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V2X Large Vehicle Shadowing at 3.5 GHz Compared to 5.9 GHz

Ignacio Rodriguez¹, Troels B. Sørensen¹, Mads Lauridsen², Erika P. L. Almeida², and Preben Mogensen^{1,2}

¹Wireless Communication Networks Section, Department of Electronic Systems, Aalborg University, Denmark, irl@es.aau.dk

²Nokia Bell Labs, Aalborg, Denmark

Abstract—This paper presents a measurement-based comparison of large vehicle shadowing at 3.5 and 5.9 GHz. Obstructed line-of-sight measurements were performed for both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) scenarios in a controlled environment. The results show how the V2I scenarios with elevated transmit antenna positions can benefit from a 2-6 dB smaller shadow loss as compared to the V2V scenarios. Due to the smaller diffraction loss experienced at 3.5 GHz, the maximum shadow levels can be up to 2-3 dB smaller than at 5.9 GHz. The absolute numbers and empirical distributions provided can be used in system level evaluations of vehicle-to-everything (V2X) and vehicle-to-network (V2N) vehicular communication scenarios.

Index Terms—vehicular networks, radio propagation, measurements, shadowing.

I. INTRODUCTION

Autonomous driving and intelligent transport systems (ITS), where vehicles coordinate their own movement with the infrastructure and with the movements of other vehicles via wireless communication, are expected to be a great revolution in road transport. In order to ensure safety and efficiency, vehicular networks will have to cope with very strict requirements in terms of latency and reliability [1], [2]. Thus, the design, evaluation and optimization of these networks need to be based on a detailed and accurate radio channel characterization. In this respect, while vehicle-to-vehicle (V2V) communications have been extensively studied and characterized from a radio propagation perspective, the vehicle-to-infrastructure (V2I) scenario has received less attention [3]. V2I scenarios with elevated transmitter positions may be less prone to vehicle shadowing, as opposed to the V2V case. However, due to the stringent requirements, even the shortest disruption of the vehicular communication link could be an issue. As non-line-of-sight (NLOS) conditions created by large vehicles, buildings and vegetation have been identified as the most critical issue [3], it is clear that an accurate characterization of the shadowing phenomena in vehicular scenarios is necessary [4].

In this paper, the shadow loss caused by large vehicles is empirically investigated in controlled environment emulating a 4-lane road scenario for different V2V and V2I configurations. Measurements were simultaneously performed at 3.5 GHz and 5.9 GHz in order to jointly evaluate the main frequency carriers targeted to providing 5G V2N (vehicle-to-network) eMBB (enhanced mobile broadband) media services along



Fig. 1. Measurement scenario and setup with stationary TXs deployed at 1.5 m (V2V configuration), 5 and 7 m (V2I configuration), large vehicle obstacle (truck), and moving RX at 1.5 m.

with virtual or augmented reality services (3.5 GHz) [5]; as well as the standard V2X (vehicle-to-everything) and 802.11p road safety and traffic efficiency applications (5.9 GHz) [6].

The rest of the paper is organized as follows: Section II describes the different aspects of the measurement campaign, and Section III provides details about the data processing. Section IV presents a selection of measurement results. The specifics on the shadowing distributions are addressed in Section V. Finally, Section IV concludes the paper.

II. MEASUREMENT SCENARIO AND SETUP

In our previous work [7], we designed a measurement campaign to study the effects of large vehicle shadowing. The extensive measurements were performed in a controlled environment (Fig. 1) with stationary transmitters (TX) emulating road side units (RSU) deployed at 1.5 m, 5 m and 7 m height (h_{TX}), a stationary truck (the large vehicle) with dimensions 8x2.6x3.6 m (length x width x height), and a moving receiver (RX) at 1.5 m (emulating a car roof antenna). The controlled environment resembled a 80 m long section of a typical vehicular scenario in any European country, with 4 lanes (2 lanes per driving direction) with a width of 3.5 m per lane. Different V2V and V2I configurations were explored by re-deploying the transmitters and the obstacle truck in different positions. By doing this, diverse obstructed link geometries were created, resulting in several distinct shadowing conditions.

TABLE I

MEASUREMENT SETUP CONFIGURATION DETAILS INCLUDING EXACT CW FREQUENCY ALLOCATIONS, TX POWER (P_{TX}), CABLE LOSS AT TX SIDE ($L_{c,TX}$), TX ANTENNA GAIN (G_{TX}), RX ANTENNA GAIN (R_{TX}), CABLE LOSS AT RX SIDE ($L_{c,RX}$), SENSITIVITY OF THE RX (S) AT 5 dB SNR, AND TOTAL MEASURABLE PATH LOSS (PL_{max}).

