Validation of a Real-Time Geometry-Based Stochastic Channel Model for Vehicular Scenarios

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***Abstract*—The performance of wireless communication systems is fundamentally determined by wireless communication channel properties. Wireless vehicular communication channels exhibit multipath propagation and non-stationary channel statistics. Methods and tools for the repeatable test of wireless communication systems and signal processing algorithms in such environments are urgently needed to enable the development of reliable communication links with low-latency. In this paper we present the measurement and validation of a real time channel emulation method for non-stationary vehicular scenarios based on a geometry-based stochastic channel model.**

***Index Terms*—real-time, channel emulation, SDR, geometry-based stochastic channel model, FPGA, sowftware defined radio**

I. Introduction

Non-stationary propagation conditions are key aspects of wireless communication channels that connect vehicles. For vehicular scenarios empiric measurement data [1–4] exists, and channel modelling techniques based on geometry-based stochastic channel models (GSCMs) [5–7] are well established and validated. GSCMs represent the propagation scenarios by a sum of propagation paths that are defined by point scatterers placed according to a spatial distribution. Different scatterer types are defined such as discrete stationary scatterer (parked vehicles, road signs), mobile scatterers (moving vehicles) and diffuse scatterers (e.g. trees). Real-time channel emulation for non-stationary scenarios based on a GSCM is a missing component that we validate for the first time in this paper.

Commercially available channel emulation solutions from Spirent [8] and Anite [9] as well as software defined radio (SDR) based channel emulator solutions [10–16] are all based on tap delay line (TDL) models. Due to the underlying TDL model, all these emulators share the main drawback that path delays can be only set in integer multiples of the sampling rate.

A new low-complexity reduced-rank subspace model was introduced by Kaltenberger et al. [17–19] to emulate a GSCM with real-valued path delay and Doppler shift. In [20] we presented a first digital fixed-point field programmable gate array (FPGA) implementation of this concept. The GSCM computation and the subspace projection is performed on a general purpose multi-core personal computer (PC). The subspace coefficients represent a highly compressed channel representation that is streamed to the SDR to compute the convolution with the input signal using an efficient fixed point FPGA implementation [21]. With this approach the computational complexity on the FPGA is *independent* of the number of multipath components.

The scientific contribution of this paper is the validation of the implementation of the GSCM by channel sounding measurements with the RUSK Lund channel sounder and comparing the measurements with a Matlab co-simulation.

II. System Model

To emulate the effects of wireless wave propagation a real-time emulator convolves the input signal with the time-variant channel impulse response. The architecture of our emulator is shown in Fig. 1 (see also [20]).

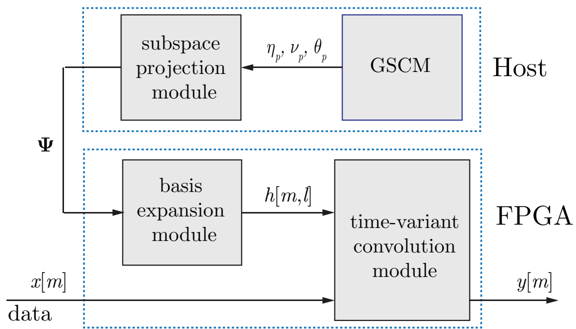

Fig. 1: Channel emulator architecture [20]

To realistically model the non-stationary properties of wireless channel propagation we assume that the channel propagation parameters originate from a GSCM [5]. We describe the non-stationary time-variant frequency response [20, 22–25],

$$g_{\text{Ph}}(t,f) = \sum_{p=0}^{P-1} \eta'_p(t) \mathrm{e}^{-\mathrm{j}2\pi\tau_p(t)f}, \tag{1}$$

as the superposition of P individual propagation paths with time-variant path delay $\tau_p(t)$. Each path is characterized by the complex time-variant weighting coefficient $\eta'_p(t) =$

$a_p(t)e^{j2\pi\phi_p}$ with amplitude $a_p(t)$ and initial phase ϕ_p. The channel can be approximated as wide-sense stationary within the stationary time T_{stat} [1, 2]. We assume that within a stationarity region the amplitude of a path does not change, i.e., $\eta'_p(t) \approx \eta'_p$ for $t_1 \leq t < t_1 + T_{\text{stat}}$ and that the velocity between transmitter and receiver stays constant. Thus, we model the time-variant path delay with a linear model [20, 22]

$$\tau_p(t) = \tau_p(0) - \frac{f_p}{f_c}t. \tag{2}$$

The initial path delay $\tau_p(0)$ is determined by the distance between transmitter and receiver, f_c denotes the carrier frequency of the system and f_p denotes the Doppler shift of path p. The Doppler shift is defined by

$$f_p = f_c\frac{v_p}{c_0}, \tag{3}$$

with v_p denoting the relative velocity between transmitter and receiver that is determined by the geometry of the scenario (see e.g. [5, 23] for more information) and c_0 the speed of light. With (2) and assuming that the system bandwidth is much smaller than the carrier frequency f_c, which is true for most communication systems [25, Ch. 1], we obtain the time-variant channel transfer function as

$$g_{\text{Ph}}(t, f) = \sum_{p=0}^{P-1} \eta_p e^{j2\pi f_p t} e^{-j2\pi\tau_p(0)f'}, \tag{4}$$

where we define $\eta_p = \eta'_p e^{-j2\pi\tau_p(0)f_c}$.

