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Usability Benefits and Challenges in mmWave V2V Communications: A Case Study

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Abstract—Recently, an active discussion on the feasibility of Millimeter Wave (mmWave) frequencies for the Vehicle-to-Vehicle (V2V) communication have been carried out in research community. We contribute to this discussion by providing a comparison between explicit three-dimensional ray-tracing simulations and field trial measurements on 39 GHz frequency. Three basic practical and relevant cases for V2V communications are considered covering several important scenarios of daily life traffic. A close match between the measured and simulated results is found through explicit ray tracing simulations; thus validating the feasibility of the simulation model and underlying assumptions. Moreover, these outcomes also shed light on the potential and challenges of using mmWave frequencies for V2V communication. The acquired results indicate that the Reference Signal Received Power (RSRP) levels are sufficiently above the noise level even up to 100 m distance between TX and RX in case of a single obstructing car. Results also reveal the impact of moving vehicle intersecting the LOS between the TX and RX vehicle at road intersection, and they indicate a notable blockage loss in case of short TX-RX separation.

Index Terms—V2V; mmWave; 5G, Ray tracing.

I. INTRODUCTION

Within the framework of Intelligent Transportation Systems (ITS) the concept of connected vehicles have long been promoted as a solution to enable better passenger safety, efficient traffic management and a smaller environmental impact. Recently wireless communication standardization organizations have also become active in this field: standards have been developed to support Vehicle-to-Everything (V2X) communications. Namely, the 3rd Generation Partnership Project (3GPP) standardization organization came up with Cellular V2X (C-V2X) based on Long Term Evolution (LTE) in Release 14 [1]. C-V2X comprises of two parts: The first part, known as Direct Communications, serves the basic safety related requirements of V2X. The second part of C-V2X is the Vehicle-to-Network (V2N) communication involving the cellular networks for providing add-on services with support for a wide area coverage and cloud-based applications [2], [3]. Similarly does, the IEEE 802.11p standard, which is an amendment to the well known IEEE 802.11 (i.e., WiFi) specification for Physical (PHY) and Medium Access Control (MAC), respectively. The amendments in IEEE 802.11p enable inter-vehicular communications by defining new functions for dynamic environment, controlled by the IEEE 802.11 MAC [4].

V2X applications can be roughly divided into four categories [4], [5]. Infotainment covers typically non-driving related services to driver and passengers, such as e.g. the streaming video. The wireless access to network resources, so V2N, is important for infotainment applications as well as high throughput while latency requirements may not be very stringent in all cases. Traffic efficiency applications include system level features such as traffic flow and car energy consumption control. For traffic efficiency applications the access to network is important. Throughput and latency requirements are moderate. In traffic safety applications the goal is to reduce the number and severity of accidents. Herein the speed of decision making is of high importance and latency requirements are strict while throughput is often relatively low. Thus, highly robust connectivity towards other cars and road users, i.e., V2V and Vehicle-to-Pedestrian (V2P), is gaining momentum, particularly in 5G-based V2X and it will be an important subsequent evolution. The fourth category is the cooperative driving where vehicle operations are coordinated within a group of cars. The latency requirements are strict like in safety applications while throughput needs are moderate or even high in some scenarios. The V2V connectivity is essential for cooperative driving.

A. Towards mmWave V2V communication

The ITS communication frequency bands in Europe are specified by ETSI and they occur between 5855 – 5925 MHz [6]. Especially the ITS-5GA band (5875 – 5905 MHz) have been defined for road safety. Therein the maximum RF output power is set to 33 dBm and the maximum spectral density is limited to 23 dBm/MHz while the maximum channel bandwidth is 10MHz, [7], [8]. It is important to notice that this frequency band is designated for road safety on a non-exclusive and license exempt (unlicensed) basis. This may lead to interference and consequently to communication reliability challenges if both IEEE 802.11p and C-V2X are operated in the same frequency band. On the other hand, if existing band is split between IEEE 802.11p and C-V2X, the frequency resources are quite scarce from many applications point of view. Therefore, one clear option is to apply higher carrier frequencies, i.e. mmWave frequencies (30 – 300 GHz) where large bandwidths can be exclusively allocated to V2X services. Actually, there is an ongoing discussion in 5G Automotive

Association (5GAA) and 3GPP about the actual spectrum needs for advance V2V use cases. Even spectrum access policy, like licensed access is considered. As a consequence, the possibility of using the mmWave spectrum is becoming a relevant option.

