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Multipath Propagation Simulator for V2X Communication Tests on Cars

Design Aspects and Feasibility Experiments

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Abstract—Test and evaluation of wireless communication performance with cars can be done in many ways. One approach, for both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) tests, is to use a multipath propagation simulator to achieve realistic signal environments for the different communication systems under test. Multipath propagation simulators have previously been shown to be useful for testing mobile handsets. Specific issues related to tests with cars are the large size of the test object and the disturbances it can cause. In this paper we experimentally study how different design parameters of the multipath propagation simulator affect the received signals. The analysis of the setup as well as the data is performed using the so-called "Design of Experiments" method.

Index Terms—Vehicular communication, V2X, Multipath simulator, Multipath propagation simulator, Impulse response, Design of Experiments, DOE.

I. INTRODUCTION

A general trend in the automotive industry is to include more and more wireless communication capabilities in the vehicles. Systems such as GSM, WCDMA and LTE are examples providing cellular services, but there is also an interest of 802.11p for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, summarized as V2X. There is a need to test the performance of these systems during product development and verification. Traditionally, such tests are performed as field trials. However, with increasing communication complexity, there is an increase in complexity and cost for the tests. In addition, during field tests it is hard to have full control of the environment.

An alternative to field trials is to build a lab test setup that can simulate real life traffic scenarios. Tests can then be performed with better repeatability at lower cost. The multipath propagation simulator (MPS) has been developed for the particular purpose of simulating realistic signal environments in a lab [1] [2]. Previously, the use of the MPS has been focused mainly on mobile phone handsets; an MPS for vehicle communication tests has not been reported earlier. Using an MPS for over-the-air testing, as opposed to using channel emulators in conducted tests, brings the advantage of including the vehicle antennas in the tests. Not only does this make the

tests more relevant, but it is also a practical advantage not to have to equip the vehicles with connector interfaces for the tested systems. Fig. 1 shows an example of MPS setup with a car (Volvo V70) as test object.



Figure 1. The MPS setup together with a car.

The test setup has to be able to represent the special behavior of the V2V channel, which is different from traditional cellular channel behavior. Typically, the V2V channel is highly dynamic, having only a few dominant scatterers in open environments but a richer channel in urban environments. Furthermore, the channel statistics can change over time, scatterers come and go, and wide sense stationarity uncorrelated scattering (WSS-US) cannot generally be assumed [3]. If the test setup is going to be used also for cellular tests, it has to be reconfigurable to take such test cases into account as well.

II. TEST OBJECTS

A. Communication Systems

Systems for external wireless communication from vehicles, i.e. excluding internal communication within the vehicle, include, e.g., GSM, WCDMA, LTE, Wi-Fi, and

802.11p. The frequency bands used by these systems are confined to the range 0.7-6 GHz, although the exact bands can vary between countries. When a car communicates with the infrastructure, or with other cars, the mean received signal strength is often very low, as determined by the distance dependent path loss and the transmitted power. In a lab setup where the distances are small, a low output power is hence enough for realistic simulations. It is enough to have a dynamic range sufficient for covering the range around the sensitivity levels in the different test cases. Depending on the system and environment, the received signal at the car has certain distributions over incident angle, polarization, delay, and Doppler shift, see, e.g., [4] for an overview of propagation conditions in V2X channels. These characteristics should be simulated in a lab setup, since they represent the stress that the test object antennas and radio are subjected to. The ability of the radio receiver to handle low power levels, realistic delay spreads, and Doppler shifts, is tested, and it is important to remember that the properties of the test object antennas have an influence on these parameters.

B. Car Antennas

Antennas on cars, for the systems at hand, can be mounted at different positions on the car, but often they are placed on the roof. The antennas used are usually some kind of monopole antennas, utilizing the roof as ground plane, giving rather pure vertical linear polarization. The car body affects the radiation properties, both because the car is part of the antenna structure, and because there will be reflection and diffraction. The size of the car means that the test zone (i.e. the volume within which the test object is placed) has to be large, both in terms of the relative size in wavelengths and in relation to the MPS antenna array radius.

