Hardware-in-the-Loop Framework for Testing Wireless V2X Communication

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***Abstract*—In this paper we present a hardware-in-the-loop (HiL) framework for testing wireless vehicle-to-everything (V2X) communication hardware, i.e., modems under realistic channel conditions. The framework includes a wireless channel emulator, which is capable of emulating non-stationary wireless channels in real-time. We validate the HiL framework by comparing the frame error rate (FER) obtained via emulation with data obtained during a V2X measurement campaign using the same IEEE 802.11p based modems. To do this we aquire measured time-variant channel transfer function and FER measurements simultaneously. The results show that our HiL approach is feasible and that we can obtain FER measurements in the laboratory that closely match the measurement results obtained on the road, giving the maximal distance of 0.099 between their cumulative distribution functions.**

***Index Terms*—IEEE 802.11p, FER, channel emulator**

I. Introduction

The test and verification of wireless vehicle-to-everything (V2X) communication is an important step towards enabling connected and automated vehicle applications. A future advanced driver assistance system (ADAS) will use data from other road users and the infrastructure to improve its accuracy and reliability by extending its own sensor horizon. Therefore, testing and verifying these future features under various conditions and in different scenarios in a controlled and repeatable manner is of high importance.

Performing wireless V2X communication tests only on the road is often not feasible due to cost, time and safety constraints. Hence, a digital twin on all relevant levels is needed. As a reliability performance metric, the frame error rate (FER) can be used. In order to overcome the computational complexity of calculating the FER, system-level simulations usually introduce some level of abstraction, such as received bit information rate (RBIR) and exponential effective signal-to-interference-plus-noise ratio (SINR) mapping (EESM) [1]. These techniques are used to map the received SINR of all data symbols to an effective SINR, since it may differ for each data symbol. The effective SINR is then used to estimate the physical layer performance.

The authors in [2] propose several physical layer abstraction techniques and show packet error rate results of IEEE 802.11p, IEEE 802.11bd, LTE-V2X and NR-V2X. Nevertheless, a comparison with real hardware modems is missing. The hardware-in-the-loop (HiL) method represents a testing and verification tool using a practical implementation of a V2X communication technology. In [3] the authors present a HiL simulation platform, which includes a traffic simulator combined with a channel emulator and ITS-G5-based hardware modems. The packet error rate is calculated by emulating a stationary tapped-delay line (TDL) channel model for line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. In [4], [5] and [6] a TDL channel model is used for HiL emulation. However, a TDL model does not allow to capture the non-stationary properties of the fading process in V2X communications [7], [8].

In this paper, we focus on emulating wireless communication channels in real-time and providing a HiL framework which allows the test and verification of wireless V2X communication in a realistic, controlled and repeatable manner, taking the non-stationarity fading process into account. Our HiL framework provides the opportunity to test V2X communication hardware under realistic propagation. It is not limited to specific wireless standards or scenarios.

Scientific Contributions of the Paper

- We present a HiL framework for testing wireless communication hardware such as algorithms and software under diverse radio channel propagation conditions. The FER can be calculated by emulating a geometry-based stochastic channel model, as well as replaying any measured channel. This framework can be applied to different communication technologies, i.e IEEE 802.11p, LTE-V2X, NR-V2X, etc.
- We use the FER results to validate our HiL framework. First, we measure the FER using the V2X IEEE 802.11p based modems during a channel measurement campaign that acquires the time-variant frequency responses simultaneously. Then, using the same modems, we obtain the FER by emulating the measured channel and compare these results.

II. Hardware-in-the-loop setup

Our HiL setup contains the AIT real-time channel emulator [9] and two hardware modems as transmitter (Tx) and receiver (Rx), see Fig. 1. Specifically, in this work we use Cohda Wireless MK5 modems [10] which are IEEE 802.11p compliant [11].

