4th URSI AT-RASC, Gran Canaria, 19 – 24 May 2024

A Tool for the Statistical Investigation of the Automotive Radar Interference

Alessandro Bazzi(1)(2), Francesco Miccoli(2), Zhuofei Wu(2)(3), Fabrizio Cuccoli(4), and Vincent Martinez(5)
(1) DEI, Università di Bologna, 40136 Bologna, Italy
(2) National Laboratory of Wireless Communications (WiLab), CNIT, 40136 Bologna, Italy
(3) College of Computer Science and Technology, Harbin Engineering University, 150001 Harbin, China
(4) National Laboratory of Radar and Surveillance Systems (RaSS), CNIT, 56124 Pisa, Italy
(5) NXP Semiconductors, 31023 Toulouse, France

Abstract

Vehicular radars, which play a key role within advanced driver-assistance systems (ADAS), sense the environment and provide distance and speed estimations about nearby vehicles and objects. However, the increasing penetration rate of such radar systems and the typically very open use of the radar bands is raising the possibility that radars' performance is vastly degraded because of the interference from the neighboring vehicles. The risk is therefore that applications failures became unacceptably frequent and features like adaptive cruise-control or autopilot are often temporarily disabled. Driven by ongoing discussions on automotive radar spectrum expansion to other bands, we are evaluating the opportunity to exploit the 140 GHz band, and the use of orthogonal frequency division multiplexing (OFDM) in addition to frequency modulated continuous waveform (FMCW). It is therefore of utmost importance to analyze the impact of the expected interference on radar devices in the scenarios of interest and study possible countermeasures. In this work, we describe a tool to derive, in realistic scenarios such as highways or urban areas, the number and characteristics (such as direction and path length) of potentially interfering signals, which can be then used to evaluate the impact of the interference and the effectiveness of mitigation solutions. Results obtained in a dense highway scenario show that with 100% penetration, the signals transmitted will often enter the field of view (FOV) of the other sensors, either directly or after a single reflection.

1 Introduction

Cars are becoming more and more equipped with advanced driver-assistance systems (ADAS). These systems aim at providing enhanced safety, more comfortable and green drive, aligned with the objectives of the authorities in many countries, such as the EU Road Safety “Towards "Vision Zero"”.[1] ADAS can use of a variety of sensors types, including Lidar, camera, V2X, and radar.

Thanks to their affordable cost and high effectiveness in object detection and tracking, especially at large distances and under various weather conditions, vehicular radars have become a key pillar of ADAS systems. Today, they operate in the 77-81 GHz band (with regional variations, such as distinct use of 76-77 and 77-81 GHz in Europe).

From a regulatory perspective, there are strict limits of out-of-band and/or spurious emissions, but a few restrictions concerning the operation inside the band. Indeed, typically only maximum mean and maximum peak power are limited, with only some regulations also mandating a maximum power spectral density. There are for example no requirements in terms of waveform type, signal bandwidth, nor in terms of duty cycle. As of today, only a small fraction of the cars on the roads are equipped with radar systems (beyond those used for parking) and the issue of reciprocal interference is restricted to very particular situations, which rarely occur. This low penetration is due to the average lifetime of a car being around 20 years. However, penetration rate will quickly increase, and it is expected that by 2030, 50% of the vehicles will be equipped with radar systems.

This inter-radar interference issue, which appears critical but difficult to overcome looking at the current deployment,[2] has recently received renewed attention because of the regulatory discussions on the possible use of a new band around 140 GHz. In such case, in fact, in-band usage rules would be still to be defined in standardization bodies [4, 5]. In this perspective, understanding the degree of the problem and investigating the effectiveness of available and new proposals for interference mitigation appears indispensable.

Given this context, in this work we describe an open source tool that we have designed and developed in MATLAB for the investigation of radar-to-radar interference in realistic vehicular scenarios and the impact of mitigation solutions.[3] The tool allows to estimate the number of potential interferers that each sensor perceives time by time, providing information that can be then used for performance evalua-

[1]EU Road Safety: Towards "Vision Zero", https://cinea.ec.europa.eu/publications/eu-road-safety-towards-vision-zero_en#details.

[2]https://www.grandviewresearch.com/industry-analysis/automotive-radar-market.

[3]The tool will be freely available after the paper presentation at https://github.com/V2Xgithub/WiLabVIsim.

tion. Example results are shown, investigating the potential impact of interference in a highway scenario.

2 Simulator description

The scope of the simulator is to provide information about the potential interferers for each radar of each vehicle moving in a realistic scenario, where *potential* means that the signals enter the reciprocal field of view (FOV).

