Vehicle-To-Vehicle Channels: Are We Done Yet?

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Abstract- **In this paper, we review the state of the field on measurements, models, and analysis for the vehicle-to-vehicle (V2V) channel. We first provide a survey of existing work on V2V models, including analytical and empirical models, and note main features and findings. Remaining work to be done in V2V modeling is then described, beginning with the logical next steps, then addressing less obvious areas of V2V channel research. We also provide some new results on statistically non-stationary models, specifically in terms of non-stationary Markov chains for modeling multipath component persistence. We show that in terms of delay dispersion measures, stationary 2nd-order Markov models perform as well as non-stationary models. The paper concludes with a summary.**

I. INTRODUCTION

Vehicle-to-vehicle (V2V) communication research has been growing steadily over the past several years [1]. Multiple papers, workshops, conference sessions and conferences attest to this. Applications range from the most important—road safety improvement—to useful and energy-saving improvements in vehicular traffic efficiency and density, to so-called "comfort" or "infotainment" applications [2]. For example, traffic warning systems may broadcast information on road obstacles, accidents, work zones, weather, etc. These broadcast applications would employ local transceivers at roadsides, and would constitute vehicle-to-roadside (V2R) or vehicle-to-infrastructure (V2I) communication. Similarly, V2V networking using multiple V2V links (hops) could be used to relay such information [3]. Much of the work on these technologies and applications lies in the area of Intelligent Transportation Systems (ITS) [1]. Mobile ad hoc networking is also a part of V2V communications, and military vehicular ad-hoc networks (VANETs) are of interest. Literature on V2V/V2R communications is burgeoning [4] so our review here is selective.

The importance of accurate channel models in optimizing communication system performance is well known [5]. Channel models are used in analysis, computer simulations, and hardware testing [6], all of which are key steps in actual system design and deployment. To cite just a few examples, channel knowledge is used for selection of equalizer length and adaptation algorithms, specification of subcarrier bandwidth, specification of pilot symbol period and pilot frequency separation, selection of cyclic extension duration, and selection of synchronization algorithms. If we broaden the discussion to include multiple antenna systems, channel knowledge is also critical in array design and processing.

Environments for V2V communication are roadways in urban, suburban, and rural areas, but significant differences from traditional cellular communication exist[1]. In V2V cases, both transmitter (Tx) and receiver (Rx) may be mobile, and both may have multiple scattering/reflecting vehicles nearby, which are also mobile. Scattering geometry will very often be non-isotropic and time-varying, yielding time varying Doppler spectra. When both Tx and Rx are mobile, fading rates can be twice as fast as in cellular. With low elevations for both Tx and Rx antennas (on vehicle roofs, or inside vehicles), obstruction of line of sight (LOS) paths will be more frequent, even when link distances are short. With obstacles around both Tx and Rx, the phenomenon of multiple scattering can arise, and this yields more severe fading than in cellular channels. These are two key differences from cellular: V2V channels can incur fading that is more severe [7], and V2V channels will be statistically stationary for shorter durations.

The frequency band of operation for V2V communications is likely to be in the 5 GHz range. In the US, 75 MHz of spectrum is available in the 5.85-5.925 GHz band. Work has also been done in the 5.1-5.2 GHz band [8], [9]. Thus, although some channel measurements have been made in other bands, such as the 2.1-2.4 GHz band [10], [11], and 900 MHz band [12], and analysis in other bands such as 60 GHz [13], most near-term V2V systems are likely to be deployed in the 5 GHz band, so that is our focus here. In addition, since most V2V systems are planned to be operated over short ranges (from a few m up to 1 km), propagation path loss is not difficult to overcome with moderate transmit power levels. Thus we concentrate on small (and medium, or "meso") scale channel fading effects.

In Section II, we summarize the "state of the field" in V2V channel modeling. In addition to recent work, we include citation of key work from the past for context. Section III covers logical next steps in the field. In Section IV we list some areas of V2V channel modeling that are uncovered, and which may see research in the future. We conclude with a summary in Section V. Due to page limitations and the need to balance subject coverage with reference citations, our reference list is necessarily incomplete. We refer the reader to [14] for a set of complementary references, which together with the references here provide a comprehensive V2V

[1] Although it is almost certain that V2V communications will be used in "off-road" conditions in the future (as they are now in ad hoc fashion), we do not address that environment in this paper.

