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Propagation aspects of vehicle-to-vehicle communications - an overview

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Abstract— **Vehicle-to-vehicle (VTV) wireless communications have many envisioned applications in traffic safety, congestion avoidance, etc., but the development of suitable communications systems and standards requires accurate models for the VTV propagation channel. This paper provides an overview of existing VTV channel measurement campaigns, describing the most important environments, and the delay spread and Doppler spreads obtained in them. Statistical as well as geometry-based channel models have been developed based on measurements and intuitive insights. A key characteristic of VTV channels is the nonstationarity of their statistics, which has major impact on the system performance. Extensive references are provided.**

I. INTRODUCTION

VTV communications systems have recently drawn great attention, because they have the potential to improve convenience and safety of car traffic. For example, sensor-equipped cars that communicate via wireless links and thus build up adhoc networks can be used to reduce traffic accidents and facilitate traffic flow. An international standard, IEEE 802.11p, also known as Wireless Access in Vehicular Environments (WAVE), was recently published.

The simulation and performance evaluation of existing systems like IEEE 802.11p, as well as the design of future, improved systems, requires a deep understanding of the underlying propagation channels. However, the time-frequency selective fading nature of such VTV channels is significantly different from the better-explored cellular (base-station to mobile) channel, and thus requires distinct measurement campaigns and models. It is thus gainful to survey the recent progress and current state of the art. This will help the communications system designers to gain an overview of the pertinent channel characteristics, and the propagation researchers to assess where the most pressing needs for further work lie.

II. MEASUREMENTS

Measurements are vital for the understanding of propagation channels, either by giving direct insights, or by verifying (or disproving) theoretical considerations. VTV channel differ from cellular propagation channels in several important respects: (i) the propagation environments are different, (ii) TX and RX are at the same height, and in similar environments (peer-to-peer communications), (iii) higher mobility can be observed, both for the TX/RX as well as for important scatterers. In the following, we first classify the environments in which measurements take place, followed by a description of the measurement equipment that can be used. A discussion of the most important measurement results concludes this section.

A. Environments

Channel characteristics of VTV channels are influenced by the properties of the environment around the communicating cars, as well as the typical traffic characteristics. In general, the following environment categories are distinguished: (i) *highways*: (two to six lanes in each direction, few surrounding buildings, high speeds); (ii) *suburban streets*: (one or two lanes, low surrounding buildings, possibly set back from curb, low traffic density), (iii) *rural streets* (few or no surrounding buildings, but possibly hills or forests; very light traffic), (iv) *urban streets* (2-4 lanes, houses closer to the curb, and high traffic density).

B. Measurement equipment

Narrowband measurement systems try to identify the channel gain and Doppler shift experienced by a narrowband (sinusoidal) signal. Such a system can be based on an arbirtary signal waveform generator (putting out a sinusoid) combined with a vector signal analyzer [1][2][3] or spectrum analyzer [4]. When analyzing the Doppler spread, a bandwidth should be chosen for the vector signal analyzer that is larger than the anticipated Doppler frequency, plus all possible frequency drifts between TX and RX.

Wideband sounders determine the impulse response of the channel. One particular form, correlation sounders, transmit a PN sequence; at the RX, the received signal is correlated with the same PN sequence The concatenation of the transmit and receive filters thus has an impulse response that is identical to the autocorrelation function (ACF) of the transmit filter which should be a good approximation of a delta function [5]; the transmit sequence can be, e.g., a maximum-length PN sequence of a zerocorrelation-zone sequence. A correlative sounder can either be a dedicated device, as in the measurements of Ohio Univ. [6], or it can be constructed from an arbitrary-waveform generator (working as TX), as in the measurements of Carnegie-Mellon University (CMU) [7], Georgiatech [8], Berkeley [9], and HHI [10]. A 50 MHz chiprate is commonly used for VTV measurements (though [9] uses 11 MHz). As RX, we can use a vector signal analyzer or sampling scope (sampling usually done with twice the chiprate), and the correlation is done offline on a computer or workstation. A different wideband sounding principle is multitone sounding, which is based on OFDM-like sounding signals [11]

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MIMO sounders can be constructed from wideband sounders by one of two principles: (i) using multiple RF chains at the transmitter and receiver, or (ii) using the switched-array principle. In the former case, multiple parallel RF chains allow the reception of multiple signals simultaneously at the receiver, while different transmit signals (e.g., an m-sequence with different offsets [12]) are put onto the TX antennas through parallel TX chains. In the switched-array sounder, a single available RF chain (at TX and RX respectively) is connected sequentially to the elements of an antenna array through an electronic switch [11]. The switched sounder has the drawback that taking a complete snapshot (from each TX to each RX element) takes longer, due to the sequential nature of the sounding. This drawback is more important in VTV environments than in cellular channels due to the higher Doppler frequency. For large antenna arrays a channel might become unidentifiable with a switched-array sounder.

