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Impact of a Truck as an Obstacle on Vehicle-to-Vehicle Communications in Rural and Highway Scenarios

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***Abstract*—Shadowing from other vehicles can degrade the performance of vehicle-to-vehicle communication systems significantly. It is thus important to characterize and model the influence of common shadowing objects like trucks in a proper way. However, the scenario of a truck as an obstacle in highly dynamic rural and highway environments is not yet well understood. In this paper we analyze the distance dependent path loss and the additional shadowing loss due to a truck through dynamic measurements. We further characterize the large scale fading and the delay and Doppler spreads as a measure of the channel dispersion in the time and frequency domains. It has been found that a truck as an obstacle reduces the received power by 12 and 13 dB on average, for roof antennas, in rural and highway scenarios, respectively. Also, the dispersion in time and frequency domains is highly increased when the line-of-sight is obstructed by the truck.**

Keywords—Vehicle-to-Vehicle, Channel Modeling, Shadowing, Truck, Obstruction, Large Scale Fading, Multiple Antennas, Diversity

I. Introduction

Vehicle-to-Vehicle (V2V) communications have been introduced, and standardized (IEEE 802.11p, WAVE) [1], in order to reduce accidents and enhance the driving experience. The functionality is achieved by exchanging cooperative road safety, traffic efficiency and other location awareness messages [2] in an ad-hoc configuration in the 5.9 GHz band. V2V is extremely beneficial in the situations where the visual line-of-sight (LOS) is obstructed by buildings or other taller vehicles. In such an obstructed-LOS (OLOS) situation scattering from the nearby objects, e.g., traffic signs, trucks and bridges, enables signal reception. Due to scattering and absence of a strong LOS component, which carries most of the power when available, the root mean square (RMS) values of delay and Doppler spreads tend to be very high and the power is spread out in both the time and frequency domains [3]. Thus, building reliable transceivers that can handle such a dynamic and lossy channel, is one of the biggest challenges in V2V communications.

New channel models have been developed and parametrized for vehicular communications based on the two-ray ground reflection model and simple path-loss models, mostly for LOS situations [4]. The effect of vehicles as physical obstructions is often disregarded in the models. There are a few studies, which investigate this impact based on theoretical considerations as well as on measurements. Meireles et al. in [5] aim to clarify the validity of this simplification, that the effect of vehicles as physical obstructions is often disregarded, in parking lot, highway, suburban and urban canyon environments. Detailed measurements in a parking lot were also reported in [6]. The conclusion is drawn that a single vehicular obstacle can cause an additional loss between 10-20 dB in the received signal strength. Boban et al. in [7], investigated further the impact of vehicles as obstacles and presented a model verified by experimental measurements that satisfies accurate positioning, realistic mobility patterns, realistic propagation characteristics and manageable complexity. A measurement-based shadow fading model based on real traffic measurements performed in urban and highway scenarios is then developed by Abbas et al. in [8], for V2V network simulations. An additional attenuation of about 10 dB, a value similar to the previous studies, was experienced on average due to obstructing vehicles. The importance of the vehicle type in the shadowing distribution is also highlighted by Segata et al. in [9]. Obstruction by a truck is investigated in terms of RF link range and packet error rate (PER) by Gallagher and Akatsuka in [10]. It has been found that the PER increases in average by 52.7 % for an average distance of 144.2 m when the transmitted power decreases from 29 dBm to 20 dBm. All of these studies considered single antenna systems, with roof mounted antennas only.

To the authors' best knowledge, besides [10] which investigates mainly packet error rate, there is no study available investigating the impact of OLOS on time-frequency selective properties as well as on multi-antenna systems with diversity arrangement, i.e., when antennas are mounted at different locations on a car. This paper deals with these aspects, where a truck is used as an obstacle in a controlled way in a highly dynamic environment. The contribution of this paper is parametrization of the path loss, shadow fading, delay-Doppler spreads, and the additional loss as a function of distance between TX and RX, that a system will exhibit when a truck acts an obstacle in rural and highways scenarios. In this paper it has been seen that sudden shadowing from a truck can cause an additional mean loss of 9-13 dB depending on the antenna location and selected scenario. In-depth characterization of the

Fig. 1: The two cars at TX/RX and the truck as obstacle used in the measurements. The total truck length was 980 cm with a container width of 260 cm and height of 400 cm from the ground.