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channel reference list. In addition to coverage of some similar topics, this paper differs from [14] by more treatment of non-stationarity and comparisons of measured results.

II. State of the Field

As with other types of channels, including cellular, indoor, etc., models come in various types. There are multiple ways one may classify such models, such as deterministic vs. statistical, analytical vs. empirical, "physical," or combinations of these. Within each type of model usually lie multiple classes, for example, the urban/suburban/rural classes for cellular. In addition, we may also classify according to frequency band, by number of antennas, V2V vs. V2R, etc. Our taxonomy here is but one possible, and classes are not perfectly disjoint; we discuss in terms of analytical, simulation, empirical, and MIMO.

A. Analytical Models

By analytical, we mean models based upon theory. An example is that of [15], arguably one of the earliest papers on V2V channels. This paper assumes rich scattering so that Central Limit Theorem (CLT) arguments yield classical Rayleigh fading, but with potentially twice the fading rate—the spaced-time autocorrelation function of the received envelope is a generalization of the classic form derived in [16]. The associated V2V Doppler spectrum was also derived. The same author extended this work in [17] to derive corresponding analytical results for level crossing rate, average fade duration, and random FM. These models are narrowband in that they do not expressly model delay dispersion, and naturally are functions of mobile velocities.

Shortly after the publication of [17], the authors of [18] extended the derivation of Doppler spectra and autocorrelations in [15] to three dimensions. These functions contain integrals that in general must be evaluated numerically, but the expressions are quite generic, allowing for arbitrary antenna gain patterns and angle-of-arrival probability density functions (pdfs). As with [15], simplifying assumptions include rich enough scattering to invoke the CLT for Gaussianity, and wide-sense stationarity (WSS).

A general-purpose analytical model for angle of arrival (AoA) and angle of departure (AoD) pdfs that allows for non-isotropic scattering is presented in [19]. This model employs the von Mises pdf, and via this density, the time-autocorrelation function of the received envelope is obtained in closed form as a product of modified Bessel functions, dependent upon Tx and Rx Doppler frequencies f_{di}, angular spreads κ_i, and mean AoD and AoA μ_i:

$$R(\Delta t) = \prod_{i=1}^{2} \frac{I_0\left(\sqrt{\kappa_i^2 - 4\pi^2 f_{di}^2 \Delta t^2 + j4\pi\kappa_i f_{di} \Delta t \cos(\mu_i)}\right)}{I_0(\kappa_i)} \quad (1)$$

The Doppler spectrum associated with this autocorrelation must be found numerically. Sum of sinusoids (SoS) simulations in [19] employing the non-isotropic pdfs showed the ability to replicate theoretical predictions fairly well—assuming stationarity—but with a generally large number of sinusoids (e.g., 100 or more).

More recently, in [20], a detailed analytical model was presented. This model could also be classified in our next class—simulation models—since due to the extraordinary level of detail, any use of the model requires a computer. We discuss it as an analytical model because it is in principle based upon plane wave (ray) theory and geometry (so called geometric stochastic channel models, GSCM). Indeed, this could also be classed as a geometric model, as it assumes two cylindrical "rings" of scattering objects surrounding the Tx and Rx. The authors develop a so-called "reference model" that assumes rich scattering and CLT applicability, and implement this via the SoS approach. This model also incorporates multiple-input/multiple output (MIMO) modeling with antenna arrays at both Tx and Rx vehicles. Numerous (1-2 dozen) geometric parameters must be specified, and values for some of these are drawn from random distributions that are user-selectable. The authors validate their SoS implementation against the theoretical (WSS) autocorrelations and Doppler spectra. Once configured, this complicated model has the ability to replicate a range of scattering conditions.

