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Wei Fan, Istvan Szini, Jesper Ø. Nielsen, and Gert F. Pedersen

***Abstract*—This paper discusses one aspect of over the air (OTA) testing for multiple input multiple output (MIMO) capable terminals in flexible multi-probe setups. Two techniques to obtain weights as well as angular locations for the OTA probes are proposed for accurate reconstruction of the channel spatial correlation at the receiver side. Examples show that with a small number of probes in a flexible setup, accurate spatial correlation can still be achieved within the test zone.**

***Index Terms*—OTA testing, flexible multi-probe setup, anechoic chamber, multi-antenna terminal**

I. INTRODUCTION

Over the air (OTA) testing of multiple input multiple output (MIMO) capable terminals has attracted huge attention in recent years due to the urgent need for testing the radio performance of mobile terminals with multiple antennas [1]. The multi-probe anechoic chamber method is a promising candidate due to its ability to reproduce desired radio channels.

One major challenge with the multi-probe method is the cost of the system and the setup complexity. Each probe is typically connected to an expensive channel emulator. The cost will likely increase dramatically for 3D probe configurations [2]. The fixed multi-probe setup may not be cost effective, as often many probes are not actually used in synthesizing the radio channels. If the probes can be placed according to the channel spatial characteristics in a flexible manner, a larger test area can be created compared with the fixed probe setups with the same number of probes. Hence, a flexible setup mechanism has the potential to save cost of the system, via reducing the number of required active probes and respective hardware.

In one possible installation for the flexible setup, a large number of probes are installed with fixed locations, and a switch box drives a subset of probes based on the target channel models [3]. To reduce mutual coupling and reflection between probes, a minimum separation between probes is required. Fixing the probe locations in the chamber may result in suboptimal probe locations for a given channel model. In this paper, we propose a flexible system arrangement, where the number of probes (consequently the channel emulator output ports) are optimized to the minimum necessary to generate the desirable spatial channel model. An illustration of the setup is shown in Figure 1, where probes are assembled in a movable semi-arc rail. The probe placement is flexible in

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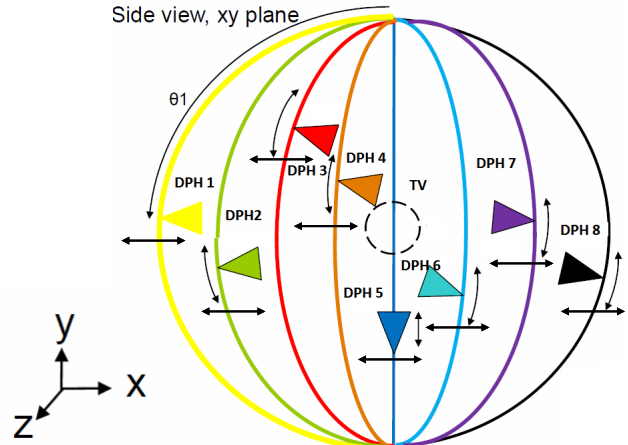Istvan Szini is with Motorola Mobility LLC., Libertyville, USA.

Figure 1. An illustration of the flexible multi-probe setup. DPH denotes dual polarized horn antenna; TV denotes test volume. The elevation and azimuth angle of each probe is to be optimized.

both the elevation and azimuth angles, enabling the placement on optimal location defined by the proposed algorithm.

Contributions on the channel emulation techniques have been mainly focused on the fixed multi-probe configurations so far, where the objective is to find the optimum probe weights [2], [4], [5]. Channel emulation for the flexible setup with a small number of probes is more challenging as both the probe weights and the probe angular locations are to be optimized. In this paper, two algorithms, namely the genetic algorithm and the so-called multi-shot algorithm, are proposed to emulate channel spatial correlation in flexible setups. Note that modeling of the other channel parameters, e.g. Doppler power spectrum, power delay profile, etc. in the flexible setups are not addressed in the paper. Modeling of those parameters is addressed in [4] for the fixed setups.

