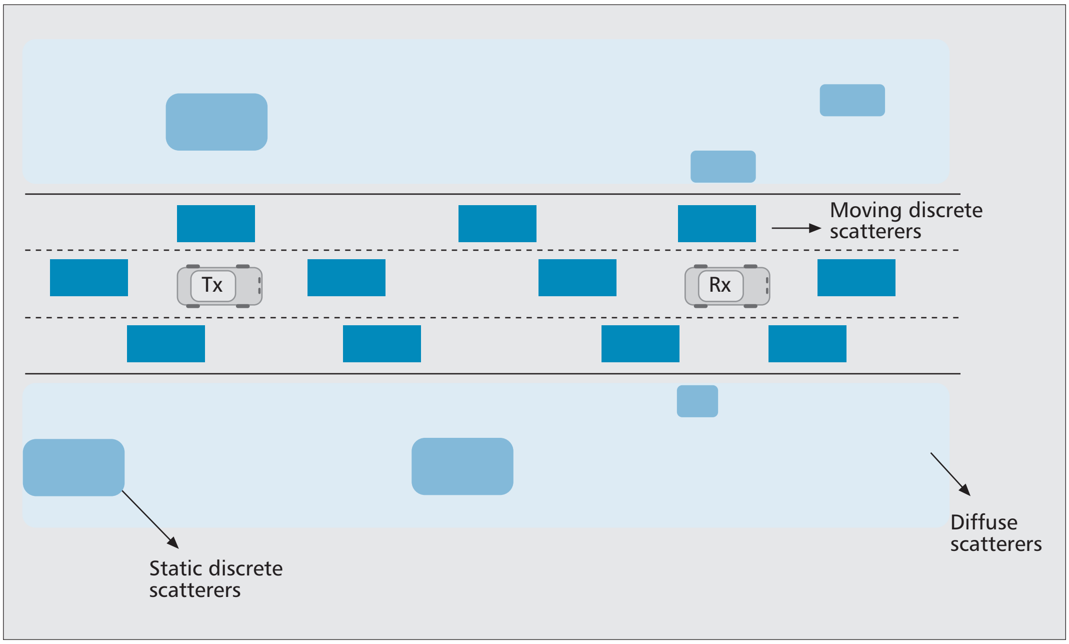

Figure 4. *The geometrical description of the IS-GBSM in [15] according to the typical V2V environment in Fig. 2.*

Unlike RS-GBSMs, IS-GBSMs intend to reproduce the physical reality and thus need to modify the location and properties of the effective scatterers of RS-GBSMs. IS-GBSMs place the effective scatterers with specified properties at random locations with certain statistical distributions. The signal contributions of the effective scatterers are determined from a greatly- simplified ray-tracing method and the total signal is summed up to obtain the complex impulse response, which can be expressed as Eqs. 1 and 2 with the assumption of the elevation angle $\upsilon_{T(R)} = 0$. In [15], to provide better agreement with the measurement results presented in [7], the channel impulse response is further divided into four parts:

- The LoS component
- Discrete components from reflections of mobile scatterers, e.g., moving cars
- Discrete components from reflections of strong static scatterers, e.g., building and road signs located on the roadside
- Diffuse components from reflections of weak static scatterers located on the roadside, as depicted in Fig. 4

Therefore, IS-GBSMs are actually a greatly-simplified version of GBDMs while suitable for a wide variety of V2V scenarios by properly adjusting the statistical distributions of the effective scatterers. With the ray-tracing approach, the IS-GBSM in [15] can easily handle the non-stationarity of V2V channels by prescribing the motion of the Tx, Rx, and mobile scatterers. Note that only single-bounced rays were considered in this IS-GBSM due to the fairly low VTD of the measurements in [7]. For a high VTD environment, it is possible that double-bounced rays should be considered as well. Compared to the NGSM in [6], the IS-GBSM in [15] can easily handle the drift of scatterers into different delay bins but with relatively higher complexity.

Future Challenges in V2V Channel Measurements and Modeling

The challenges discussed in this section can be considered as guidelines for setting up future measurement campaigns and proposing more realistic V2V channel models.

Impact of the VTD on Channel Statistics

So far in the literature, the measurements in [6] are the only ones which studied the impact of the VTD on some channel statistics, e.g., frequency correlation, for expressway environments. More comprehensive measurement campaigns are needed, preferably in the 5.9 GHz band, to investigate the impact of the VTD on a wide range of channel statistics, e.g., amplitude distributions, space-time CFs, and space-Doppler PSDs, for various environments.

Non-Stationarity of V2V Channels

Due to the high velocity of the Tx/Rx and the existence of many moving scatterers around the Tx/Rx in V2V environments, the time variation in V2V channels can be more rapid than that in F2M channels. This essentially means that V2V channels are in most cases statistically non-stationary, since the stationarity conditions pertain to a much shorter time period than in F2M channels. Although the non-stationary nature of V2V channels has been considered in NGSMs [6] by using a birth/death process to account for the appearance and disappearance of taps, and in IS-GBSMs [15] by prescribing the motion of the Tx, Rx, and mobile scatterers, the trade-off between the model accuracy and complexity of the NGSMs and IS-GBSMs needs more comprehensive investigations. For example, it is interesting to investigate whether the effect of the drift of scatterers into different delay bins on the non-stationarity of V2V channels is significant, and whether it is worth sacrificing the complexity for capturing this effect by using IS-GBSMs. How to properly incorporate the non-stationarity into V2V channel models is still an open problem.

IMPACT OF THE ELEVATION ANGLE ON CHANNEL STATISTICS

In practical V2V channels, waves travel in three dimensions, instead of two dimensions. This means that 3D channel measurements and models are necessary, especially for urban canyon scenarios and some expressways with high walls or sound blockers on both edges. We need to investigate the impact of the elevation angle on various channel statistics in different V2V scenarios.

CONCLUDING REMARKS

This article has provided a brief survey of V2V channel measurements and models. We have classified some important V2V channel measurements according to carrier frequencies, frequency-selectivity, antennas, environments, Tx/Rx direction of motion, and channel statistics, and classified V2V channel models as GBDMs, NGSMs, RS-GBSMs, and IS-GBSMs. Finally, we have discussed some future challenges in V2V channel measurements and modeling. These discussions will hopefully serve as guidelines for setting up future measurement campaigns and developing more realistic V2V channel models.

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