Damper-to-Damper Path Loss Characterization for Intra-Vehicular Wireless Sensor Networks

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***Abstract* — Intra-Vehicular Wireless Sensor Networks (IVWSNs) is one of the major advances in electrical smart cars. It could extend the driving distance of E-cars by reducing the weight of bulky cables. It can also bring more sensing functions, turning the car into smart units for Intelligent Transportation Systems (ITS). Until now, most works of IVWSNs channel characterization are focused on in-car wireless communication. This paper presents for the first time, to author's knowledge, the channel characterization of a non-line-of-sight damper-to-damper wireless communication at 2.4 GHz frequency band, including the signal reflection from ground. A method of 3D EM simulation is provided. Static and dynamic on-field car measurement is also performed on a commercial car with different road profiles. It shows that different road profiles equally impact path loss specification because of similar permittivity. From on-field measurements, it proves that 5.25 MHz frequency isolation leads to uncorrelated channels.**

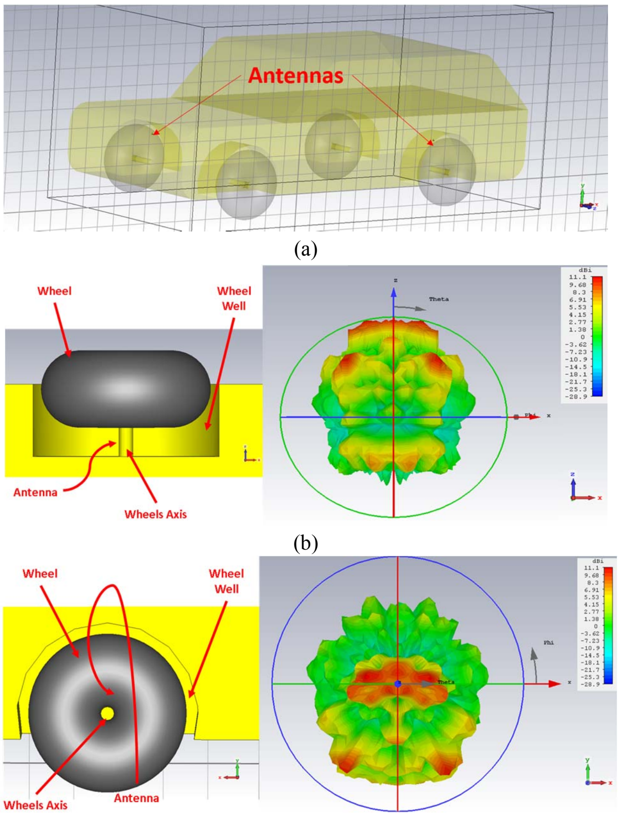
***Index Terms*—Path Loss, NLOS, IVWSN, ITS, 2.4 GHz.**

I. INTRODUCTION

Intra-Vehicular Wireless Sensor Networks (IVWSNs) is one of major advances in electrical smart cars. By bringing more smart sensing functions, the IVWSN would turn cars into smart units for Intelligent Transportation Systems. In traditional wireline based smart sensor network, the increased number of sensors and actuators inter-connected with bulky cables adds cable routing complexity, as well as impacts electric cars' driving range dramatically. IVWSN is an important alternative technique to enable intelligent vehicle and minimize vehicle weight. It also achieves enabling plug-and-play functionality for easy maintenance.

Improving car performance and comfort, while complying with stringent safety regulations is a crucial requirement. Therefore, intra-vehicular wireless communication systems should be reliable, low latency and interference robust in order to functional in a complex electromagnetic environment. In addition, the frequency band of such systems should be internationally available. In order to fulfill those requirements, an IVWSN has to be designed considering the characteristics of communication channels. Previous works are focused on inside car wireless communication. [1] [2] [3] performed on Ultra-Wideband (UWB) characterization, [4] [5] [6] performed on 2.4 GHz band channel characterization, and [7] on UHF bands.

Recently, IVWSN is also applied to smart (active or semi-active) suspension systems. The smart suspension system with wireline communication is expensive, because of vehicle structure changes and installation costs. Compared with wireline network, IVWSN is a more economy solution. Nevertheless, there are no reported previous works on path loss characterization of a damper-to-damper wireless communication at 2.4 GHz frequency band. This paper evaluates for the first time, to author's knowledge, a NLOS Damper-to-Damper (D2D) path loss characterization for a wireless suspension system based on both static and dynamic on-field car measurements at 2.4 GHz frequency band



(a)

(b)

(c)

Fig. 1: (a) EM model for car simulation with concrete floor, aluminum body, rubber wheels and antennas placed behind the wheels. (b) Antenna far field at 2.45 GHz in XZ view, and (c) in XY view.

including signal reflection caused by the road. It is also provided a 3D EM simulation method for channel characterization.