The characteristics and the placement of the antennas have significant impact on the measurement results. In most of the campaigns in the literature, antennas were either placed at an elevated position within a van [11][13], or outside the van [6]. When antennas were placed inside a car (e.g., on a seat or near a dashboard), higher delay spread [6] and larger channel richness [12], but also higher pathloss ($5-10$ dB [14]) resulted. The exact antenna placement inside a car can also have a strong impact on the packet error rate [15].

C. Measurement results

1) Narrowband fading statistics: : The narrowband small-scale fading statistics in VTV communications have been subject to considerable debate in the literature. [2] argue that small-scale and large-scale fading cannot be easily distinguished, and proceed to suggest the Nakagami distribution for the compound (narrowband) fading statistics. The Nakagami *m*-factor can be quite high (3-4) if the distance between TX and RX is less than 5 m, but decreases to less than unity when the distance exceeds $70-100$ m. Other authors did distinguish between small-scale and large-scale fading, eliminating the large-scale (shadowing) fading before analyzing the small-scale distributions. For the narrowband fading statistics, [4] found good agreement of measured data with either Rice or Nakagami distributions; [16] also found good agreement with Rice.

A somewhat different problem is the analysis of fading in each resolvable delay bin in wideband measurements. Ref. [18][19] describe the fading in each resolvable delay bin as Rician, and show from their experiments that the Rice factor in the first delay bin can be very high (up to 20 dB), while it is much lower for later delay bins. Similar behavior, though with somewhat different Rice factors, is found in [22] where fading of individual scatterers is studied. Ref. [6] fitted the measurement results with a Weibull distribution. Summarizing, we can say that in LOS situations, the first delay bin shows "better than Rayleigh" fading characteristics, while bins with longer delays generally follow Rayleigh fading, with "worse than Rayleigh" also occuring in a significant percentage of cases.

2) Doppler spreads: VTV channels tend to show higher Doppler spreads than conventional mobile-radio channels, because the *relative* velocities of TX and RX can be higher, and because multiple reflections (which can be associated with higher Doppler shifts) tend to be more important in VTV channels.A linear correlation of the average maximum Doppler spread and rms Doppler spread with the "effective speed" of the TX and RX $v_{\text{eff}} = \sqrt{v_{\text{TX}}^2 + v_{\text{RX}}^2}$ has been observed [3] so that $f_{\text{rms,D}} = K v_{\text{eff}}/\lambda\sqrt{2}$. It must be noted that a scatterer-ring model (see below) predicts $K = 1$, but measurements show $K = 0.43$. Also, there can be a considerable spread around this average, and furthermore an offset, so that even at zero velocity, the maximum Doppler spread is not zero (due to moving scatterers). The Doppler shift of the line-of-sight component was found - not surprisingly - to be exactly explained by the relative speed of TX and RX [3], [13].

3) Delay dispersion: The delay dispersion or frequency selectivity is another important parameter of the propagation channel, because it determines the available frequency diversity, and also dictates the required length of cyclic prefix (for an OFDM system) or equalizer (for a single-carrier system). Statistics of the rms delay spreads and maximum excess delays, as well as the coherence bandwidth, were measured by a number of authors. The distribution of the rms delay spread can often be fitted by a lognormal distribution [20]. In general, median rms delay spread are on the order of $100-200$ ns [7][16][6], though [17] measured approx. 50 ns. Among the various environments, suburban and rural environments show the lowest delay spreads, while highways are slightly higher [7][16][9]. Delay spreads in urban environments can be considerably higher, with 370 ns median observed in [16].

