Site-Specific Radio Channel Emulation

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***Abstract*—This demo presents a hardware-in-the-loop (HiL) framework for validating and verifying wireless communication hardware under controlled and repeatable laboratory conditions. The setup integrates modems as transmitters and receivers with a real-time channel emulator. To simplify the hardware interfaces we exchange multi-path component parameters between the channel model and the radio channel emulator, following the proposed structure in the ongoing IEEE P1944 standardization for site-specific radio channel representations. The demo features an urban vehicular communication scenario, demonstrating the capability to replicate realistic propagation conditions with non-stationary propagation conditions. Our HiL test system allows dynamic motion changes of the vehicles based on the received data during the emulation process. Site-specific channel emulation enables the lab-based validation of realistic vehicular applications, 5G and 6G physical layer technologies, and the training and testing of AI/ML based receiver architectures.**

I. Introduction

To ensure reliable vehicular communication in different environments a comprehensive testing strategy is needed. Cost-efficient validation and verification of wireless communication and its hardware components are preferably done in a laboratory environment. Using a hardware-in-the-loop (HiL) setup for testing transmitter (TX) and receiver (RX), we can vary their parameters as well as radio channel parameters, in a defined, controlled and repeatable manner, see [1]. The channel impulse response in vehicular scenarios generally has non-stationary statistical properties, i.e., the Doppler spectrum, power delay profile, K-factor and spatial correlation are all spatially variant (or time-variant for mobile receivers and transmitters) [2].

Here, we demonstrate our hardware-in-the-loop (HiL) framework for the validation and verification of wireless communication hardware, algorithms, and protocols under site-specifically defined propagation conditions [2].

II. System Architecture

The HiL setup shown in this demo can be used with any wireless communication system. TX and RX modems are connected to the radio channel emulator to repeatedly test the communication system under well-defined propagation conditions. The channel emulator consists of the host PC, where the channel model is computed, and the field programmable gate arrays (FPGA) part, where the time-variant convolution is computed, as it can be seen in Fig. 1.

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We use a geometry-based quasi-deterministic channel model (QDM) that is based on a sum of P_m multipath components (MPCs) [2], [3]:

$$g_{m,q}(\boldsymbol{\alpha},\boldsymbol{\beta}) = \gamma_q \sum_{p=1}^{P_m} \eta_{p,m} e^{-j2\pi\theta_{p,m}q} \cdot \delta(\boldsymbol{\beta}-\boldsymbol{\beta}_{p,m})\delta(\boldsymbol{\alpha}-\boldsymbol{\alpha}_{p,m}), \quad (1)$$

where m is the time index sampled at time T_S, $q \in \{-Q/2,\ldots,Q/2-1\}$ is the frequency index and Q is the even number of samples in the frequency domain, $\boldsymbol{\alpha}_{p,m} = (\phi_m,\theta_m)^\mathrm{T}$ denotes the direction of arrival vector in terms of azimuth ϕ_m and elevation θ_m of MPC p at the TX side and $\boldsymbol{\beta}_{p,m}$ the corresponding direction of departure at the RX side, respectively, and for all $\boldsymbol{\alpha},\boldsymbol{\beta} \in \mathbb{R}^2$ we define $\delta(\boldsymbol{\alpha}-\boldsymbol{\alpha}_{p,m}) := \delta(\phi-\phi_{p,m})\delta(\theta-\theta_{p,m})$ as the natural extension of the one dimensional Dirac distribution. The combined band-limited impulse response of the TX and RX hardware is denoted by γ_q. The normalized path delay is denoted by

$$\theta_{p,m} = \tau_{p,m}/(T_\mathrm{S}Q),$$

the path weight is denoted by $\eta_{p,m}$, and $\tau_{p,m}$ is the delay of path p at time index m.

The channel frequency response at the base point of the antennas, is finally obtained by integrating over the unit sphere surfaces $\mathcal{T}$ and $\mathcal{R}$ at TX and RX side, taking the antenna pattern of TX, $\xi_\mathrm{T}(\boldsymbol{\alpha})$, and RX, $\xi_\mathrm{R}(\boldsymbol{\beta})$, into account

$$g_{m,q} = \oint_{\mathcal{R}}\oint_{\mathcal{T}} g_{m,q}(\boldsymbol{\alpha},\boldsymbol{\beta})\xi_\mathrm{R}(\boldsymbol{\beta})\xi_\mathrm{T}(\boldsymbol{\alpha})\,\mathrm{d}\boldsymbol{\beta}\,\mathrm{d}\boldsymbol{\alpha}\,. \quad (2)$$

It was shown that a non-stationary fading process can be divided into local regions of stationarity [4] containing M channel impulse response samples. Within a local region of stationarity, indexed by s, the path weight $\eta_{p,s}$ and the normalized Doppler shift $\nu_{p,s}$ are assumed to be constant, leading to a linear delay change within a stationarity region

$$\theta_{p,m} = \theta_{p,sM} - \frac{1}{f_\mathrm{C}T_\mathrm{S}Q}\nu_{p,s}m'\,. \quad (3)$$

The stationarity region index s defines the relationship $m = sM + m'$ between the global time index m and the local time index within a stationarity region $m' \in \{0,\ldots,M-1\}$. Based on the above considerations, we follow the suggestions in the ongoing IEEE P1944 standardization [2] and exchange MPC parameters for each stationarity region between the QDM and the emulator, see Fig. 1.