III. MULTIPATH PROPAGATION SIMULATOR

The MPS consists of an array of antennas encircling the test object with a radius of 5 m. Each antenna represents one particular delay. For highway and rural scenarios this often corresponds to one signal path since the channel is sparse. The signals on the different MPS antennas are processed so as to resemble real-life signals. In previous work, the basic design and function of the MPS is reported [5]. Its usefulness for passive antenna measurements [5] as well as active signaling tests [6] has been demonstrated.

In the setup, as shown in Figs. 2 and 3, an MPS is designed for the frequency range 0.7-6 GHz, with eight directional antennas with linear polarization pointing towards the center of the test zone at a radius of 5 m. The antennas can be positioned differently in order to vary the signal distribution over azimuth angle and polarization. Excess delays from zero up to 5 μ s are included in the feed network. Doppler shifts and attenuation can be set arbitrarily up to ± 2 kHz and 0-90 dB by the software installed in the Laptop 1 shown in Fig. 3. The MPS is located in an outdoor antenna test range which is covered with thin plastic sheets on a wooden structure, see Fig. 1. The ground is tarmac, with a metal turntable on which the car is placed.

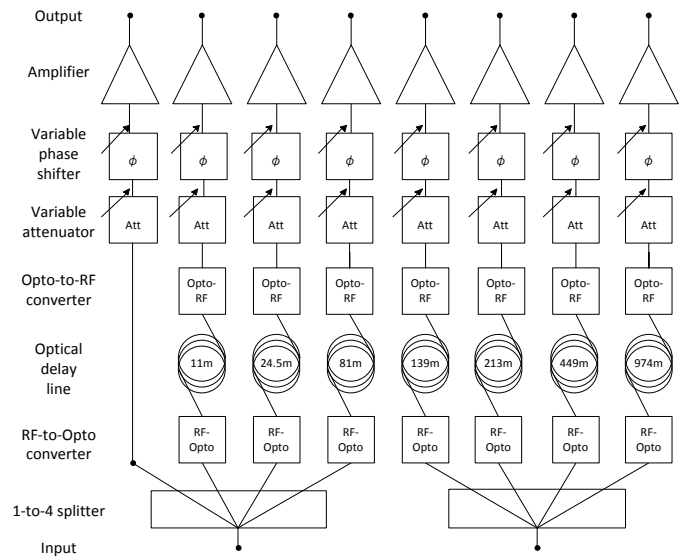


Figure 2. MPS Box block diagram.

Fig. 3 shows an example of the active signaling V2X MPS setup together with a car. Laptop 2 controls the transmitting V2X Electronic Control Unit (ECU) in the way that it sends a radio packet according to the standard 802.11p [7] with the data length of 1000 bytes and with a unique PacketID at regular intervals around 100 times per second. This packet is processed in the MPS Box: Each branch has its individual delay, and a Doppler shift (frequency shift) is applied to each branch by the time variable phase shifters. Furthermore, the instantaneous power level for each branch is controlled by the variable attenuators before the signal is transmitted by the corresponding antenna. The software in Laptop 3 counts received packets from the receiver V2X ECU installed in the car and store the Received Signal Strength Indicator (RSSI) value for each packet hence Packet Error Rate (PER) can be calculated vs. the RSSI.

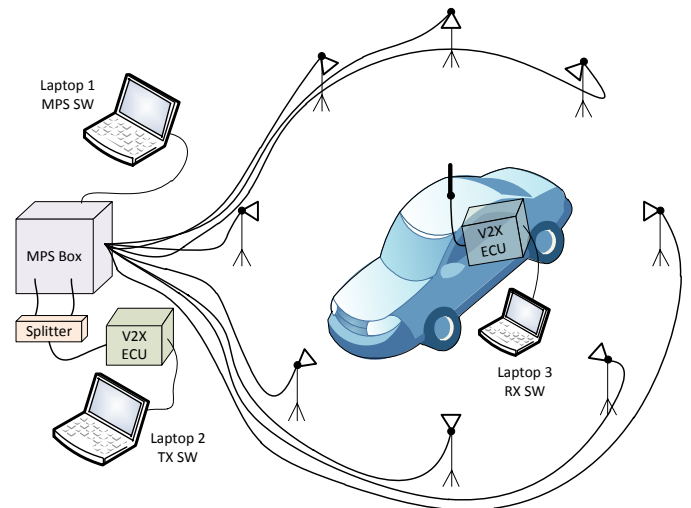


Figure 3. Example of an active signaling V2X MPS setup.