Frequency	CW allocations	TX: NI USRP-2953R			RX: R&S TSMW			PL_{max}
		P_{TX}	$L_{c,TX}$	G_{TX}	G_{RX}	$L_{c,RX}$	S	
3.5 GHz	3400-3407 MHz	+10 dBm	1.7-5.8 dB	2.6 dBi	5.5 dBi	1.5 dB	-115 dBm	126-130 dB
5.9 GHz	5800-5807 MHz	+10 dBm	1.9-7.7 dB	3.5 dBi	6 dBi	1.8 dB	-115 dBm	125-131 dB

Each of the transmitters was equipped with two independent RF continuous-wave (CW) branches, one per carrier frequency (3.5 GHz and 5.9 GHz), with collocated antennas. Measurements were performed by driving the receiver along each of the 4 lanes recording simultaneously the signal strength received from the different transmitters. The antennas used at both TX and RX sides were omnidirectional and vertical-polarized. Additional details on the measurement setup, system calibration and exact frequency allocations are given in Table I.

A total of 11 TX positions (displayed as black circles in Fig. 2) were considered in the study. Each of the positions, with different distances to the road and incident angles on the truck, was independently tested with the truck located in the central part of lanes 1, 2 and 3 (displayed as a black rectangle in Figs. 3 and 4). Altogether, by considering the 11 TX positions, the 3 obstacle truck positions, and the 3 TX antenna height combinations, the measurement examined a total of 99 geometrical combinations over the complete 4-lanes test area, simultaneously for both of the carrier frequencies.

It should be noted that our previous paper [7] focused on the analysis of the measurement results on 5.9 GHz only, so we put the focus of this paper on presenting some of the 3.5 GHz measurement results and performing a comparison between them. As it has been detailed above for the measurement collection, and as it will be detailed in the next section for the data processing, the procedures followed have been exactly the same for both frequencies.

III. DATA PROCESSING

The received CW power samples measured over each lane were averaged over chunks of 1 m distance (10-20 wavelengths), in order to remove fast-fading effects. At the configured sampling rate, 72 samples/m were available on average, which guarantees an accuracy of ± 1 dB around the true mean [8], [9]. This procedure resulted in measurement sets of 80 samples per lane per frequency. The received power was translated into calibrated path loss by accounting for the reference transmit powers, antenna gains and cable losses in the system. As indicated in Table I, the measurement system offered comparable capabilities at both frequencies of interest, allowing for a maximum measurable path loss (PL_{max}) of approximately 130 dB at both 3.5 GHz and 5.9 GHz.

The shadowing effect was characterized in term of excess path loss (ΔPL), by subtracting the theoretical free space

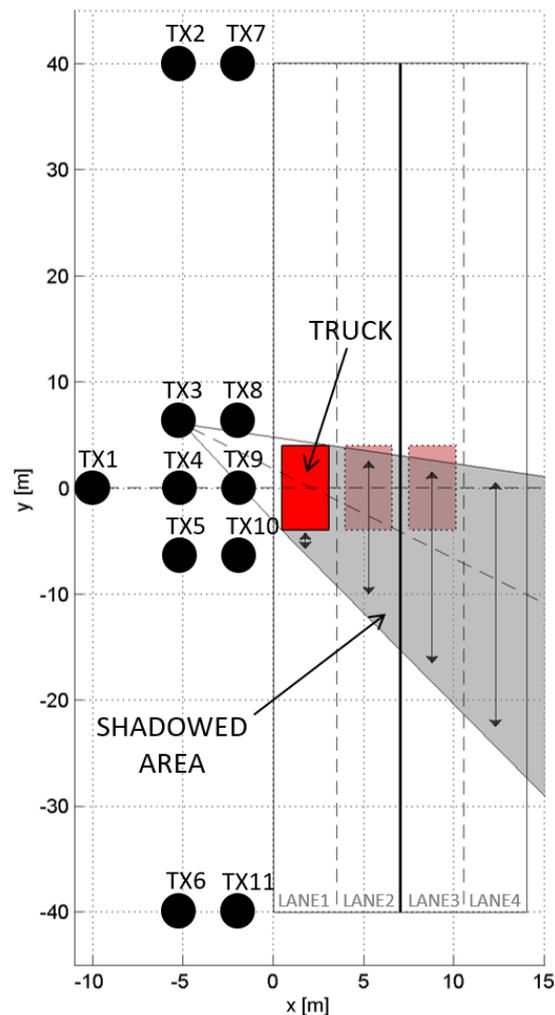


Fig. 2. Overview of the controlled measurement scenario, including the 11 TX positions and the 3 truck positions. The figure exemplifies the 2D geometry of the shadow created by the truck when located on lane 1 for TX 3.

path loss ($FSPL$) reference from the calibrated measured path loss (PL_{meas}), as indicated in (1).

$$\Delta PL = PL_{meas} - FSPL \quad [\text{dB}] \quad (1)$$

By using this metric, a positive excess path loss ($\Delta PL > 0$), would indicate negative contributions to the overall propagation due to blockage caused by the obstacle truck considered in the study. In contrast, a negative excess path loss, which is also physically feasible, would indicate favorable contributions to the overall propagation (e.g. due to reflections on the truck).