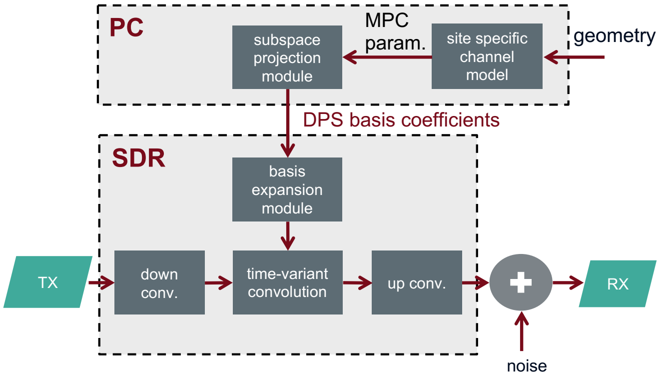

Fig. 1. Schematic of our HiL framework for site-specific radio channel emulation.

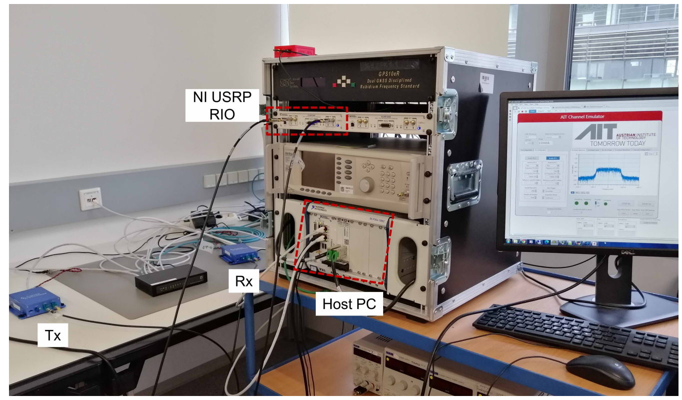

Fig. 2. HiL lab setup, showing the SDR based channel emulator, the host PC as well as the TX and RX modems.

In [5] we develop a subspace projection method to compress the channel impulse response sequence of each stationarity region exploiting the MPC parameters and the bandlimited properties of the fading process $p_{m,q}$ in time and frequency, i.e., we can assume

$$|\nu_{p,s}| \leq \nu_{\mathrm{Dmax}} \tag{4}$$

and

$$0 \leq \theta_{p,sM} \leq \theta_{\mathrm{Pmax}} \,, \tag{5}$$

where both the normalized maximum Doppler shift ν_{Dmax} and the maximum normalized delay θ_{Pmax} are given by the application scenarios of the communication system.

The subspace is spanned by two-dimensional discrete prolate spheroidal (DPS) sequences with dimension $D \ll MQ$ [6], [7]. The DPS coefficients are transmitted to the emulator where they are expanded and the resulting channel impulse response is used to compute the convolution with the signal of the TX modem.

The subspace projection approach allows to avoid the quadratic data rate increase $R \propto c_1 B^2 T_{\mathrm{D}}$ of the communication link between the radio channel model and the convolution unit, where the radio signal bandwidth $B = 1/T_{\mathrm{S}}$, and T_{S} denotes the sampling time. The number of bits per complex sample are denoted by c_1 and T_{D} is the support of the delay spread.

III. Accuracy of Subspace Projection

The subspace dimension D is chosen such that the residual square bias of the projection on the two-dimensional DPS subspace is smaller than the numerical precision ε of the analog/digital converter

$$\mathrm{bias}^2 \leq \varepsilon = 2^{-(N_{\mathrm{b}}-1)} \tag{6}$$

where the bit-width of the analog/digital converter is denoted by N_{b}, see [5], [8]. The efficient computation of the two-dimensional DPS subspace is described in [6, Sec. III].

The square bias of the subspace projection can be expressed in terms of the eigenvalues of the two dimensional DPS sequences λ_i,

$$\mathrm{bias}^2 = \frac{1}{2\nu_{\mathrm{Dmax}}\theta_{\mathrm{Pmax}} MQ} \sum_{i=D}^{MQ} \lambda_i \tag{7}$$

Please see [5, Table 1] for the detailed definition of the simulation parameters.

The subspace projection algorithm of the emulator [5], [8] exploits the relationship between the DPS sequences and their Fourier transform, the DPS wave functions [7]. Hence a simple table lookup and interpolation step can replace the explicit projection of each MPC on the DPS subspace. Please see [5, Sec. II.D.] for the detailed algorithm and [8] for the mathematical theory.