IV. EXPERIMENTS

Measurements are performed for the purpose of verifying the MPS test setup for V2X Communication Tests on Cars using the 802.11p standard [7].

Specifically, we investigate the ability to:

- simulate various realistic signal environments in terms of the desired signal vs. interference from the MPS Setup and environment.
- resolve differences in received signal between different antenna positions at the car.

Some difficulties can be expected from having a large MPS antenna array and large metallic test objects. A method called "Design of Experiments" (DOE) [8] is employed, which is a powerful tool for extracting as much information as possible from a limited number of measurements on a system with many degrees of freedom.

The measurements are based on broadband S_{21} measurements within the frequency range 4-6 GHz, using an Agilent 8753E vector network analyzer, so-called passive measurements, see Fig. 4. In the measurements only one MPS antenna is used and therefore the MPS Box is disconnected. To identify the desired signal power vs. interference from the environment the time-domain impulse response is calculated using the inverse Fourier transform. From the impulse response, see Fig. 5, the power of the desired signal, here defined as the maximum sum of powers from 3 consecutive delay bins, and the interference, defined as the power of all the delay bins outside the main peak, are extracted. The level of the interference relative to the desired signal is typically around -10 dB, for a car antenna on the same side of the roof (front/back) as the transmitting MPS antenna. For a car antenna on the opposite side of the roof, the relative interference level is between -10 dB and 0 dB. It should be noted that a real 802.11p receiver is not able to resolve delay bins with a difference of delays less than around 100 ns due to the system bandwidth of 10 MHz.

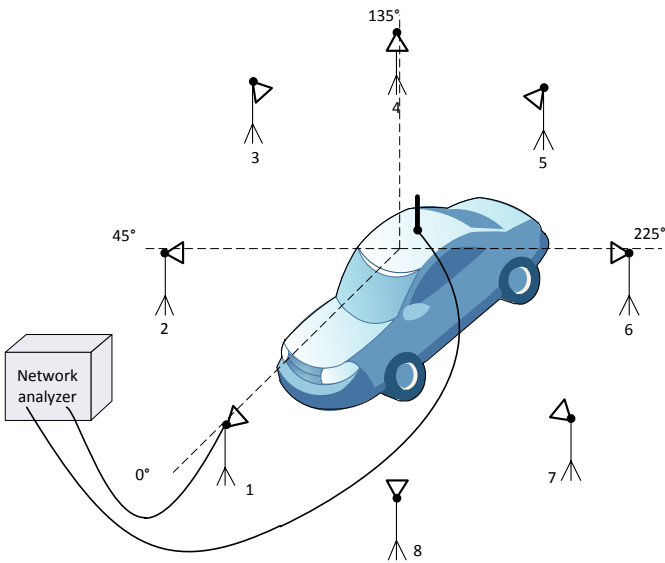


Figure 4. MPS setup, passive measurements.

A comparison of the results with previous results from MPS setups [5] indicates that the outdoor site used for the presented MPS is comparable to using an anechoic room. Both magnitude and duration of the ringings are low. With a large metal test objects such as a car, much reflections and diffractions can be expected. Measurements with a sensor antenna around the test zone also confirm that there are very strong reflections from the car. Because of the rather clean impulse response, the conclusion is that these reflections do not to any significant amount enter the car antenna. This means that the setup allows for accurate control of the signal environment, i.e. various signal environments can be realized in practice with only minor unwanted distortions.

