Double-Directional Channel Characterization of Truck-to-Truck Communication in Urban Environment

Rui Wang¹, Student Member, IEEE, Olivier Renaudin¹,², Member, IEEE, C. Umit Bas¹, Student Member, IEEE
Seun Sangodoyin¹, Student Member, IEEE, Andreas F. Molisch¹, Fellow, IEEE
¹University of Southern California, Los Angeles, CA USA
²Austrian Institute Of Technology

Email: ¹{wang78,cbas,sangodoy,molisch}@usc.edu, ²olivier.renaudin@ait.ac.at

Abstract—This paper reports the first truck-to-truck (T2T) wireless channel measurement conducted at 5.9 GHz with multiple antennas at both transmitter and receiver. We present directional analysis of a sample route in downtown Los Angeles, CA USA, where two trucks drive towards each other. Measurements are performed with a self-built real-time MIMO channel sounder and evaluated with RiMAX, a high resolution parameter estimation algorithm, providing time-of-arrival, directional of departure, directional of arrival and Doppler shift for discrete multipath components as well as diffuse multipath scattering. Compared to vehicular channels for passenger cars, our measurements show that the metallic trailer, which is higher than the installed antennas, acts as a strong reflector in line-of-sight (LOS) condition and increases the average received power and angular spread. The extra power attenuation however can be as high as 35 dB after two trucks pass each other and the trailers obstruct the LOS.

I. INTRODUCTION

Research on vehicle-to-vehicle (V2V) communication technology has been a trending topic in the last decade, mostly because applications such as intelligent transportation systems (ITS) and autonomous driving can bring huge social and economic benefits. The grand vision for the future vehicular technology is that all vehicles are connected and they can share critical information with each other and with the road infrastructure. The more information is available for the driver or computer that controls the vehicles, the safer the driving will be. The vehicles can also keep a shorter distance between each other so that traffic jams are reduced. However these benefits rely on the design of a reliable and low-latency communication system. While the attention of the popular press has been mostly drawn to communication between passenger cars, T2T and truck-to-passenger communications is a very important area of application. Trucks are generally big safety concerns and accidents involving trucks tend to result in severe casualties, because of their large size and inability to stop within a short distance.

Channel measurements and modeling are indispensable for the design of any wireless system since it is the wireless channel that ultimately determines the performance of a wireless communication system. There is a rich literature on the V2V propagation channel, see the survey papers [1], [2]. IEEE 802.11p [3] is a well-known standard for vehicular communications, but it was developed and tested mostly based on channel models/measurements between regular passenger vehicles, so its suitability for truck-to-truck (T2T) communication is still unknown. The shape of trucks is different from that of passenger cars, because trucks are generally bigger and higher. Most of the trucks come with a metallic trailer, which is expected to impact the channel response, if antennas are installed on top of the driving cabin.

There have been some studies characterizing the V2V propagation channel where trucks are treated as obstructing obstacles that shadow the communication link between passenger cars. For example, Abbas et al. [4] presents a directional analysis for the V2V propagation channel on a highway, where with a truck acting as an obstruction object. A more comprehensive study on the obstruction of large vehicles is done in [5]. Similarly He et al. [6] provides a signal attenuation model due to the shadowing of a large school bus based on a stationary experiment. To the best of our knowledge, there have been no reported measurements or analysis about the T2T channel in a dynamic environment, despite their importance in ensuring the road safety. Our work attempts to close this gap.

In order to alleviate the lack of measurement data, we have carried out extensive measurement campaigns to study T2T propagation channel in various environments such as downtown, rural, and highway [7]. Employing a real-time multiple-input multiple-output (MIMO) channel sounder that we have developed the University of Southern California (USC), we perform continuous measurements between two trucks in dynamic environments. We analyze the measurement data and extract parameters of specular paths (SPs), such as time-of-arrival, direction of departure (DoD), direction of arrival (DoA), Doppler shift and signal power, as well as the characteristics of the diffuse multi-path components (DMC) with the help of RiMAX, a high resolution parameter estimation (HRPE) algorithm [8]. The extracted dominant paths are consistent with the environment as observed from maps and video recordings.

The main contributions of this paper are as follows,

• performing and reporting the first truck-to-truck MIMO
channel measurements at 5.9 GHz in a dynamic environment;
• analyzing the MIMO measurement data with an HRPE algorithm to extract parameters for each path;
• observing that the metallic trailer has a significant impact on the T2T propagation channel.

The rest of the paper is organized as follows. In Section II we introduce the measurement campaign, which includes the environment, the setup and the evaluation techniques. Section III presents the sample results based on the data analysis. In Section IV we draw the conclusion.