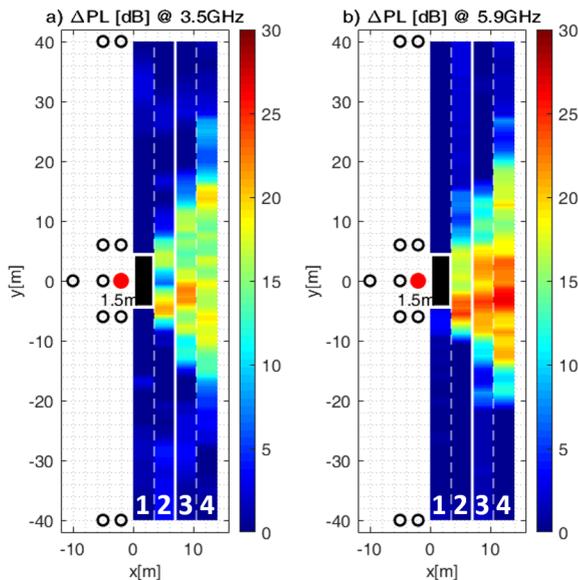


Fig. 3. Comparison of shadowing levels at 3.5 GHz and 5.9 GHz for a selected V2V scenario ($h_{TX} = 1.5$ m, $h_{RX} = 1.5$ m) with the truck (black rectangle centered at $y = 0$ m) located on the first lane.

IV. SELECTED MEASUREMENT RESULTS

In this section, selected 3.5 GHz measurement results are presented and compared with the 5.9 GHz measurements results - previously reported in [7].

Fig. 3 illustrates a selected V2V scenario, where the TX is placed in the closest position right in front of the truck at 1.5 m (red dot). Geometrically speaking, this case is the worst in terms of shadowing for all the 99 combinations, since the area shadowed by the obstacle truck is larger than in any other case. It can be immediately noticed from the heatmap, how the 3.5 GHz case results in lower shadow loss than the 5.9 GHz case. The main propagation mechanism is two diffractions around or over the truck, leading to a maximum shadow loss of 23 dB at 3.5 GHz and 27 dB at 5.9 GHz. It can also be observed in the figure how, in both cases, the shadow loss is less severe in areas close to the truck on the first shadowed lane (lane 2). This is due to some extra positive contributions to the received signal from below the truck via ground reflection between the wheel axes.

Fig. 4 presents the results from a V2I scenario, where the obstacle truck is placed on the second lane and the TX in an elevated position at 5 m, with an interaction angle between the TX and the center truck of approximately 40 degrees in azimuth and 20 degrees in elevation. The figure illustrates the benefits of using an elevated TX position. Compared to the previous case, the shadow impact is reduced both in shadow footprint area and absolute levels (maximum 19 dB for 3.5 GHz and 23 dB for 5.9 GHz). In this case, diffraction over the truck is the main propagation mechanism, and no strong reflection below the truck is observed.

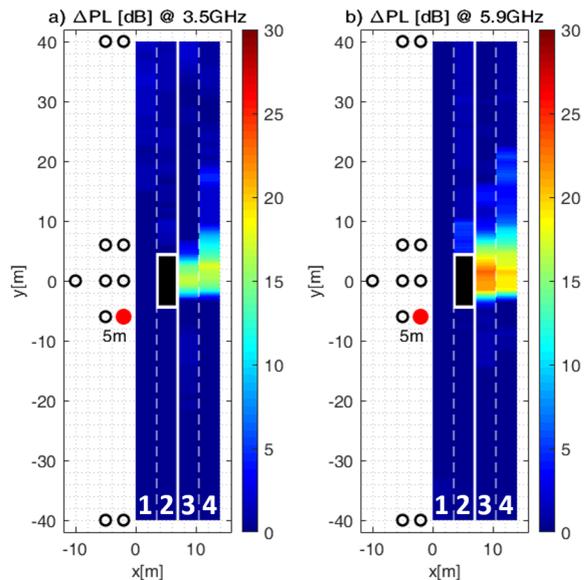


Fig. 4. Comparison of shadowing levels at 3.5 GHz and 5.9 GHz for a selected V2I scenario ($h_{TX} = 5$ m, $h_{RX} = 1.5$ m) with the truck (black rectangle centered at $y = 0$ m) located on the second lane.