II. PROBLEM FORMULATION

Channel emulation for fixed multi-probe setups have been detailed in [4], [5], where the focus is on recreating the channel spatial characteristics where the device in located. Spatial correlation is used as a figure of merit to model the channel spatial characteristics. A location pair is used to represent the locations of two spatial samples where two hypothetical isotropic antennas u and v are placed [5]. The spatial correlation for the mth location pair, for a single polarization, is:

$$\rho(m) = \oint \exp(j\beta(\overline{r}_{u,m} - \overline{r}_{v,m}) \cdot \overline{\Omega})p(\Omega)d\Omega, \qquad (1)$$

where $\overline{r}_{u,m}$ and $\overline{r}_{v,m}$ are vectors containing the position information of antenna u and v at the mth location pair,

respectively. $\overline{\Omega}$ is an unit vector corresponding to the solid angle Ω. β is the wave number. $p(\Omega)$ is spherical power spectrum (SPS) satisfying $\oint p(\Omega)d\Omega = 1$. $(\cdot)$ is the dot product operator. Similar to (1), the emulated spatial correlation for the mth location pair can be calculated as [4], [5]:

$$\hat{\rho}(m,\overline{\Phi}) = \sum_{n=1}^{N} w_n \exp(j\beta(\overline{r}_{u,m} - \overline{r}_{v,m}) \cdot \overline{\Phi}_n), \quad (2)$$

where $\boldsymbol{w} = [w_1, ..., w_N]^T$ is a power weighting vector to be optimized. $\overline{\Phi}_n$ is a unit position vector of the nth probe. $\overline{\Phi} = [\overline{\Phi}_1, ..., \overline{\Phi}_N]^T$ is a matrix that contains the positions of all probes. N is the total number of probes.

To minimize the emulation error over M location pairs, the following objective function is used:

$$\min \left\| \hat{\boldsymbol{\rho}}(\boldsymbol{w},\overline{\Phi}) - \boldsymbol{\rho} \right\|_2^2, \quad (3)$$
$$\text{s.t. } 0 \le w_n \le 1, \ \forall n \in [1, N]$$

where $\hat{\boldsymbol{\rho}}$ and $\boldsymbol{\rho}$ are the emulated spatial correlation and the target spatial correlation vectors of size M, respectively, with the mth element described in (2) and (1), respectively. $\hat{\boldsymbol{\rho}} = \mathbf{F_N} \boldsymbol{w}$ with $\mathbf{F_N} \in \mathbb{C}^{M \times N}$ being the transfer matrix for N probes, whose elements are given by:

$$(\mathbf{F_N})_{m,n} = \exp(j\beta(\overline{r}_{u,m} - \overline{r}_{v,m}) \cdot \overline{\Phi}_n), \quad 1 \le m \le M \quad (4)$$

For fixed multi-probe setups (i.e. $\overline{\Phi}$ fixed), the objective function (3) is a convex optimization problem, which is easily solved in [2], [5]. For flexible multi-probe setups, the objective function (3) is a non-convex optimization problem as both the probe weights and the probe angular locations are to be optimized. The solution for this non-convex problem for the flexible setups is not trivial and more complicated.

In the following, probes are limited to a possibly large set of discrete locations for practical reasons. Let us define $\overline{\Psi} = [\overline{\Phi}_1, ..., \overline{\Phi}_K]^T$ $(K > N)$ as a matrix that contains the K possible discrete locations for the probes. The channel spatial correlation emulation for flexible setups can be treated in two steps as:

1) Select N locations out of K possible discrete locations for the N probes. The problem formulation for the probe selection is as follows:

$$\min_{\mathbf{c}} \ \|\mathbf{F_K c} - \boldsymbol{\rho}\|_2^2 \quad (5)$$
$$\text{s.t. } \|\mathbf{c}\|_0 = N$$

where the norm-0 operation $\|\cdot\|_0$ is defined to be the number of nonzero entries in the vector. $\mathbf{F_K}$ is the transfer matrix for the K possible locations with its element defined in (4). $\boldsymbol{c} = [c_1, ..., c_K]$ is the weighting vector to be optimized.

The problem in (5) is non-convex and NP-hard due to the norm-0 constraint. A brute force method where the optimization is performed for each possible combination of the N locations out of K potential locations can be used, and a total number of combinations is $\begin{pmatrix} K \\ N \end{pmatrix}$.