The approximate subspace projection accuracy can be improved by oversampling the DPS sequences by a factor r. This over-sampled DPS sequences increase the storage requirement for the table lookup but are not required for the actual real-time reconstruction of the channel impulse response to compute the convolution in the emulator.

IV. Demonstration

The demo uses the emulator structure shown in Fig. 1. For the specific implementation, we use the IEEE 802.11p Cohda Wireless MK5 modems. The real-time emulation employing a HiL setup enables frame error rate (FER) measurements [1]. The HiL setup in our laboratory is depicted in Fig. 2.

A control script written in Python manages the complete emulation procedure. The TX and RX modems are controlled via secure shell connections (SSH). The geometry data for the emulation is a vehicular scenario on a street around the AIT building in Vienna based data obtained from OpenStreetMap.

The geometry-based QDM used for the computation of the MPCs takes the surroundings of the communication system into account by considering the environment geometry, including buildings, vegetation, and mobile objects. Simplified ray

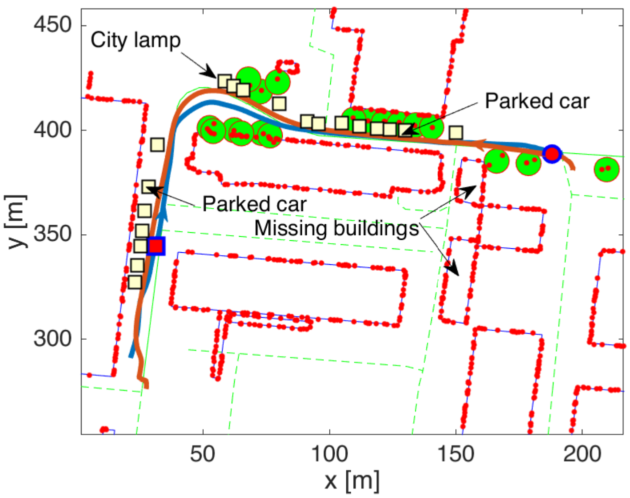

Fig. 3. Quasi-deterministic environment model for a vehicular scenario, see [3, Fig. 4b]. Red dots indicate point scatterers randomly distributed along walls and vegetation to represent static diffuse scattering, mobile discrete scatterers are represented by blue squares and circles, black squares represent static discrete scatterers such as parked cars or street lamps.

tracing is performed on a low-resolution environmental map to deterministically find the dominant MPCs. Point scatterers are placed (i) according to a given distribution close to surfaces of objects to represent surface roughness and (ii) in small clusters to represent other objects such as vegetation, moving vehicles, and pedestrians. The QDM is depicted in Fig. 3

The demonstration proceeds in the following steps:

1) The MPCs per stationarity region are computed and projected on the DPS subspace providing the DPS basis coefficients.
2) TX and RX modems are controlled via an SSH connection to start the transmission and reception process.
3) The DPS basis coefficients are streamed to the emulator, where the channel impulse response sequence and the convolution with the TX modem signal is computed.
4) The RX modem collects the successfully received frames and the received signal strength.
5) The resulting FER vs. time is computed, see Fig. 4.

The emulation as a service (EaaS) capability of our setup allows an interactive demonstration at remote locations.

V. Conclusions

Our site-specific radio emulation demo combines an SDR based convolution unit and a geometry-based QDM. The MPC based channel model structure is exploited to perform efficient subspace compression to achieve a low-rate communication link between the channel model and the convolution unit. This approach follows the suggestions in the ongoing IEEE P1944 standardization effort for site-specific channel representations. The TX and RX modem are connected to the emulator to perform repeatable HiL test, enabling dynamic motion changes

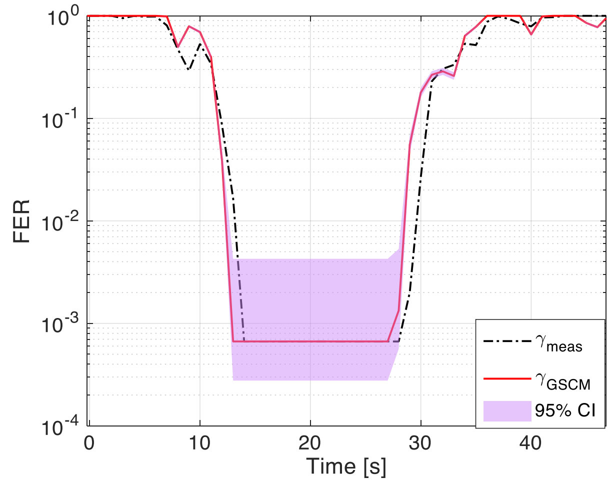

Fig. 4. FER vs time for a vehicular scenario with vehicles driving in opposite directions.

of the vehicles based on the received data during the emulation process. The site-specific channel emulation enables for the first time the lab-based validation of realistic vehicular applications, 5G and 6G physical layer technologies, and the training and testing of AI/ML based receiver architectures.

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