B. Simulation Models

We classify as simulation models those that use established theoretical principles, but because of complexity of evaluation, closed form expressions are not available. Some of these simulations take the form of Monte Carlo simulations, i.e., repeated trials of a probabilistic experiment in which the parameter distributions are selected a priori.

A good example of this type of model is that found in [21]: a ray tracing model for the V2V channel. In these simulations, local environment characteristics must be specified. In general, in addition to object dimensions, electrical parameters such as conductivity and permittivity must also be included, so these simulations require large numbers of inputs. Many software packages are available with built-in databases for common materials, e.g., [22], thus simplifying this task somewhat. In [21], the authors construct a model for V2V channels in which other vehicles and roadside obstacles are modeled stochastically: basic properties are specified (e.g., building shape, vehicle size), and then the simulation runs by first placing these objects according to the appropriate distributions, and then running the ray-tracing program to compute the channel characteristics. The program can compute either narrowband (~amplitude) characteristics or wideband characteristics, with the latter requiring more computation. The model in [21] was an updated version of that in [23], in which the simulation of propagation was only a single part of a larger, system-level simulation. The authors continued their work in [24], in which they simulate the performance of an IEEE 802.11a system in the V2V channel.

A perhaps more traditional simulation is that described in [25]. In this paper, the authors presume Rayleigh fading a priori, and develop a simulation to efficiently emulate fading that agrees with the reference model of [15]. The SoS approach is used, and the authors show that this narrowband model reproduces desired fading envelope correlation properties.

C. Empirical Models

These are models based on measurements, and are typically "physical" models for the channel impulse response (CIR). As with analytical or simulation models, these models can pertain to either narrowband (flat, or frequency non-selective) fading or wideband (dispersive, or frequency selective) fading. An example of the former is [26], in which the authors explored fading characteristics in the 5.9 GHz Dedicated Short Range Communication (DSRC) [27] band. The DSRC system is a modified version of the IEEE 802.11a wireless LAN standard [28], also known as WAVE for Wireless Access in Vehicular Environments [29]. The authors of [26] measured and modeled large scale path loss and flat fading in suburban Pittsburgh, and found some severe fading (worse than Rayleigh statistics). Fading was modeled using the Nakagami distribution [30], with shape parameter ("*m* factor") ranging from 0.5 to 4. In [31], these authors employed wideband measurements to help specify criteria for DSRC system parameters. In contrast to the commonly-used root-mean-square delay spread (RMS-DS), they used excess delay [32] to characterize delay dispersion (this excess delay is equivalent to the *delay interval* I_X, the duration of the power delay profile containing all energy equal to or above X dB below the power delay profile peak). They also provided results for 90% coherence bandwidth, 90% coherence time, and maximum Doppler spread. Explicit models were not provided.

In [33], the authors provide a measurement-based model for expressway V2V channels. The dispersive channel model takes the usual tapped delay line (TDL) form, and pertains to a 10 MHz bandwidth. The developed model was aimed at implementation on a commercial channel emulator, so flexibility was limited: fading had to be Rayleigh or Ricean, and Doppler spectra could take only a few basic shapes (or sums of these basic shapes). The authors measured time-varying Doppler spectra, indicating statistical non-stationarity.

The authors of [34] also did expressway measurements at 5.2 GHz. They developed a TDL model with Rayleigh/Ricean coefficients. This model has a significantly smaller RMS-DS than those in [6], [10]. Interestingly, delay spread values in [8] lie between those of [34] and [6], [10]. The authors of [8] developed TDL models for channel bandwidths of 5 MHz and 10 MHz (additional models for other bandwidths are provided in [35]). In [8], both severe fading and NS behavior were observed and modeled. Reference [36] provides additional measured results in terms of delay and Doppler spread. Table I summarizes some of the RMS-DS values discussed here.