The number of combinations to be tested becomes huge when K is large. Two algorithms are proposed to address the non-convex optimization problem later.

2) After knowing the locations of the N probes, the optimization is simplified to be a convex problem:

$$\min_{\mathbf{c}_{sel}} \|\mathbf{F c}_{sel} - \boldsymbol{\rho}\|_2^2$$

where $\mathbf{F}$ is the $M \times N$ matrix with N selected columns from $\mathbf{F_K}$, and $\mathbf{c}_{sel}$ is the $N \times 1$ vector with the N selected probe locations.

III. SPATIAL CORRELATION EMULATION WITH FLEXIBLE SETUPS

A. Genetic algorithm

The genetic algorithm (GA) has been widely used in electromagnetics [6]. The GA is basically a search technique inspired by the principles of genetics and natural selection. A very useful aspect of GA is that it can deal with a large number of variables and it can optimize variables with extremely complex cost surfaces [6]. A limitation is that it can stop in a local optimum, and often, it is not possible to know whether the solution is local or global. We can think of the target channel as the environment and the selected probe locations as the biological species that need to fit in the environment (the channel). The fitness of the probe locations to the environment can be measured by the channel emulation accuracy. In this section, a GA applied to the problem of selecting the optimum probe locations is described. The concept is straightforward: The GA seeks for a set of probe locations that would minimize the channel emulation error. The number of selected probes (N) designates the search space.

A population is the array of chromosomes under examination for the GA. A chromosome contains N variables which represent the N probe locations. Each chromosome will have a cost evaluated by the cost function f, as:

$$f = \min_{\boldsymbol{w}_{GA}} \|\mathbf{F}_{GA}\boldsymbol{w}_{GA} - \boldsymbol{\rho}\|_2^2, \quad (6)$$

where $\mathbf{F}_{GA}$ and $\boldsymbol{w}_{GA} = [w_1, ..., w_N]^T$ are the transfer matrix and probe weight vector of the chromosome under evaluation. The cost function actually contains a convex optimization process. A flowchart of the GA shown is shown in Figure 2. The description of the employed GA algorithm is given in [6] and is not detailed here. This complexity of GA is:

$$\underbrace{N_{pop}}_{\text{initial population}} + \underbrace{(N_{pop} - 1)}_{\text{cost evaluations per generation}} \times \underbrace{N_g}_{\text{generations}}$$
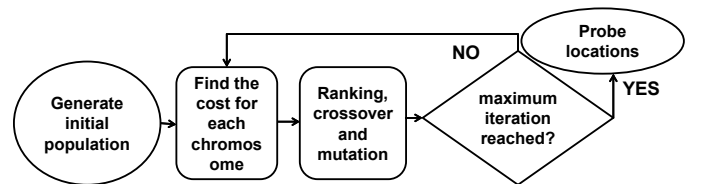
cost function evaluations.

Figure 2. Brief flowchart of the employed GA.

Table I
GA PARAMETER SETUPS

Parameter	maximum number of iterations N_g	population size N_{pop}	selection rate
Value	50	8	50%

Table II
NUMBER OF PROBES AND TEST AREA SIZE FOR THE CONSIDERED SETUPS.

Channel models	Flexible setup	Reference setup	Test area size
Single cluster	$N = 3$	Uniform setup with 8 probe	1λ
SCME Umi TDL	$N = 8$	Uniform setup with 16 probe	1.5λ

B. Multi-shot

One alternative to select the optimum set of probe locations is to use the so-called multi-shot algorithm. The basic idea is that probes with negligible contribution in synthesizing the channels should be removed. Probe locations can be removed in a sequential manner. We denote by k_n the number of potential locations we remove in the nth iteration and we have $K - \sum_{m=0}^{n-1} k_m$ selected locations in the nth iteration. In the multi-shot algorithm, we first perform the optimization for K potential locations. In the nth iteration, based on the individual probe power values $|c_{n,index}|$ ($1 \leq index \leq K$) in $\mathbf{c}_n$, we remove k_n locations with the least power values. We repeat the location removal process until only $K - \sum_{m=0}^{n-1} k_m = N$ locations are left. In the end, we return both the final probe weights and the corresponding probe locations. The complexity of the multi-shot algorithm is $\frac{K-N}{k} + 1$ convex optimizations if the number of removed locations per iteration is always k.