In mmWave frequencies the most potential access technology for V2X is the 5G New Radio (NR) that is optimized for beamforming and providing in near future the Ultra-Reliable Low-Latency Communication (URLLC) technology to support e.g. traffic safety and cooperative driving applications [9]. These developments make the 5G forthcoming releases an attractive framework for V2V and V2P communications.

While 5G URLLC may provide feasible access technology solution for time critical applications, the fact is that mmWave channels are vulnerable to blocking [10] where some obstacle between transmitter and receiver block the line-of-sight. To understand the impact of blocking is essential before time critical applications can be developed and applied in mmWave bands. While blocking have been studied to some extent in literature, there are some practical challenges. Blocking depends on the radio environment and the applied frequency. The typical road environment has some widely common characters but e.g. the roadside structures may vary (rails, buildings, trees, etc) impacting to the measured channel and accordingly, to the channel models, see e.g. [11]. Therefore, it is important that channel models and simulations can be verified against practical measurements.

B. Contributions

In this paper the focus is on three practical connectivity scenarios that are related to traffic safety and cooperative driving. Namely, we model first the direct V2V connectivity with and without obstructing vehicles in between the vehicle-mounted transmitter and receiver. Then we model the V2V connection over a crossroad when obstructing vehicle is passing by. These scenarios appear, for example, in collision avoidance, emergency braking and platooning. Simulation results are verified against measurements done in [12]. We apply 39 GHz carrier frequency and the same antenna/transmission parameters as in [12]. The channel simulator is based on a comprehensive ray-tracing model and obtained simulation results are well in line with measurements. This shows that simulations can be used to obtain reliable results for many important wireless connectivity scenarios within V2V communications provided that the modeling of the radio channel and environment is explicit, and realistic link parameters are applied. That is, obtained simulation environment can be used to study in a cost-effective manner many V2V communications scenarios. Results can be also used to e.g. create mapping tables for V2V system level simulations. Finally, results indicate that 39 GHz frequency is feasible for short-range time critical traffic safety and cooperative driving applications but challenges also occur. Blocking by a close-by vehicle can be strong and the roadside structures may impact on the channel reliability.

The remainder of this paper is as follows. In Section II, we present the simulation environment and discuss about the

simulation cases. Section III presents and evaluates the results, and finally the Section IV concludes the paper.

II. MEASUREMENT AND SIMULATION SETUP

This section describes the measurement setup and explains the simulation methodology. It provides detail about the simulation tool, simulation environment, and explains the considered cases.

A. Simulation Tool and Parameters

The focus is on mmWave V2V communications in different traffic scenarios. For the simulation of radio propagation and channel characterization a MATLAB based 3D ray tracing tool were developed by the authors. This tool not only considers the LOS path but it also finds the propagation paths between the TX vehicle and the RX vehicle by using an image theory with a defined number of reflections, diffraction and mix of reflected and diffracted paths. It also considers the ground reflected path. The measurement results were reproduced from [12] by extracting the point values from figures.

We note that it is of immense importance to model the physical environment and to use realistic simulation parameters in order to get accurate results. The reference [12] provides the field measurement results for some test cases, and one of the targets of this paper were to provide the simulation results for test cases of [12]. Therefore, we have considered the same set of parameters for simulations as was used for the measurements. The general simulation and measurement parameters used in this research work are given in Table. I.