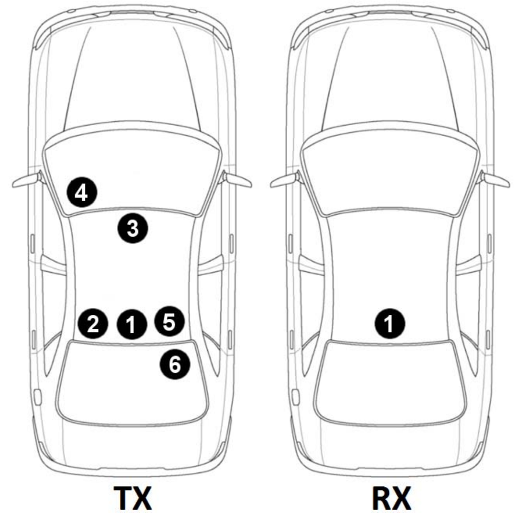


Fig. 2: Antennas placement on the TX and RX cars. **TX:** Antennas 1, 2, 3 and 5 were omni-directional shark-fin antennas mounted on the roof of the car. Antennas 4 and 6 were omni-directional antennas mounted inside of the front and rear windshields respectively. **RX:** A single omni-directional antenna was mounted on the roof of the car.

OLOS situation, with a truck as an obstacle, is very important as it may occur often in real traffic.

The paper is organized as follows: In section II the channel measurements including measurement setup and selected scenarios are described in detail. In section III, the results are presented and discussed. Among the results there is path-loss modeling, characterization of the loss due to shadowing from the truck, description of the large scale fading and plots of the root mean square (RMS) delay and Doppler spreads. Finally, in section IV, conclusions are presented.

II. Measurements

Measurements were conducted in the surroundings of the city of Lund, Sweden. Two cars acted as transmitter (TX) and receiver (RX) and one truck as an obstacle. GPS coordinates and videos were recorded from each vehicle. The participating vehicles can be seen in Fig. 1. Two major measurement scenarios were considered: Rural and Highway. For each scenario there were both line-of-sight (LOS) and obstructed line-of-sight (OLOS)[1] short term (ST) and long term (LT) measurements.

A. Measurement Setup

Multiple-input single-output (MISO) measurements were performed by collecting channel transfer functions $H(f, t)$ for each TX - RX antenna pair based on the switched-array principle, using the RUSK LUND channel sounder [11]. The TX car incorporated 6 antennas while the RX car incorporated a single roof antenna. On the TX four antenna elements were mounted on the roof and two additional antennas were mounted inside the vehicle, at the front and rear windshields, in order to analyze the possibility of having hidden antennas inside the car. The antennas were mounted as seen in Fig. 2. The most important measurement parameters are shown in Table I.