The output includes all information, including length of the path, direction, position and speed of source and victim radars. This can then be used by other tools to assess whether and how much they effectively interfere depending on the specific power level, waveform and time-frequency resources that are used, and allow to verify the effectiveness of mitigation solutions acting for example on the waveform, bandwidth, or duty cycle to be used.

2.1 Main assumptions

The main assumptions of the simulator are as follows:

Vehicle positions: The starting point is the position, instant by instant, of the vehicles in the considered scenario, which is currently obtained by the microscopic traffic simulator SUMO [3], where each vehicle is modeled as a rectangle.

Sensors: All the vehicles are equipped with one or a set of sensors. Each sensor is identified by a certain position relative to the car, a direction, and a FOV. The simulator does not need to include details such as the power level or the gain diagram, since results are provided in terms of length and direction of the path covered by the signal, and those aspects can be later added in a post-processing phase.

Obstacles: Each vehicle in the scenario corresponds to a rectangular object that can reflect the signal. The reflection is performed in any direction, meaning that two sensors interfere with each other after one reflection if they both see the same obstacle without obstructions. At the moment, the reflecting objects consist in the other cars.

Definition of interferers: The simulator calculates the presence of signals in the field of view of the various sensors that either: (i) are in line of sight (LOS) conditions and thus come directly from another sensor, called *direct* interferers, or (ii) are in non line of sight (NLOS) conditions but reach the sensor after a single reflection, called *first reflection* interferers. Neglecting first reflection interferers is not possible, given that the radar works with reflected signals, but considering signals with two or more reflections appears unnecessarily complicated at this stage.

2.2 Evaluation of potential interferers

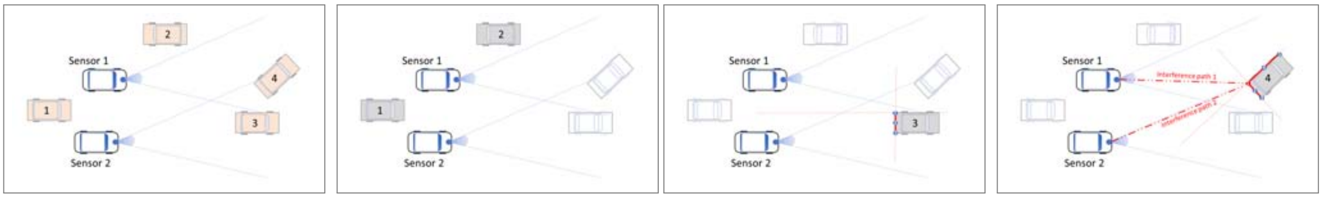
The evaluation of direct or first reflection interference is performed through the following steps, with an example for the first reflection interference shown in Fig. 1:

1. If the two sensors are in LOS and in the FOV of each other, there is a direct path;
2. If there is no direct path, the neighboring vehicles are sorted by the sum distance of their barycenter from the two sensors; as an example, the neighbors are sorted from 1 to 4 in Fig. 1a; the vehicles that are far from the sensors by more than a given distance are not considered, since they may only cause negligible interference;
3. Focusing on the nearest remaining neighbor, if all sides of the rectangle are out of the FOV of the two sensors, that neighbor can be excluded; as an example, cars 1 and 2 are excluded in Fig. 1b;
4. Otherwise, the two sides that are nearest to the sensors are considered; the other two sides cannot cause a first reflection link; this is the case for cars 3 and 4 in the example;
5. Extending the two considered sides as two straight lines, as shown in Figs. 1c and 1d, the corresponding side is excluded if the sensors are on opposite sides of the generated line; in such case, in fact, the side cannot cause a first reflection link; see, as an example, Fig. 1c;
6. In the remaining side or sides, the endpoints and the midpoint are considered; if one of these points is in LOS and in the FOV of both sensors, that point causes a first reflection link and the process ends; see, as an example, Fig. 1d;
7. If none of the points is in LOS and in the FOV of both sensors, the process goes back to Step 3 with the next neighbor. If there are no neighbors left, the process ends: there is no direct nor first reflected interference between these two sensors.

2.3 Simulator output

The output of the simulator is a table including, per each considered sensor and in each time instant, information of each potential interfering signal, as hereafter specified:

- Time instant;
- ID, position, direction and speed of the interfered vehicle; ID, position, direction (center of the FOV), and FOV of the interfered sensor;
- ID, position, direction and speed of the potentially interfering vehicle; ID, position, direction (center fo the FOV), and FOV of the potentially interfering sensor;
- First path length: length of the path from the potentially interfering sensor to the interfered sensor if the potential interference is direct, or length of the path from the interfering sensor to the obstacle if the potential interference is not direct;



(a) Scenario. **(b)** Obstacles 1-2: no reflections. **(c)** Obstacle 3: no reflections. **(d)** Obstacle 4: reflection.

