# Phenomenological Driving Behavior Model of the Suburban Vehicle-to-Vehicle Propagation Channel at 5.9 GHz

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***Abstract*— Through a field implementation of Vehicular Ad hoc NETworks (VANET), we report the observation of a monotonic dependence of maximum relative velocity between two vehicles and their separation, for typical suburban driving. We introduce a hierarchical phenomenological model of driving behavior to describe this observation. As an example, we illustrate how we use this model to predict the expected Doppler shift with vehicle separation. Doppler shift computed from field measured spectra confirms the effectiveness of the model predictions. The model can be used to provide guidance in designing experiments with specific combinations of maximum velocity and separation, and to provide more accurate Intelligent Transportation Systems (ITS) simulations.**

## I. INTRODUCTION

Significant recent attention has been focused on the emerging intelligent transportation system infrastructure based on vehicle-to-vehicle wireless communications [1]–[3]. IEEE 802.11p based Dedicated Short Range Communication (DSRC) technology is being projected as the fundamental enabling technology to form large-scale Vehicular Ad hoc NETworks (VANET), facilitating a wide range of applications from transportation safety to traffic efficiency to social networks [4]–[6]. Implementation and field tests of VANET systems are therefore of fundamental importance to achieve this objective.

VANET serves as a rapidly advancing initiative to help to improve the efficiency over the existing transportation infrastructure. Computer simulation (as used in the conventional Intelligent Transportation Systems (ITS) initiative [7] [8]) has been shown to be an indispensable component in engineering analysis to thoroughly understand the dynamics of traffic movement and operations. Obtaining measurements from real on-road experiments and developing ITS simulation models are critical in the development and evaluation of VANET systems.

In VANET, radio communications are enabled among multiple mobile vehicles in dynamically changing on-road environments. Channel studies can help understand the impact of the propagation environment on wireless signals. Reported work in empirical studies include narrow-band measurements at 5.2 GHz [9] and joint Doppler-delay power profile measurement at 2.4 GHz [10]. Vehicle-to-vehicle measurements at 915 MHz in a mobile environment were reported in [11]. Measurements and modeling of the vehicle-to-vehicle channel at 5.9 GHz have also been reported [12], but real-time distance information was not provided.

Motivated by the above, we believe additional experimental VANET implementation and field studies at the 5.9 GHz DSRC band are needed to validate and extend existing studies. The implementation and empirical field measurements for the vehicle-to-vehicle channel serve the dual purpose of both understanding fundamental channel characteristics and developing real on-road experiments for ITS simulation models.

To this end, we have constructed an RF platform for the purpose of studying the propagation issues regarding VANET systems through field tests. A re-configurable digital signal generator (DSG) and a vector signal analyzer (VSA) in the system make possible a flexible yet precise platform for our study. We propose a phenomenological model in a hierarchical manner to describe the expected relative velocity vs. distance of two mobile vehicles in suburban environments. This model is able to describe the linkage between maximum relative velocity and vehicle separation distance, which is caused by individual driving behavior. An intuitive explanation of the modeled behavior is also discussed.

This model could be useful in the development of realistic traffic simulations for DSRC networks. It serves as a flexible tool that enables a convenient methodology to simulate real-life situations, allowing the possibility to create, evaluate and modify ITS [7] [8] designs, with or without actual field implementations. Although we developed the model from the suburban driving environments at 5.9 GHz DSRC frequency range, it is based only on driving behavior and not on the frequency or transmission technology. It can be easily extended to other environments using the same methodology to simulate other real-life situations.

Finally, as an example we use this model to predict a dependence of Doppler shift on separation and confirm the prediction using measurement spectra. In this way, the model can help to develop more accurate simulation platforms.

The remainder of this paper is organized as follows. Section II illustrates our measurement system in detail. Section III describes the hierarchical driving behavior model derived from experimental measurement data. Section IV utilizes the developed model to explain the observed dependence of Doppler shifts on both relative velocity and separation. This section also illustrates how to use this driving behavior model as a flexible tool to make accurate predictions in simulations. Summary and conclusions are given in Section V.

