Limits of Experimental Channel Characterization Related to Antenna Calibration

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Abstract

Some limitations on the performance of parameter estimation algorithms are imposed by the random phenomena contained in channel-sounding data and typically characterized by the Cramer-Rao-Lower-Bound. There are, however, additional limitations stemming from the achievable accuracy of the model of the measurement system that is used for estimation purposes. More specifically, inaccuracies of the antenna array model will reduce dynamic range of the measurement data that can be reliably characterized. In this paper, effects of antenna array model distortion on the high-resolution estimation of the specular component parameters are illustrated. Artifacts resulting from this distortion are discussed in the context of channel characterization/modeling.

1. Introduction

The process of experimental channel characterization involves a measurement experiment and subsequent parameter extraction. In order to able to resolve directions of departure (DoD) and arrival (DoA) for transmitted waves, a radio channel is observed using multiple Tx and Rx antenna pairs [1]. The proprietary RIMAX algorithm [2] is employed afterwards for joint high-resolution parameter estimation (HRPE) of specular component parameters, polarimetric weights, prop. delay, DoD, DoA, and Doppler shift. Due to inherent spatial characteristics of antennas, their separation from the propagation channel can not be performed prior to HRPE. Therefore, the HRPE procedure has to rely on a model of the antenna array (AA) that is used throughout the measurements. Required AA model is created through the calibration procedure. Since the accuracy of the obtained AA model may be impaired by multiple causes (e.g. phase noise, disregarded frequency dependence of radiation pattern, or by unavoidable parasitic reflections present in the anechoic chamber during antenna calibration), some impact on channel parameter estimation is to be expected. In this paper, we will investigate effects of antenna model distortion that originate from parasitic reflections in the anechoic chamber.

2. Accuracy of Antenna Array Model

AA calibration, being conducted in an anechoic chamber, typically assumes the existence of a single direct path between the reference antenna and the antenna under test and disregards possible parasitic reflections. However, this may not fully correspond to reality: for frequencies between 4 GHz and 6 GHz, the reflection coefficients of the chamber walls are between −10 dB and −40 dB, depending on the angle of the incoming wave and the height of the cones of the absorbing material [3].

Effects of multipath propagation in the anechoic chamber could be partially observed in 120 MHz bandwidth, (also used for channel-sounding) as parasitic reflections cause evident spread of energy in the delay domain. The impact of parasitic reflections on the model accuracy can be therefore quantified as the ratio of powers between strongest delay bin and its subsequent bin. Without observable modeling errors, all signal energy is concentrated in the strongest bin, while subsequent delay bin contains only noise. In this case, the model accuracy is equivalent to dynamic (observation) range in the Channel-Impulse-Response (CIR).

In calibration measurements, it is observed that the accuracy of the antenna model is strongly dependent on the direction of the incoming wave and the polarization excitation. The achievable model accuracy will also depend on properties of the anechoic chamber, positioning system, and analyzed antenna arrays; however, average values in the range from 25 dB to 30 dB can be expected [4]. The parasitic reflections have the largest impact for the directions that are close to the zeros of the radiation patterns. These effects are stronger in cases with lower received power, e.g. in a cross-polarized case.

3. Distortion Modeling

To reproduce effects of parasitic reflections on an AA representation and parameter estimation results, an artificial distortion of synthetic antenna model is simulated. Distortion is constructed with a simple multipath model consisting of 10 scatterers, being randomly distributed (uniform PDF) in the area of the positioning system. All scatterers share the same reflection coefficient that is chosen according to absorbing material specifications (-25 dB). It is assumed that scattering rotates the polarization vector over 45°, resulting in equal power for both orthogonal polarizations. Depending on array construction, not all elements are visible from all directions. In a synthetic model these non-visible components are ignored.

In order to validate this model of the distortion, a distorted version of the synthetic model is compared with antenna calibration results. Please note that the objective is not to exactly characterize the distortion of the AA model created during calibration, but to be able to create qualitatively "similar" effects that would later distinguish ideal and distorted synthetic AA models. Figure 1 shows Effective-Aperture-Distribution-Functions (EADFs) of synthetic (with and without distortion), and measured Polarimetric-Uniform-Circular-Patch-Array (PUCPA) with 24 dual-polarized (V/H) patches. EADF is the two-dimensional Discrete Fourier Transformation of a sampled antenna radiation pattern, that offers a more compact representation and efficient interpolation, and it is therefore used in RIMAX algorithm for HRPE.

