Evaluation of Vehicle-in-the-Loop Tests for Wireless V2X Communication

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***Abstract*—The performance of wireless communication systems is fundamentally determined by the properties of the underlying wireless communication channel. Vehicular communication channels exhibit time-variant multi-path propagation with non-stationary channel statistics. Thus, channel emulation tools for the reproducible test of wireless communication systems are urgently needed to enable the development of ultra-reliable low-latency communication links. In this paper we validate the vehicle-in-the-loop (ViL) test of vehicle-to-everything (V2X) communication links by means of time-variant channel emulation. The validation is performed by comparing the received signal strength indicator (RSSI) and packet error rate (PER) of measurements on a proving ground with the RSSI and PER obtained from ViL tests. For the ViL tests, the wireless communication channel is emulated using a geometry-based stochastic channel model, which is updated in real-time, dependent on the position and velocity of the vehicles. We collect results of different scenarios on the proving ground and from ViL tests. The results show an qualitative match between ViL test and measurement on the proving ground. An exact quantitative match can be obtained with the calibration parameters from the measurements.**

***Index Terms*—vehicle-in-the-loop, real-time, channel emulation, SDR, geometry-based stochastic channel model, 802.11p**

I. Introduction

Connected autonomous vehicles exchange information using wireless vehicle-to-everything (V2X) communication to improve road safety and travelling convenience, reducing traffic congestion, minimizing fuel consumption and enhancing the overall driving experience [1, 2]. In fully automated driving systems real-time control algorithms integrated in the automated vehicle's control unit, will use this information to adapt the driving route and velocity to the current situation.

The wireless communication channel between vehicles exhibits multi-path propagation and non-stationary fading characteristics, which depend on the position, velocity and the environment (geometry and physical properties) of the communication device [3, 4]. In safety relevant scenarios ultra-reliable low-latency communication (URLLC) links are of paramount importance. For developing and validating URLLC links, the wireless communication system together with the real-time control algorithm has to be tested in a repeatable fashion in vehicular environments. Vehicle-in-the loop (ViL) tests [5] have the benefit of being repeatable, while tests on the road are labor intensive and hard to repeat due to the influence of variables that cannot be controlled. A ViL test combines a real vehicle with a virtual environment where all relevant stimuli for sensors are simulated. In order to mimic wireless communication effects, wireless channel emulators are used. However, in most ViL tests only very simple channel models are utilized, such as basic path-loss (e.g., Friis' law) or delay models and stationary statistics [6, 7]. A realistic validation of wireless communication systems in ViL tests requires the update of wireless propagation characteristics in *real-time* with continuous variations in delay and Doppler according to the change of the position and velocity of the transmitter (TX) and receiver (RX). All wireless channel emulators introduced and discussed in [8–18] share the main drawback that path delays can only be set to integer multiples of the sampling rate.

Scientific contribution: In this work we show the validation of wireless V2X communication in ViL tests with measurements obtained on a proving ground. For the ViL test the wireless channel propagation effects are emulated using a real-time geometry-based channel emulator [19] that allows to emulate continuously changing path delays and Doppler shifts. The channel emulator is parameterized using a geometry-based stochastic channel model (GSCM) [20]. The position and velocity of the vehicles are updated in real-time by Virtual Test Drive ® by VIRES Simulationstechnik GmbH. We compare the received signal strength indicator (RSSI) and packet error rate (PER) from measurements and ViL tests on the same track. To the best of our knowledge this is the first time ViL communication system tests are performed where the channel characteristics are updated in real-time dependent on the vehicle position and velocity.

II. Scenario Description

From a conceptual point of view we selected the following driving routes and traffic scenarios, where we are particularly interested on measuring and emulating the wireless channel statistics for a left turning vehicle, as illustrated in Figure 1. The vehicle of interest is a Volkswagen (VW) E-Golf and henceforth denoted as *test vehicle*, which is confronted with different traffic situations such as, (a) another vehicle (VW T5;

length: 5292 mm, height: 2476 mm, width: 1959 mm) crossing before turning left, (b) another vehicle (VW T5) blocking the line of sight to the base station while a vehicle (VW Passat; length: 4767 mm, height: 1516 mm, width: 1832 mm) is approaching the intersection from the opposite direction, and (c) two vehicles (VW T5 and VW Passat) approaching the intersection where the VW T5 is blocking the line of sight to the VW Passat. In each scenario there is at least one incoming