Maximum excess delays, which play an important role for the required duration of OFDM cyclic prefix, have also been analyzed. While some measurements found only 0.5 μs on highways [11], other campaigns showed very high maximum excess delays (up to 5 μs occured in rare circumstances) in highway and urban environments [7].[1] These results can be explained by the fact that far-away objects (which can lead to very high excess delays) exist only in certain locations. Measurements in a variety of morphologies are thus essential to get better insights into the statistical importance of these effects.

4) MIMO measurements: Ref. [22] evaluated the correlation coefficient between the elements of a 4-element patch array that are pointing into different directions, and found them to exhibit considerable variations with time. The same conclusion was drawn regarding the multipath richness (sum of the logarithms of the eigenvalues) by [14].

III. MODELING APPROACHES

In general, there are three fundamental approaches to channel modeling: deterministic (ray tracing), stochastic, and geometry-based stochastic; for their principles, advantages and drawbacks, see [5], [23].

Ray tracing for VTV systems, which was pioneered by Wiesbeck and coworkers [24][25][4][26], allows an extremely realistic simulation of the VTV propagation channel. By appropriately modeling the environment (houses, but also traffic signs, parked cars, etc.), agreement between measured and simulated receive powers can be brought within 3 dB standard deviation [26], [24].

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[1] [6] did not evaluate the maximum excess delay, but found rms delay spreads up to 1.7 μs, and 90 % delay windows [21] up to 2.5 μs.

Narrowband stochastic models focus on the characteristics of the Doppler Spectrum, a key quantity that distinguishes a VTV channel from a cellular channel. Assuming that the angles of incidence are independent at transmitter and receiver, a uniform angular power spectrum and antenna pattern at TX and RX, the temporal autocorrelation function is [27]

$$R(\Delta t) = \sigma_1^2 J_0(k\mathrm{v}_{\mathrm{TX}}\Delta t) J_0(k\mathrm{v}_{\mathrm{RX}}\Delta t) \qquad (1)$$

where k is the wavenumber, σ_1 is the mean received power of the in-phase or quadrature component, and J_0 is the Bessel function of the 0th order. The Doppler spectrum is

$$S(f) = \frac{\sigma_1^2}{\pi^2 f_{\mathrm{max,TX}}\sqrt{a}} K\left(\frac{1+a}{2\sqrt{a}}\sqrt{1-\left(\frac{f}{(1+a)f_{\mathrm{max,TX}}}\right)^2}\right) \qquad (2)$$

where $K(x)$ is the complete elliptical integral of the first kind, $f_{\mathrm{max,TX}}$ is the maximum Doppler frequency due to the movement of the transmitter, and $a = f_{\mathrm{max,RX}}/f_{\mathrm{max,TX}}$. Further interesting results, and generalizations are given in [28][29]. Channel simulators need to create channel realizations whose autocorrelation functions or Doppler spectra obey Eq. (1) or (2), respectively [30]. Two fundamentally different approaches have been developed: a *statistical* simulation model that essentially performs simplified ray tracing (see also the geometrical models below); the autocorrelation function Eq. (1) is satisfied in this model when an expectation over different scatterer locations is taken. An alternative is a *deterministic* channel model, based on the sum-of-sinusoids that recovers Eq. (1) when *time-averaged* correlation is considered.

VTV *geometry-based stochastic channel models* (GSCMs) are based on the “classical‘’ GSCM approach, i.e., by simulating the channel using randomly placed (according to suitable statistical distributions) scatterers around TX and RX, and then performing a simplified ray tracing. The simplest geometrical VTV channel model is the two-ring model, where one ring of scatterers is placed around TX and RX, each; this model can be made to correspond to Eq. (1). Generalizations of the two-ring model also allow for the existence of a LOS component [31], and single-scattering either near the TX or the RX, where the relative strengths of those processes are model parameters [32]. A geometrical model, in particular the two-ring model, also allows to derive a joint space-time correlation function, from which the temporal evolution of the correlation coefficient between the antenna elements in a MIMO system can be derived [33].

The conventional two-ring model assumes that all scatterers are placed in the x-y plane, i.e., have zero elevation. This need not be a realistic assumption, especially in NLOS situations in urban environments. A generalization of the two-ring model to the three-dimensional case was analyzed in [34], who considered the double-scattering case, as well as a series of papers by Zajic and Stuber [35].