TABLE I
REPRESENTATIVE ROOT-MEAN-SQUARE DELAY SPREAD VALUES σ_τ FOR V2V EXPRESSWAY SETTINGS

Reference	Frequency Band (GHz)	σ_τ (nanosec)	Comments
[6]	5.9	40.2 67.6	Oncoming Same direction, w/wall
[34]	5.2	15	Doppler > $2v/\lambda$ found
[8]	5.1	20 48	Median, low traffic density Median, high traffic density
[36]	5.7	40	Oncoming

Our last representative citation in this section is [37], in which the authors employ time-frequency analysis [38] to estimate "stationarity times" for V2V channels. For expressways, these times were as small as 23 millisec for vehicles driving in opposite directions and as large as 1.4 sec for vehicles traveling in the same direction.

D. MIMO Models

Multiple-input, multiple output, or MIMO channels and systems have seen enormous attention recently [39], and V2V applications are no exception. We have already cited several MIMO references in the previous section [34], [36], and [38]. Most measurements use between 2-4 antennas, typically roof-mounted. Two analytical MIMO models are [40], [41]. In [40], the authors employ the "2 ring" scattering model and, akin to previously cited analytical work, assuming the CLT and WSSUS apply, they derive correlation functions and Doppler spectra for a narrowband V2V channel. Similarly, [41] extends the work in [20] to the MIMO case. The "2-cylinder" geometric model is employed to assess correlations and Doppler spectra, and these are compared to measurement results. Agreement with measurements is reasonably good.

In [42] the authors used two diversity measures to assess achievable diversity orders via estimated MIMO correlation matrices for an expressway setting. As known from non-V2V MIMO studies, they found very high correlations among antennas for LOS cases. They also clearly show time-varying diversity order, reflecting the NS nature of the V2V channel.

III. THE LOGICAL REMAINING WORK

In this section, based on the findings in existing work described in the previous section, we discuss logical next steps. From the review of the literature, one can observe a clear trend from the fairly simple (assumed WSSUS and narrowband Rayleigh fading) in early works, to MIMO, NS, and severe fading in more recent results based on measurements.

A. Additional Frequency Bands

Although the 5 GHz band will be the band of interest for any commercial ITS applications, clearly V2V communications can be employed in other bands. Two primary candidates are two public safety bands in the US: 750 MHz and 4.9 GHz [43]. The 4.9 GHz band will have characteristics essentially the same as the 5 GHz bands, but the 700 MHz band (allocated from recently-vacated television bands) is largely unexplored for V2V applications. In addition, the public safety community is not in any way committed to 802.11p or WAVE; in fact, both in [43] and [44], the newer IEEE 802.16e standard [45] is noted as being the primary candidate technology for deployment. Other bands may also see use of V2V communications, such as dedicated military bands, aeronautical bands, at VHF and other frequencies.

B. More on MIMO

As noted, MIMO models come in both analytical and measured forms. The analytical work cited presents some clear guidelines for selection of antenna element separation and array type required for the best exploitation of rich scattering.

Yet rich scattering is not always present, particularly in expressway environments. In addition, both economic [46] and aesthetic considerations will likely limit antenna arrays to a few elements, with placement not always on vehicle roofs. Thus effects of the vehicle body on MIMO performance should be quantified when antenna elements are placed in a variety of locations (e.g., trunk, hood, interior, etc.). The use of dual polarizations also needs further exploration [56], as this can provide at least moderate link capacity gains.

C. Non-stationarity or Not?

Bello's framework [47] for modeling channels statistically has seen widespread use. The WSSUS assumptions are in fact so common that many simply tacitly assume these conditions apply. The growth of V2V measurements has forced researchers to re-evaluate the validity of the WSSUS conditions, and treat it as the special case it actually is [48].

As true for other channels, the V2V channel can be modeled as a linear time varying filter, hence the channel is completely described by the CIR. For simplicity of exposition, we discuss a SISO model, but this is easily generalized to MIMO cases. For durations within the stationarity time, the channel impulse response $h(\tau;t)$ is defined as the response of the channel at time t to an impulse input at time t-τ,

$$h(\tau,t)=\sum_{k=0}^{L(t)-1} z_k(t)\alpha_k(t)e^{j\phi_k(t)}\delta[\tau-\tau_k(t)] \qquad (2)$$

where $\alpha_k(t)$ is the k^{th} resolved multipath amplitude at time t, and $\phi_k(t)=\omega_{Dk}(t-\tau_k)-\omega_c\tau_k$ is the k^{th} resolved multipath component (MPC) phase. The radian carrier frequency is ω_c and $\omega_{D,k}$ is the Doppler frequency shift associated with the k^{th} resolved MPC. The delta function is a Dirac delta and $\tau_k(t)$ is the time-varying delay of the k^{th} resolvable MPC.