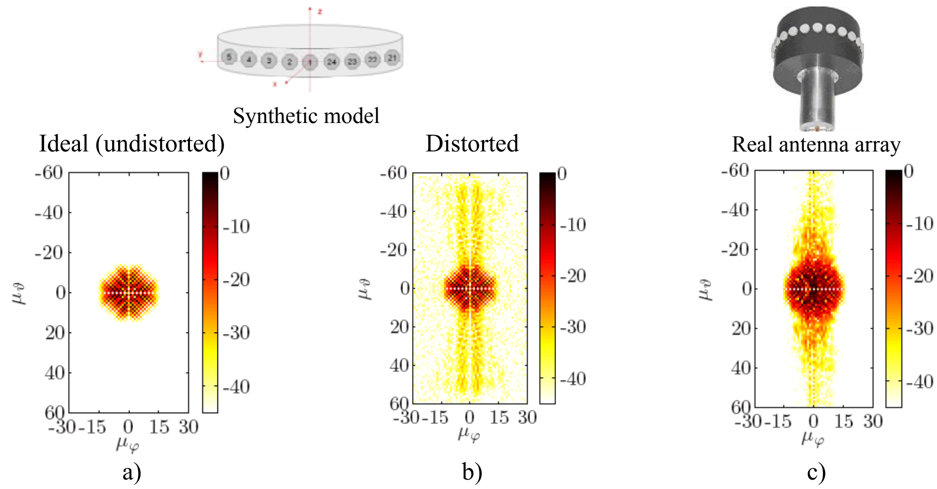

Figure 1. Normalized EADFs for horizontal excitation of vertical port of the PUCPA 24: (a) synthetic without distortion, (b) synthetic with distortion, and (c) measured, real array.

From Figure 1.a and 1.b it can be concluded, that additional EADF samples for spatial frequencies $|\mu_\varphi| > 15$ and $|\mu_\theta| > 15$ have occurred as a consequence of the radiation pattern distortion due to parasitic reflections. Consequently, their removal by simple 2D truncation (limitation of the number of EADF samples in both dimensions) reduces the distortion. In the following analysis, the performance of parameter estimation will be investigated for two different AA models: i) the distorted and complete EADF (CEADF) with $|\mu_\varphi| \leq 15$ and $|\mu_\theta| \leq 60$, and ii) the distorted but windowed EADF (WEADF) with $|\mu_\varphi| \leq 15$ and $|\mu_\theta| \leq 15$.

4. Impact of Modeling Errors

One of the problems in high-resolution parameter estimation from channel sounding data is the lack of the "true" multipath profile. Therefore it is not easy to quantify the accuracy of obtained results. Usage of complex databases with highly detailed environment description can not resolve this, since we still have only a model with limited accuracy. Additionally, deterministic propagation tools (ray-tracing, FDTD) that are typically used in conjunction with environment data bases, may introduce biasing inherent to their concepts/theories. Some findings presented in this paper will therefore use a synthetic ("controlled") propagation environment to analyze estimator performance under extremely simple setups.

One of the crucial problems in high-resolution parameter estimation is order determination, meaning the appropriate number of specular components (SCs) to be characterized for a given channel snapshot. The incorrect SC number may result in erroneous (non-physical) SC parameters since the ML optimization procedure attempts to compensate for missing or superfluous components. The RIMAX algorithm proposed the usage of Cramer-Rao-Lower-Bound (CRLB) to marginally estimate the relevance of SC's. Accordingly, only a limited number of specular components is resolved while the remaining power is characterized jointly by Dense-Multipath-Components (DMC) [2]. In this paper, the number of specular components to be estimated is limited to K_{max} (1 or 10). The parameter estimation results are evaluated for a simulated single-path excitation, where the arrival direction of the wave is varied over the full 4π solid angle. The estimation quality depends on the direction of the incoming wave and can be expressed by the number of artifacts (ghost SCs), their relative powers, and the deviation of their estimated directional parameters from the true arrival direction.