Sampled Channel Transfer Function

We emulate the channel for a finite system bandwidth B. To allow for realistic input/output filters of an implemented system we oversample $g_{\text{Ph}}(t, f)$ by a factor f_{OSF}, i.e., $B' = f_{\text{OSF}}B$. We sample with $T_C = 1/B'$. Considering a band-limiting filter $g_R(f)$ and using (2) we obtain

$$\begin{aligned} g[m, q] &:= g_R(qF_s)g_{\text{Ph}}(mT_C, qF_s) \\ &= g_R[q] \sum_{p=0}^{P-1} \eta_p e^{-j2\pi q\theta_p} e^{j2\pi m\nu_p} \end{aligned} \tag{5}$$

where $\nu_p = f_pT_C$ denotes normalized Doppler shift and $\theta_p = \tau_p(0)/(NT_C)$ normalized path delay with $|\nu_p| < \frac{1}{2}$ and $0 \leq \theta_p < 1$.

To emulate the effects of a wireless propagation channel the emulator convolves the input signal $x[m]$ with the time-variant channel impulse response (CIR) $h[m, l]$ to obtain the output signal

$$y[m] = \sum_{l=0}^{L-1} h[m - l, l]x[m - l], \tag{6}$$

with l denoting the index in the delay domain and L the number of delay taps. We obtain $h[m, l]$ by the inverse discrete Fourier transform (IDFT) of the time-variant transfer function $g[m, q]$.

To reduce the streaming bandwidth between SDR and PC we compress the CIR using a reduced-rank basis-expansion model (BEM) as explained in [17, 20]. A subspace-projection module utilizes the path weight η_p, normalized Doppler shift ν_p and normalized path delay θ_p of each propagation path to obtain the basis coefficient matrix $\mathbf{\Psi}$ that describes the evolution of the channel. The accuracy of the description depends on the number of utilized basis coefficients as shown in [20]. On the FPGA the CIR is reconstructed using the basis coefficient matrix $\mathbf{\Psi}$ and basis vectors, see Fig. 1. We utilize discrete prolate spheroidal sequences [26] for the compression and reconstruction of the CIR. The basis coefficients are periodically updated in *real-time* with T_{stat}.

III. Measurement and Validation of the Channel Emulator

For the validation of our real-time GSCM implementation we use a road intersection crossing scenario. In [6] a GSCM model for this particular road intersection scenario was developed. We validate the functionality of the channel emulator by comparison with a numerical co-simulation that is explained in [20]. In the following we introduce the emulation parameters, show the measurement setup and describe the evaluation method in more detail.

A. Emulation Parameters

We set the carrier frequency of the system to $f_c = 5.7\,\text{GHz}$. We implement the emulator for a bandwidth of $10\,\text{MHz}$, a maximum path delay of $\tau_{\text{max}} = 1.6\,\mu\text{s}$ and a maximum speed of $v_{\text{max}} = 400$ km/h. The oversampling factor is set to $f_{\text{OSF}} = 2$ which leads to $T_C = 50\,\text{ns}$. We choose the stationarity region length to $T_{\text{stat}} = 256\,\mu\text{s}$ ($M = 5120$) which is equal to an update rate of the subspace coefficients $1/T_{\text{stat}} \approx 3.907\,\text{kHz}$. The number of sample points in the frequency direction is set to $N = 128$.

As SDR we use a National Instruments (NI) USRP-2954R [27] that is equipped with an Xilinx Kintex-7 FPGA. The measured overall system delay is $\tau_{\text{proc}} \approx 5.3\,\mu\text{s}$.