The CIR representation in (2) differs from traditional ones [5] via a time-varying number of MPCs $L(t)$ and the MPC persistence process $z_k(t)$. The persistence process takes values in the set {0,1}, and was used in our models in [8] to account for finite "lifetimes" of MPCs. Fig. 1 shows example persistence processes of the 3rd and 5th taps for a segment of measurement data from a small city, from [49]. As can be seen the later (generally weaker) MPC of the 5th tap is present for a smaller fraction of time than the 3rd tap. Causes for this medium-scale or "mesoscale" [52] effect are hypothesized to be rapid obstruction from nearby vehicles, and delay "drift," where the MPC absolute delay changes over time so that MPCs move from one delay bin to another.

We showed in [50], [51] that if non-stationarity is *not* taken into account in modeling the channel, system performance results do indeed change. As noted in [14], this "birth-death" process introduces abrupt discontinuities in the fading samples, but this is easily remedied via interpolation if desired. We termed this persistence effect a "mesoscale" effect, which occurs at a rate slower than small scale multipath fading, but faster than large scale shadowing effects. In the V2V case, one example cause of this is blockage by another vehicle. The channel models in [53] provide multiple ways for modeling this "medium-scale" behavior, such as via 2D spatial filtering, turning entire clusters of multipath components ON/OFF, etc. Our binary persistence processes are modeled using Markov chains, as in [54] for a similar phenomenon in indoor environments, and we show next some new results.

In [49] we explored the use of higher-order Markov models for multipath persistence, and found that model order need not be larger than 2nd-order. We recently evaluated NS Markov chains, in which multiple 1st-order chains were used, sequentially, to represent different segments of measured data. The gains we observe in terms of agreement with measured data were marginal, thus indicating that our 2nd-order models are likely adequate to represent this phenomenon. Fig. 2 shows some histogram RMS-DS results for an urban V2V channel, in which it is clear that the use of persistence does make simulations better agree with measured data, but that NS Markov model improvements over stationary 2nd-order results are minimal. This is more apparent in Fig. 3, in which we plot similar histograms for delay interval I_{25} (the width of the PDP containing all multipath components within 25 dB of the peak). Logarithmic scales were used only for clarity.

D. Model Standardization

For widespread acceptance, V2V models must be standardized. Although results in [10] were used for the IEEE 802.11p (WAVE) standard, it is clear from Table I that even considering only delay dispersion on expressways, consensus has not yet been attained! Similar comments pertain to other modeling features (e.g., Doppler spectra) and other environments (e.g., urban). In addition, as far as we are aware, there are as yet no standardized MIMO V2V models.

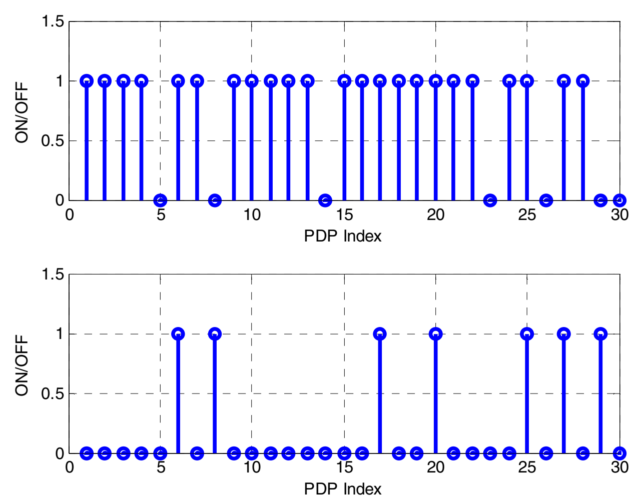

Fig. 1. Example persistence processes for taps 3 (top) and 5 (bottom) for segment of travel in small city, from [49].