The AIT real-time channel emulator consists of two modules: the propagation and the convolution module. The propagation module is implemented on a multi-core PC where we obtain the time-variant channel frequency response (CFR). The CFR can be either calculated from a specific channel model, as it is done in [9], [12], [13], or it can be obtained directly from radio channel measurements [14]. The channel emulator and the channel sounder have different sampling rates and bandwidths (cf. Table I) which leads to a mismatch in the measured CFR for emulation. We interpolate the measured CFR as described in Section III. After interpolation, we obtain the basis coefficient matrix $\boldsymbol{\Upsilon}$ of the CFR [9]. This matrix is transmitted to the convolution module of the channel emulator where the basis coefficient matrix is used to reconstruct the interpolated CFR. This particular method allows a strong reduction of the communication bandwidth between the multi-core PC and software defined radio. Finally, the input signal produced by the Tx modem is convolved with the reconstructed CFR. The convolution is triggered by the input signal such that sending the first frame coincides with the beginning of the CFR sequence. We implement the convolution module on the FPGA of an USPR 2954R [15], which is a software defined radio (SDR) produced by National Instruments.

The HiL testing is implemented as an automated process which is controlled by the host multi-core PC (cf. controller in Fig. 1). From there, via a secure shell (SSH) connection, we access the Tx and Rx modem. The AIT channel emulator is connected via RF cables to the Tx and Rx modem. To ensure that the power on the input of the USRP is not exceeding the maximal allowed power of $-15\,\text{dBm}$ we add an attenuator γ_1. At the output of the USRP we add another attenuator γ_2 as compensation for amplifying the channel on the host side.

After establishing the SSH connection to the Tx and Rx modem and configuring them, in each measurement iteration we run a reception command on the Rx modem and calculate the basis coefficient matrix $\boldsymbol{\Upsilon}$. Then, after starting the emulator, we execute the transmission command on the Tx modem. On the Rx modem we obtain the number of successfully received frames as well as the received signal strength indicator (RSSI) in dB. Finally, the FER is calculated as a ratio of the number of not received frames and the total number of the transmitted frames. Fig. 2 depicts the laboratory HiL setup.

III. Interpolation of Channel data

In our setup the measured time-variant CFR has different sampling rates in time and frequency in comparison to the sampling rates that our channel emulator uses. Therefore, we need to interpolate the measured time-variant CFR. For the interpolation we follow the approach given in the appendix

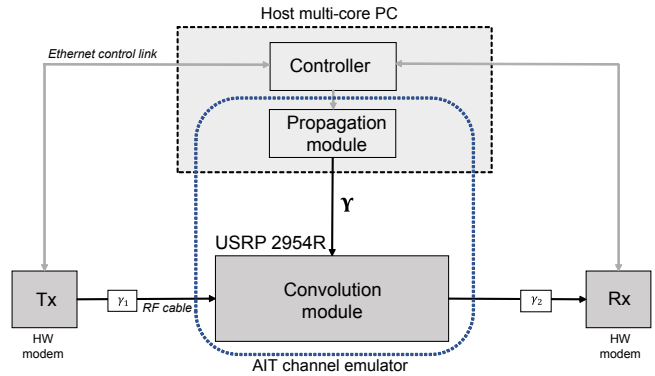


Fig. 1: Schematic of the HiL setup including the AIT channel emulator and the hardware modems.

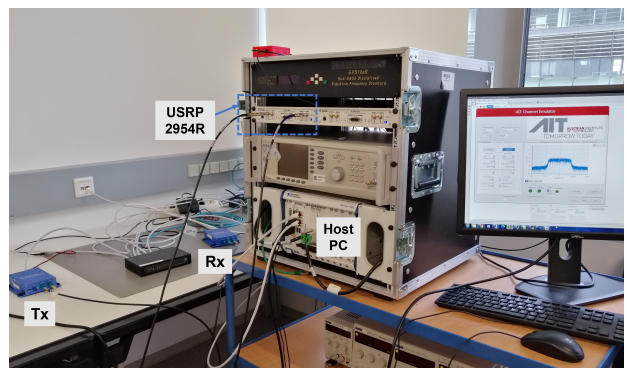


Fig. 2: HiL setup in the laboratory environment.

of [14]. We briefly summarize the methodology here, but we point the interested reader to [14], [16] and [17] for a more detailed explanation.