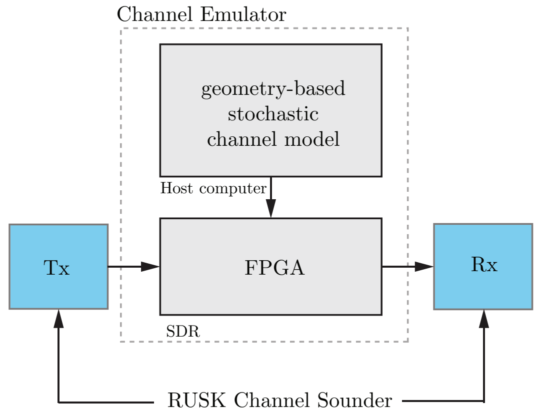

Fig. 2: Measurement Setup

B. Measurement Setup

The measurement setup is shown in Fig. 2. The RUSK channel sounder measures the discrete frequency response $g[u,q] = g(t_s u, f_s q)$ of the channel emulator by periodically sampling $g(t,f)$ in time and frequency direction [1, 2]. Here, $u \in \{0,\ldots,U-1\}$ represents the discrete time index sampled at t_s with U being the total number of snapshots and $q \in \{0,\ldots,Q-1\}$ denotes the discrete frequency index with Q the number of frequency bins. The frequency resolution is defined by $f_s = B_M/Q$.

The length of the sounding sequence was set to $T = 12.8\,\mu$s which corresponds to the maximum measurable excess delay, i.e., $\tau_{\text{Mmax}} = T$. We recorded the CIR with a repetition rate of $t_\text{s} = 102.4\,\mu$s which results in a maximum resolvable Doppler shift of

$$\nu_\text{D} = \frac{1}{2t_\text{s}} = 4.883\,\text{kHz}. \tag{7}$$

For the measurement we record $S_t = 100000$ snapshots which is equal to a measurement time of $T_\text{meas} = 10.24$ s. We set the measurement bandwidth to $B_M = 100$ MHz. The bandwidth was separated in $Q = 1281$ frequency bins which results to $f_s = B_M/Q = 78.06$ kHz. To minimize the local oscillator (LO) leakage due to I/Q impairments in the direct down/up conversion in the radio frequency front ends of the USRP, we utilize a digital I/Q impairment correction. Furthermore, we use single side band emulation with a digital intermediate frequency to shift the LO leakage out of the emulated channel.

C. Measurement Evaluation

The performance of the channel emulator is characterized by the local scattering function (LSF) $\hat{\mathcal{C}}[k_t;n,p]$ explained in [1, 28–33]. We denote $n \in \{0,\ldots,M_f-1\}$ as the delay index and $p \in \{-M_t/2,\ldots,M_t/2-1\}$ as Doppler index, respectively. The time index of each stationarity region is $k_t \in \{0,\ldots,\lfloor S_t/M_t - 1\rfloor\}$ and correspond to the center of the stationarity regions. For the LSF evaluation we set $M_t = 400$ and $M_f = 128$ which corresponds to a stationarity region of $T_\text{LSF} = 41$ ms in time and $B = B_\text{LSF} \approx 10$ MHz in frequency.

The power delay profile (PDP) and Doppler spectral density (DSD) are calculated as a summation of the LSF over the Doppler or delay domain, respectively [1, 2], i.e.,

$$\hat{\mathcal{P}}_\tau[k_t;n] = \frac{1}{M_t}\sum_{p=-M_t/2}^{M_t/2-1} \hat{\mathcal{C}}[k_t;n,p] \tag{8}$$

and

$$\hat{\mathcal{P}}_\nu[k_t;n] = \frac{1}{M_f}\sum_{p=0}^{M_f-1} \hat{\mathcal{C}}[k_t;n,p]. \tag{9}$$

As validation we show a comparison of the time-variant PDP and the time-variant DSD obtained by means of the LSF [1]. The results are normalized to the maximum received power of the LSF. In Fig. 3 we show the PDP of (a) the numerical GSCM evaluation and (b) the measurement data of the channel emulator. In Fig. 4 we show the same comparison for the DSD.

We compare Fig. 3 and Fig. 4 via visual inspection and obtain an excellent match between numerical co-simulation and channel emulation. The emulator is capable of emulating the non-stationary channel properties of the road-intersection crossing scenario. The difference in the noise floors originates from not considering thermal noise for the numerical co-simulation.

IV. Conclusion

In this paper we present the validation measurement of a real-time channel emulator. The emulator uses a separation in two components, the first one being the GSCM calculated on a general purpose multicore PC in *real-time* and the second one being the convolution implemented on a SDR. The emulator uses a reduced-rank channel model to compress the CIR that is transmitted to the SDR where it is convolved with the input signal. A measurement with the RUSK Lund channel sounder showed an excellent match of the emulated channels with a numerical co-simulation via visual inspection. The real-time emulation method allows repeatable testing of vehicular communication scenarios. The high flexibility of our channel emulator, i.e., the possibility to adapt the GSCM to other scenarios like highway, merging lanes, etc., makes it a key component for testing wireless communication systems and closely linked control algorithms for connected autonomous vehicles.

