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Performance Evaluation of Real Antenna Arrays for High-Resolution DoA Estimation in Channel Sounding

Part 1: Channel Parameter Resolution Limits

Part 2: Experimental ULA Measurement Results

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Part 2:

Experimental ULA Measurement Results

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Abstract: *In the second part of this paper we present experimental results on the performance evaluation of uniform linear antenna arrays (ULA) for high resolution direction-of-arrival (DoA) estimation in channel sounding. The evaluation method is derived in the first part of this paper. It is based on the Cramer-Rao-Lower-Bound (CRLB) which is calculated from the calibration data of a real antenna array. This data results from a precision measurement in an anechoic chamber using a broadband MIMO channel sounder. For the ULA example, the CRLB determines the minimum achievable estimation variance of the complex path weight and the azimuth angle. The CRLB plots are given for the typical cases “single path scenario” and “coherent two path scenario” thus demonstrating the performance degradation for closely spaced coherent paths. Since the proposed method relies only on antenna beam pattern measurements, it can easily be applied to any real antenna array and clearly indicates the performance limits imposed by the array and its imperfections to high-resolution DoA estimation.*

Introduction

Various types of antenna array architectures have been applied for real-time MIMO channel sounding [1], [2]. Depending on their spatial shape they allow estimation in azimuth and/or elevation with more or less complete angular coverage. With a suitable design of the antenna array elements also the polarimetric channel response can be estimated. Moreover, high-resolution DoA parameter estimators such as ESPRIT [8] or ML (with its derivatives SAGE or RIMAX [5], [6]) may be applied in order to enhance the resolution considerably. Sometimes, the impression was produced that some of these algorithms will solve all problems with accuracy and resolution of impinging paths for arbitrary array architectures. This is not true. Based on an empirical investigation of several arrays (see [7], [8]) we have shown that there are limits on the reliability of the estimates and on the resolution of impinging waves in a given propagation scenario which depend on the array design. Obviously, design parameters such as the effective array aperture (as seen from specific DoA), the number, and the characteristics of the array elements have a strong influence. This relates also to any kind of mechanical and electrical tolerances, mutual element coupling, and amplitude- and phase mismatch. From experimental studies it became clear that also closely spaced coherent paths may cause severe degradation in variance and resolution. It is, however, not commonly understood what the fundamental limits to the achievable resolution performance are and how they depend on the given propagation scenario.

In the first part of this paper [3], a performance evaluation method of real antenna arrays was derived that is based on the Cramer-Rao-lower-bound (CRLB) of the estimation variance and, hence, describes the fundamental limitations of DoA estimation w.r.t. resolution and accuracy. The required data is based solely on the measured complex polarimetric array response. It is the same response required for calibration in case of an iterative ML DoA estimator. The structure of this data model was also described in the first part of this paper. Here, in the second part of the paper we demonstrate experimental results. The measurements were taken with a polarimetric uniform linear array (ULA)

and the sounder in an anechoic chamber. Then we calculate the CRLB for the estimated DoA and the path weight. We will also show the performance degradation in a coherent wave scenario.

ULA calibration measurements

In this section the investigated ULA will be described. The array consists of eight active dual-polarized dielectric patch antenna elements (amended with two dummy passive elements at both ends of the array). The spacing between the elements has been chosen to 0.4943 of the wavelength at the upper frequency in the band thus satisfying the sampling theorem in space.

The ULA and its measured element beam patterns are depicted in Fig. 1. The calibration measurement was conducted in an anechoic chamber using a MEDAV RUSK channel-sounder [9]. The sounder delivers instantaneous frequency responses at 5.2GHz within a 120MHz bandwidth. The beam patterns are calculated from the maxima of the corresponding channel impulse responses, thus further reducing the remaining parasitic echoes. This single path LOS scenario is used as reference to construct the calibration data model as described in [3]. Because of the 2π periodic property of this data model, the complex beam patterns are recorded in the full 360 degree coverage azimuth domain. The transmit antenna was a high gain horn with vertical polarization matched to the vertical polarization vector of the array. Hence we limit our experiment to single polarization. Because of the polarization match between transmit and receive antennas there is no restriction w.r.t to the performance limits. However, if in a real scenario polarizations of the impinging waves are unknown, dual polarized processing at the receiver would result in a considerable performance gain [4]. The reference measurement scenario can easily be extended to include polarization by using a dual polarized reference antenna. However, high polarization decoupling in the far field of this antenna is of primary importance.