Key to interpolating the measured time-variant CFR is to find suitable natural numbers $r_{\text{t,s}}, r_{\text{f,s}}, r_{\text{t,e}}, r_{\text{f,e}}$ (sample spacings), i.e., such that

$$T_{\text{s}}/T_{\text{i}} = r_{\text{t,s}}\,, T_{\text{e}}/T_{\text{i}} = r_{\text{t,e}} \tag{1}$$

and

$$F_{\text{s}}/F_{\text{i}} = r_{\text{f,s}}\,, F_{\text{e}}/F_{\text{i}} = r_{\text{f,e}}, \tag{2}$$

where T_{e}, T_{s} and T_{i} represent the sampling times for emulation, sounding and interpolation, F_{e}, F_{s} and F_{i} denote the subcarrier frequency spacing for emulation, sounding and interpolation, respectively. We use a sliding window in time to reduce the computational complexity. We interpolate the measured time-variant CFRs consisting of $M_{\text{e}} \times N_{\text{e}}$ samples, where M_{e} denotes the samples in frequency and N_{e} the number of time samples. Next, we use a subspace spanned by discrete prolate spheroidal sequences (DPSS) with D_{t} time and D_{f} frequency dimension [16], as basis matrix for the following linear estimation problem

$$\boldsymbol{y} = \boldsymbol{\mathcal{D}}\boldsymbol{\psi} + \boldsymbol{z}, \tag{3}$$

where $\boldsymbol{y} \in \mathbb{C}^{M_{\text{s}}N_{\text{s}}}$ denotes the vectorized CFR samples obtained by our measurements, $\boldsymbol{\mathcal{D}} \in \mathbb{C}^{M_{\text{s}}N_{\text{s}} \times D_{\text{t}}D_{\text{f}}}$ holds

Name	Variable	Value
carrier frequency	f_c	5.9 GHz
maximum time delay	τ_{max}	4 μs
maximum velocity	v_{max}	100 km/h = 27.8 m/s
channel sounding		
bandwidth	B_s	150.250 MHz
time spacing	T_s	250 μs
frequency spacing	F_s	$B_s/N_s = 250$ kHz
subcarrier	N_s	601
block length	M_s	64
emulation		
bandwidth		
(two times oversampling)	B_e	20 MHz
time spacing	T_e	$1/B_e = 50$ ns
frequency spacing	F_e	$B_e/N_e = 156.25$ kHz
subcarrier	N_e	128
block length	M_e	$M_s r_{t,s} = 64000$
oversampling in time		
sounding	$r_{t,s}$	5000
emulation	$r_{t,e}$	1
oversampling in frequency		
sounding	$r_{f,s}$	8
emulation	$r_{f,e}$	5
interpolation		
time subspace dim.	D_t	44
frequency subspace dim.	D_f	600
overlap	Δ	4
subcarrier	N_i	$N_s r_{f,s} = 4800$
block length	M_i	$(M_s + 2\Delta) r_{t,s} = 72000$

TABLE I: Numerical implementation parameters

the downsampled DPS sequences with only $M_s N_s$ rows, $\boldsymbol{\psi}$ denotes the coefficient vector which we want to estimate and $\boldsymbol{z}$ is the noise vector where each component z_i is i.i.d. with $\mathbb{E}[z_i] = 0$ and $\mathbb{V}[z_i] = \sigma^2$. The least square estimator reads

$$\hat{\boldsymbol{\psi}} = (\boldsymbol{\mathcal{D}}^{\mathrm{H}} \boldsymbol{\mathcal{D}})^{-1} \boldsymbol{\mathcal{D}}^{\mathrm{H}} \boldsymbol{y}.$$

Finally we obtain the interpolated time-variant CFR by $\tilde{\boldsymbol{y}} = \tilde{\mathcal{D}} \hat{\boldsymbol{\psi}}$, where $\tilde{\mathcal{D}} \in \mathbb{C}^{M_e N_e \times D_t D_f}$ is the full basis matrix. We summarize the parameters in Table I.

IV. Measurement campaign

For the validation of the presented HiL framework, we use the data of a measurement campaign conducted in an urban environment in Vienna, Austria. We measured the radio channel using the AIT OFDM-based multi-band channel sounder [9], with central frequencies at 3.2 GHz and 5.81 GHz. The system bandwidth $B_s = 150.25$ MHz, the subcarrier spacing $F_s = 250$ kHz and snapshot rate is 250 μs. Besides the radio channel, we record the results from Cohda Wireless MK5 on-board unit (OBU) modems which implement the IEEE 802.11p standard, with the center frequency at 5.9 GHz. The Tx modem generates and transmits test frames, while the Rx modem records the report files with the received frames, which are used to obtain the FER. Every node of the AIT channel sounder, as well as both Cohda Wireless MK5 OBU modems, are equipped with GPS antennas and their readings are therefore used to synchronize the radio channel and FER recording. All antennas are mounted on the rooftop as shown in Fig. 3.