The reference models described above do not aim to reproduce the physical reality, but rather are intended for the comparison of different transmission schemes. A more realistic model modifies the location as well as the properties of scatterers. It makes a distinction between discrete and diffuse scattering (more precisely: "interaction"). Discrete scatterers are typically cars, houses, road signs and other significant (strong) scattering points along the measurement route. Diffuse scattering is found to mainly stem from the sides of the measurement route (TX-RX path). Discrete scatterer statistics can be extracted using a high resolution algorithm that describes identification of peaks in the scattering function with interference cancellation and tracking of scatterers. A detailed parameterization of such a model is given in [22].

Stochastic channel models provide the statistics of the power received with a certain delay, Doppler shift, angle-of-arrival etc. In particular, the tapped-delay-line model, which is based on the wide-sense-stationary uncorrelated scattering (WSSUS) assumption is in widespread use for cellular system simulations. For VTV channels, the IEEE 802.11p models use this approach, as well. The most important VTV tapped-delay-line models are the 6-tap and 12-tap models developed by Georgia tech based on their measurement campaigns. In addition to several models derived from measurements at 2.45 GHz, models based on measurements in the 5 GHz range, are given in [19]. The models consist of several taps, each of which can contain several paths (where each path can have a different type of Doppler spectrum); this allows to synthesize almost arbitrary Doppler spectra for each tap even though the spectrum of each path is selected from a small class of shapes (flat, round, classic 3dB, and classic 6dB).

Nonstationarities one of the most important points that distinguishes VTV channel models from conventional channel models is the nonstationarity of the channel, i.e., that the channel *statistics* (not only the channel impulse responses) can change within a rather short period of time. The well-known WSSUS (wide-sense stationary uncorrelated scattering) model introduced by [36] is not applicable anymore. Rather, the statistics are valid only for a short period of time ("region of stationarity"). For example, in each region of stationarity, the Doppler spectrum of the first delay tap can be different, because the Doppler shift of the LOS component can change. If we would just average the Doppler spectra over the different regions of stationarity, a broadening of the spectrum of the first tap (that has no correspondence to physical reality) would result. The nonstationarities can be modeled by (i) a *birth/death process* to account for the appearance and disappearance of taps [6]; it must be noted that while this approach provides a nonstationary description, it does not account for the "drift" of scatterers into a different delay bin, and can also lead to a sudden appearance and disappearance of strong MPCs. (ii) *defining different tap models* for regions of a measurement route that have significantly different delay spreads, or whose PDPs lead to significantly different BERs [18]; however, such an approach does not provide a continuous (with time) characterizationof the channel; or (iii) using geometry-based channel models, which take nonstationarities into account automatically [22].

The nonstationarities of the channel have a significant impact on system performance. Ref. [18] showed that for each region of stationarity, a different tap-model should be used; if the simulation model is based on a *single* averaged PDP from which the realizations are drawn, the resulting BERs in a system simulation deviate considerably from the BERs resulting from the raw measured channel data. Ref. [37] showed that the assumption of WSSUS leads to optimistic BER simulation results in single-carrier and multi-carrier systems.

IV. SUMMARY AND CONCLUSIONS

The VTV propagation channel has strong impact on the coverage, reliability, and real-time capabilities of VTV networks. Wrong assumptions about the fading lead to erroneous conclusions on the effectiveness of inter-vehicle warning systems at intersections [38]. Thus, it is vital to have and use proper (measurement-based) models of VTV communications channels. While much progress has been made since 2005, many open topics remain. The small amount of available VTV channel measurements does not allow the formulation of statistically significant statements about real-world VTV channels. Little explored is the impact of vehicles inbetween the TX and RX in VTV links which lead to shadowing of the desired paths, the effects of the placement of antennas on vehicles, and the gains from multiple antennas. Finally, little information about directional and MIMO characteristics are available. This lack of definitive data, combined with the increasing importance of VTV communications, will make sure that VTV propagation channels will remain a vibrant research area in the next years.

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REFERENCES

[1] L. Cheng, B. Henty, D. D. Stancil, F. B., and P. Mudalige, “A fully mobile, GPS enabled, vehicle-to-vehicle measurement platform for characterization of the 5.9 GHz DSRC channel,” in *2007 IEEE Ant. Prop. Int. Symp.*, pp. 2005–2008, 2007.

[2] L. Cheng, B. Henty, D. Stancil, F. B., and P. Mudalige, “Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band,” *IEEE J. Selected Areas Comm.*, vol. 25, pp. 1501–1516, 2007.