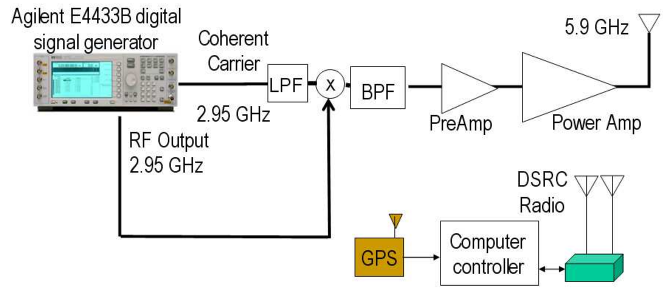
## II. Measurement System

This work is based on our implementation and field tests of studying the wireless signal propagation issues regarding VANET systems. To characterize channel characteristics, we have taken a measurement oriented approach to gain a better understanding of the vehicle-to-vehicle wireless channel. As can be seen from Fig. 1, the RF measurement system we constructed has several key features that combine and extend the strengths of those previously reported. We have combined the advantages of Ref. [12] by performing measurements at the designated 5.9 GHz DSRC frequency, and of Ref. [10] by performing measurements in a mobile environment. Furthermore we extend the work by incorporating differential GPS (DGPS) receivers into our measurement platform to allow dynamic measurement of the DSRC channel, while the vehicles are being driven in actual roadway conditions. The accuracy of DGPS is on the order of one meter. The use of DGPS receivers allows us to characterize the vehicle-to-vehicle channel in a complete and systematic fashion, by collecting channel statistics over a wide range of vehicle speeds, separations and locations. The DGPS receivers also help us overcome the difficulties in properly synchronizing measurements performed while the two vehicles are in motion during field tests.

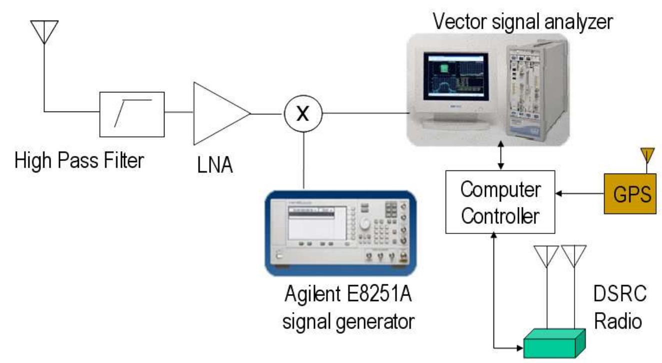
The transmitter and receiver system architecture are depicted in Fig. 1(a) and Fig. 1(b), respectively. For the implementation details we refer the readers to [13]–[15].

All of the transmitted data packets are also stored on the local computer along with the recorded GPS data. Location statistics such as distance and velocity are computed from raw GPS recordings. The distance between vehicles is computed by the Haversine formula, using the latitude and longitude coordinates of the two vehicles, where the radius of the earth is optimized for locations approximately 39 degrees from the equator (i.e., the latitude of the measurement location near Pittsburgh, PA, USA).

We conducted measurements using continuous wave (CW) and OFDM signaling schemes (employing the 802.11p DSRC standard) in suburban driving environments near Carnegie Mellon University in Pittsburgh, PA. To preserve normal driving behavior, both vehicles were driven at each driver's prerogative, resulting in a vehicle separation distance varying from 2 to 600 meters. The experiments recorded about 7000 data sweeps for the CW system and 3000 data sweeps for OFDM. Thus we believe the experimental data is large enough to draw statistically meaningful conclusions.




(a)




(b)

Fig. 1. RF system setup for the channel sounding measurements: (a) the setup on the transmitting vehicle, and (b) the setup on the receiving vehicle.

The above experimental platform is capable of providing the building blocks for simultaneously measuring the properties of the vehicle-to-vehicle DSRC wireless channel together with a variety of location statistics in real time, such as relative velocity, GPS location, separation distance, etc. However, it is also of critical importance to decouple location statistics, in order to identify the important impact factors to vehicle-to-vehicle wireless signals. To this end, in this paper we primarily focus on the phenomenological driving behavior model. We leave the topic of using the measured building blocks for channel modeling for another study.

## III. Driving Behavior Model

Observed from empirical measurement data, we describe a correlation between separation distance and relative velocity. We present a total of 10,000 measured data sweeps in three sets of measurements. In these measurement campaigns the vehicle drivers were not always the same, the routes were different, and the traffic conditions varied.

