3D channel emulation in a multi-probe setup
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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 academia and industry, 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 cannot 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 ($\theta$) and azimuth angle ($\phi$). In [3], it is shown that PES and PAS are independent and the SPS can be expressed as:

$$p(\theta, \phi) = p(\theta)p(\phi)$$

(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

$$\int p(\theta, \phi) d\Omega = \int_{0}^{\pi} \int_{0}^{2\pi} p(\theta, \phi) \cos \theta d\theta d\phi = 1$$

which is 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 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:

$$\rho_{m} = \frac{\int \mathbf{G}_{u}(\Omega)^{*}\mathbf{G}_{v}(\Omega)p(\Omega)d\Omega}{\sqrt{\int \mathbf{G}_{u}(\Omega)^{*}p(\Omega)d\Omega \int \mathbf{G}_{v}(\Omega)^{*}p(\Omega)d\Omega}}$$

(2)

where $\mathbf{G}$ denotes complex conjugate operation, $\mathbf{G}_{u}$ and $\mathbf{G}_{v}$ 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:

$$\rho = \exp(j k (\mathbf{r}_{u} - \mathbf{r}_{v}) \cdot \mathbf{\Omega}) d\Omega,$$

(3)

where $\mathbf{r}_{u}$ and $\mathbf{r}_{v}$ are vectors containing the position information of antenna $u$ and $v$, respectively. $\mathbf{\Omega}$ is an unit vector corresponding to space angle $\Omega$. $k$ 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:

$$\hat{\rho} = \sum_{m=1}^{M} w_{m} \exp(j k (\mathbf{r}_{m} - \mathbf{r}_{u}) \cdot \mathbf{\Omega}),$$

(4)

where $w_{m}$ is the power weight for the $m$th probe, $\mathbf{\Omega}$ is a unit position vector of the $m$th probe. $M$ is the number of probes. We will discuss two objective functions:

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

$$\min_{w} \| \hat{\rho}(w) - \rho \|_{2}^{2}$$

(5)

s.t. $0 \leq w_{m} \leq 1$, $\forall m \in [1, M]$

where $w = [w_{1}, ..., w_{M}]^{T}$ is a power weighting vector to be optimized.

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

$$\min_{w} \max_{i} | \rho_{i}(w) - \rho_{i} |$$

(6)

s.t. $0 \leq w_{m} \leq 1$, $\forall m \in [1, M]$

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

Simulations results and discussions: 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 test volume and emulation accuracy might be critical 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 $v$ ($\mathbf{r}_{u}$ and $\mathbf{r}_{v}$) 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.
Table 1: Probe configurations. Value in () denotes the number of probes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Probe Setup</th>
<th>Test volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (16)</td>
<td>( \theta_1 = 0^\circ, \theta_2 = -180^\circ + i \cdot 30^\circ, i \in [1, ... , 4] )</td>
<td>major axis: 0.83A minor axis: 0.93A</td>
</tr>
<tr>
<td></td>
<td>( \theta_3 = 15^\circ, \theta_4 = -180^\circ + i \cdot 45^\circ, i \in [1, ... , 4] )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \theta_5 = 30^\circ, \theta_6 = -180^\circ + i \cdot 50^\circ, i \in [1, ... , 4] )</td>
<td></td>
</tr>
<tr>
<td>B (32)</td>
<td>( \theta_1 = 0^\circ, \theta_2 = -180^\circ + i \cdot 45^\circ, i \in [1, ... , 16] )</td>
<td>major axis: 1.83A minor axis: 0.93A</td>
</tr>
<tr>
<td></td>
<td>( \theta_3 = 15^\circ, \theta_4 = -180^\circ + i \cdot 22.5^\circ, i \in [1, ... , 16] )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \theta_5 = 30^\circ, \theta_6 = -180^\circ + i \cdot 45^\circ, i \in [1, ... , 8] )</td>
<td></td>
</tr>
<tr>
<td>C (48)</td>
<td>( \theta_1 = 0^\circ, \theta_2 = -180^\circ + i \cdot 30^\circ, i \in [1, ... , 12] )</td>
<td>major axis: 3.3A minor axis: 0.93A</td>
</tr>
<tr>
<td></td>
<td>( \theta_3 = 15^\circ, \theta_4 = -180^\circ + i \cdot 15^\circ, i \in [1, ... , 24] )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \theta_5 = 30^\circ, \theta_6 = -180^\circ + i \cdot 30^\circ, i \in [1, ... , 12] )</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Statistics of the emulation results \(|\rho - \rho^*|\)

<table>
<thead>
<tr>
<th>Case</th>
<th>Channel emulator</th>
<th>Min-Sum</th>
<th>Min-Max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rms</td>
<td>max</td>
<td>rms</td>
</tr>
<tr>
<td>A</td>
<td>0.07</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>B</td>
<td>0.07</td>
<td>0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>C</td>
<td>0.07</td>
<td>0.21</td>
<td>0.05</td>
</tr>
</tbody>
</table>

a sphere, and the elevation angle \( \theta \) and the azimuth angle \( \phi \) are specified for each probe. The probes are organized on three elevation rings. \( \theta_k \) denotes the elevation angle for all the probes on kth elevation ring. \( \phi_{ij} \) 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.

Table 3 summarizes the performance of each probe in terms of \( \rho \) and the associated emulated \( \rho^* \) for all cases detailed in Table 1. Case x is along the AoA of the target channel. The power weights are obtained by the Min-Sum algorithm.


Conclusion: This letter presents a channel emulation technique for 3D geometry-based channel models for a multi-probe based setup. The proposed methods provide a general emulation framework for all spherical power spectrums and offers globally optimal emulation accuracy with low computational complexity.

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References

![Fig. 2 Target spatial correlation \(|\rho|\) between antenna u and v on the surface of the test volume and the associated emulation results \(|\rho - \rho^*|\).](image_url)

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