Doppler Component Analysis of the Suburban Vehicle-to-Vehicle DSRC Propagation Channel at 5.9 GHz

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Abstract— **This study presents Doppler component analysis of the mobile vehicle-to-vehicle propagation channel at 5.9 GHz. The measurements were conducted via a VANET field implementation under realistic suburban driving conditions in Pittsburgh, Pennsylvania. Different components in the observed spectrum were analyzed with vehicle speeds and compared with theoretical mobile-to-mobile scenarios. Intuitive understandings are also provided based on our analysis from on-road measurements.**

I. Introduction

Recently, Vehicle Ad hoc NETworks (VANET) have received considerable attention. As an emerging wireless communication system, VANET features wireless information exchange between mobile vehicles towards on-road networking, enabling a wide range of applications from safety alert, congestion control, to multimedia infotainment [1]. The importance of having dedicated wireless communications between vehicles has been recognized by the FCC, resulting in the allocation of 75 MHz of spectrum at 5.9 GHz for the purpose of Dedicated Short Range Communications (DSRC) in vehicular environments.

For a large-scale Vehicular Ad hoc NETwork (VANET) to function reliably in rapidly changing environments in real driving conditions, the vehicle-to-vehicle (V2V) DSRC link needs to be understood as a radio communication channel. A deep understanding of the propagation characteristics is therefore of critical importance to DSRC system designers.

Theoretical models for the mobile-to-mobile channel have been discussed in a number of existing studies [2]–[4]. Many of these models are derived from the existing analytical infrastructure-mobile models, which typically assume that the distribution of angles of arrival (AOA) for multipath components is uniformly distributed over all angles in the horizontal plane of interest, as, e.g., the double ring model [2] [3] shown in Fig. 1.

However, for V2V scenarios, the assumptions of the geometric symmetry are not always adequately satisfied. Considering a typical on-road scenario shown in Fig. 2, the vehicles that talk to each other could be just a few meters apart, scatterers around them may not be isolated, a line-of-sight (LoS) path usually exists, and communications may be primarily along the road. All of these factors could potentially affect the RF channel properties, such as the Doppler spectrum.

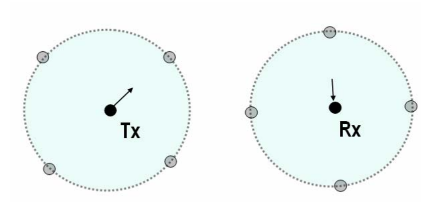


Fig. 1. Schematic of the theoretical double ring model [2] [3].

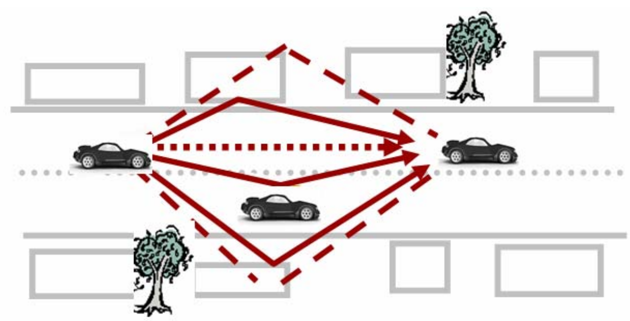


Fig. 2. Schematic of on-road environment.

Reported empirical studies include narrow-band measurements at 5.2 GHz [5] and joint Doppler-delay power profile measurements at 2.4 GHz [6]. Measurements and modeling of the vehicle-to-vehicle channel at 5.9 GHz at a specific highway location have also been reported [7].

We believe additional experimental VANET implementation and field studies are needed to validate and extend existing studies, especially on natural road conditions at the 5.9 GHz DSRC band. Among various channel impairments, the Doppler spectrum is an important characteristic that contributes to fading and therefore the reliability and robustness of VANET systems. This motivates us to experimentally examine the Doppler spectrum under natural on-road driving conditions.

In this paper, we consider the following questions:

1) What does the experimental Doppler spectrum measured during natural driving conditions look like? Are the observed spectra in agreement with theoretical models, e.g., the double-ring model [2] [3]?

2) How do various speed parameters such as relative velocity and ground speed affect the Doppler spectrum in the actual driving environment?
3) How do the scatterers on road affect the Doppler spectrum?