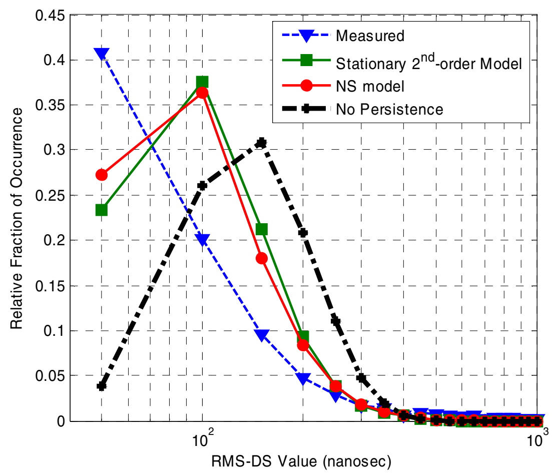

Fig. 2. Histograms for RMS-DS for measured data, and for various implementations of multipath persistence processes.

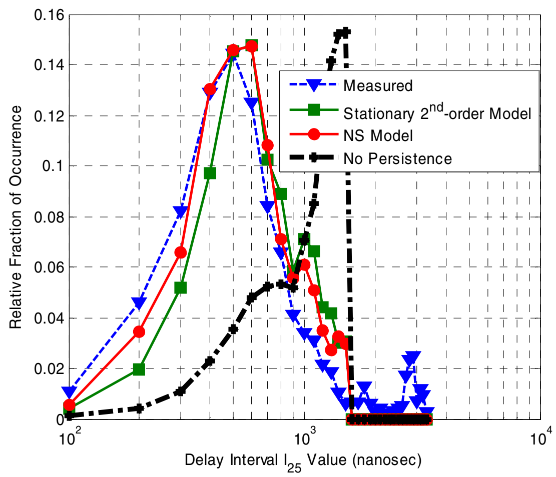

Fig. 3. Histograms for delay interval for measured data, and for various implementations of multipath persistence processes.

IV. Additional Remaining Work

Beyond the areas already mentioned for future V2V channel work, we briefly note several others in this section. One area is the use of non-stationarity. For the greatest accuracy, NS effects must be modeled. The question—as noted in [48]—is "how much nonstationarity" is needed. The tradeoff here is the usual one between accuracy and complexity, hence more work on understanding the effect of NS on system performance (at the PHY and higher layers) is needed.

Although the geometric models (e.g., [41]) appear to be able to mimic actual environments, they obtain only reasonable agreement with measurements, and can not easily model diffuse scattering. These models require a substantial "set up" on the computer—in short, they are complex to use, and may not be easily tailored for standardized models.

A. Traffic-Dependent Models

In certain situations, such as when traffic density is high and links are short-range, multihop V2V communications may be prevalent. If accurate power control can be applied, simple short-range channel models may be of use. Similarly, for very low traffic densities, simple new models (simpler than the expressway models cited) may be of use.

B. Outlier Terrain & Environments

Certain types of terrain may induce channel characteristics not yet modeled. For example, in roadways that form "U" or "V" shapes, downhill then uphill, long-delay echoes may arise. Tunnels form another atypical environment; work in [55] is a good beginning. There may be other types of terrain and conditions such as mountainous areas or other off-road settings that should also be modeled, including three-dimensional highway models near expressway interchanges.

V. Summary

In this paper we reviewed the state of the field in V2V channel modeling. We described various types of models for V2V channels, the obvious differences between V2V and cellular settings, and the ranges of some channel parameters found by multiple researchers. As do other researchers in this area, we believe that the statistical non-stationarity of the V2V channel should be modeled in some form, and that standardized models (incorporating MIMO), and models for additional frequency bands and V2V environments should be developed. In the conference presentation, we will provide more comparisons among existing models and additional coverage of recommended future work. In answer to the question posed in the title, our answer is, "no, not yet!"

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