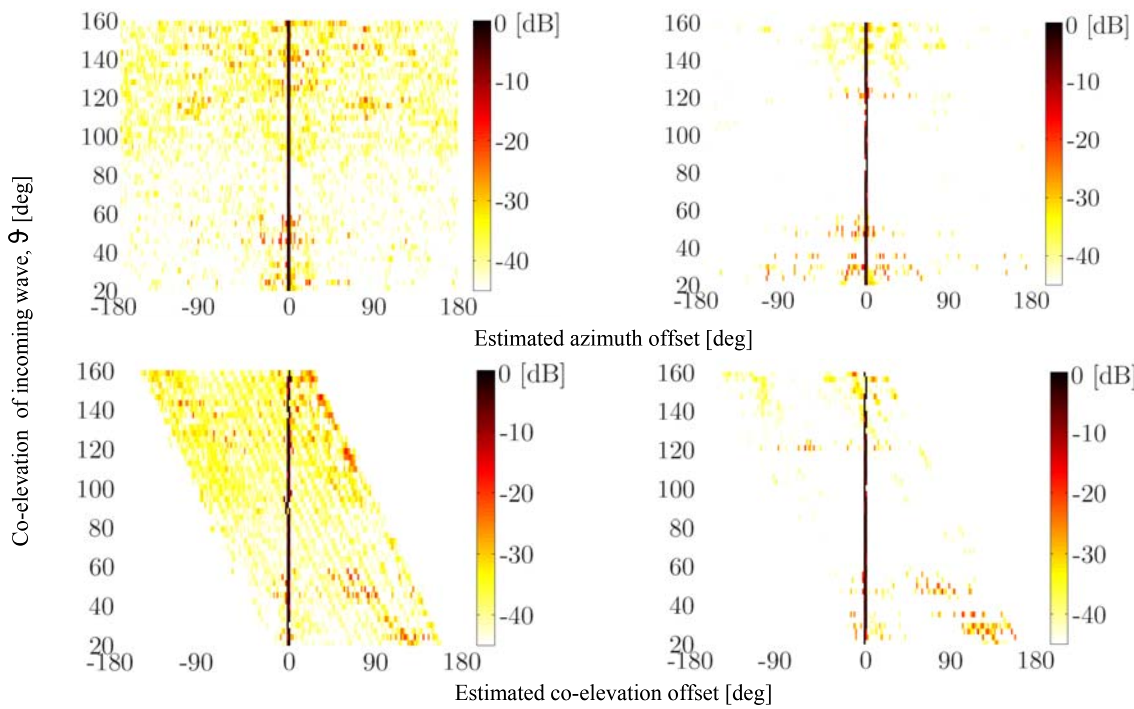

Figure 2. Mean estimated power distribution of K ≤ 10 specular components for single-path excitation and the synthetic PUCPA 24, as a function of incoming wave co-elevation, estimated angular deviations in azimuth (top row) and co-elevation (bottom row), and different AA models: Complete-EADF (left column) and Windowed-EADF (right column).

The results shown in Figure 2 are containing up to 9 artifacts (K_{max} = 10). The maximum power of the artifacts is around 25 dB lower than the estimated power of the SC coming from the true direction. More significant artifacts are detected around the poles of the spherical coordinating system since in this region AA models are generally showing a lower accuracy. The angular offsets of detected artifacts are considerable in both azimuth and co-elevation. The power contribution of the artifacts related to the WEADF model is approximately 10 to 15 dB lower than for the CEADF. The advantage of the WEADF model becomes obvious for co-elevation angles of incidence around ϑ = 90° where estimated artifacts are almost negligible.