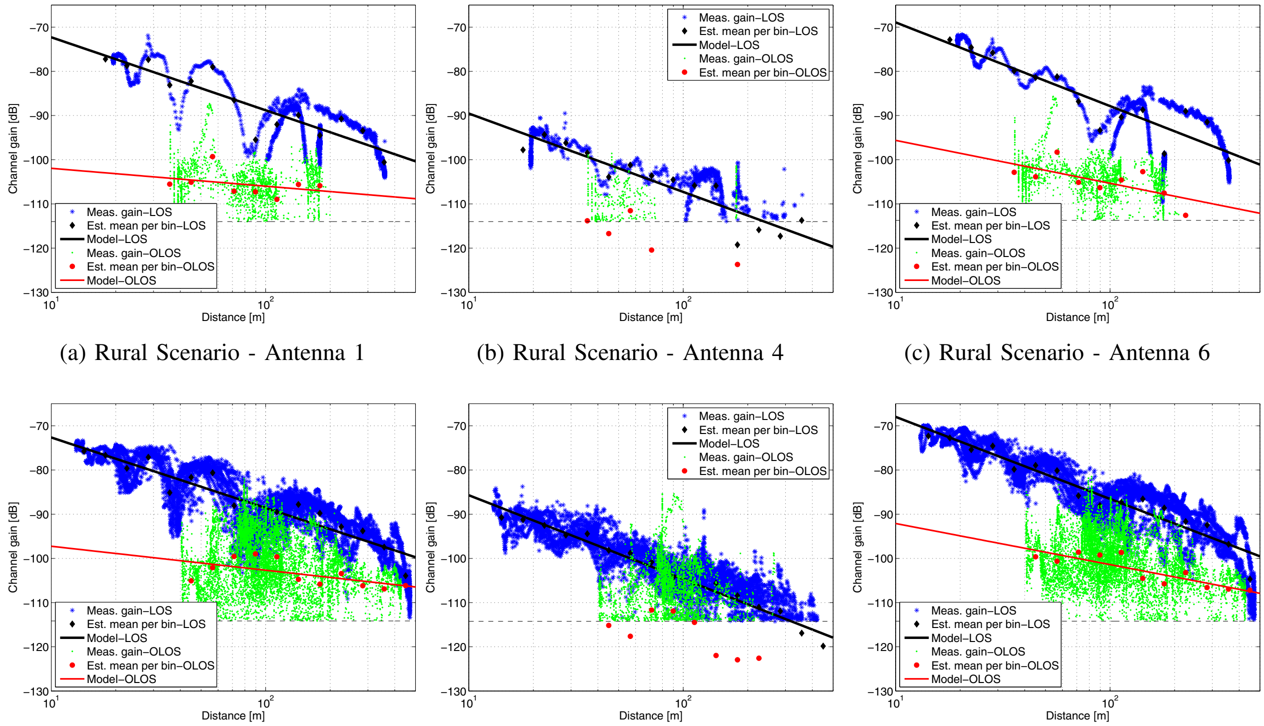
TABLE I: Measurement Parameters

Parameter	Value
Center frequency, f_c	5.75 GHz
Bandwidth, B	200 MHz
Test signal length, $\tau_{\max}$	3.2 μs
Time between snapshots, $t_{\rm rep}$	268.8 μs (ST), 93 ms (LT)
Number of samples in time, N_t	65000 (ST), 120000 (LT)
Number of samples in frequency, N_f	641
Recording time, $t_{\rm rec}$	18 s (ST), 563 s (LT)
Number of TX antennas	6
Number of RX antennas	1
TX antenna height	145 cm (roof), 135 cm (windshield)
RX antenna height	160 cm (roof)

All the antenna elements were omni-directional in the azimuthal plane, but the antenna pattern after mounting them is certainly not. This is important when investigating which antenna positions are the most appealing for different traffic scenarios. Abbas et al. in [12] have shown that the best reception performance can be obtained by combining antennas with complementary properties, e.g., a roof and a bumper antenna. In this paper we do not investigate bumper antennas but a comparable diversity gain is expected from the windshield antennas since they experience similar shadowing properties to some degree.

While many measurements were performed, only a few were selected for the analysis in this paper. In the paper we have used measurements with a high dynamic range, which was determined by visual inspection of power delay profiles and the video recordings from within the vehicles.

[1]OLOS is defined as the situation were the truck was purposely placed in-between the RX and TX during measurements.