To this end, we describe our study on the Doppler from real-world suburban environments at the designated DSRC frequency. In particular, using our recent channel sounding measurements, this paper characterizes the time-variant behavior of the V2V channel at DSRC by its Doppler spectrum, using on road data taken in suburban Pittsburgh. The analysis consists of estimating the position of LoS components from velocity, extracting base spectrum structure and comparing it with the theoretically predicted spectrum. We also illustrate the impact on the spectrum from the realistic road traffic.

II. Measurement system

To characterize channel characteristics, we performed Continuous Waveform (CW) measurements at the designated DSRC frequency of 5.9 GHz. As shown in Fig. 3, the platform we constructed is aimed at providing us the flexibility of performing measurements with many signaling schemes (e.g., continuous wave, OFDM signals employing DSRC standard, etc).

At the transmitter side, for CW, a 2.95 GHz signal from the Agilent E4433B Digital Signal generator (DSG) is upconverted using a mixer, and the signal from the coherent carrier output of the DSG serves as the local oscillator to minimize the carrier drift.

At the receiver side, a broadband, low noise amplifier is used to maximize the sensitivity of the receiver. A mixer is used to down-convert the received RF signal into the 0 to 40 MHz range that can be analyzed by the Agilent 89600 Vector Signal Analyzer (VSA). The VSA samples the signal with a high-speed, wide-dynamic-range analog-to-digital converter (ADC). Automation software is used to record a 200 ms data capture of the signal at 1-second intervals. For the CW system, each of these 200 ms data frames captured from the VSA serves as the basis for our Doppler analysis.

In addition to the RF components, we describe how our system measures and calculates separation distance and relative speed. To ensure the precision of our measurements, both vehicles are equipped with a CSI wireless Differential GPS (DGPS) receiver and a Linux laptop computer that logs GPS data. The accuracy of DGPS is at the order of 1 meter. Thus, we believe that the location information provided by the DGPS receiver is accurate enough for our analysis. 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.

We conducted the sounding experiments 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 6000 data sweeps for Doppler spectra; thus we believe the experimental data is large enough to draw statistically meaningful conclusions. A detailed description of the system implementation and data sets is given in [8].

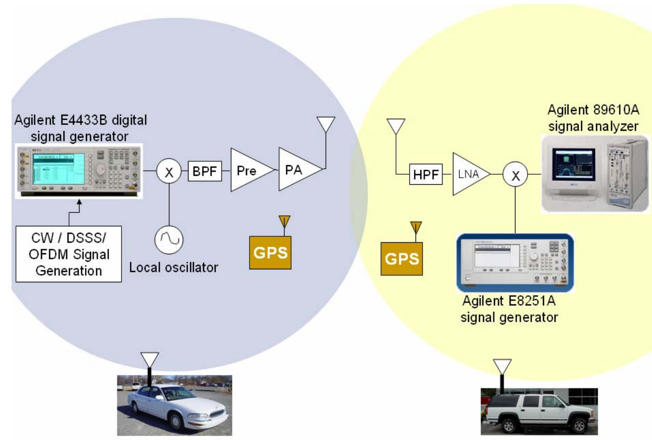
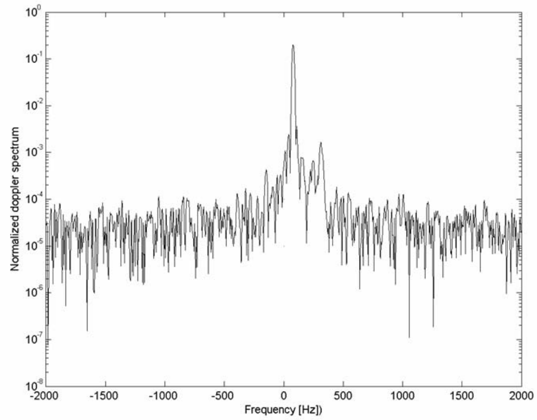


Fig. 3. System setup diagram.