Additionally, we record LiDAR and radar data of the environment. In Fig. 3 we can see the sensor system mounted on the ego vehicle of AVL. The usage of the sensors data is out of the scope of this paper and hence we do not describe it. The data used in this paper is available at https://project-relevance.org/wili-open-dataset/.

V. Results

A. Validation

We validate the correctness of our HiL framework for testing V2X communication by the recorded data from the measurement campaign which we introduced in the previous section. We interpolate the measured CFR obtained by the AIT channel sounder and emulate it in real-time using the AIT channel emulator with the very same MK5 OBUs connected to the emulator (cf. Fig. 1 and Fig. 2). We set the modems to a transmission rate of 1500 frame per second like in the measurement campaign. In order to reduce random unknown effects of the HiL setup, we repeat each emulation 15 times and compute the average RSSI and FER values obtained by the MK5 OBUs per second. The scenario used for the validation is shown in Fig. 4. Measurements are performed on a small road behind the AIT campus in Vienna, and represents a situation where both vehicles move towards each other with a maximum speed of 30 km/h.

Fig. 5 depicts selected results from different runs showing the FER from the measurement and the FER obtained by the HiL framework. The passing points of the selected runs are different due to varying traffic conditions on the road. In all measurement runs we notice the same behavior: At the beginning, two vehicles have a distance of approx. 300 m without LOS, and the FER is close to 1. While the vehicles are getting closer to each other, the FER decreases until the passing point, when the FER reaches its minimal possible value. Since the passing point happens at the corner (see Fig. 4), the vehicles stay in the LOS condition and the FER remains low for approx. 15 seconds. Afterwards, the FER continues to increase. The transmit symbol set is quadrature phase shift keying (QPSK) with a frame length of 100 bytes. We observe that the position of the antennas on the ego vehicle's roof has a slight impact on the RSSI as the mountings of LiDAR in some cases block the line of sight for the MK5 OBU antenna (cf. Fig. 3).

In order to compare the FER and RSSI results obtained from the HiL and the measurement, we show their empirical cumulative distribution functions (CDF) in Fig. 6. The CDFs are calculated for all measurement runs. The CDF figures lead to the null hypothesis (H_0) that in both cases the samples are drawn from the same distribution. We investigate this hypothesis by performing a Kolmogorov-Smirnov (KS) two-sample test [18] which defines the following test statistics

$$D_{\mathrm{FER}} = \sup_{\gamma} |F_{\mathrm{HiL}}(\gamma) - F_{\mathrm{meas}}(\gamma)|, \tag{4}$$

Fig. 3: The vehicles used in the measurement campaign. On the left side is the AIT vehicle equipped with the AIT channel sounder as Rx and the Tx MK5 OBU modem. On the right side is the AVL vehicle (ego vehicle) with the LiDAR and radar sensor system, the AIT channel sounder as Tx and the Rx MK5 OBU modem. Additionally, both vehicles are equipped with GPS antennas.

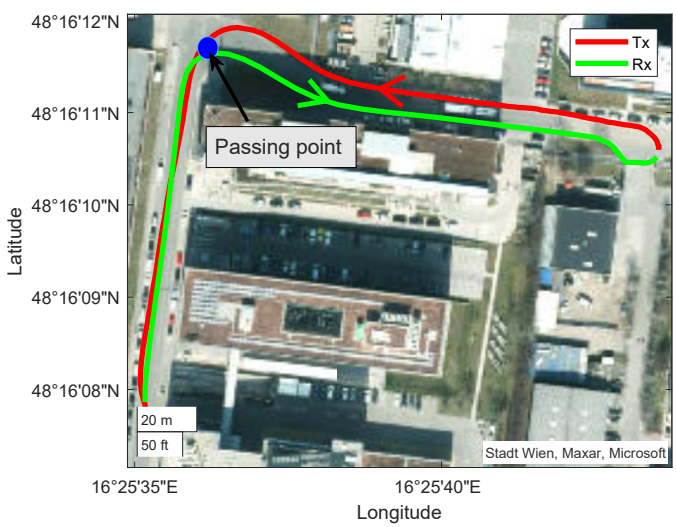


Fig. 4: Scenario used for the validation.