In order to access estimation quality, the Signal-to-Remainder-Ratio (SRR) will be used. This quantity is defined as the ratio between the power of the estimated specular paths and the signal power that remains after subtraction of the estimated specular paths $\mathbf{s}(\hat{\boldsymbol{\theta}}_{SC})$ from the measured data $\mathbf{x}$ (i.e. DMC power):

$$SRR = 10 \cdot \log\left(\frac{\left\| \mathbf{s}(\hat{\boldsymbol{\theta}}_{SC}) \right\|_F}{\left\| \mathbf{x} - \mathbf{s}(\hat{\boldsymbol{\theta}}_{SC}) \right\|_F - \hat{P}_N} \right). \tag{1}$$

where $\hat{P}_N$ denotes the estimated power of the noise. If SRR goes toward infinity, all observed energy in the measured data $\mathbf{x}$ can be represented by specular components.

From SSR results shown in Figure 3.a), it can be observed that a signal representation with less artifacts, corresponding to WEADF model, provides approximately 8 dB higher SRR values. This means that the WEADF AA model is the better match to the "real" (undistorded) model from which the reference data $\mathbf{x}$ were created.

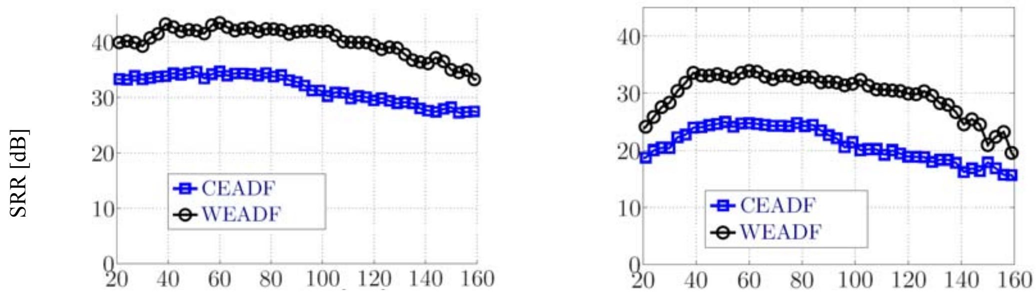

Figure 3. Signal-to-Reminder-Ratio (SRR) for distorted CEADF and WEADF models of synthetic UCA 24 DP array when number of specular components in RIMAX is limited to (a) K_{max}=10 and (b) K_{max}=1. Single-path excitation of non-disturbed synthetic array is used to create reference data.

In the following an unexpected and probably unwanted effect will be demonstrated. Since the multipath structure of the synthetic scenario is known, the proper number of SCs (K_{max}=1) can be used for HRPE. Obtained SRRs (Figure 3.b) are approximately 10 dB worse than in the previous case (Figure 3.a). The inability to obtain infinite SRR, even in this case, comes from the AA model distortion: namely, SRR values are here equivalent to the AA model accuracy. Therefore, inaccuracy of the AA model implies that the better solution is achieved by using multipath profile different from the "true" one. In this example, a better fitting (higher SRR) is obtained with artifacts (K_{max}=10), then with using the proper model order (K_{max}=1).

The consequence is that each SC will tend to spread in parameter space, producing clusters of estimated SC parameters. This important effect may lead to the false conclusion that clustering of SC parameters observed in measurements is a characteristic of radio-propagation. Instead, clustering may come solely from the usage of inaccurate AA models in parameter estimation algorithms.

5. Discussion / Conclusion

An antenna independent channel characterization can be performed under the assumption that it is possible to characterize all received energy with specular components only and that an ideal model for the measurement system (including antenna arrays) can be constructed. Unfortunately, inaccuracies incorporated into the AA model during antenna calibration will increase the number of artifacts in the overall channel representation. For ML parameter estimation algorithms without a proper model order control, the distorted radiation patterns will increase computational time due to estimation of physically meaningless components. The resulting power distribution and angular spreads could lead to a wrong interpretation of the channel characteristics, w.r.t. e.g. clustering properties. These effects are similar to those caused by an incomplete AA model (meaning non-polarimetric or not-3D or both) [5].

In this contribution, suppression of artifacts is achieved by windowing of the (complete) EADF model representation. These results can not be generalized, since the extent of the improvement will depend on array size, specific radiation patterns of antenna elements, and power contribution of parasitic reflections during antenna array calibration.

6. References

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