(a) Rural Scenario - Antenna 1 (b) Rural Scenario - Antenna 4 (c) Rural Scenario - Antenna 6

(d) Highway Scenario - Antenna 1 (e) Highway Scenario - Antenna 4 (f) Highway Scenario - Antenna 6

Fig. 3: Channel gain for each antenna for the rural and highway scenarios and the best path-loss fit in a least-squares sense [13]. The estimated bin-mean values are plotted for each dataset according to [14].

B. Scenario Description

Two scenarios were considered during these measurements; Rural and Highway. There were 16 measurements taken in total.

1) Rural Scenario: The rural scenario took place on Odarslövsvägen (55°44'07.7"N, 13°15'46.3"E). The average speed was 19.4 m/s (70 km/h). It consisted solely of short term measurements. All measurements were conducted in a convoy formation where the TX was in the front, the RX was in the back and the truck was in the middle whenever present. Rural measurements were conducted as reference measurements in an environment where few or no scatterers are present. Odarslövsvägen is characterized by low traffic and wide open fields. Houses are few and distant, 100-200 m from the road. Such a poor scattering environment is expected to provide clear and controlled measurements with the only multipath components arising either from the line-of-sight or the diffraction around the truck.

2) Highway Scenario: The highway scenario took place on E22 in both the North and South directions outwards from Lund. The average speed was 25 m/s (90 km/h). It consisted of 7 short term and 2 long term measurements. Of those, 4 were LOS and 5 were OLOS measurements. E22 is a European highway characterized as a road with low to heavy traffic, guard rails on its outer edges, separating concrete blocks, bridges and other structures. These measurements are expected to characterize a rich scattering environment.

III. Results and Discussion

The subsequent analysis will include only three TX antennas 1, 4 and 6. There are three main reasons that these three antennas are preferred over others. First, the antennas 1, 2, and 3 on the back of the roof are all highly correlated, which is concluded by looking at the channel gains, however antenna 1 is the best antenna from a design point of view and it also gave the best results in most of the cases among the three located at the back of the roof. Most modern vehicles already have a shark fin antenna installed there for other wireless applications (GPS, LTE/WCDMA/GSM). Second, antennas 3 and 4 exhibit similar behavior, where as reception at antenna 4 is the best among the two due to multipath components that arrive from the front of the car. Finally, antenna 6 is the one that complements antenna 4 and in turn provides a significant diversity gain compared to each other. Therefore, antenna 4 and 6 together can be used as a multi-antenna solution with complementary arrangement.

All losses from cables and channel sounder equipment were measured prior to these measurements. Therefore all gain values that are presented here are from TX antenna switch to RX antenna. Similar cables were used between switch and antenna connectors, thus any changes in the gain are only due to the effect of the channel.

A. Path Loss

Since the measurements were conducted in a controlled environment, it was easy to separate LOS and OLOS situations. However, sometimes other vehicles interrupted LOS momentarily. By inspection of video recordings from inside the vehicles, those interruptions were considered as OLOS during the analysis.

The channel gain is plotted in Fig. 3 as a function of distance for both LOS and OLOS. The path loss is modeled using log-distance power law given as,

$$P(d) \quad = \quad P_{d_0} - 10nlog_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (1)$$