II. MEASUREMENTS

A. Channel Sounder

The measurement campaign uses a real-time MIMO channel sounder developed at USC. The sounder is equipped with a pair of software defined radios (National Instruments USRP-RIO) as the main transceivers, two GPS-disciplined rubidium references as the synchronization units and a pair of 8-element uniform circular arrays (UCAs) which is based on the switched array principle [9]. It measures with a bandwidth of 15 MHz around 5.9 GHz carrier frequency. The maximum transmit power is 26 dBm. The main advantage of this sounder setup, compared to the existing V2V sounders used in [4] and [10], is the fast MIMO snapshot repetition rate, which provides a more accurate representation of the channel dynamics. More details about the sounder setup can be found in [11].

B. Vehicle and Route

For the two trucks involved in the T2T channel measurements, we select a pair of 16-feet studio trucks as our test vehicles, as shown in Fig. 1(a). Each truck has a load capacity about 2722 kg and up to 27 m³ of cargo space.

The sufficient space in the driving cabin allowed us to place the equipment rack of the sounder inside, see Fig. 1(b), the platform that holds transmitter (Tx) or receiver (Rx) antenna arrays is tightly clamped on metallic cross-bars installed on top of the driving cabin, in order to ensure the safety of the array and reduce the vibration while we drive the trucks.

The measurement campaigns were carried out on two days in suburban, downtown and highway near Los Angeles, CA USA. The total number of measured MIMO snapshots is about 2.5 million (corresponding to 150 million impulse responses).

C. Data analysis

A generic spatial and temporal model for the wireless channel proposed in [12] describes the channel response as a sum of contributions from $P$ plane waves, when each of them is characterized by parameters such as delay $\tau_p$, DoD $\Omega_{T,P}$, DoA $\Omega_{R,P}$, Doppler shift $v_p$ (summarily called “structural parameters”), and polarimetric path weights (signal strength) $\gamma_p$. From the measured multi-dimensional channel response, we evaluate the measurement data with an HRPE algorithm [8]. The algorithm is based on RiMAX [13], which is a joint maximum likelihood estimator (MLE) for both SP and diffuse multipath components (DMC) in the wireless channel.

A vectorized model of $T$ MIMO snapshots for the measurement data is given by

$$\mathbf{y} = \mathbf{s}(\mathbf{\theta}_s) + \mathbf{n}_{dmc} + \mathbf{n}_0,$$

where the three terms represent the contributions from SP, DMC, and measurement noise. The vector $\mathbf{\theta}_s$ consists of the parameters of the SPs, such as polarimetric path weights, and the structural parameters $\mu$. The joint MLE can be written as follows

$$\hat{\mathbf{\theta}} = \arg\max_\theta \{ \mathcal{P}_r(\mathbf{y}|\mathbf{\theta}) \}$$

$$\mathcal{P}_r(\mathbf{y}|\mathbf{\theta}) = \frac{1}{\pi^M \det(\mathbf{R})} e^{-||\mathbf{y} - \mathbf{s}(\mathbf{\theta}_s)||^2 - M\sigma_n^2},$$

We assume DMC has a complex Gaussian probability distribution, i.e., $\mathbf{n}_{dmc} \sim \mathcal{CN}(\mathbf{0}, \mathbf{R})$ with zero-mean and a covariance matrix $\mathbf{R}$. We further assume that DMC has a single exponentially decaying delay profile [14], and the vector $\mathbf{\theta}_d$ consists of the decay time constants. We can also compute diffuse power ratio (dPR), which is defined as

$$\text{dPR} = \frac{||\mathbf{y} - \mathbf{s}(\hat{\mathbf{\theta}}_s)||^2 - M\sigma_n^2}{||\mathbf{y}||^2}.$$

III. EVALUATION RESULTS

In this paper, we present the evaluation results based on the scenario where two trucks drive in the opposite direction on
S. Hope Street in downtown Los Angeles. Fig. 3 shows the satellite image of the street where we conduct the T2T urban opposite direction measurement. The blue arrow represents the trajectory of the Tx truck while the red one is for the Rx truck. We analyze a total of 900 MIMO burst snapshots, which occupies a measurement time of 90 s. Each MIMO burst snapshot consists of 30 consecutive MIMO snapshots and each is separated by 100 ms.