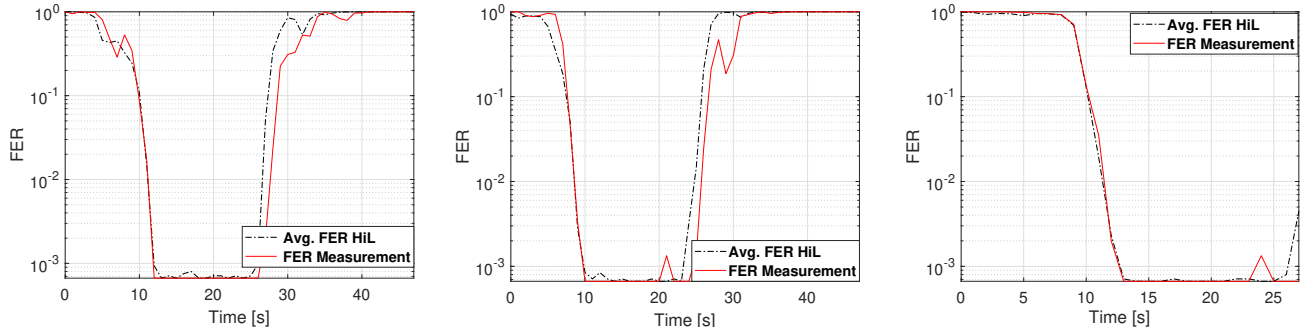
where F_{HiL} and F_{meas} are the empirical distributions for the FER obtained using the HiL and during the measurements, respectively. We further assume a significance level of $5\,\%$. We obtain a p-value of 0.3577 stating that our null hypothesis cannot be rejected. Hence, we infer that our HiL methodology provides a good match between FER obtained by our HiL methodology and the measured FER.

B. Usage of the HiL framework

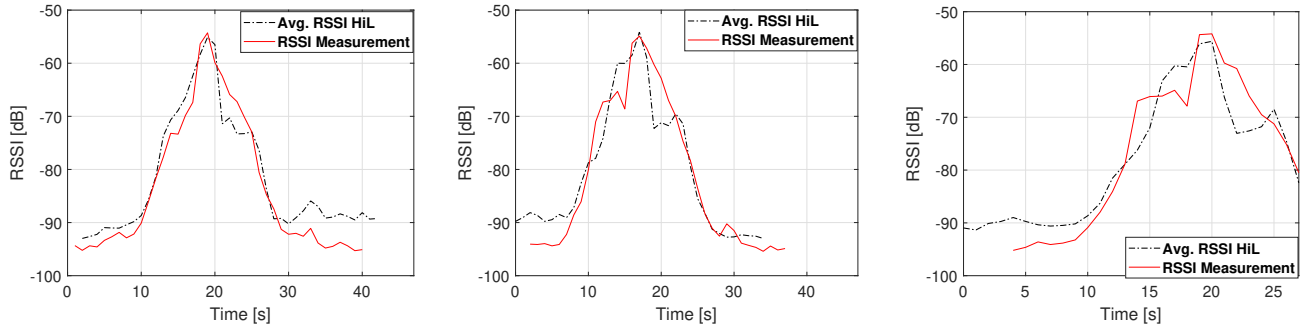
With our HiL framework we are able to reproduce the FER on the road accurately. This enables the repeatable testing of V2X communication hardware, algorithm and software which substantially relies on V2X communication such as ADAS features. These tests can now be done in a laboratory environment by producing realistic radio channel conditions. In Fig. 7 we compare the FER for different modulation schemes and convolutional coding rates. We put the FER and RSSI results obtained by emulating the interpolated channel from one of the runs of the same scenario demonstrating the utility of the HiL framework for the analysis and test of the V2X communication links. We can clearly see that while increasing the data rate, the robustness of the system is getting reduced. Hence the highest FER is obtained for the 64 quadrature amplitude modulation (64QAM) with $R = 2/3$ convolutional coding rate.