The paper is organized as follows. In Section II, a method of 3D EM simulation of the antennas within the car environment is provided. In Section III, a detailed description of the measurement campaign is presented. The analysis of measurement results is discussed with a summary of path loss worst case scenario in Section IV. The analysis of coherence bandwidth is provided in Section V. In the end, the conclusions are drawn in Section VI.

II. 3D EM CHANNEL CHARACTERIZATION SIMULATION

The 3D EM channel characterization simulation is shown in Fig. 1. The car size is based on a minivan sized commercial car. A simplified 3D car model is used in the simulation. It contains an aluminum car frame with rubber wheels and two monopole antennas placed inside the wheel wells. The car is surrounded by air and it is sitting on a concrete floor, similar to the real case. For general application, a normalized car frame was used. The distance between the antennas is 3.3 m, which is the same as the real car later used on the on-field measurements. It consisted of (1) an antenna far field simulation, and (2) an S-parameter simulation, S_{21} between the furthest pair of antennas (Front-Left and Rear-Right, or simply FL-RR) and S_{11}.

The monopolar antenna is simulated as shown in Fig. 1(a). In the on-field D2D path loss characterization, the antennas are enclosed by the wheel well. Therefore, in the simulation, the antennas were placed enclosed by a metallic reflector. It is noticeable from the simulation that the antenna performance is influenced by the metallic reflector, as shown in Fig. 1(b)-(c). Due to the signal reflected from the surrounding metal, the antenna gain is greater out and downwards. Nevertheless, the NLOS propagation of the D2D communication system can be developed as a result of signal reflections bouncing underneath the car between the car metallic floor and the road. Consequently, the dielectric permittivity, and the reflection coefficient of the road surface plays an important role in the D2D path loss. During the on-field car measurement, the influence of road profile on D2D PL is evaluated, which will be presented in Section III.

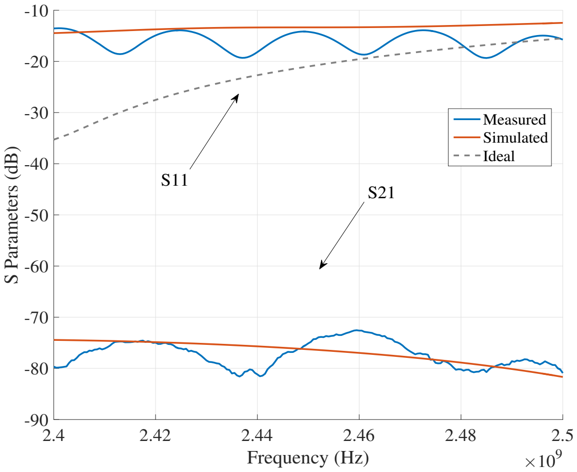
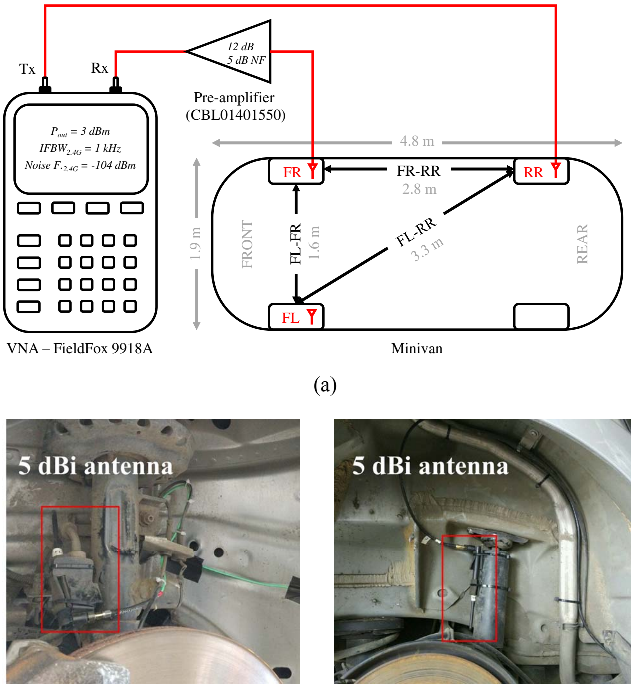


Fig. 2: Simulated S-parameters vs. Measured S-parameter for damper-to-damper wireless communication.

The simulated S-parameters of the two antennas are shown in Fig. 2. A comparison of the simulated data with measured data is also provided in Fig. 2. It shows the simulated S-parameter matches the measurement data. The extra ripple is due to the cable reflection during car driving. The S_{11} of the mounted antenna is below -10 dB for the entire bandwidth. The simulated S_{21} between the FL-RR antennas on a concrete floor has also matched the measured FL-RR antennas on a car situation besides the ripple from the cable reflection.