TABLE I
GENERAL SIMULATION AND MEASUREMENT PARAMETERS

Parameters	Unit	Value
Frequency	GHz	39
TX power	dBm	23
TX antenna height	m	0.5
TX antenna		Directional
RX antenna height	m	0.7
RX antenna gain	dBi	Omnidirectional 2
Tx antenna model		3GPP extended model
Slow Fading Margin	dB	8

One aim of this work is to verify the communication range of V2V link when utilizing mmWave frequency, i.e. 39 GHz frequency, with basic wide beam antenna at the transmitter side and an omnidirectional antenna at the receiver side. Advanced beamforming techniques provide higher directivity and higher antenna gain but impact of beamforming is left for future studies since in reference measurements a basic antenna with 115° Half Power Beamwidth (HPBW) in horizontal domain and 60° HPBW in vertical domain was used. For simulation purposes the antenna radiation pattern is generated by using the 3GPP antenna model presented in [13]. The antenna radiation modeling parameters i.e. Half Power Beamwidth (HPBW) in horizontal domain (θ_H), HPBW in vertical domain (θ_V), Front to Back ratio in azimuth plane (FBR_H), Side Lobe Level in elevation plane (SLL_V), and antenna maximum gain (A_M) are provided in the Table. II.

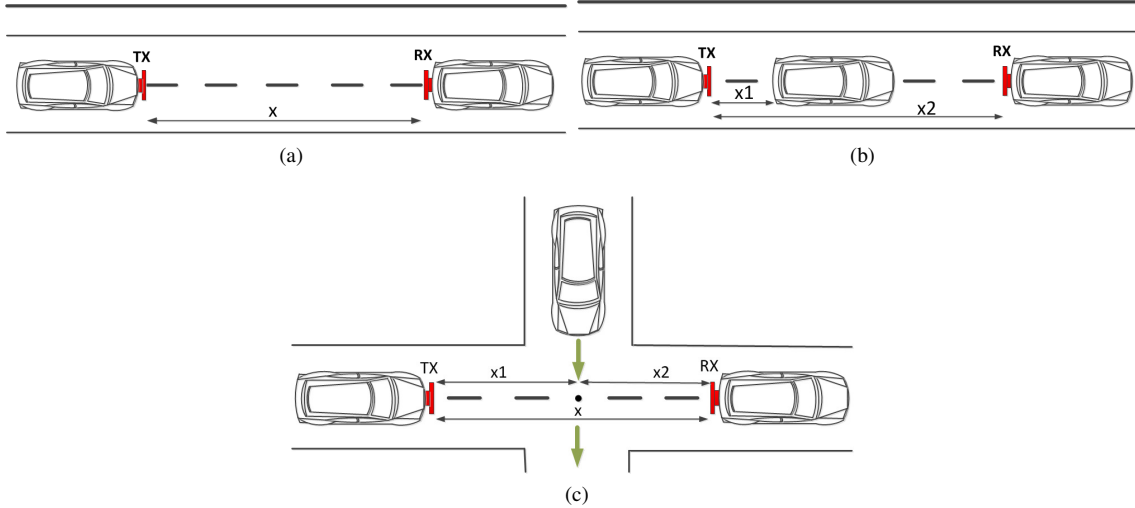


Fig. 1. Illustration of (a) LOS case, (b) Single car obstruction case, and (c) Car crossing case.

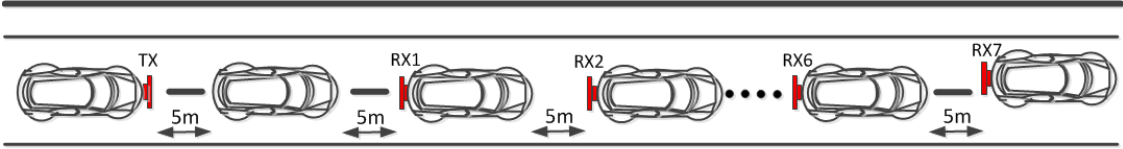


Fig. 2. Illustration of Platooning case.