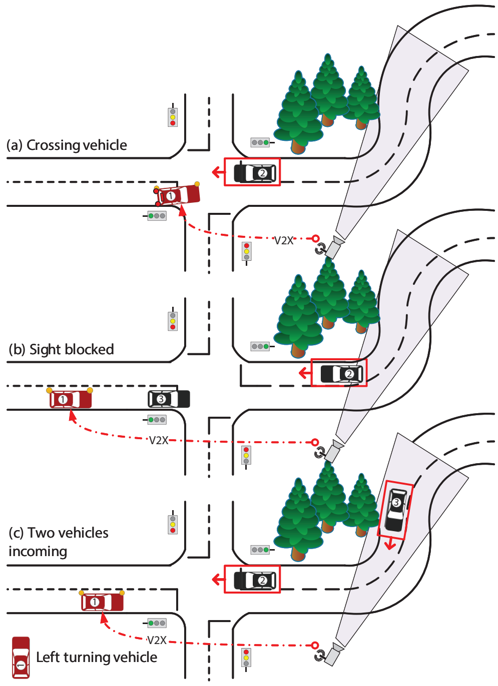

Fig. 1: Illustration of the basic scenarios.

vehicle approaching from the opposite site of the intersection. Since both vehicles (the test vehicle and another vehicle) meet at the center of the intersection, the driver of the test vehicle has to decide to turn before or after the incoming vehicle. Thus, each of the scenarios bear different challenges for the driver of the test vehicle where additional information received via V2X communication could prove beneficial.

The incoming vehicle follows an s-curve with trees blocking the line of sight to the test vehicle. We assume that the incoming vehicles are legacy vehicles with no means of wireless communication. To compensate for the blocked view, a traffic tower is placed at the end of the s-curve, observing the vehicles approaching the intersection. The position of the visually detected vehicles is transmitted using wireless vehicle-to-infrastructure (V2I) communication based on IEEE 802.11p [21] towards the test vehicle, allowing it to compensate for the lack of sight and communicate a turn decision recommendation for the driver. The TX modem is mounted on the traffic tower at a height of 4.2 m, the RX modem is mounted in the test vehicle. At TX the antenna ECO12-5800-WHT of MobileMark with 12 dBi gain was utilized, at RX the antenna SMW-404 also of MobileMark with a gain of 5 dBi was used. Both antennas are omni-directional.

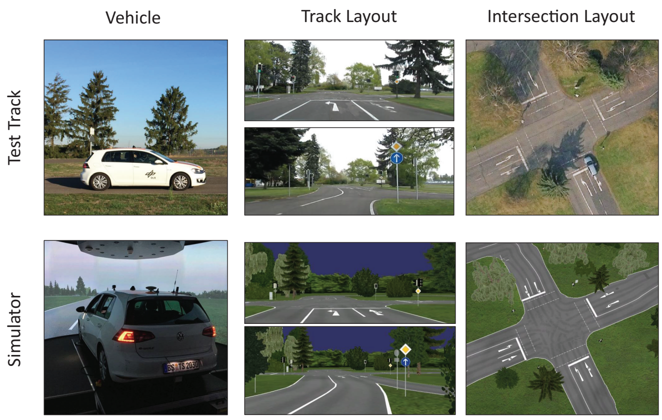

Fig. 2: The test track was recreated in the simulation.

III. Vehicle-in-the-Loop Tests

A. *Description of the ViL Test*

For the ViL test, the system-under-test (SUT) (in our case the test vehicle) is connected to a simulation environment where everything except the SUT is simulated. In our experiments, this includes, besides the visual representation, the physical properties of the environment, a virtual representation of the SUT and every moving object in the scene that modifies the measured variable(s). In order to reproduce the experiment on the test track as close as possible, the ViL tests are conducted at the Virtual Reality Laboratory (VRLab) at the German Aerospace Center (DLR). The VRLab is a 360° projection dome [22] with enough space to accommodate the complete test vehicle. The front tires of vehicle are positioned on a special designed force injection system that is able to simulate the forces a driver or an automation system would feel / measure on the real track. The experiment is conducted as a co-simulation, using Virtual Test Drive (VTD) ® by VIRES Simulationstechnik GmbH as environment simulation and the DLR in-house framework Dominion [23]. A custom built highly accurate map of the test course is used for the simulator depicted in Figure 2. In the ViL test the three different scenarios were reproduced (cf. Figure 1). The test driver drives the same route as on the actual test site.

B. *Wireless Channel Emulation*

The wireless V2I communication channel is emulated using a real-time geometry-based wireless channel emulator [19]. A schematic representation is shown in Figure 3. The emulator consists of a propagation module that is implemented on a general purpose multi-core off-the-shelf machine and a convolution module that is implemented on a software defined radio (SDR) equipped with a field programmable gate array (FPGA). The propagation module is parameterized by the channel model, which periodically updates the geometry (position and velocity) and calculates the attenuation, delay and Doppler shift of each propagation path. The convolution