[3] L. Cheng, B. Henty, D. Stancil, and F. B., “Doppler component analysis of the suburban vehicle-to-vehicle DSRC propagation channel at 5.9 GHz,” in *2008 IEEE Radio Wireless Symp.*, pp. 343–346, 2008.

[4] J. Maurer, T. Fugen, and W. W., “Narrow-band measurement and analysis of the inter-vehicle transmission channel at 5.2 GHz,” in *IEEE 55th Vehicular Techn. Conf.*, pp. 1274–1278, 2002.

[5] A. F. Molisch, *Wireless Communications*. IEEE Press - Wiley, 2005.

[6] I. Sen and D. Matolak, “VehicleŰvehicle channel models for the 5-GHz band,” *IEEE Trans. Intelligent Transp. Syst.*, vol. 9, pp. 235–245, 2008.

[7] L. Cheng, B. Henty, R. Cooper, D. Stancil, and F. B., “Multi-path propagation measurements for vehicular networks at 5.9 GHz,” in *IEEE Wireless Comm. Networking Conf.*, 2008.

[8] G. Acosta and M. Ingram, “Model development for the wideband expressway vehicle-to-vehicle 2.4 GHz channel,” in *IEEE Wireless Comm. Networking Conf.*, pp. 1283–1288, 2006.

[9] I. Tan, W. Tang, K. Laberteaux, and A. Bahai, “Measurement and analysis of wireless channel impairments in DSRC vehicular communications,” in *2008 IEEE Int. Conf. Comm.*, pp. 4882–4888, 2008.

[10] P. Paschalidis, M. Wisotzki, A. Kortke, W. Keusgen, and M. Peter, “A Wideband Channel Sounder for Car-to-Car Radio Channel Measurements at 5.7 GHz and Results for an Urban Scenario,” in *IEEE 68th Vehicular Techn. Conf.*, 2008.

[11] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, C. Mecklenbrauker, and A. Molisch, “First results from car-to-car and car-to-infrastructure radio channel measurements at 5.2GHz,” in *Proc. IEEE 18th Int. Symp. Personal, Indoor Mobile Radio Comm. PIMRC*, pp. 1–5, 2007.

[12] G. F. Pedersen, J. B. Andersen, P. C. F. Eggers, J. O. Nielsen, H. Ebert, T. Brown, A. Yamamoto, T. Hayashi, and K. Ogawa, “Small terminal MIMO channels with user interaction,” in *Second European Conf. Antennas Propagation, EuCAP 2007*, pp. 1–6, 2007.

[13] A. Paier, J. Karedal, N. Czink, H. Hofstetter, C. Dumard, T. Zemen, F. Tufvesson, A. Molisch, and C. Mecklenbrauker, “Car-to-car radio channel measurements at 5 GHz: Pathloss, power-delay profile, and delay-doppler spectrum,” in *Proc. 4th Int. Symp. Wireless Comm. Systems ISWCS 2007*, pp. 224–228, 2007.

[14] P. Eggers, T. Brown, K. Olesen, and G. Pedersen, “Assessment of capacity support and scattering in experimental high speed vehicle to vehicle MIMO links,” in *IEEE 65th Vehicular Techn. Conf.*, pp. 466–470, 2007.

[15] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar, and T. Nadeem, “Effect of antenna placement and diversity on vehicular network communications,” in *4th IEEE Conf. Sensor, Mesh and Ad Hoc Comm. Networks*, pp. 112–121, 2007.

[16] O. Renaudin, V. M. Kolmonen, P. Vainikainen, and C. Oestges, “First results of 5.3 GHz car-to-car radio channel measurements,” in *IEEE 68th Vehicular Techn. Conf.*, 2008.

[17] J. Kunisch and J. Pamp, “Wideband Car-to-Car Radio Channel Measurements and Model at 5.9 GHz,” in *IEEE 68th Vehicular Techn. Conf.*, 2008.

[18] G. Acosta-Marum and M. Ingram, “A BER-based partitioned model for a 2.4GHz vehicle-to-vehicle expressway channel,” *Wireless Personal Communications*, vol. 37, pp. 421–443, 2006.