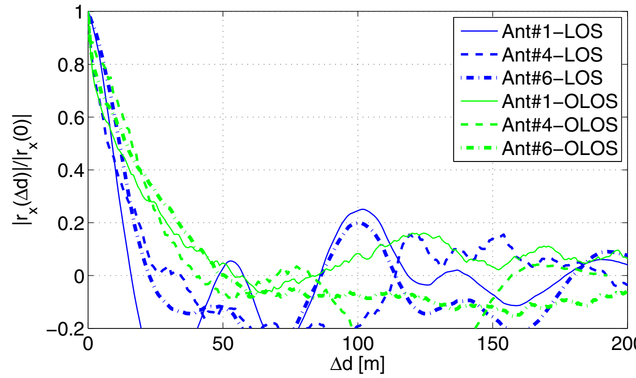
where $P(d)$ is the received power at a given distance d. The path-loss exponent n and channel gain P_{d_0} at 10 m reference distance, which give deterministic value of path loss, were estimated by fitting equation (1) to both the LOS and OLOS datasets using linear regression in the least square sense. X_σ is the large scale fading on top of the deterministic path loss, which is zero mean Gaussian random variable with some time correlation. The standard deviation (σ) of the large scale fading is estimated by subtracting the distance dependent path loss from the channel gain data and looking at the distribution properties of the remaining Gaussian dataset. As evident from Fig. 3, the channel gain due to poor channel conditions momentarily falls below noise threshold at certain distances. Since the exact count of the data points below noise threshold is known, we can easily estimate the standard deviation from incomplete data via expectation maximization (EM) by using a broadly applicable algorithm presented in [14], [15] that iteratively computes maximum likelihood estimates (MLE). The estimated parameters can be found in Table III. Path loss was not modeled for the OLOS case of antenna 4 since most of the data is below the noise floor and such an estimation would not be accurate. However the estimated bin-mean values are still presented as a reference as seen in Fig. 3.

The expected critical distance breakpoint due to two-ray ground reflection model where the path loss exponent is equal to 4 according to theory could not be clearly observed here. Thus it was not taken into consideration as one single slope seems to fit the data well in both the LOS and OLOS cases. However, the power received adjacent to the truck in the OLOS case is quite low in comparison with the power received at a small distance from the truck. That causes the path-loss exponent n to be quite small for the OLOS cases.

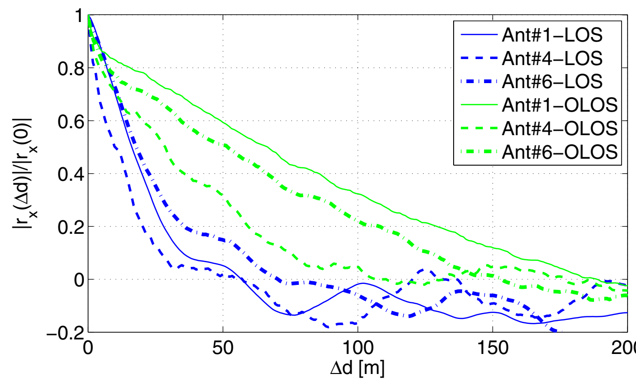
Another interesting fact is that the highway scenario exhibits a higher gain for the OLOS case in comparison to the rural scenario. That is due to a rich scattering environment with guard rails, separating concrete blocks, bridges and other structures, with multipath components arising from more sources than solely diffraction around the truck. This behavior can be observed in Fig. 3 as well as in Table II.

B. Large Scale Fading

The large scale fading was modeled as a Gaussian random variable with mean equal to zero and standard deviation σ. The results can be found in Table III. Since the distance dependent mean path loss is already subtracted from the data, the large scale fading can assumed to be a stationary time series whoes joint distribution does not change over time. The spatial correlation of the large scale fading, which is also an interesting parameter to investigate, can then be obtained by an auto-correlation of this time series as:



(a) Rural scenario.



(b) Highway scenario.

Fig. 4: Spatial correlation of large-scale fading in rural and highway scenarios.

$$r_x(\Delta d) = E\{X_\sigma(d)X_\sigma(d + \Delta d)\} \qquad (2)$$

The spatial correlation of the shadow fading is shown in Figs. 4a and 4b. From the figures it can be seen that the spatial correlation in the OLOS situation is higher than that in the LOS situation. It is mainly due to the difference in underlying propagation mechanisms, i.e., the measured path loss in the LOS, follows the two-ray ground reflection model that results in fluctuations in the power at regular distance intervals for the distances below breakpoint distance. However, that is not the case in OLOS in which the measured path loss is more random with larger variations than that in LOS and it does not follow the two-ray ground reflection model either. Moreover, the spatial correlation in the highway scenario is higher than that in the rural scenario because of differences in the scattering environment, e.g., on the highway, in contrary to the rural scenario, there are several scattering objects such as road signs and overhead bridges that provide strong specular reflections and in turn better received power as long as they are visible to both TX and RX.