III. MEASUREMENT SETUP

The path loss measurements were performed with a Handheld Vector Network Analyzer (HVNA-FieldFox 9918A) in a minivan, as shown in Fig. 3(a). The recording rate was 1 sample per second in the 2.4 GHz band. Each sample collected by the VNA presents the signal power attenuation versus frequency for a given time. Dipole antennas with 5 dBi antenna gain were mounted in three dampers as shown in Fig. 3, Front-Left (FL), Front-Right (FR) and Rear-Right (RR). Each cable provides extra 5 dB loss. Because of car body symmetrical structure, the measurements were carried out for three pairs of dampers, FL-RR, FR-RR and FL-FR. The VNA noise floor is



(a)

(b)

(c)

Fig. 3: (a) Measurement setup diagram for FR-RR path and minivan lengths; (b) 5 dBi antenna is placed in Front chamber; and (c) 5 dBi antenna is placed in back chamber.

improved by setting the Tx output power to 3 dBm and adopting a pre-amplifier with 12 dB gain and 5 dB noise figure. For reference purposes, a static car path loss is recorded. Whereas in dynamic on-field, real life scenarios are reproduced by driving the car on asphalt, cobblestone and sand roads.

IV. PATH LOSS MEASUREMENT RESULTS

Dynamic on-field measurements were performed by driving on roads with asphalt, cobblestone and sand surfaces, as shown in Fig. 4. From this dynamic measurement channel property of path loss can be derived for D2D Communication System (D2D CS).

Fig. 4 Fig.shows the FL-RR path loss error bar graphs for 2.4 GHz band on (a) asphalt, (b) cobblestone and (c) sand surfaces; and their respective roads (d) asphalt, (e) cobblestone and (f) sand. Each situation has 150 seconds of recording. During measurement configuration, the IF bandwidth and pre-amplifier are configured to keep the measured data above noise floor (NF).

The asphalt permittivity is 6 [8], and the dry sand permittivity is within the range from 4 to 6 [9]. The granite (cobblestone) permittivity can go from 4 to 6 [10]. Consequently, the similarity on the roads permittivity, which are also related to their reflection coefficient, explains the statistically similar path loss among different road profiles. On the other hand, the large values of standard deviations, mainly due to multipath effects, indicates that the PL strongly depends on frequency over measured time. Thus, in a frequency dependent path loss scenario, Frequency Diversity (FD) techniques can increase reliability by taking advantage of the different channel qualities.

The Free-Space Path Loss (FSPL) [11] is a reference for measurement, which can be derived from the measured car size (Fig. 3(a)),

$$FSPL(dB) = 20\log(d) + 20\log(f) + 20\log(4/\pi\times c), \quad (1)$$

where d is the distance between the antennas, f is the signal frequency and c is the speed of light in the vacuum.

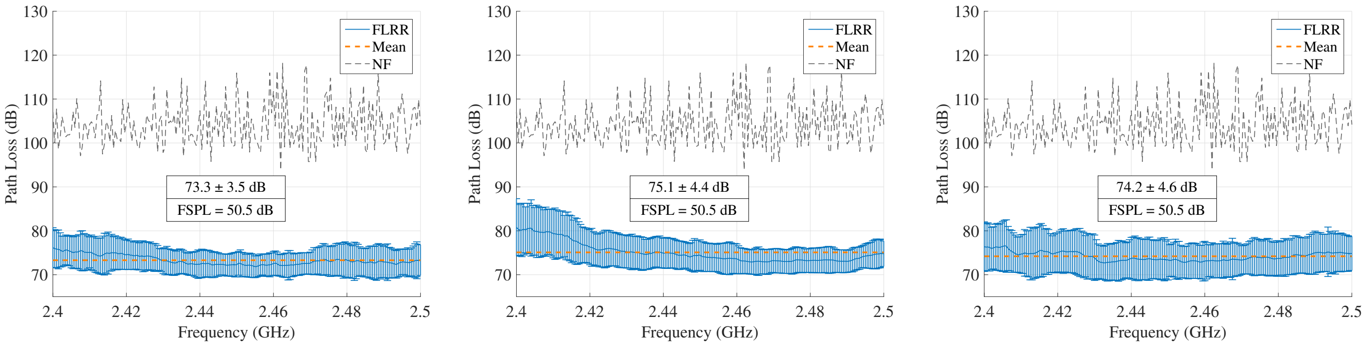
The deviation of measured data from FSPL (shown in Fig. 4(a) - 4(c)) is due to multipath fading caused by car metal structure. The measured FL-FR path loss is 56 dB, while the FSPL is 44 dB at a distance of 1.6 m. The measured FL-RR path loss is 75 dB, while the FSPL is 51 dB at a distance of 3.3 m. The 12 dB extra loss in the FL-FR situation and 24 dB extra loss in FL-RR situation is introduced by the multipath fading effect.