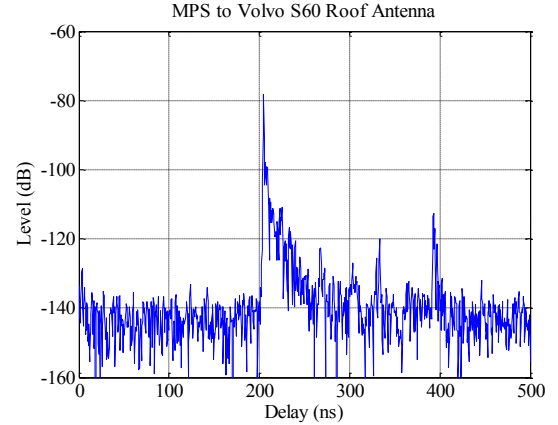


Figure 5. Example of measured impulse response, showing desired signal (first large peak) and interference (following lower peaks).

Eight design parameters for the test setup are defined in the DOE study with the following design levels.

1. MPS antenna height: 0.8 m and 1.8 m.
2. Attenuation to the MPS antennas: 0 dB and 20 dB.
3. MPS antenna polarization: vertical and horizontal.
4. MPS antenna position in the ring: pos.1, 2, and 3.
5. Car direction: 45°, 135°, and 225°.
6. Car size: Volvo V70 and a ground plane with ϕ 1.0 m on a wooden stand 1.0 m above ground.
7. Receiving antenna position on the car (a Volvo S60¹): Back of the roof, front of the roof, and front of the car.
8. Frequency band: 0.8-1 GHz, 1.7-2.7 GHz, and 4-6 GHz.

The reason for adding factors that obviously will have a significant effect on the received signal strength (frequency band, MPS antenna polarization, attenuation to the MPS antennas...) is that by comparing the DOE analysis correlation coefficients for the factors, the relative importance between the factors can be estimated. A full factorial test, which represents a test with the above design parameters with all the combinations of the levels, will result in 1296 runs. The

¹ For practical reasons a Volvo V70 was used in DOE_1, whereas a Volvo S60 was used in DOE_2 and DOE_3.

performed DOE was divided into three different DOE setups with the following number of runs: 16 (DOE_1), 27 (DOE_2) and 21 (DOE_3) which results in total of 64 runs.

In the performed DOEs two responses were defined, namely main peak level (desired signal) and interference level. To understand the dependence between the eight MPS design parameters and the two responses and correlation between different MPS design parameters, an analysis of the regression coefficients plot is made for DOE_1, DOE_2 and DOE_3. The coefficient plot shows the scaled and centered regression coefficients with 95% confidence intervals. Several indicators describing the performance of a regression model exist and two important ones are the companion R^2 and Q^2 , both are based on analysis of variance (ANOVA). The indicator R^2 is called *goodness of fit* and is measure of how well the regression model can be fit to the raw data. R^2 varies between 0 and 1, where 1 indicates perfect model and 0 no model at all. A more useful indicator is the Q^2 indicator, which is called *goodness of prediction* and estimates the prediction power of the model. Q^2 varies between $-\infty$ and 1, where a value >0.5 is good. A more detailed description can be found in [8].

In the first DOE (DOE_1) with 16 runs, design parameters 1 to 6 were investigated on a Volvo V70. Analysis of the DOE_1 shown in Fig. 6 gives that design parameters 1 to 3 have a statistically significant effect on the main peak level since they are the only factors where the confidence interval does not cross the zero level. An analysis of the interference level also pointed towards the same design parameters.

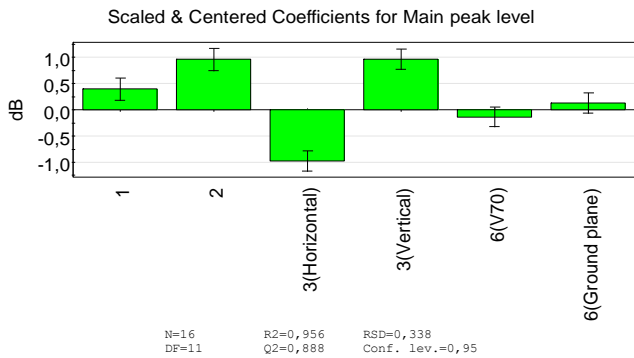


Figure 6. Analysis of Main peak level in DOE_1.