The shadow fading correlation can be modeled by a well known analytical model by Gudmundson [16], which is a simple negative exponential function,

$$r_x(\Delta d) = e^{-|\Delta d|/d_c} \qquad (3)$$

where Δd is equally spaced distance vector and d_c is the decorrelation distance at which the value of the auto-correlation function is equal to e^{-1}. The d_c distance for both scenarios is specified in Table III.

C. Shadowing Loss

The loss due to shadowing from the truck, which is a function of distance between the TX and RX, was calculated by subtracting the mean path loss in LOS from the OLOS dataset. As an example, the resulting dataset for one of the antennas can be seen in Fig. 5. It was found that it can be described as a Gaussian random variable with a mean μ_{loss} and a standard deviation σ_{loss}. Those values are reported in Table II for each TX - RX antenna pair.

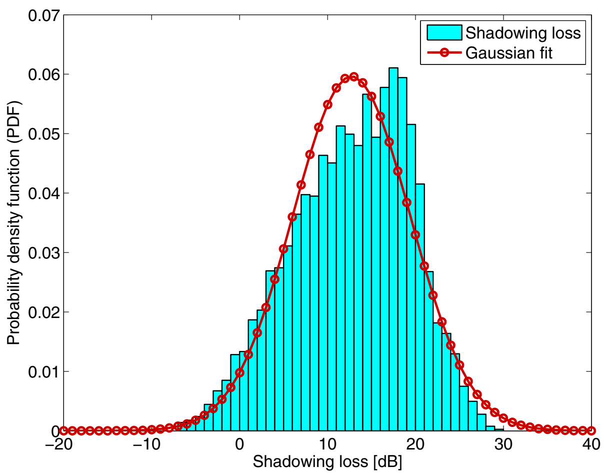


Fig. 5: Shadowing loss due to the truck for antenna 1 in the highway scenario.

TABLE II: Shadowing Loss, $L_{shadow} \sim \mathcal{N}(\mu_{loss}, \sigma^2_{loss})$

	Rural			Highway		
Antenna	A1	A4	A6	A1	A4	A6
μ_{loss} [dB]	11.9	10.0	8.9	12.7	10.7	10.8
σ_{loss} [dB]	5.2	6.2	5.0	6.7	6.0	6.0

D. RMS Delay and Doppler Spreads

The RMS delay and Doppler spreads are measures of the channel dispersion in the time and frequency domains respectively. By looking at Figs. 6a and 6b one can conclude that both the RMS delay and Doppler spreads increase for the OLOS case. Moreover, one can see that antenna 4 behaves differently in comparison to antennas 1 and 6. That is due to the fact that it is shadowed by the body of the car itself and no dominant multipath component is arriving at antenna 4.

TABLE III: Analyzed Parameters. Values for P_{d_0} and n are not included for antenna 4 due to the fact that most of the samples were below the noise floor, thus they were not modeled as seen in Fig. 3.

		LOS			OLOS		
	Antenna	A1	A4	A6	A1	A4	A6
Rural	P_{d_0} [dB]	-72.3	-89.6	-68.9	-101.9	——	-95.6
	n	1.65	1.77	1.89	0.41	——	0.97
	σ [dB]	3.9	8.4	4.9	5.4	13.9	5.1
	d_c [m]	10.1	11.3	13.6	16.8	20.2	21.0
	$\mu_{\tau_{rms}}$ [ns]	8.0	8.0	8.0	23.1	23.1	23.1
	$max_{\tau_{rms}}$ [ns]	331.5	702.0	97.5	651.7	604.6	645.6
	$\mu_{\nu_{rms}}$ [Hz]	13.8	47.2	13.2	12.1	1.3	8.1
	$max_{\nu_{rms}}$ [Hz]	375.7	816.0	167.7	281.1	14.1	261.6
Highway	P_{d_0} [dB]	-72.6	-85.7	-68.0	-97.2	——	-92.1
	n	1.60	1.90	1.86	0.54	——	0.93
	σ [dB]	4.4	7.9	4.0	7.3	17.0	6.5
	d_c [m]	20.5	14.3	24.0	89.0	40.9	69.5
	$\mu_{\tau_{rms}}$ [ns]	9.9	9.9	9.9	24.7	24.7	24.7
	$max_{\tau_{rms}}$ [ns]	304.6	595.2	388.6	620.3	545.8	581.0
	$\mu_{\nu_{rms}}$ [Hz]	24.8	45.2	28.9	44.2	117.1	52.9
	$max_{\nu_{rms}}$ [Hz]	353.7	534.3	361.1	789.9	737.4	712.6