Figure 1. Example of first reflection path evaluation, considering two sensors and four neighboring cars. (a) Scenario. (b) Neighbors 1 and 2 are not in the FOV of both sensors and are therefore excluded. (c) Neighbor 3 has only one side which may reflect the radar signals; looking at the second side of neighbour 3, in fact, the two sensors are on opposite sides of the line generated by that side; none of the three points considered on the side that may reflect is in LOS of both sensors. (d) Neighbor 4 has two sides which may reflect the radar signals; the first point considered is in LOS of both sensors and therefore causes first reflection interference.

Table 1. Main simulation settings.

Scenario	Straight highway segment of 8 km with 3+3 lanes and variable vehicle density. To avoid border effects, results do not include the interferers of those sensors that are located in 1.5 km at the beginning and end of the segment. Wrap-around is applied to keep the number of vehicles always constant during the simulation.
Sensors	All the vehicles are modeled as rectangles of 3.58 m length and 1.65 m width, which is the size of a common city car.
Vehicles	All the vehicles are equipped with either one front radar or four corner radars, with settings derived from the ECC Report 351 [4]. When one front radar is assumed, it is in the same direction as the vehicle with a FOV of 30 degrees. When four corner radars are assumed, they are placed in the four corners of the rectangle, with FOV of 60 degrees.

- Second path length if the potential interference is not direct: length of the path from the obstacle to the interfered sensor;
- Position of the reflecting point if the potential interference is not direct.

3 Results in a highway scenario

Results in terms of number of potential interferers in a highway scenario are shown from Fig. 3 to Fig. 4.

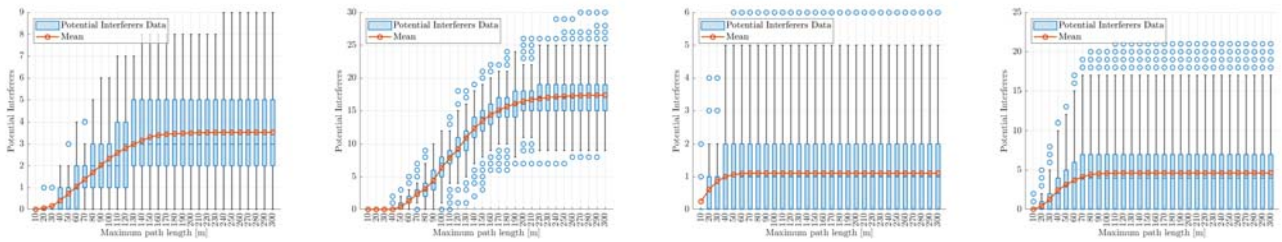
Scenario and settings: The scenario and settings are detailed in Table 1. A key input parameter is the *maximum path length*. Potential interfering sensors are in fact defined as those that generate a signal, which reaches the victim sensor (either directly or after reflection) traveling a total path lower than the maximum path length. If the interference is direct, the path not exceeding the maximum path length is the Euclidean distance between the sensors. Otherwise, it is the sum of the distance from the interfering radar to the point of reflection and that from the point of reflection to the interfered radar.

Statistics of the number of interferers in heavy traffic conditions: Assuming 150 vehicles/km, in Fig. 2 detailed statistics of potential interferers varying the maximum path length are shown, assuming that all vehicles are equipped with either front or corner radars, and separating direct and first reflection interferers. The plots include the median, the lower and upper quartiles, any outliers, and the minimum and maximum values that are not outliers.[4] As Expected, increasing the maximum path length, the average number of potential interferers increases as well. It is however interesting to note that the increase attenuates and eventually saturates after a certain maximum path length. This is in part due to the geometry of the scenario, especially when corner radars are considered, and in part because farthest sources of interference are more likely to be hidden by obstacles around the victim. Notably, up to 30 potential first reflection interferers can be noted for front radars and up to 21 first reflection interferers for corner radars.

[4] More information at https://it.mathworks.com/help/matlab/ref/boxchart.html.