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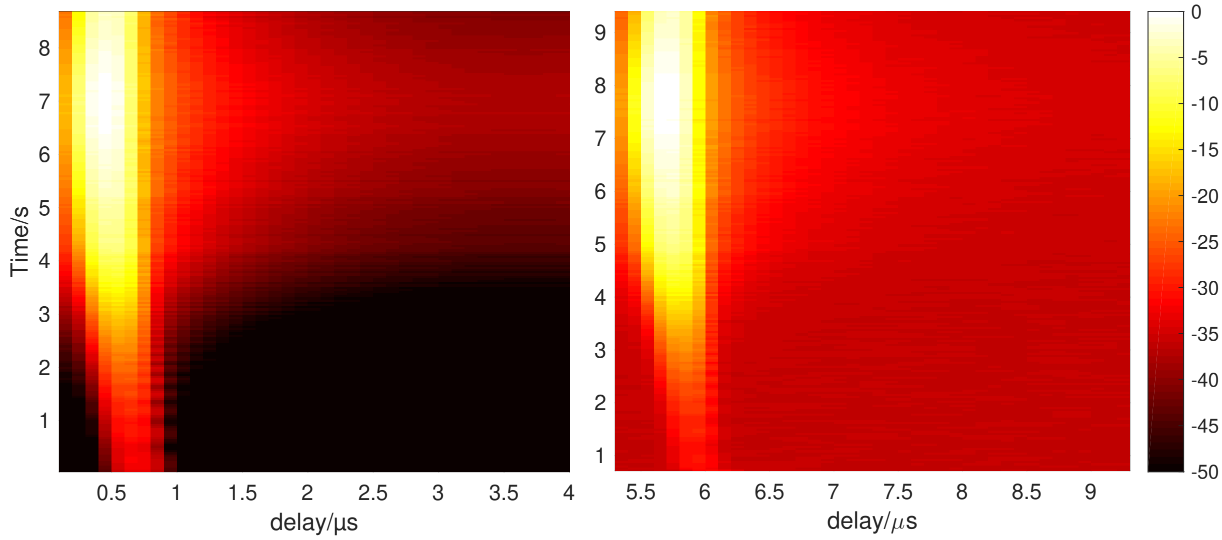
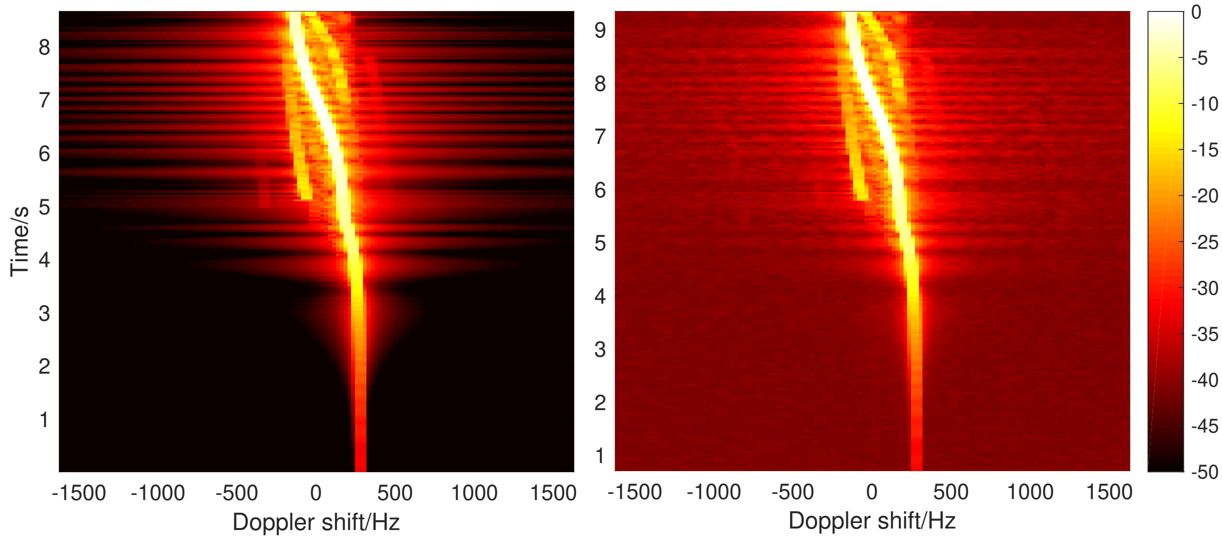


(a) Numerical GSCM evaluation (b) Measured channel emulator

Fig. 3: Comparision of the PDP for the road intersection.



(a) Numerical GSCM evaluation (b) Measured channel emulator

Fig. 4: Comparision of the DSD for the road intersection.

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