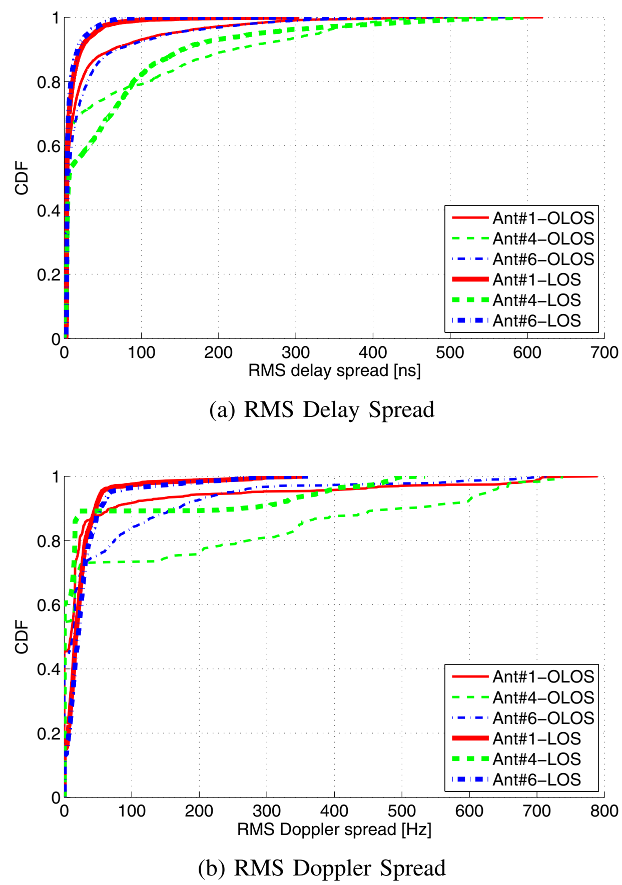


Fig. 6: RMS Delay and Doppler spreads for LOS and OLOS for all antenna pairs.

IV. Summary and Conclusions

Vehicular communications in rural and highway scenarios often experience power degradation due to the shadowing effect from other vehicles. Previous work has been done in this subject [5], [6], [7], [8], [9], [10]. However, to the authors' best knowledge, the scenario of a truck as an obstacle in a controlled highly dynamic environment hasn't been investigated in-depth before. This paper considers that scenario. Additional losses of 12 and 13 dB have been found for the antenna with the best placement, from a channel and design point of view, in rural and highway scenarios respectively when shadowed by a truck, confirming previous results.

Switched array 1x6 SIMO measurements were performed with the RUSK LUND channel sounder. The rural scenario took place in a poor scattering environment with wide open fields. The highway scenario took place on a busy European highway with many scatterers.

The analysis includes three different antenna placements. The path loss was modeled for each antenna pair individually. Losses due to the shadowing of the truck were also characterized. The large scale fading distribution and auto-correlation were also described. The RMS delay and Doppler spreads were given as measures of channel dispersion in time and frequency domains respectively. It can be concluded that the dispersion of the channel in both the time and frequency domains increases for the OLOS case.

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