[19] G. Acosta-Marum and M. Ingram, “Six time- and frequency- selective empirical channel models for vehicular wireless lans,” *IEEE Vehicular Techn. Mag.*, vol. 2, no. 4, pp. 4–11, 2007.

[20] D. Matolak, I. Sen, W. Xiong, and N. Yaskoff, “5 GHz wireless channel characterization for vehicle to vehicle communications,” in *MILCOM 2005*, pp. 1–7, 2005.

[21] A. F. Molisch and M. Steinbauer, “Condensed parameters for characterizing wideband mobile radio channels,” *Int. J. Wireless Information Networks*, vol. 6, p. 133-154, 1999.

[22] J. Karedal, F. Tufvesson, N. Czink, A. Paier, C. Dumard, T. Zemen, C. F. Mecklenbraeuker, and A. F. Molisch, “A geometry-based stochastic MIMO model for vehicle-to-vehicle communications,” *IEEE Trans. Wireless Comm.*, submitted, 2008.

[23] A. F. Molisch and F. Tufvesson, “Multipath propagation models for broadband wireless systems,” in *CRC Handbook of signal processing for wireless commmunications* (M. Ibnkahla, ed.), 2004.

[24] W. Wiesbeck and S. Knorzer, “Characteristics of the mobile channel for high velocities,” in *2007 Int. Conf. Electromagnetics in Advanced Application*, pp. 116–120, 2007.

[25] J. Maurer, T. Schafer, and W. Wiesbeck, “A realistic description of the environment for inter-vehicle wave propagation modelling,” in *IEEE 54th Vehicular Techn. Conf.*, pp. 1437–1441, 2001.

[26] J. Maurer, T. Fugen, T. Schafer, and W. Wiesbeck, “A new inter-vehicle communications (IVC) channel model,” in *IEEE 60th Vehicular Techn. Conf.*, pp. 9–13, 2004.

[27] A. Akki and F. Haber, “A statistical model of mobile-to-mobile land communication channel,” *IEEE Trans. Vehicular Techn.*, vol. 35, pp. 2–7, 1986.

[28] A. Akki, “Statistical properties of mobile-to-mobile land communication channels,” *IEEE Trans. Vehicular Techn.*, vol. 43, pp. 826–831, 1994.

[29] F. Vatalaro and A. Forcella, “Doppler spectrum in mobile-to-mobile communications in the presence of three-dimensional multipath scattering,” *IEEE Trans. Vehicular Techn.,*, vol. 46, pp. 213–219, 1997.

[30] C. S. Patel, G. L. Stuber, and T. G. Pratt, “Simulation of Rayleigh-faded mobile-to-mobile communication channels,” *IEEE Trans. Comm.*, vol. 53, pp. 1876–1884, 2005.

[31] L. C. Wang and Y. H. Cheng, “A statistical mobile-to-mobile Rician fading channel model,” in *IEEE 61st Vehicular Techn. Conf.*, pp. 63–67, 2005.

[32] A. Zajic and G. Stuber, “Space-time correlated mobile-to-mobile channels: Modelling and simulation,” *IEEE Trans. Vehicular Techn.*, vol. 57, pp. 715–726, 2008.

[33] M. Patzold, B. Hogstad, and N. Youssef, “Modeling, analysis, and simulation of MIMO mobile-to-mobile fading channels,” *IEEE Trans. Wireless Comm.*, vol. 7, pp. 510–520, 2008.

[34] T. M. Wu and C. Kuo, “3-D space-time-frequency correlation functions of mobile-to-mobile radio channels,” in *IEEE 65th Vehicular Techn. Conf.*, pp. 334–338, 2007.

[35] A. Zajic and G. Stuber, “Statistical properties of wideband MIMO mobile-to-mobile channels,” in *2008 IEEE Wireless Comm. Networking Conf.*, 2008.

[36] P. Bello, “Characterization of Randomly Time-Variant Linear Channels,” *IEEE Trans. Comm.*, vol. 11, pp. 360–393, 1963.

[37] D. Matolak, “Channel modeling for vehicle-to-vehicle communications,” *IEEE Communications Mag.*, vol. 46, pp. 84–91, May 2008.

[38] M. Sepulcre and J. Gozalvez, “On the importance of radio channel modeling for the dimensioning of wireless vehicular communication systems,” in *7th Int. Conf. ITS Telecommunications*, pp. 1–5, 2007.