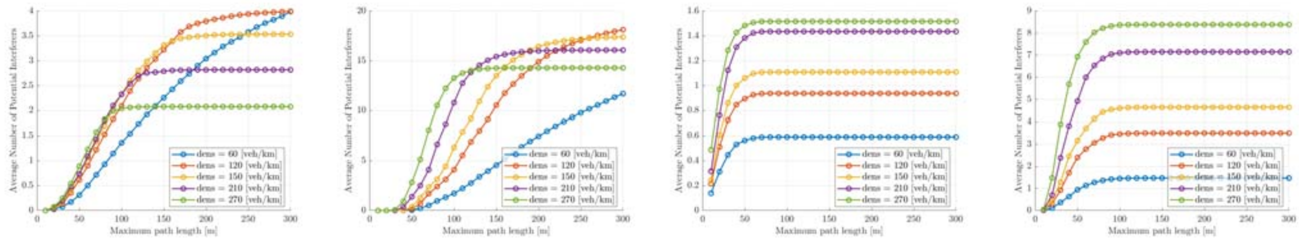
Average number of interferers varying the vehicle density: In Fig. 3, the average number of potential interferers is shown varying the maximum path length for various densities, again separating front from corner radars and direct from first reflection interference. In general, an obvious increase of the average number of interferers increasing the density is observed. However, when comparing the curves related to front radars, it also appears evident the hiding effect of cars between possible interfering sensors at larger distances, which causes a reduction of the maximum number of potential interferers when the density increases; in Fig. 3a, for example, the maximum of the average number of potential interferers decreases from 4 to 2 when the vehicle density increases from 120 to 270 vehicles/km.

Time variability of the number of interferers: The results discussed so far are derived averaging over all cars and summarizing over a large interval of time, which does not allow to have indications about the time correlation. Detailed analysis of specific vehicles and time variability are however also possible, as shown through an example in Fig. 4. The figure shows the time variability of the number of potential interferers for one car under test located in the rightmost lane, equipped with four corner radars suffering from direct interference, and where the number of potential inter-



(a) Front, direct interferers. (b) Front, first reflection interferers. (c) Corner, direct interferers. (d) Corner, first reflection interferers.

Figure 2. Highway with 150 vehicles/km. Cumulative distribution of the potential interferers varying the maximum path length.



(a) Front, direct interferers. (b) Front, first reflection interferers. (c) Corner, direct interferers. (d) Corner, first reflection interferers.

Figure 3. Average number of potential interferers varying the maximum path length, for various vehicle densities.

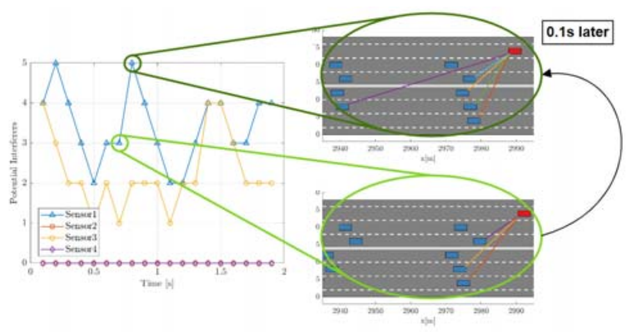


Figure 4. Time variability of the number of direct potential interferers of four sensors of a generic vehicle, with steps of 100 ms. An example situation where the number of potential interferers suddenly increases from 3 to 5 in 100 ms is also detailed on the right.

ferers are collected within a maximum path length of 100 m every 100 ms. As observable, the number of potential interferers continuously varies, although only by one or, rarely, two. The sensors on the right of the car (sensors 2 and 4) do not have any potential interferers because there are no other cars or obstacles at the right side of the car. This observation also remarks that, depending on the position of the generic vehicle on the road, the average number of potential interferers it perceives can be higher or lower than the general average, especially in the case of corner radars.

4 Conclusion

In this paper, we described an open-source simulator aiming at facilitating interference studies with any kind of radar device and any solutions designed for interference mitigation. The simulator identifies the presence of potential interferers in realistic scenarios and determines all the characteristics of the path taken by the interfering signals, remaining independent of the specific signal settings, such as waveform or bandwidth, signal processing algorithms used by devices for the target detection, or methods to reduce the effect of interference. The output will be used in future work: (i) to investigate the performance of detection algorithms in the presence of interference, assuming both OFDM and FMCW waveform; and (ii) to assess possible approaches to mitigate the interference at a network level.

References

[1] A. Ossowska et al., "IMIKO-Radar Project: Laboratory Interference Measurements of Automotive Radar Sensors," *IRS*, Warsaw, Poland, 2020.

[2] M. Kunert, "The EU project MOSARIM: A general overview of project objectives and conducted work," *RadCon*, Amsterdam, Netherlands, 2012.

[3] P. A. Lopez et al., "Microscopic Traffic Simulation using SUMO," *ITSC*, Maui, HI, USA, 2018.

[4] ECC Report 351, "UWB radiodetermination applications within the frequency range 116 GHz to 148.5 GHz for vehicular use", Feb. 2023.

[5] A. Filippi, V. Martinez and M. Vlot, "Spectrum for Automotive Radar in the 140 GHz Band in Europe," *EuRAD*, Milan, Italy, 2022.

[6] F. Roos et al.,"Radar Sensors for Autonomous Driving: Modulation Schemes and Interference Mitigation," in *IEEE Microwave Magazine*, 2019.