TABLE II
3GPP ANTENNA MODEL PARAMETERS

θ_H [$^\circ$]	θ_V [$^\circ$]	FBR_H [dB]	SLL_V [dB]	A_M [dBi]
115	60	26	-18	6

B. Measurement and Simulation environment description

We consider four different measurement and simulation scenarios. The description of each scenario is given here:

1) *Line of Sight (LOS) case*: In this case, a vehicle with the Transmitter (TX) stays static at one point while the vehicle with a Receiver (RX) moves away from the transmitter in a straight line in the direction of main lobe of TX antennas as shown in Fig. 1(a). There is no obstruction between the TX and the RX. In Fig. 1(a) the x refers to the distance between the front bumper of the TX vehicle and the trunk bumper of the RX vehicle.

2) *Non-LOS (NLOS_v) single vehicle blockage*: This case represents a NLOS scenario in which the LOS between the transmitter and receiver is obstructed by another sedan vehicle as shown in Fig. 1(b). Again the transmitter stays static while the vehicle with the receiver drives away from the transmitter. The thick line at the top in Fig. 1(a) and Fig. 1(b) represents the railings on the side of the road. In Fig. 1(b), x_1 refers to the distance between the front bumper of the TX vehicle and the trunk bumper of the obstructed vehicle, and x_2 is the distance between the front bumper of the TX vehicle and trunk bumper of RX vehicle.

3) *Moving vehicle obstructing LOS at road intersection*: A road intersection is considered here where the TX vehicle and Rx vehicle are static and admit LOS with each other, and another sedan vehicle drives the crossing road and obstructs the LOS as illustrated in Fig. 1(c). The green arrows show the direction of motion of the obstructing vehicle. In Fig. 1(c), x denotes the distance between the front bumper of the TX vehicle and the trunk bumper of the RX vehicle, and x_1 is the distance between the centre of the obstructed vehicle and the transmitter, and x_2 is the distance between the centre of the obstructed vehicle and the trunk bumper of the vehicle with the receiver. It can be seen in Fig. 1(c) that x_1 equals to x_2 , meaning that for different values of x the obstructed vehicle always passes through the mid point keeping x_1 equal to x_2 .

4) *Platooning*: This case is considered to analyze the impact of multiple blocking cars. We consider a platoon of vehicles staying static in a line. For better visualisation, the illustration of platooning case is separately shown in Fig. 2. A static environment is considered, where the LOS between the TX and first vehicle mounted receiver (RX1) is obstructed by another sedan vehicle. There is a fixed distance of 5 m between the front bumper and the trunk bumper of any two consecutive vehicles. There are seven vehicles with receiver antennas and the distance between the TX and the RX vehicle depends on the number of obstructing vehicles in between them. It is necessary to note that all of the vehicles stay in line with the TX vehicle except the RX7 vehicle, as it is intentionally shifted off the line as shown in Fig. 2.

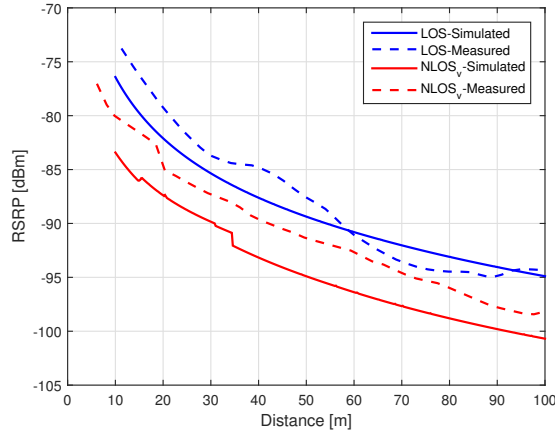


Fig. 3. Measured and simulated Reference Signal Received Power (RSRP) for LOS and single vehicle obstructed case.

