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Fan, Wei; Sun, Fan; Kyösti, Pekka; Nielsen, Jesper Ødum; Carreño, Xavier; Knudsen, Mikael; Pedersen, Gert Frølund

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A technique to emulate 3D geometry-based channel models in a multi-probe over the air test setup is presented. The proposed technique provides a general emulation framework for any spherical incoming power spectrum. The emulation method results in two optimization objectives, which are both convex. They give optimal emulation accuracy and allow relatively low computational complexity.

Introduction: As a solution to evaluate multiple input multiple output (MIMO) device performance in realistic conditions in the lab, MIMO over the air (OTA) testing has attracted huge interest from both industry and academia, see e.g. [1]. One promising candidate is the multi-probe based anechoic chamber method. Several papers have discussed OTA testing setups for MIMO devices with emphasis on channel modeling, where the goal is to accurately reproduce realistic 2D channels in the test area with a limited number of OTA probes [1]. However, the 2D channel model is not generally valid. Measurements have demonstrated that elevation spread can not be ignored in many propagation environments, see e.g. [2, 3], and thus emulation of 3D models is required. Very few contributions have addressed this issue. In [4], it was briefly mentioned that probes in a 3D setup were used to emulate 3D channel models, but no algorithm description is given. The 3D channel emulation technique has also been implemented in a commercial channel emulator, the Elektrobit Propsim F8, where the Laplacian distributions are defined for the power azimuth spectrum (PAS) and the power elevation spectrum (PES). However, a description of the implemented channel emulation algorithm is not available. This letter presents a new channel emulation technique for arbitrary 3D channel models.

Method: The modeling of radio channel parameters such as delay, Doppler, channel polarization and transmitter (Tx) side spatial characteristics is detailed in [1] and can be easily modeled. Thus, the focus is on reproducing the channel in the test volume at the receiver (Rx). The device under test (DUT) should be smaller than the test volume to ensure that the target propagation environment is accurately reproduced around the DUT.

The spherical power spectrum (SPS) needs to be modeled as a function of both elevation angle (θ) and azimuth angle (ϕ). In [3], it is shown that PES and PAS are independent and the SPS can be expressed as:

$$p(\theta, \phi) = p(\theta)p(\phi) \tag{1}$$

where $p(\theta)$, $p(\phi)$ are the PES and PAS, respectively. In order to be used as an angular power density function, the SPS $p(\theta, \phi)$ needs to satisfy $\oint p(\Omega)d\Omega = \int_{-\pi}^{\pi} \int_{-\pi/2}^{\pi/2} p(\theta, \phi) \cos\theta d\theta d\phi = 1$ with Ω being the solid angle.

The spatial correlation is a statistical measure of the similarity of the received signals at different positions in space and it is selected as a figure of merit (FoM) to model 3D channel spatial characteristics at the Rx side, as adopted for the 2D case [1]. Isotropic antenna patterns are used for the 3D channel emulation, as the emulated channel model itself will assume some DUT antennas if antenna patterns are otherwise embedded for channel emulation. The polarizations are independent and can be treated individually and hence explained for any one polarization. The spatial correlation can be determined according to [5], for a single polarization, as:

$$\rho_a = \frac{\oint G_u(\Omega)G_v^{\star}(\Omega)p(\Omega)d\Omega}{\sqrt{\oint |G_u(\Omega)|^2 p(\Omega)d\Omega}\sqrt{\oint |G_v(\Omega)|^2 p(\Omega)d\Omega}}, \tag{2}$$

where $()^{\star}$ denotes complex conjugate operation, G_u and G_v are the complex radiation patterns of antennas u and v, respectively, with a common phase center. Based on the assumption about the isotropic antenna pattern, we can rewrite equation (2) as:

$$\rho = \oint \exp(jk(\overline{r}_u - \overline{r}_v) \cdot \overline{\Omega})p(\Omega)d\Omega, \tag{3}$$
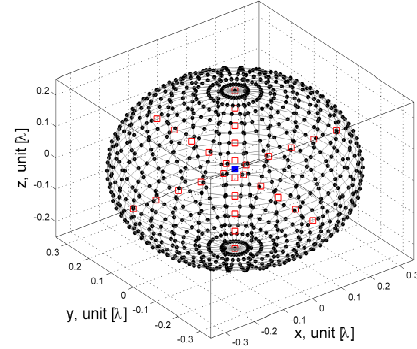

Fig. 1 *Different ways to sample the test volume: On line segments (squares) and on the surface of an ellipsoid (dots).*

where $\overline{r}_u$ and $\overline{r}_v$ are vectors containing the position information of antenna u and v, respectively. $\overline{\Omega}$ is an unit vector corresponding to space angle Ω. k is the wave number. $(\cdot)$ is the dot product operator.