While the data sets are from different collection efforts, data points associated with the separation and speed exhibit similar scatter plots, which we denote as relative-speed separation (RS-S) diagram. To make it more concrete, Fig. 2(a) and Fig. 2(b) depict two data sets collected using the CW excitation and Fig.2(c) describes a sample data set obtained using the OFDM signaling scheme employing the 802.11p DSRC standard. Although the three data sets were measured at different experimental settings, an interesting observation is that the data exhibit similar scatter plots, which we interpret in terms of driver behavior. Beyond a minimum separation of about five meters, the maximum speed increases with separation up to the speed limit, then remains constant with further increases in distance. The increase of maximum speed with vehicle separation distance reflects the natural tendency of drivers to require greater vehicle separation as vehicle speed increases. Assuming both vehicles are traveling in the same direction, the maximum relative velocity will be the speed limit $v_{\max}$. Stated differently, when one vehicle follows the other with a small separation, the following vehicle speed is highly likely to be affected by the leading vehicle's speed, keeping the relative velocity small. As the separation increases, the driver of the following vehicle becomes less influenced by the leading vehicle's speed, allowing larger relative velocities.

This underlying correlation between separation and maximum relative velocity must be taken into account when analyzing the data for dependence on relative velocity and distance. We model in a hierarchical manner consisting of two levels of sophistication. The level used is based on the availability of the points representing the driver behavior (e.g., the points in Fig. 2). The first level assumes RS-S diagram points are available from field tests or simulations. We describe a histogram method together with the RS-S diagram as a prediction tool. In the second level, we do not have points available for the the RS-S diagram but we still want to make predictions under the same scenario, so we introduce a phenomenological exponential model as the prediction tool. We illustrate both techniques in detail in the following subsections.

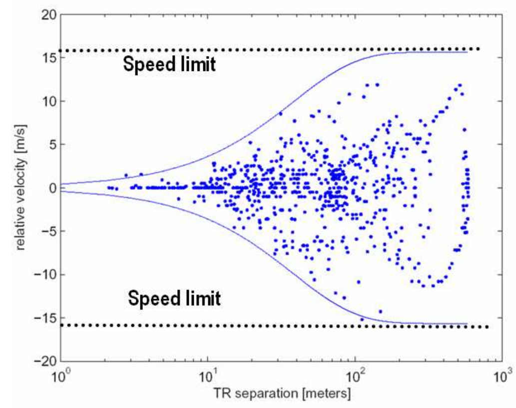
### *A. Prediction with RS-S diagram points*

In this sub-section we focus on the case when the RS-S diagram points are available. The points in these diagrams could be generated by field implementation tests as we did, or based on simulation. In fact, there are specific projects ongoing simulating driver behavior based on surveillance and steering experience [8]. Points in RS-S diagrams could also be generated based on similar simulations of driver behavior.

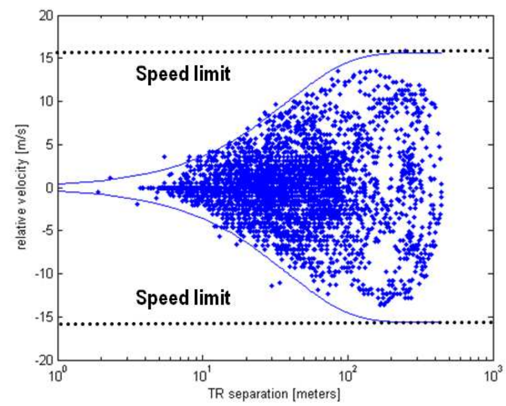
As shown in Fig. 3, to use the RS-S diagram, we consider the points that lie in a particular range of distances $d$, and construct a histogram of the points at each relative velocity. Since the number of points in each velocity bin should be proportional to the amount of time spent at that relative velocity, the probability density function at $d$ can be derived, we denote it as $g_{RS-S}(v|d)$, where $v$ is the magnitude of the relative velocity (always positive).

Based on the histogram of the points at each relative velocity at separation $d$, the expected value of speed with separation is therefore estimated as

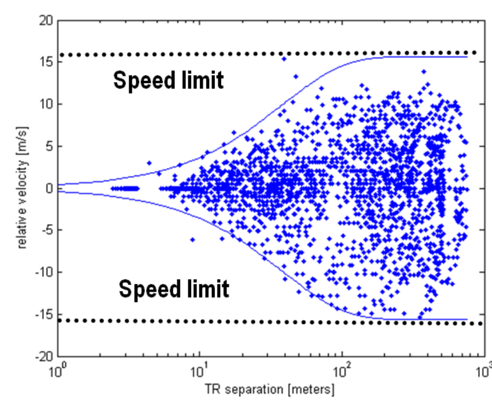
$$E(v|d)_{with\ pts} = \int_0^{v_{\max}} v g_{RS-S}(v)dv. \quad (1)$$




(a) Continuous wave data set 1




(b) Continuous wave data set 2




(c) OFDM data set

Fig. 2. Example relative speed - separation diagrams for three datasets. The solid lines show the bounds given by the phenomenological model adjusted to fit the observed driving behavior.(a) Continuous wave data set 1, (b) Continuous wave data set 2, (c) OFDM data set.