VI. Conclusion

In this paper, we showed the validation process of the HiL framework for testing vehicular wireless communication in a non-stationary drive-by scenario. Firstly, we described the architecture of our HiL setup which consists of the AIT real-time channel emulator and two specific IEEE 802.11p modems. Secondly, we introduced the measurement campaign performed in an urban scenario. There we recorded the channel impulse responses via the AIT channel sounder and the FER via the same IEEE 802.11p hardware modems in parallel. Due to the different sampling rates of the channel sounder used in the measurement campaign and the channel emulator, we needed to interpolate the measured channel frequency response. Then, we used the measured channel impulse response to measure the FER and the RSSI via our HiL framework. These results were compared with the FER and the RSSI obtained during the measurement campaign



(a) FER of the measurement and the HiL test. (b) FER of the measurement and the HiL test. (c) FER of the measurement and the HiL test.



(d) RSSI measured by the MK5 OBU on the receiver side. (e) RSSI measured by the MK5 OBU on the receiver side. (f) RSSI measured by the MK5 OBU on the receiver side.

Fig. 5: Validation results for three runs from the measurement campaign.

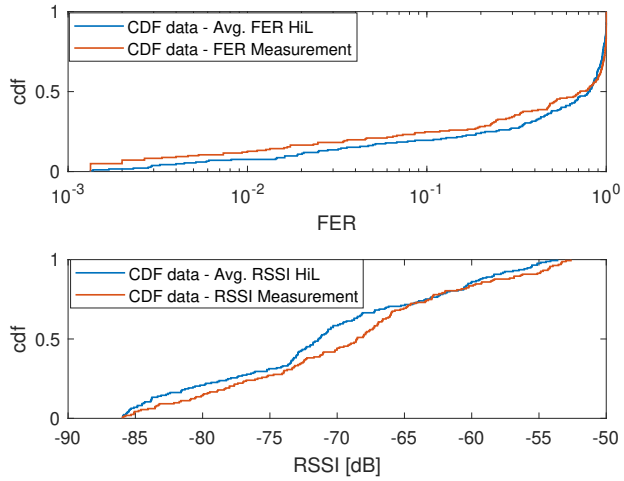


Fig. 6: CDF FER and RSSI.

showing a good match. By performing the K-S two-sample test we obtain the maximal difference of 0.099 between the CDFs of the FER from the HiL and the measurements. Hence, we demonstrated that the FER measurements performed in the laboratory environment by our HiL framework can be an adequate replacement for the FER measurements performed on the road.

VII. Acknowledgments

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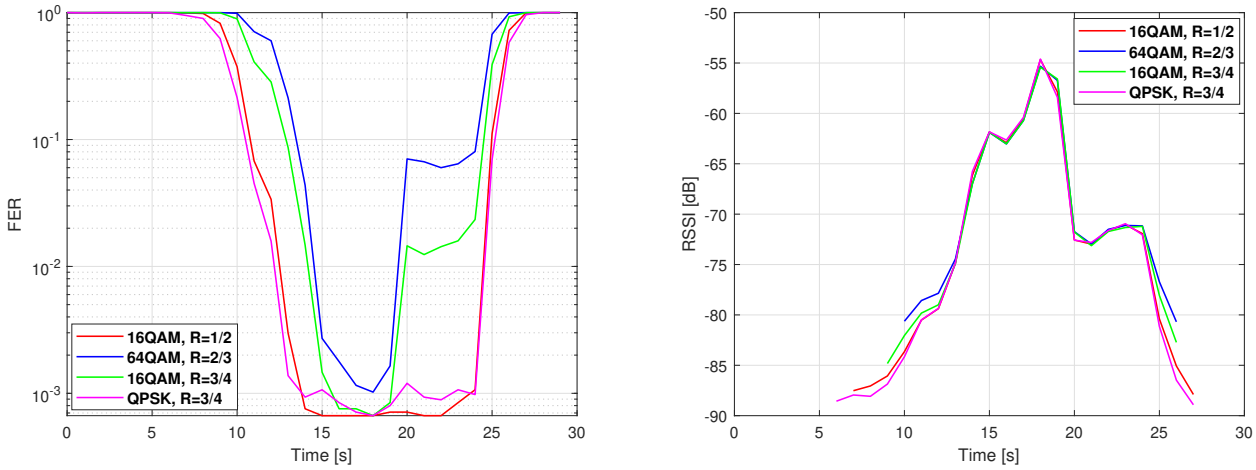

(a) FER of the HiL test.

(b) RSSI measured by the MK5 OBU on the receiver side.

Fig. 7: FER and RSSI results for different modulation schemes and convolutional coding rates of one run from the measurement camapign.

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