The goal is to obtain OTA probe power weights which minimize the deviation between the theoretical spatial correlation of the target continuous SPS, and the emulated correlation of the discrete SPS characterized by power weights of the probes. Similar to (3), the emulated spatial correlation can be calculated based on the discrete spherical power spectrum characterized by M probes as:

$$\hat{\rho} = \sum_{m=1}^{M} w_m \exp(jk(\overline{r}_u - \overline{r}_v) \cdot \overline{\Phi}_m), \tag{4}$$

where w_m is the power weight for the mth probe. $\overline{\Phi}_m$ is a unit position vector of the mth probe. M is the number of probes. We will discuss two objective functions:

- Minimize the summation over the total emulation error (Min-Sum):

$$\min_{\boldsymbol{w}} \quad \|\hat{\boldsymbol{\rho}}(\boldsymbol{w}) - \boldsymbol{\rho}\|_2^2 \tag{5}$$

$$s.t. \quad 0 \le w_m \le 1, \ \forall m \in [1, M]$$

where $\boldsymbol{w} = [w_1, ..., w_M]^T$ is a power weighting vector to be optimized. $\hat{\boldsymbol{\rho}}$ and $\boldsymbol{\rho}$ are the emulated spatial correlation and target spatial correlation vectors, respectively, with each element corresponding to the spatial correlation between two isotropic antennas at a certain location pair on the test volume.

- Minimize the maximum emulation error (Min-Max):

$$\min_{\boldsymbol{w}} \max_{i} |\hat{\rho}_i(\boldsymbol{w}) - \rho_i| \tag{6}$$

$$s.t. \ 0 \le w_m \le 1, \ \forall m \in [1, M].$$

Through this objective function unacceptable high emulation errors are avoided, at the expense of larger total emulation error $\|\hat{\boldsymbol{\rho}}(\boldsymbol{w}) - \boldsymbol{\rho}\|_2^2$, as demonstrated below.

Eq. (5) is a convex problem and (6) can be easily converted to a convex problem, which can be handled efficiently.

In [4], the test volume is sampled by selecting locations for u and v from three orthogonal segments of line centered inside the sphere, as shown in Figure 1. This way of selecting all points within the test volume will give optimal results on the three axes. However, it might not present optimal emulation results for sample points within the entire test volume and emulation accuracy might be critically low in certain situations. To avoid this, samples on the surface of an oblate ellipsoid shaped test volume is proposed. The ellipsoid is chosen, since the number of OTA probes in the azimuth plane is likely different from that in the elevation plane. The sample locations for u and v ($\overline{r}_u$ and $\overline{r}_v$) are selected to be directly opposite to each other w.r.t the test volume center and are obtained by sweeping the location pairs over the whole surface of the ellipsoid.

Simulation results and discussions: An example target channel is considered with an azimuth angle of arrival (AoA) = 0° and azimuth spread of arrival (ASA) = 35° defined for the Laplacian shaped PAS; the elevation angle of arrival (EoA) = 15° and elevation spread of arrival (ESA) = 10° for the Laplacian shaped PES. Three different probe configurations are assessed for the target SPS, as detailed in Table 1. The probes are placed on

Table 1: Probe configurations. Value in () denotes the number of probes.

Case	Probe Setup	Test volume
A (16)	$\theta_1 = 0^o; \phi_{1i} = -180^o + i \cdot 90^o, i \in [1, ..., 4]$ $\theta_2 = 15^o; \phi_{2i} = -180^o + i \cdot 45^o, i \in [1, ..., 8]$ $\theta_3 = 30^o; \phi_{3i} = -180^o + i \cdot 90^o, i \in [1, ..., 4]$	major axis: 0.8λ minor axis: 0.9λ
B (32)	$\theta_1 = 0^o; \phi_{1i} = -180^o + i \cdot 45^o, i \in [1, ..., 8]$ $\theta_2 = 15^o; \phi_{2i} = -180^o + i \cdot 22.5^o, i \in [1, ..., 16]$ $\theta_3 = 30^o; \phi_{3i} = -180^o + i \cdot 45^o, i \in [1, ..., 8]$	major axis: 1.8λ minor axis: 0.9λ
C (48)	$\theta_1 = 0^o; \phi_{1i} = -180^o + i \cdot 30^o, i \in [1, ..., 12]$ $\theta_2 = 15^o; \phi_{2i} = -180^o + i \cdot 15^o, i \in [1, ..., 24]$ $\theta_3 = 30^o; \phi_{3i} = -180^o + i \cdot 30^o, i \in [1, ..., 12]$	major axis: 3λ minor axis: 0.9λ