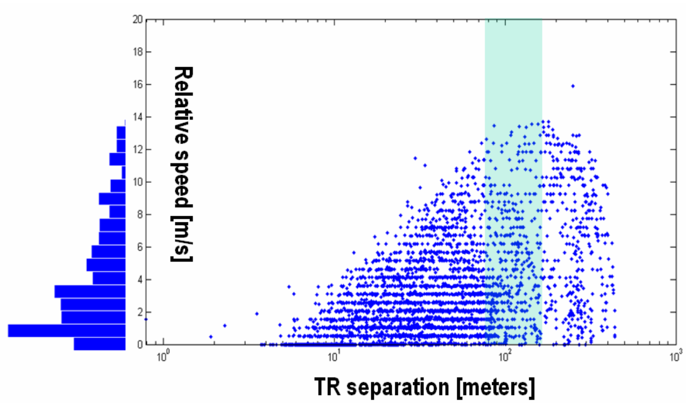



Fig. 3. Illustration of the prediction from a relative speed-separation diagram.

Eq. (1) is the basis for the predictions using the RS-S diagrams. We leave the demonstration of this technique in Section IV.

### B. Prediction without RS-S diagram points

There are cases where we do not have simulated points available in an RS-S diagram, but still wish to develop models or predictions. For example, if the detailed driver model representing the actual behavior is missing or hard to model, then our knowledge in this case may come primarily from the traffic management information (e.g., the speed limit). We show in this sub-section that we can still extend our modeling and predictions in the scenario using a relationship between the maximum relative velocity and the separation distance.

To describe this correlation, we introduce a phenomenological model to estimate the relationship between the maximum relative velocity $v_{\max}(d)$ and separation distance $d$

$$v_{\max}(d) = v_{limit}(1 - e^{-\alpha d}). \tag{2}$$

Here $v_{limit}$ is the speed limit, and $\alpha$ is an adjustable parameter. In our analysis, we tune the $\alpha$ parameter to control the steepness of the function and to make the phenomenological model match with actual measured data, here $\alpha = 1/38m^{-1}$ is found to bound the bordering values. As shown in Fig. 2, this phenomenological model bounds the points in the scatter plots from different experiments with reasonable accuracy.

While the previous sub-section derives the expected value of speed exploiting the information from the RS-S diagram, we have no direct information from those RS-S diagram points. Instead of deriving directly from the RS-S diagram points, we rely on the prior knowledge on the general trend observed from the histograms from three different sets of experiments shown in Fig. 2. One of the commonalities they have is a decreasing number of points as the relative speed increases. Based on the commonality of the histogram shape from these three sets of experiments, we introduce a simple triangle-shaped probability density function (PDF) prediction for the speed versus separation in the phenomenological model

$$g(v|d) = \begin{cases} A(d)(1 - \frac{v}{v_{\max}(d)}) & 0 \le v \le v_{\max}(d) \\ 0 & \text{elsewhere} \end{cases} \tag{3}$$

where $v$ is the magnitude of the relative velocity (always positive). For a distance $d$, once $v_{\max}(d)$ is determined by Eq. (2), $A(d)$ is given as $2/v_{\max}(d)$, which ensures the total area under the PDF sums to unity.

The expected value of speed with separation is therefore

$$E(v|d)_{without\ pts} = \int_0^{v_{\max}} v g(v|d) dv. \tag{4}$$

Together with Eqn. (3), we have

$$E(v|d)_{without\ pts} = \frac{1}{3} v_{\max}(d). \tag{5}$$

Applying Eqn. (2) for $v_{\max}(d)$, we have

$$E(v|d)_{without\ pts} = \frac{1}{3} v_{limit}(1 - e^{-\alpha d}). \tag{6}$$

## IV. Demonstration of the Model in Doppler Prediction

This section use an example to demonstrate the usefulness of the model. In this example, we use the model to predict an increase of expected Doppler shift with velocity, which has been verified by many wireless measurement campaign results. To relate the model to the Doppler shift, we translate the speeds into Doppler shifts using

$$f = v/\lambda, \tag{7}$$

where $\lambda$ is the wavelength of the signal.