IV. OPTIMIZATION RESULTS

A. Optimization setups

To illustrate the algorithms, 2D multi-probe setups are considered for simplicity. $K = 360$ uniformly placed locations are defined as possible locations. The parameters for the GA have been chosen through repeated trials, following the guideline in [6]. The number of generations is a tradeoff between the convergence rate and the computational complexity. The parameters used in the GA are summarized in Table I. In the following computations, the number of removed locations per iteration $k_n = 1$ is defined for the multi-shot algorithm.

We examine a set of representative channel models that are used in standardization for the MIMO OTA testing [1]. The models are: a) Single Laplacian shaped spatial cluster with angle of arrival (AoA) 22.5° and azimuth spread (AS) 35°, b) SCME Urban micro (Umi) TDL model (six Laplacian shaped clusters) and c) SCME Urban macro (Uma) TDL model from [7]. Note that a critical single cluster model for the eight probe uniform setup, i.e. the spatial cluster impinging from an angle exactly between two adjacent OTA probes, is selected to show the robustness of the algorithms [5]. A uniform configuration is used for comparison for each considered flexible setup, as detailed in Table II. The eight probe uniform setup is compared with the 3 probe flexible setup, as both of them are able to create a single cluster with an arbitrary AoA without relocation of the probes The idea is to show that with a small number of probes in a flexible setup, accurate spatial correlation can still be achieved.

B. Results

The spatial correlation $|\rho|$ for the single spatial cluster model and correlation error $|\hat{\rho} - \rho|$ are shown in Figure 3. The radius

d and polar angle ϕ of each point on the plots correspond to the value at antenna separation d and antenna orientation ϕ [5]. Test area size shown in the optimization results denotes the distance between the two antennas and corresponds to the maximum d in the polar plots. A maximum deviation of 0.15 and 0.3 is achieved over the test area size of 1λ for the flexible setup with 3 probes for the GA and multi-shot algorithm, respectively. In contrast, the correlation error is much larger for the uniform setup with 8 probe. The optimized angle locations for the 3 probes with the two proposed algorithms are shown in Figure 4 (left), where the angular locations are in good agreement with the target single spatial cluster. Figure 5 (left) shows the GA algorithm convergence curve in terms of the minimum and mean cost for each generation for the single cluster model.
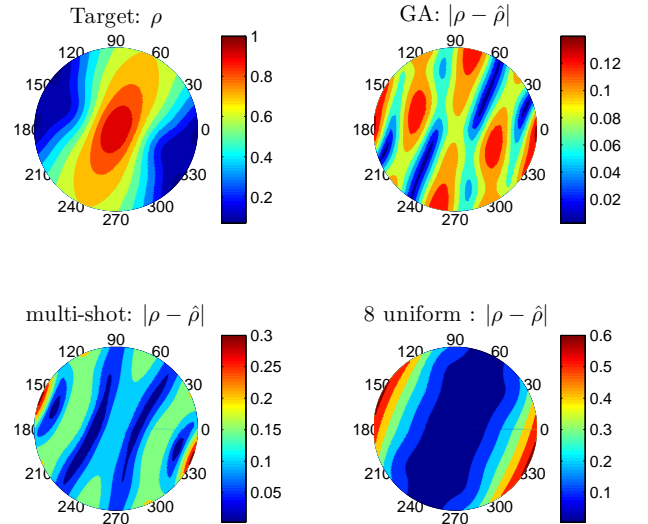

Figure 3. The target spatial correlation $|\rho|$ for the single cluster channel model and the associated correlation error $|\rho - \hat{\rho}|$ for 3 probes with the GA algorithm, 3 probes with the multi-shot algorithm and the uniform probe configuration with 8 probes. Test area size: 1λ.
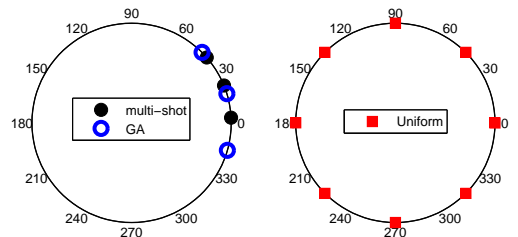

Figure 4. An illustration of the probe configurations detailed in Table II.