A statistical analysis can accurately quantify the dynamic situation into D2D CS specification, while log-distance path loss model only works for static environments [12]. Eq. (2) – (3) show, for a confidence interval of 2σ (95%), the final path loss for 2.4 GHz, which should be consider to design a reliable and robust IVWSN system. To accommodate unexpected variables, e.g. different car bodies, an extra margin is also added up.

$$PL_f = PL_{ave} - L_{ant} + G_{cab} + 2\sigma + Margin, \quad (2)$$

$$PL_{2.4G} = 74.2 - 3 + 4 + 2\times 4.6 + 5 = 89.4\ dB, \quad (3)$$

where PL_f is the path loss specification at f frequency, PL_{ave} is the averaged path loss among all FL-RR scenarios, L_{ant} is the



(a) Asphalt at 2.4 GHz (b) Cobblestone at 2.4 GHz (c) Sand at 2.4 GHz

(d) Asphalt ($\varepsilon_r = 6.0$ [8]) (e) Cobblestone ($\varepsilon_r = 4\text{-}6$ [10]) (f) Sand ($\varepsilon_r = 4\text{-}6$ [9])

Fig. 4: FL-RR path loss error bars for 2.4 GHz frequency band on (a) asphalt, (b) cobblestone, (c) sand road surfaces; and their respective roads (d) asphalt, (e) cobblestone and (f) sand.

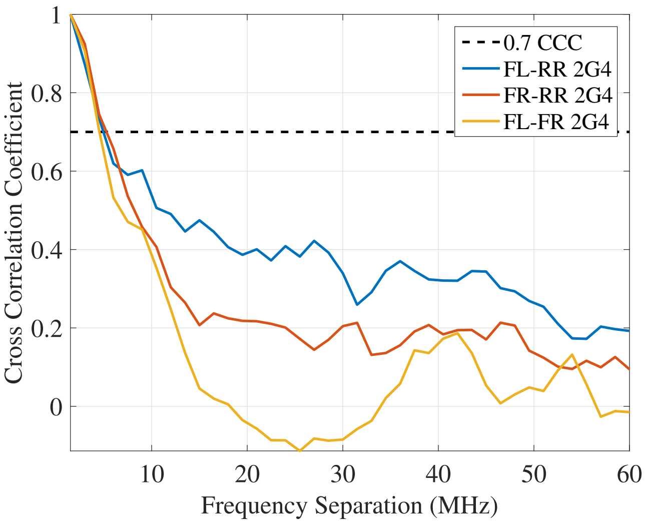


Fig. 5: Cross-correlation coefficient for all damper pairs in cobblestone driving situation at 2.4 GHz frequency band.

attenuation due to eventual lower gain antenna (2 dB lower), G_{cab} is the gain thanks to direct transceiver-antenna connection (no cables), 2σ is the confidence level and a *Margin* is used to account for different cars.

V. COHERENCE BANDWIDTH

The path loss frequency dependence exposed by the dynamic on-field measurements can benefit from Frequency Diversity (FD) techniques. The Cross-Correlation Coefficient (CCC) versus frequency separation and the Coherence Bandwidth (CB) can be obtained from the measurement data. Independent frequency channels have frequency separation larger than the CB, which is indicated by CCC below 0.7 [13].

Fig. 5 shows the CCC for frequency separation varying from 1.5 MHz to 60 MHz in the cobblestone scenario. It shows that a frequency separation larger than 5.25 MHz allows channels to have a path loss independent property from other channels. In fact, as seen by the convergence to low CCC at 60 MHz, the larger the frequency separation, the lower is the correlation. The NLOS path and the car maneuvers affecting antenna surroundings prevent the shaping of resonant cavity. Therefore, there is no presence of periodic behavior in the CCC graphic. Additionally, FD techniques may allow the use of parallel links throughout different uncorrelated channels to either increase reliability by sending redundant data, or to reduce latency by sending complementary data.

VI. CONCLUSION

Intra-Vehicular Wireless Sensor Networks (IVWSNs) is one of major advances in the electrical smart cars. A 3D EM simulation model for damper-to-damper channel characteristic is build. On-field static and dynamic measurement for damper-to-damper wireless communication at 2.4 GHz is also performed. The 3D EM simulation fit to the measured data, which could provide a NLOS path loss specification for system level calculation of 89.4 dB. From measurements, it has also been shown that different road profiles do not significantly influence the average path loss between two dampers due to similarity on their permittivity. Furthermore, a cross correlation coefficient analysis from on-field measurement indicates that 5.25 MHz frequency separation leads to uncorrelated channels. Therefore, transceivers using multiple channel frequencies with at least 5.25 MHz frequency spacing can improve system reliability and latency.

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