In the case where the RS-S diagram points are available, the expected Doppler shift with separation is therefore

$$E(f|d)_{with\ pts} = \int_0^{v_{\max}} \frac{v}{\lambda} g_{RS-S}(v) dv. \tag{8}$$

In the case where the RS-S diagram points are not available, the expected Doppler shift at distance $d$ is

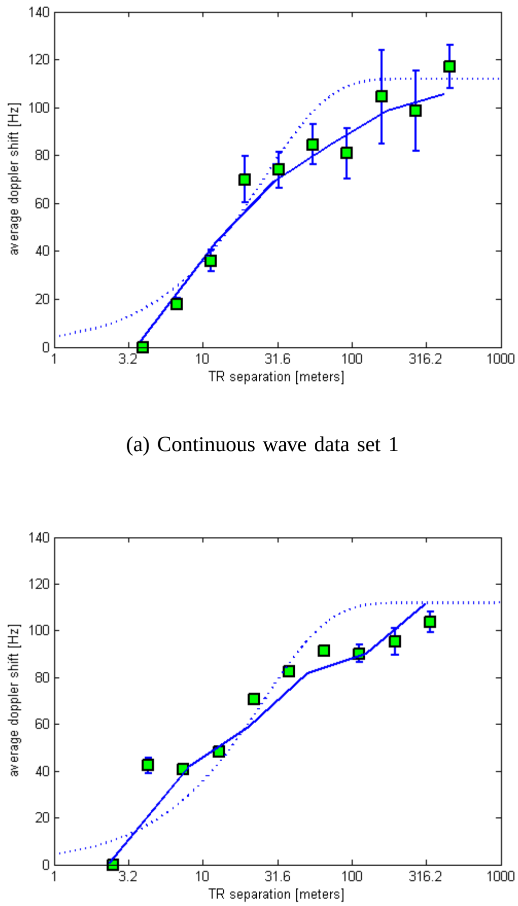
$$E(f|d)_{without\ pts} = \frac{1}{3} \frac{v_{limit}}{\lambda} (1 - e^{-\alpha d}). \tag{9}$$

To confirm this model prediction, the actual measured Doppler shift can be obtained from the experimental spectrum measurements using

$$E(f)_{meas} = \int_0^{\infty} f p(f) df, \tag{10}$$

where $p(f) = k(S(f) + S(-f))/2$ (to take into account the magnitude of the relative velocity), and $S(f)$ is the averaged spectrum for the given distance bin. Drift compensation is performed to ensure the spectrum is centered so that $S(0)$ is the un-shifted frequency after correcting for drift, and $k$ is a normalization factor to make $p(f)$ a probability density function (PDF).

The two estimates of the Doppler (i.e., with and without RS-S diagram points) together with the measured data are shown in Fig. 4 for the two CW data sets in which we have measured the experimental Doppler spectrum. As we can see, predictions made with RS-S diagram (the solid line) are in good agreement with the measured data. When we don't have the actual points in RS-S diagram, the predictions (shown in the dashed curve)




(a) Continuous wave data set 1



(b) Continuous wave data set 2

Fig. 4. Doppler shift versus Distance. (a) Continuous wave data set 1, (b) Continuous wave data set 2. The squares are from spectrum measurements averaged at each distance bin. Solid curves are Doppler shift estimates with the RS-S diagram points. Dashed curves are estimated without the RS-S diagram points.

is also in reasonable agreement with the trend.

Therefore we believe the proposed hierarchical phenomenological model is useful from several perspectives. First, it helps decouple the underlying connection between separation and relative velocity, which is important when analyzing field data. Second, it provides guidance for the design of experiments with specific combinations of maximum velocity and separation. Third, it enables a histogram based method together with the RS-S diagram as a prediction tool, providing reasonably accurate estimates for ITS simulations.