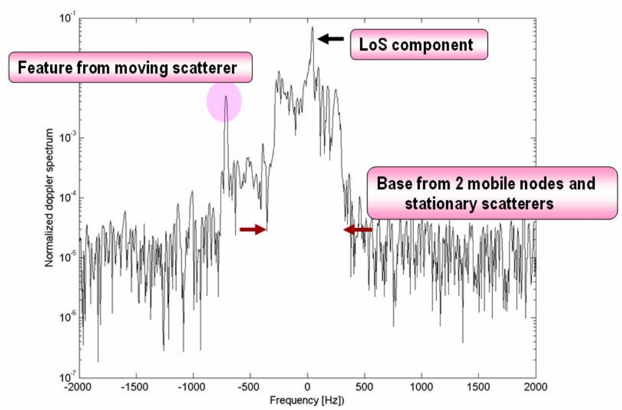
III. General observations on the Doppler shape of the experimental spectrum

The two vehicles under study travel at various separations and with different velocities. Considering the scenario depicted in Fig. 2, there are several sources of reflection and scattering – buildings, trees, hills, other vehicles, etc. – in a typical link between the two mobile vehicles. We refer to these objects generically as scatterers. While moving down the road, the cars pass through multiple kinds of local scatterers. Some of these scatterers such as buildings and trees are stationary, while others such as vehicles and pedestrians are in motion. If a narrowband continuous wave (CW) signal is transmitted through the channel, severe changes in the amplitude and phase of the received signal occur as a result of such motion. These changes manifest themselves as Doppler spreading of the signal spectrum.

Fig. 4 shows two examples of observed Doppler spectra. The strongest peak in the spectra is the line-of-sight (LoS) component. While the double-ring model has not considered the line-of-sight component, our measurements show that a line-of-sight path usually exists while traveling on the road. A lower amplitude structure is also typically observed in these experimental spectra to which we refer as a base. We show that the width of this base structure is in general agreement with the spectral width predicted by the double-ring model [2] [3]. We begin the analysis by looking at the LoS, then we discuss the base.



(a) Sample Doppler spectra when both vehicles are stationary



(b) Sample Doppler spectra with base outliers

Fig. 4. Sample experimental Doppler spectra.

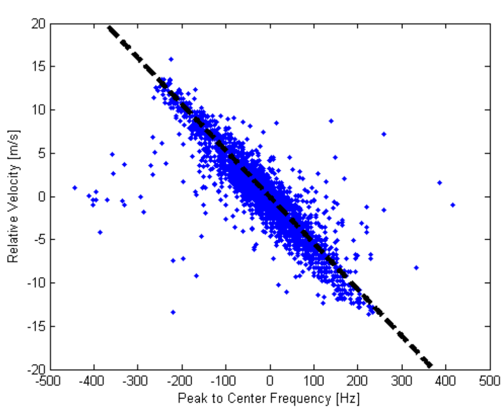


Fig. 5. Relative velocity versus frequency offset of LoS peak from ω_0.

IV. LoS COMPONENTS

We first confirm from experimental spectra that the position of the observed LoS components is associated with relative velocity. In the collection of the measured spectrum samples, we compute the first order moment ω_0 of the frequency response function. As depicted in Fig. 5, the position of the observed LoS components $(\omega_{LoS} - \omega_0)$ exhibits a strong correlation with relative velocity between two vehicles of interest, as expected. The dashed line shown in Fig. 5 corresponds to the well-known Doppler shift

$$f_{rel} = \frac{v_{rel}}{\lambda}, \tag{1}$$

where v_{rel} is relative velocity between the vehicles. We attribute the scatter of the data shown in Fig. 5 to errors in identifying and measuring the shifts of the LoS components in the often complicated spectra. This behavior is consistent with the assumptions in [4] regarding the LoS component.

V. BASE COMPONENTS

Apart from the LoS components, we also notice a widened base of the Doppler spectra. It is natural to relate the base to the theoretical spectra in the double-ring model [2] [3], which takes into account the movement of the two mobile nodes surrounded by stationary scatterers. To further analyze the observed phenomenon, we first formulate a reliable component detection algorithm to detect the base. We then analyze the base and its dependence on the vehicle speed variables, and contrast it with the double-ring model.

A. Extracting base

Reliably extracting the base from noisy spectra is critical to our analysis. One method to remove the noise from the spectra is to define a power threshold. This can be done by setting a threshold just above the noise floor. All measured values below this level are eliminated from the calculations. The base width would then be taken as the separation between the points where the spectrum crosses the threshold.