III. SIMULATION RESULTS AND DISCUSSION

The performance metric for V2V link in the analysis is the Reference Signal Received Power (RSRP). Fig. 3 shows the simulated and measured RSRP in [dBm] at RX vehicle for *LOS* and *NLOS_v* case. In Fig. 3, the x-axis shows the distance in meters between the transmitter and receiver vehicle i.e. TX-RX separation. For *NLOS_v* case the obstructed vehicle is placed at a distance of 1 m from the front bumper of the TX vehicle. It is illustrated in Fig. 3 that a sufficient RSRP levels are maintained in both *LOS* and interestingly also in *NLOS_v* case, the measured RSRP being around -95 dBm and -98.2 dBm at a distance of nearly 100 m in *LOS* and *NLOS_v*, respectively. Moreover, simulation results have a good match with the measurement results validating the simulation tool and the applied models. We note that the obtained simulation results for *NLOS_v* are 2-3 dB more pessimistic as compared with the measurement results. However, both the simulation and measurement results reveal that the blocking effect due to obstructing vehicle at a distance of 1 m has caused a loss of around 5-7 dB with respect to the *LOS* case.

The impact of distance between the TX vehicle and the obstructing vehicle is seen from the Fig. 4 that shows the RSRP at the RX vehicle for different TX-OB vehicle distances against TX-RX distance. Furthermore, Fig. 4 shows the RSRP plots for 1, 3, 5, 7, and 10 m distances for the TX-obstructing vehicle, while the *LOS* plot is shown for a reference. First, it is found that the blockage effect is significant with 1 m TX-OB separation, while the blockage becomes less significant when TX-OB vehicle distances are larger. Second, it is observed that for the large TX-OB separation i.e. for 3 m and more, the RSRP at RX starts to converge with the RSRP level of *LOS* case at large TX-RX separation. However, for small TX-OB separation i.e. for 1 m the blockage effect stays even at large TX-RX separation.

The Fig. 5 shows the simulated RSRP for the case of moving vehicle obstructing the *LOS* at road intersection. The four curves shown in Fig. 5 correspond to different TX-RX

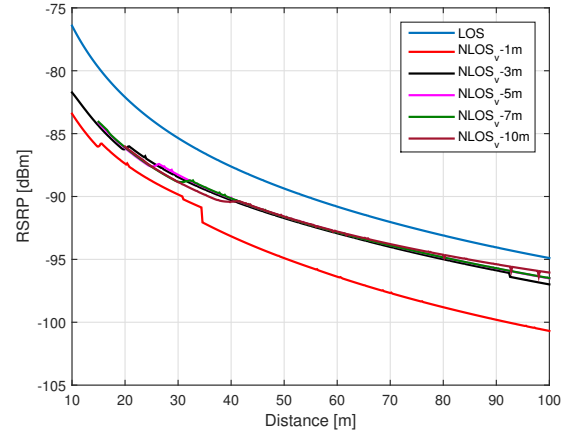


Fig. 4. RSRP in *NLOS* single vehicle obstruction environment for different distances between TX and obstructed vehicle.

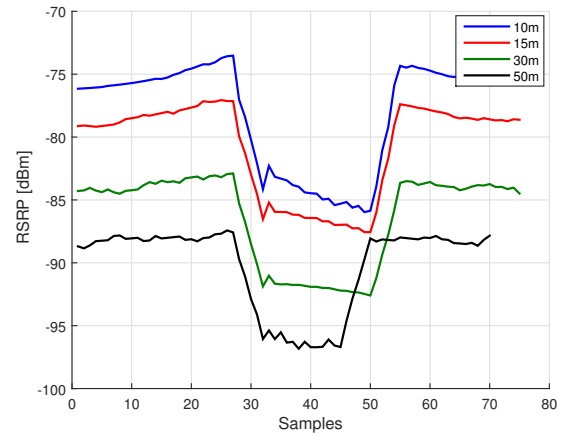


Fig. 5. RSRP in case of moving vehicle obstructed the *LOS* at the road crossing.

separations i.e. 10, 15, 30, and 50 m. It can be clearly seen from Fig. 5 that there is a knife edge effect when the moving vehicle obstruct the *LOS*. It also found that the knife edge effect is dominant and the dip in the RSRP level due to blockage is more deep in case of small TX-RX separation. The knife edge effect becomes mild with the increasing TX-RX separation. The RSRP level difference between the maxima and minima is 12.3, 10.4, 9.7, and 9 dB for 10, 15, 30 and 50 m TX-RX separation, respectively. The simulation results present the minimum RSRP value of -96 dB in case of 50 m TX-RX separation which is still above the noise floor. It also shows that by using basic wide beam antenna at TX, even at 50 m TX-RX separation the V2V communication with single car obstructing the *LOS* at the mid distance is possible at road crossings.