## V. Summary

Wireless communication based vehicular safety applications have motivated a great deal of research and development efforts on DSRC technology. From our recent sounding measurements, we have developed insight into the correlation between maximum relative velocity and separation distance, and have interpreted this in terms of driver behavior. Using a phenomenological model of this behavior along with the well-established dependence of Doppler shift on maximum velocity, we have proposed a model that describes the dependence on separation distance as well as relative velocity. We have provided intuitive explanations of our understanding based on our analysis from field tests. The result is a flexible tool that provides guidance on the distance vs. relative velocity dependency, as well as a convenient methodology to develop realistic traffic simulations in DSRC networks, with or without actual measurements.

## VI. Acknowledgement

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## References

[1] "Standard specification for telecommunications and information exchange between roadside and vehicle systems - 5GHz band dedicated short range communications (DSRC) medium access control (MAC) and physical layer (PHY) specifications, astm e2213-03," Sep. 2003.

[2] Fan Bai and Hariharan Krishnan, "Reliability analysis of dsrc wireless communication for vehicle safety applications," *Proceeding of the 9th International Conference of Intelligent Transportation System*, 2006.

[3] Fan Bai, Tamer Elbatt, Gavin Hollan, Hariharan Krishnan, and Varsha Sadekar, "Towards characterizing and classifying communication-based automotive applications from a wireless networking perspective," *1st IEEE Workshop on Automotive Networking and Applications (AutoNet 2006)*, 2006.

[4] Jijun Yin, Tamer ElBatt, Gavin Yeung, Bo Ryu, Stephen Habermas, Hariharan Krishnan, and Timothy Talty, "Performance evaluation of safety applications over DSRC vehicular ad hoc networks," *VANET '04: Proceedings of the 1st ACM international workshop on Vehicularad hoc networks*, pp. 1–9, 2004.

[5] Jeremy J. Blum, Azim Eskandarian, and Lance J. Hoffman, "Challenges of intervehicle ad hoc networks," *IEEE Trans. on Intelligent Transportation Systems*, vol. 5, pp. 347–351, 2004.

[6] Franois Spies Dominique Dhoutaut, Anthony Rgis, "Impact of radio propagation models in vehicular ad hoc networks simulations," *Proceedings of the 3rd ACM international workshop on Vehicular ad hoc networks*, pp. 40 – 49, 2006.

[7] J. Clark and G. Daigle, "The importance of simulation techniques in ITS research and analysis," *Proceedings of the 1997 Winter Simulation Conference*, pp. 1236–1243, 1997.

[8] J. A. Tenreiro Machado Jose Rui Ferreira Lino Figueiredo, Isabel Jesus and J. L. Martins de Carvalho, "Towards the development of intelligent transportation systems," *IEEE Proceedings on Intelligent Transportation Systems*, pp. 1206–1211, 2001.

[9] J. Maurer, T. Fugen, and W. Wiesbeck, "Narrow-band measurements and analysis of the inter-vehicle transmission channel at 5.2 ghz," *Vehicular Technology Conference, 2002. VTC Spring 2002. IEEE 55th*, vol. 3, pp. 1274 – 1278, 2002.

[10] Guillermo Acosta, Kathleen Tokuda, and Mary Ann Ingram, "Measured joint doppler-delay power profiles for vehicle-to-vehicle communications at 2.4 GHz," *GLOBECOM '04. IEEE*, vol. 6, pp. 3813 – 3817, 2004.

[11] Ratish J. Punnoose, Pavel V. Nikitin, Josh Broch, and Daniel D. Stancil, "Optimizing wireless network protocols using real-time predictive propagation modeling," pp. 39–44, 1999.

[12] Guillermo Acosta and Mary Ann Ingram, "Doubly selective vehicle-to-vehicle channel measurements and modeling at 5.9 ghz," *Proceedings 2006 Wireless Personal Multimedia Communications Conference (WPMC'06)*, September 17-20, 2006.

[13] Lin Cheng, Benjamin Henty, Daniel Stancil, Fan Bai, and Priyantha Mudalige, "Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band," *under review*.

[14] Lin Cheng, Benjamin Henty, Daniel Stancil, Fan Bai, and Priyantha Mudalige, "Properties and applications of the suburban vehicle-to-vehicle propagation channel at 5.9 GHz," *International Conference on Electromagnetics in Advanced Applications, Torino, Italy*, 2007.

[15] Lin Cheng, Benjamin Henty, Daniel Stancil, Fan Bai, and Priyantha Mudalige, "Fully mobile, gps enabled, vehicle-to-vehicle measurement platform for characterization of the 5.9 GHz DSRC channel," *IEEE International Symposium on Antennas and Propagation*, 2007.