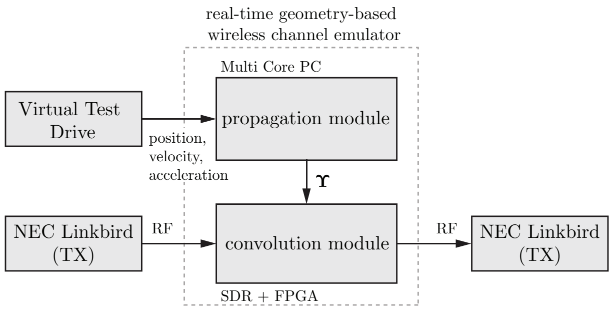

Fig. 3: Schematics of wireless channel emulation in ViL.

module convolves the input signal with the time-variant channel impulse response to obtain the output signal. For the ViL tests a multi-core x64 machine with 16 cores is available, as SDR we use an NI USRP-2954R [24]. The SDR is connected to TX and RX via attenuators.

We parameterize the propagation module by a GSCM [20]. The model takes the traffic lights as static discrete, the vehicles as mobile discrete and the vegetation as diffuse scatterers into account. The vegetation is modeled by octagons of different sizes where the diffuse scatterers are placed randomly inside the octagons according to a certain distribution. For each test drive in each scenario a random scatterer realization of the vegetation is utilized. A schematic representation of the second traffic scenario (sight blocked) with different scatterers including the trajectories of all involved vehicles is depicted in Figure 4. The start position of the test vehicle (RX) is shown by a pink square, the position of TX is shown by a pink circle. The path loss coefficients of the model are adapted from a road intersection scenario with buildings [25]. The attenuation of the vegetation is modeled according to [26, (2)]. For each position of the test vehicle the line of sight (LOS) condition is checked and in case of an obstructed LOS due to the vegetation the signal is attenuated according to the selected vegetation model.

The wireless propagation coefficients, i.e., path delay, Doppler shift and attenuation, are updated in real-time every $256\,\mu$s [19] ensuring a phase continuous transition for the parameter update. The positions, velocities and accelerations of the vehicles are updated by Vires VTD every 16.6 ms. We linearly extrapolate the position and velocity until the GSCM receives a position/velocity/acceleration update.

IV. Measurement and Validation

For wireless communication, off-the-shelf NEC Linkbird-MX 802.11p modems are used. The center frequency is set to 5.9 GHz (CH 180) and the frame repetition rate is set to 100 frames per second. We set the transmit power in both tests to 15 dBm. The data collection is split into two parts: In the first part, the measurement data on the proving ground/test site is collected at a non-public drivers testing course, north to the research airport in Braunschweig (Germany). In the second part, the ViL test is conducted using the 360° DLR driving simulator. The RSSI and PER are recorded at the RX using the NEC Linkbird-MX 802.11p modem. We calculate the PER over 100 transmitted frames. On the proving ground we additionally collect global positioning system (GPS) data for obtaining a nearest fit to the trajectory used in the ViL tests. In this paper we compare the results of the “sight blocked” scenario between the ViL tests and the measurements on the proving ground.

Figure 4 shows the trajectories of the different involved vehicles in the sight blocked scenario. The white trajectory corresponds to the test vehicle, the yellow trajectory to the sight blocking VW T5 and the black trajectory to the crossing vehicle (VW Passat). For the measurement on the proving ground the same trajectories are driven using real vehicles. Please note, that due to the utilized measurement method on the proving ground in the ”sight blocked” scenario, the measurement on the proving ground is stopped in the middle of the road intersection.

We compare the measurement on the proving ground with the ViL test using the recorded GPS- and xy-positions obtained by the simulation. We use a common zero coordinate to transform (sphere to Cartesian, which induces a neglectable error due to the rather small area) the GPS positions to Cartesian positions in $\mathbb{R}^3$. In order to provide a meaningful comparison of the RSSI and PER between the measurement on the proving ground and the ViL test, we pair those ViL test positions ($V \subset \mathbb{R}^3$) and proving ground positions ($G \subset \mathbb{R}^3$), which have the smallest error with respect to the Euclidean distance

$$M = \{(v, g) : v \in V, g = \arg\min_{u \in G}\{||v - u||_2\}\}. \quad (1)$$

From the obtained data points we calculate the RSSI of the ViL test and the measurement on the proving ground as an average of 30 subsequent positions in space. With an average speed of 20 km/h and 10 ms between samples, the 30 subsequent positions result in an averaging distance of 1.67 m ($\approx 33\,\lambda$ for 5.9 GHz). We evaluate the RSSI and the PER versus the traveled distance of the RX. The traveled distance is calculated as the Euclidean distance between the current position of the test vehicle (in the ViL test or the measurement on the proving ground) and its start position. Please note, that for the utilized transmit power (15 dBm) no signal was received within the first 30 m of the travel distance. Hence, we omitted this part in the following plots.