At the beginning, the Tx truck parks close to the road curb on the southern part of S Hope street, when the Rx is on the northern part and turning around. The initial distance between Tx and Rx is about 210 m. Afterwards Rx and Tx start driving towards each other, and they both stop behind the traffic light at the intersection. In the last segment of this experiment, two trucks continue driving toward each other once the traffic light turns green and finally passes each other. The cumulative distribution function (CDF) of dPR based on these 900 MIMO burst snapshots is given in Fig. 4, among which the last 251 corresponds snapshots where two trucks have passed each other. The results suggest that in the presence of line-of-sight (LOS) a significant portion of power is manifested as SPs according to our HRPE algorithm introduced in Section II-C.

A sample average power delay profile (APDP) for the original data, SPs and DMC is given in Fig. 5. We present the extracted time-varying structural parameters in the color-weighted scatter plots given in Figs. 8-11. The dominant paths match well with the environment and the channel dynamics. Let us define the forward direction of the vehicle as 0° and the backward direction as 180° or equivalently -180°. Between 1755 s and 1765 s, the Tx stays static close to the road curb, when the Rx is initially in the middle of the road and attempting to turn around, as shown in Fig. 6(a). The azimuth DoD is around 0° while the azimuth DoA is around 70°. At about 1765 s a third truck drives through the intersection along W 8th St and momentarily blocks LOS, which leads to about 15 dB attenuation of total power in Fig. 7 and a few paths displaying negative Doppler shifts in Fig. 11. The attenuation is comparable to those reported in [5], [6], although in our case the driving direction of the obstructing truck is perpendicular to, rather than parallel with, the Tx-Rx link.

Apart from the LOS component, in Figs. 9 and 10 we also observe that there exist strong paths reflected off the metallic trailers on both Tx and Rx trucks (±180 degree DoD and DoA). Between 1765 s and 1775 s, the Rx truck turns around, and starts to drives toward the Tx. As a result we observe a decrease of delay and an increase of Doppler for strong SPs in Figs. 8 and 11. Meanwhile we observe the evolution of DoA from 70° to about 0°, as well as for the reflected path off the metallic trailer from 110° to 180°. From 1775 s to 1800 s, the Rx continues driving towards the Tx. An interesting phenomenon is that there are no significant paths with negative Doppler shifts between 1775 s and 1805 s when the Rx drives towards the intersection and the Tx. The shape of Doppler spectrum is asymmetric and different compared to one observed in a car-to-car propagation channel, see Fig. 11(b) in [11]. We conjecture it is because the metallic
Fig. 6. The screenshots of the video taken from the $360^\circ$ camera at the Rx truck, with the center being $0^\circ$ in azimuth, the left edge being $180^\circ$, and the right edge being $-180^\circ$.

Trailer at the Rx blocks the paths that could have reflected or diffracted from the static scatterers behind the Rx. Between 1790 s and 1805 s, the Rx approaches the intersection as shown in Fig. 6(b), and meanwhile the Tx also starts slowly driving forward as well. As a result we observe an increase of angular spread and Doppler spread in Figs. 9-11 during this period of time.

From 1805 s to 1820 s Tx speeds up and drives towards Rx after the traffic light turns green, which leads an increase of Doppler and a decrease of delay for the dominant SPs in Figs. 8 and 11. Between 1815 s and 1820 s the Tx passes the Rx in the opposite lane as shown in Fig. 6(c). The results also track and reflect well this rapid change of channel response in Figs. 9-11, where we can observe a sudden change in both azimuth DoD and DoA for the LOS component, which also explains the rapid decrease of Doppler for strong SPs. Meanwhile the strong reflection from the metallic trailers appears to “meet” the LOS component and they converge to $100^\circ$ in azimuth DoD and DoA, which also agrees with the geometric relations. After 1820 s Tx truck and Rx truck pass each other, and we can observe the approximately 35 dB attenuation of the received power because of the position of metallic trailers, as shown in Fig. 7.

IV. CONCLUSION

In this paper we report the first T2T MIMO channel measurement using a real-time MIMO channel sounder at 5.9 GHz, and present the analysis for a route located in downtown Los Angeles where two trucks drive towards each other. We present a double-directional characterization of the T2T channel based on an HRPE algorithm. Particularly we highlight the impact of the metallic trailer, who acts as a strong reflector in LOS conditions and greatly attenuates the signal when two trucks pass each other.

In the future we plan to analyze other scenarios such as urban, suburban and highway. We also will characterize the important scenario where trucks drive in a convoy formation along the same direction.
ACKNOWLEDGMENT

The authors would like to thank Caltrans and MRI for providing the financial support, and thank Aditya Sundar, Vinod Krishem, Daoud Burghal and He Zeng for efforts in helping the measurement campaign. The work of O. Renaudin was mostly done during a PostDoc at USC, which was partly funded by Belgian Fonds Spécial de la Recherche Scientifique (FRS).

REFERENCES