In the second DOE (DOE_2), design parameters 5 and 6 were removed because they did not have a statistically significant effect on the main peak or interference level. Design parameters 2 and 3 were set to a fixed value since both had a statistically significant effect on the main peak and interference level, which was expected and therefore no more analysis of these two design parameters was needed. DOE_2 then investigated the design parameters 1, 4, 7, and 8. In Fig. 7, the analysis of DOE_2 is shown for the response main peak level. Only one design parameter had a statistically significant impact on the main peak level, and that is number 8, the frequency band. Interaction between some design parameters also had statistical significance on the main peak level but compared to design parameter 8 these effects were small and therefore this is not shown in Fig. 7. This design parameter impact was much stronger than all the others, because the received power by the

receiving antenna on the car changed drastically with the frequency.

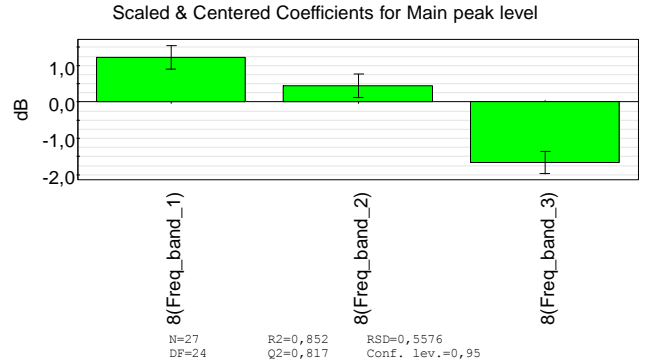


Figure 7. Analysis of Main peak level in DOE_2.

In the last DOE (DOE_3), design parameter 8 was set to the fixed frequency band 4-6 GHz. The design parameters investigated were number 1, 4, and 7, while all others were set to fixed values or removed. Analysis of DOE_3 shows that design parameters 4 and 7 have statistically significant impact on the main peak and interference levels. Also the interaction between design parameters 4 and 7 has statistically significant impact on main peak and interference levels. This can be explained by the fact that the antenna diagram around the car changes over azimuth angle. Fig. 8 shows the analysis of the main peak level.

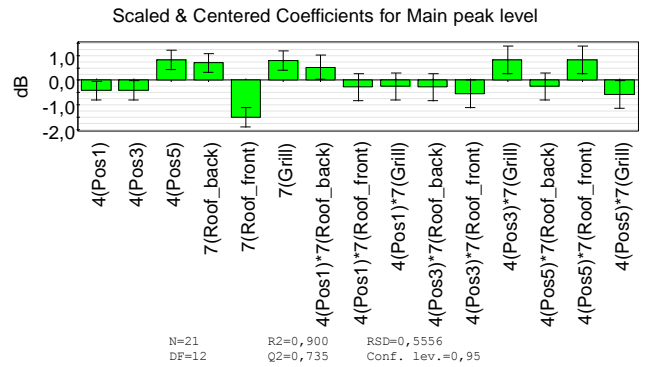


Figure 8. Analysis of Main peak level in DOE_3.

The results show that the signal environment within the MPS is well under control. The analysis of DOE_3 further shows that the method has potential to resolve the difference in received signal strength at different antenna positions at the car.

V. CONCLUSIONS

In this paper we have presented first results and an analysis from an over-the-air test setup for V2X communication based on an MPS. The test setup consists of an MPS box with control laptop, eight MPS antennas, an open area test site with a turntable, coaxial cables and a car as the device under test. The MPS box itself contains optical delay lines, attenuators, and phase shifters, where the two last can be set by the MPS software. The dependencies between the test setup parameters and the received signal characteristics were analyzed with a

method called “Design of Experiments”. The value of the regression coefficients depends on the different DOE setups but the overall picture shows that the signal environment within the MPS is well under control and the concern about large size of the test objects could cause specific disturbance can be largely rejected. Therefore, these initial results seem positive when it comes to using the MPS for simulating channels for V2X communication.

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