The spatial correlation $|\rho|$ for the SCME Umi TDL model and correlation error $|\hat{\rho} - \rho|$ are shown in Figure 6. Narrowband multi-cluster models (with delay information removed) are used to obtain the optimal probe locations. Then each cluster is emulated with the selected probe locations, as described
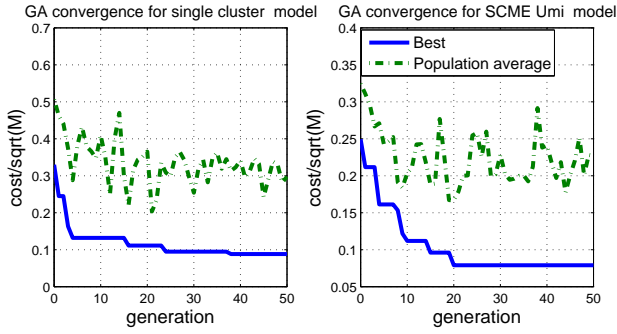
Figure 5. GA convergence curve for the single cluster model (left) and for the SCME Umi TDL model (right).

in [5]. A maximum deviation of 0.12 is achieved over the test area of 1.5λ for the flexible setup with 8 probes for the multi-shot algorithm. The multi-probe algorithm outperforms the GA for the SCME Umi TDL model. Figure 5 (right) shows the GA convergence curve for each generation for the SCME Umi TDL model. The channel emulation accuracy with the 8-probe flexible setup and the multi-shot algorithm offers slightly worse results than the channel emulation accuracy with the 16 uniform probe setup. The optimized angle locations for the 8 probes with the proposed algorithms for the SCME Umi TDL and the SCME Uma TDL models are shown in Figure 7.
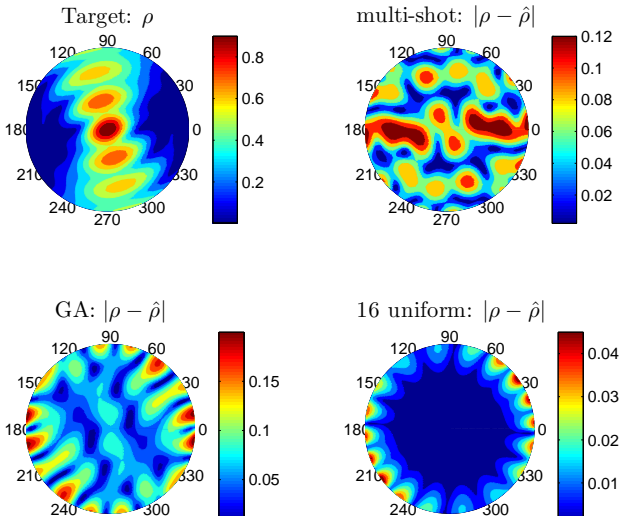

Figure 6. The target spatial correlation $|\rho|$ for the SCME Umi TDL channel model and associated correlation error $|\rho - \hat{\rho}|$ for 8 probes with the multi-shot algorithm, 8 probes with the GA algorithm and uniform probe configuration with 16 probes. Test area size: 1.5λ.
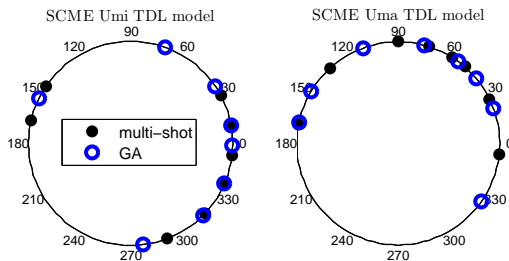

Figure 7. Illustration of optimized locations for SCME Umi TDL (left) and SCME Uma TDL models (right).