Finally, the Fig. 6 shows the measured and simulated RSRP results for platooning case along with *LOS* case used as a reference. In Fig. 6 the simulated and measured RSRP values are reported at seven different RX vehicles staying in the line. It

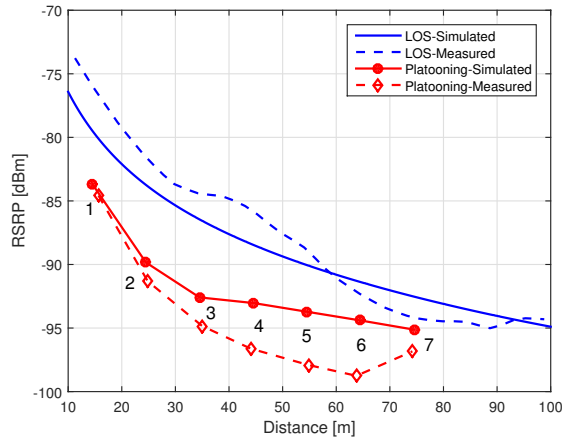


Fig. 6. RSRP at different vehicles moving in platoon.

can be seen from Fig. 6 that again the simulated and measured results are fairly close to each other. It is found that the first blocking vehicle mainly adds the blockage effect whereas the rest of the vehicles contribute only marginally to the blockage loss. Also, the impact of additional vehicles becomes less significant with the increasing number of blocking vehicles. The measured RSRP level differences are 6.7 dB, 3.5 dB, and nearly 1.8 dB and the simulated RSRP level differences are 6.2 dB, 2.8 dB, and nearly 0.5 dB between 1st and 2nd, 2nd and 3rd, and 3rd and 4th vehicle, respectively.

In measurement results, due to some additional gain the RSRP level of 7th vehicle is better than 6th vehicle whereas simulation results were not able to catch that additional gain. However, the simulation results were bit optimistic as compared with the measured results. The measured and simulated RSRP levels at the 7th vehicle in platoon is higher than -100 dBm which shows a good potential for using 39 GHz frequency in this V2V communications scenario. However, it is important to mention here that in considered platoon scenario all the vehicles were in the same lane with no other vehicle in another lane. In more practical case, there can be more blockers randomly placed in between TX and RX. Therefore, for future work it would be interesting to study the impact of other vehicles moving in adjacent lane as well.

IV. CONCLUSION

We considered the mmWave frequency for the V2V communications by comparing 3D ray-tracing simulations and field trial measurements on 39 GHz. Three relevant scenarios for V2V communications were considered. Namely, we focused on the case of a LOS link between vehicles, the scenario with a non-LOS link where obstruction occurs between vehicles, and a simple platooning case.

It was found that in the case of a single vehicle obstruction, the location of the obstructing vehicle relative to the TX is essential. Results indicate that the RSRP level better than -100 dBm can be obtained even with the 100 meters distance between the TX and RX while there is a single obstructing

vehicle located at a distance of at least one meter from the TX. While moving away from the TX the blockage attenuation due to the obstructing vehicle becomes flat after a certain break point distance. Similarly, in the case of a moving vehicle intersecting the LOS between two vehicles, the blockage effect is more significant for small TX-RX separation. While a moving vehicle intersects the LOS connection between vehicles at the road crossing the RSRP level difference between the maxima and minima is 12, 11, 10, and 8 dB for 10, 15, 30 and 50 m TX-RX separation, respectively. In case of platooning, the major impact of blocking is due to the first blocking vehicle. The impact of additional vehicles in the platoon less significant and it marginally increases the blockage loss. Although being case specific, results suggest that 39 GHz frequency has great potential for V2V communications.

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