V. EMPIRICAL SHADOWING DISTRIBUTIONS

The shadow loss cumulative density function (CDF) as a function of transmitter height and carrier frequency is presented in Fig. 5. Each CDF has been calculated for a given antenna height configuration, by grouping the data obtained for the 33 geometrical combinations of transmitter and obstacle truck positions. As illustrated in the figure, in case of being shadowed by a large vehicle, the impact is more significant for the V2V scenario than for the V2I scenario; and for 5.9 GHz compared to 3.5 GHz. For example, by considering a shadowing threshold of 12 dB as a reference, the probability of experiencing higher shadowing is approximately 34% at 3.5 GHz and 42% at 5.9 GHz for the V2V scenario. For the V2I scenario with elevated TX antennas, this probability is significantly reduced to 22% at 3.5 GHz and 30% at 5.9 GHz with TX antennas at 5 m, and to only 13% for 3.5 GHz and 17% at 5.9 GHz with TX antennas at 7 m. On average, V2I communication scenarios with elevated antennas presents a gain of 2-6 dB in comparison with the V2V scenario.

For quick reference, Table II summarizes the median (50%-ile) and higher percentiles (90%-ile and 99%-ile) values for the different cases. It is important to note that the shadowing is highly correlated between these two frequencies. While the distributions at 3.5 GHz and 5.9 GHz are very similar up to their median values; a clear difference is observed for the higher percentiles. The results indicate that, frequency-wise, in bad geometrical conditions, shadowing can be up to 2-3 dB smaller at 3.5 GHz in comparison with 5.9 GHz. The average inter-frequency cross-correlation factors (ρ), close to 0.8 in all cases, have been included in the table as well.

TABLE II
LARGE OBSTACLE SHADOWING (ΔPL) 50%-ILE, 90%-ILE, AND 99%-ILE VALUES AT 3.5 GHz AND 5.9 GHz AND INTER-FREQUENCY SHADOWING CROSS-CORRELATION (ρ) FACTORS FOR THE DIFFERENT V2V AND V2I SCENARIOS.

h_{TX}	ΔPL , 50%-ile		ΔPL , 90%-ile		ΔPL , 99%-ile		ρ
	3.5 GHz	5.9 GHz	3.5 GHz	5.9 GHz	3.5 GHz	5.9 GHz	
1.5 m (V2V)	9.4 dB	9.6 dB	18.5 dB	20.6 dB	23.5 dB	26.8 dB	0.81
5 m (V2I)	6.9 dB	7.5 dB	14.9 dB	17.3 dB	20.7 dB	23.9 dB	0.80
7 m (V2I)	4.5 dB	4.7 dB	12.8 dB	14.9 dB	18.6 dB	21.8 dB	0.77

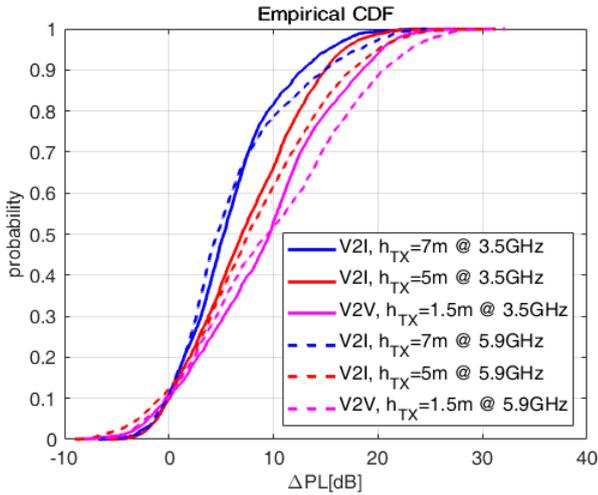


Fig. 5. Shadow loss probability as a function of transmitter antenna height and frequency for the different V2V and V2I scenarios at 3.5 GHz and 5.9 GHz.

The reported observations and values can be useful for consideration and implementation in system-level simulators targeting the simultaneous evaluation of 3.5 GHz V2N and 5.9 GHz V2X systems supporting the design of reliable ITS vehicular communication systems based on the requirements detailed in [1], [5], [6].

VI. CONCLUSION

In this paper, a measurement-based comparison of large vehicle shadowing at 3.5 GHz and 5.9 GHz was presented for various V2X/V2N configurations. The measurements, covering 99 different geometrical combinations of a 4-lane road scenario with different transmitter positions, antenna heights and large obstacle locations, were performed simultaneously for both frequencies. From the measurement results, realistic shadow levels and statistical distributions were provided, quantifying the potential benefits of using infrastructure with elevated transmitter antenna positions in the vehicular scenarios. The use of frequencies around 3.5 GHz could improve the robustness of the links by 2-3 dB compared to frequencies around 5.9 GHz.

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