The emulation accuracy for the 6 clusters in the SCME Umi TDL model is shown in Table III. Note that the probe locations

Table III
ERROR STATISTICS OF CORRELATION ERROR $|\rho - \hat{\rho}|$ FOR THE 6 CLUSTERS IN THE SCME Umi TDL CHANNEL MODEL FOR DIFFERENT ALGORITHMS.

Algorithm	$|\rho - \hat{\rho}|$	1	2	3	4	5	6
multi-shot	max	0.16	0.09	0.44	0.09	0.10	0.15
	rms	0.07	0.05	0.25	0.05	0.05	0.07
GA	max	0.17	0.20	0.65	0.24	0.21	0.18
	rms	0.05	0.06	0.35	0.07	0.06	0.05

are selected based on the SPS of the multi-cluster model, so the emulation accuracy for each of the clusters might be bad. The correlation error $|\rho - \hat{\rho}|$ for the 3rd cluster is up to 0.44 with the multi-shot algorithm due to the fact that the locations selected are favoring the dominant clusters.

The correlation error $|\hat{\rho} - \rho|$ for the SCME Uma TDL model with the multi-shot and the GA are shown in Figure 8. The GA slightly outperforms the multi-shot algorithm, with correlation error up to 0.25 over the test area of 1.5λ.
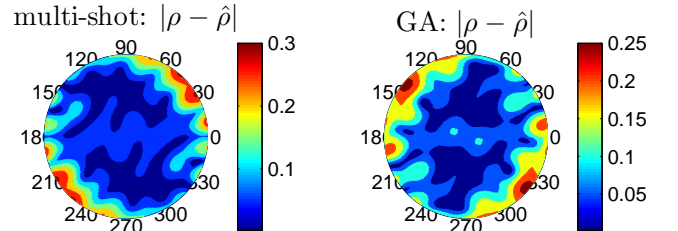

Figure 8. The correlation error $|\rho - \hat{\rho}|$ for 8 probes with the multi-shot algorithm and 8 probes with the GA for the SCME Uma TDL model. Test area size: 1.5λ.

V. CONCLUSIONS

We have introduced two algorithms to determine the weights and angular locations for the probes in flexible setups, i.e. the multi-shot algorithm and the GA. The proposed algorithms offer good spatial correlation accuracy for the flexible setups. The optimization results show that a test area of 1λ can be created for the single cluster channel model with 3 probes, with an spatial correlation error up to 0.14 with the GA. A test area of 1.5λ can be created with 8 probes for the SCME Umi TDL model, with an correlation error up to 0.12 with the multi-shot algorithm, and for the SCME Uma TDL channel model, with an correlation error up to 0.25 with the GA.

REFERENCES

[1] "Verification of radiated multi-antenna reception performance of User Equipment," 3GPP, TR 37.977 V1.0.0, Sep. 2013.
[2] W. Fan, F. Sun, P. Kyosti, J. Nielsen, X. Carreno, M. Knudsen, and G. Pedersen, "3D channel emulation in multi-probe setup," *Electronics Letters*, vol. 49, no. 9, pp. 623–625, 2013.
[3] P. Kyösti, J. Nuutinen, and J. Malm, "Over the air test," Patent US 20 130 059 545 A1, Mar. 7, 2013.
[4] P. Kyösti, T. Jämsä, and J. Nuutinen, "Channel modelling for multiprobe over-the-air MIMO testing," *International Journal of Antennas and Propagation*, 2012.
[5] W. Fan, X. de Lisbona, F. Sun, J. Nielsen, M. Knudsen, and G. Pedersen, "Emulating Spatial Characteristics of MIMO Channels for OTA Testing," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 8, pp. 4306–4314, 2013.
[6] R. L. Haupt and D. H. Werner, *Genetic algorithms in electromagnetics*. Wiley. com, 2007.
[7] D. Baum, J. Hansen, and J. Salo, "An interim channel model for beyond-3G systems: extending the 3GPP spatial channel model (SCM)," in *Proc. IEEE VTC-Spring*, May 2005.