A problem arises with this method when the measured spectrum has outliers (e.g., shown in Fig. 4(b)). In this case, the base width is likely to be overestimated. To correct his, the method is modified using the following algorithm: we first identify all crossings of the spectra at a threshold that is well above the noise floor (to serve as base detection). Next, the interval between the upward crossing (positive derivative) and the following downward crossing (negative derivative) is calculated and recorded for all crossings. When there exists a component rising above the threshold, it induces a pair of such crossings. A second user-defined parameter, minimum base gap, is used to search for component regions in the spectra. The gaps between crossings in each pair are compared with

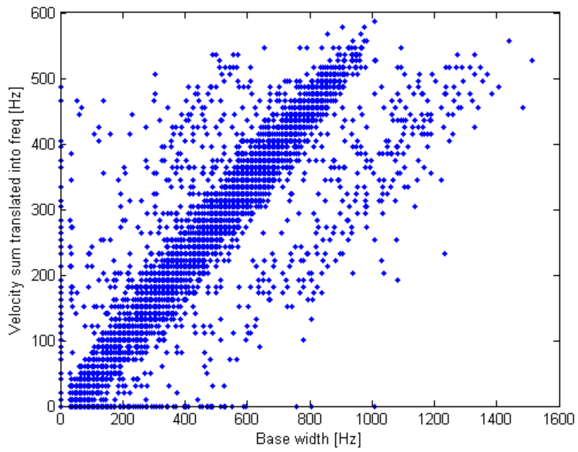


Fig. 6. Base width versus frequency induced by effective velocity and by the sum of ground speed.

the minimum base gap parameter, and gaps that exceed the minimum base gap are identified as base component regions.

B. Velocities and base shape

According to models with isotropic stationary scatterers, the width of the spectrum is given by $2|f_1 + f_2|$ [2] [3], where $f_1 = \frac{v_1}{\lambda}$ and $f_2 = \frac{v_2}{\lambda}$ (both are non-negative). The base widths extracted using the above algorithm are compared with the frequencies translated from summation of ground speeds $(v_1 + v_2)$ (speed relative to the ground), across all the data points at 5.9 GHz DSRC band in Fig. 6.

While good agreement is observed on our identification of this base region with the stationary scatter model, the trend observed in Fig. 6 suggests that the base width can be larger than the theoretical case surrounded by stationary scatterers.

A closer examination of the recorded spectra on road suggests the existence of other components that were not included in the double-ring model. For example, Fig. 4(a) is a spectrum recorded with both vehicles stationary. However, the base width is not zero, as would be predicted by the double-ring model. This is because in real V2V environments there are moving scatterers (such as other moving vehicles).

Fig. 4(b) depicts another spectrum recorded at $v_1 = 7.7$ m/s and $v_2 = 8.7$ m/s. At 5.9 GHz this translates into $\pm(f_1 + f_2) = \pm 322.53$ Hz. In the double-ring model, the power spectra outside $\pm(f_1 + f_2)$ is not defined, however we observe other components beyond ± 322.53 Hz. First we note the presence of the strong peak at about -700 Hz. This peak is most likely caused by a strong reflection from a vehicle in the oncoming lane. Further, we note a continuous spread of energy to the right of this outlying peak, resulting in an effective widening of the base.

VI. SUMMARY

The observed experimental spectra in the suburban V2V environment can be generally decomposed into three components. The first and strongest component is that from line-of-sight. This component exhibits a Doppler shift proportional to the relative velocity, but no Doppler spreading. The second component is a weaker, roughly continuous base or pedistal. The observed width of this base is in reasonable agreement with the double-ring mobile-to-mobile model [2] [3], and arises from stationary scattering sources. Finally, additional features are observed beyond the base width predicted by the double-ring model, including narrow, shifted peaks and broadened base structures. These features result from moving scattering objects in the environment, particular vehicles in the oncoming lanes.

VII. CONCLUDING REMARKS

The Doppler spectrum is an important factor that affects the reliability and robustness of Dedicated Short-Range Communications dedicated to VANET. We have studied experimental Doppler spectra obtained in suburban environment under realistic driving conditions. Existing models that assume stationary scattering objects account some, but not all of the observed features in these spectra. The effects of moving objects must be taken into account – particularly vehicles in oncoming lanes, owing to their large relative velocity and often close proximity.

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