Table 2: Statistics of the emulation results $|\rho - \hat{\rho}|$

Case	Channel emulator		Min-Sum		Min-Max	
	rms	max	rms	max	rms	max
A	0.07	0.16	0.07	0.23	0.08	0.10
B	0.07	0.19	0.05	0.18	0.06	0.09
C	0.07	0.21	0.05	0.14	0.05	0.08

Fig. 3 *Target spatial correlation $|\rho|$ between antenna u and v and emulated spatial correlation $|\hat{\rho}|$ on two orthogonal axes (on azimuth plane) for the 3 cases detailed in Table 1. Axis x is along the AoA of the target channel. The power weights are obtained by the Min-Sum algorithm.*

a sphere, and the elevation angle θ and the azimuth angle ϕ are specified for each probe. The probes are organized on three elevation rings. θ_k denotes the elevation angle for all the probes on kth elevation ring. ϕ_{kj} is the azimuth angle of the jth probe on the kth elevation ring. The test volume is larger for case C than case A due to the larger number of probes.

The target spatial correlation $|\rho|$ for case C and emulation results with different algorithms are shown in Figure 2. The spatial correlation between the antennas on the surface of the test volume varies with locations of u and v. Statistics of the emulation results for all cases with different algorithms are summarized in Table 2. Generally, the Min-Sum algorithm presents the best performance for all scenarios in terms of rms error, while the Min-Max algorithm offers the smallest maximal error for all cases, as expected.

Target spatial correlations $|\rho|$ between antenna u and v and emulated spatial correlations $|\hat{\rho}|$ on two orthogonal axes (azimuth plane) for 3 cases are shown in Fig 3. A clear relation between the test volume and number of probes is shown.

Conclusion: This letter presents a channel emulation technique for 3D geometry-based channel models for a multi-probe based setup. The proposed methods provides a general emulation framework for all spherical power spectrums and offers globally optimal emulation accuracy with low computational complexity.
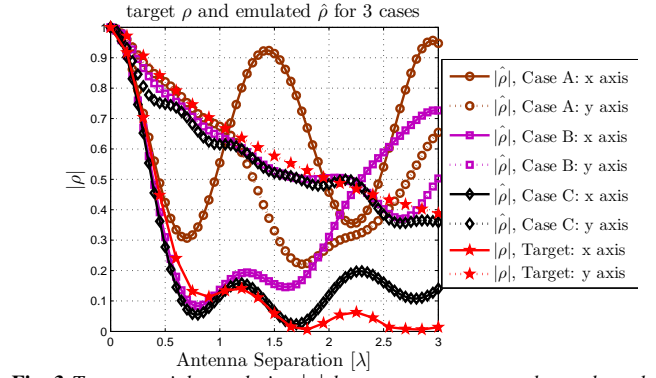
W. Fan, F. Sun, J. Nielsen, G. Pedersen (*Department of Electronic Systems, Faculty of Engineering and Science, Aalborg University, Denmark*)

E-mail: wfa@es.aau.dk

P. Kyösti (*Anite Telecoms Oy, Finland*)

X. Carreño and M. Knudsen (*Intel Mobile Communications, Denmark*)

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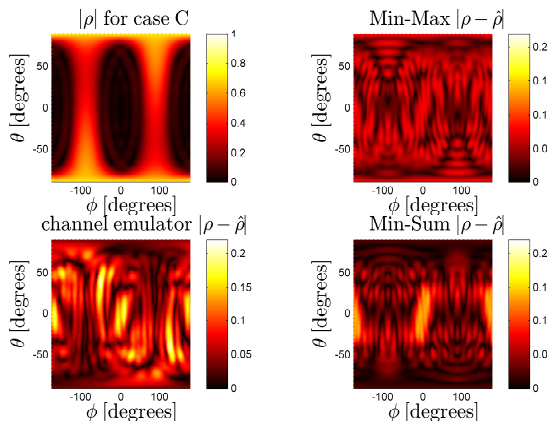
Fig. 2 *Target spatial correlation $|\rho|$ between antenna u and v on the surface of the test volume and the associated emulation results $|\rho - \hat{\rho}|$.*