Figure 5 shows the average RSSI (dashed lines) versus the traveled distance for the ViL test and the measurement on the proving ground, respectively. We additionally plot the 95 % confidence intervals of the averaged RSSI, which are calculated from 30 subsequent positions in space. As expected, the average RSSI increases with the traveled distance, since the RX moves closer to the TX. Comparing the average RSSI of the ViL test and corresponding measurement on the proving ground it can be observed that the GSCM is able to capture the changing path loss due to the changing distance over time. The, on average, higher received RSSI of the ViL test can be explained by the too small assumed path loss coefficients in the GSCM. Furthermore, it can be observed

Fig. 4: Trajectories of the vehicles for the “sight blocked” scenario and the geometry considered for real-time channel emulation with the GSCM. The white trajectory corresponds to the test vehicle, the yellow trajectory to the sight blocking VW T5 and the black trajectory to the crossing vehicle (VW Passat)

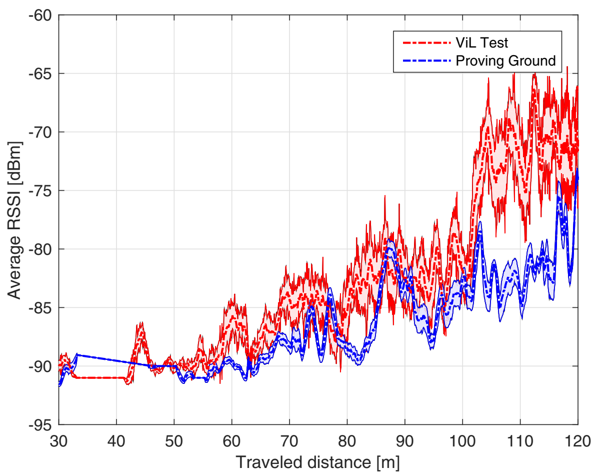

Fig. 5: Average RSSI with (dashed line) 95 % confidence intervals (filled area) of the ViL test and the measurement on the proving ground versus the travel distance for the “sight blocked” scenario

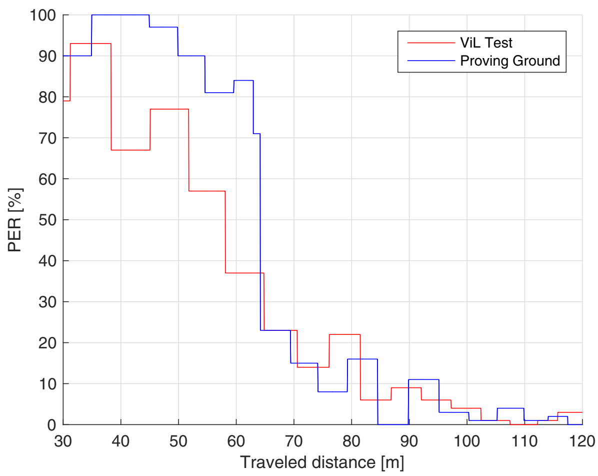

Fig. 6: PER of the ViL test and the measurement on the proving versus the travel distance for the “sight blocked” scenario.

that the variance of the short term average RSSI of the ViL test is higher than the variance of the short term average RSSI of the measurement on the proving ground. This can be explained by the utilized large-scale fading model of the path loss coefficients which assumes a too high variance of the large-scale fading coefficient. Lastly, due to the available computing hardware for the ViL test, the geometry of the proving ground has not been modelled to its full extent in the GSCM, which also has an influence on the accuracy of the obtained results. Thus, we think, that for future measurements, changing the utilized parameterization of the GSCM, i.e., path loss and large-scale coefficients and increasing the level of detail for the geometry used in the ViL test will lead to a further improved match between the results form proving ground and ViL test.

Figure 6 shows the PER versus the traveled distance for the ViL test and the measurement on the proving ground, respectively. The PER curves show similar behavior. From 40 m to approximately 60 m traveled distance the PER of the ViL test is smaller compared to the measurement on the proving ground. This can be explained by the higher RSSI in the ViL test. After around 70 m traveled distance the PER of the ViL test and the measurement on the proving ground match approximately. In this case the RSSI of both measurements is high enough such that the sensitivity of the modems does not have a significant influence on the PER.

V. Conclusion

In this paper we showed the validation of V2X communication system tests using a ViL setup. We introduced the scenario and the measurement setup in detail. In the ViL test the wireless communication channel is updated in real time using a GSCM that obtains the positions of the vehicles via Virtual Test Drive. The results show that the ViL test can reproduce the PER and RSSI values which were obtained by measurements on a proving ground with some deviations. We conclude that for future tests the paramterization of the utilized GSCM for this scenario, especially the large-scale fading and the path loss coefficients, has to be updated to obtain a closer match. To the best of our knowledge this is the first time a real-time updated GSCM was used for ViL communication system tests.

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