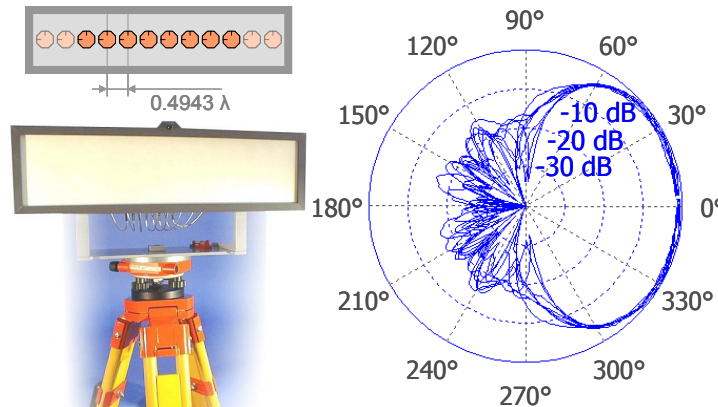


Fig. 1: Investigated uniform linear array - schematic illustration and photo (left) and normalized magnitude of the beam patterns in azimuth of the elements @vertical excitation (right)

Transformation of the beam patterns into the aperture domain

As described in detail in the first part [3], the calibration data model is constructed by a discrete Fourier transform of the recorded complex beam pattern to the effective aperture distribution function (EADF). This step, however, not only requires precise rotation of the array in the horizontal plan around a suitable defined pivot axis lying in the element plane but also excellent phase stability throughout the whole measurement cycle.

Other than a network analyzer, a sounder is designed for remote Tx/Rx operation. This means that it has separate L.O. generation at Tx and Rx which may cause phase errors. Notice that this is not so important for standard sounding measurement since high phase stability is required within a time interval of one snapshot only. In this case the limiting factor is phase noise. But the situation in calibration measurement is completely different since a calibration measurement cycle, where phase

stability has to be maintained, may take several hours (despite of the high measurement speed of the sounder). Nevertheless, using the sounder system for array calibration is advantageous because of its superior recording speed for broadband measurement and since the whole system is involved. Although phase stability maybe considerably enhanced by Tx/Rx reference synchronization which is no problem for the calibration setup, there can still be a considerable phase drift. Fig. 2 (left) shows the observed phase drift over the whole measurement cycle of 6000 s. This phase drift can be further reduced by hardware measures. In this case, e.g., the cause for the drift was identified to be a filter at the reference frequency input. However, it could not be changed in the available setup. Another measure which could be applied is to use an auxiliary RF reference connection between Tx and Rx. However the available antenna hardware did not provide input/output at the switches and even in this case the phase error as a result of cable bending might easily exceed 10 degrees. Therefore we developed a correction procedure which estimates the phase slope and then removes it from the recorded data. It uses the assumption that there is no relevant phase drift over one snapshot which corresponds to all array outputs for one single DoA.

If we transform the beam patterns without correction of the phase drift, we obtain the EADF in Fig. 3 (left). With a correction of the phase drift we obtain the much more concentrated EADF plots in Fig. 3 (right). The individual curves clearly indicate the contribution of the patch elements and their position in the array. Both plots already show reduced size support regions of the EADF which are used to reconstruct the beam patterns in terms of the proposed data model (see equation (2.19) of [3]). In the right part of Fig. 2 the resulting rms-error of both cases is shown. In the corrected phase case the resulting reconstruction error is mainly determined by the measurement noise. Optimum determination of the EADF size for error minimization is still an open question.

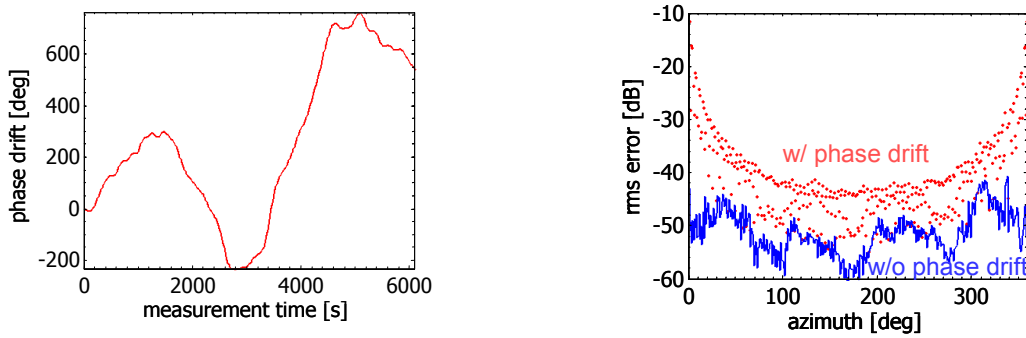


Fig. 2 Observed phase drift during the array measurements (left) and matching of the determined apertures to the measured beam patterns (right) – w/ phase drift stands for ignoring the phase drift, w/o means phase drift corrected

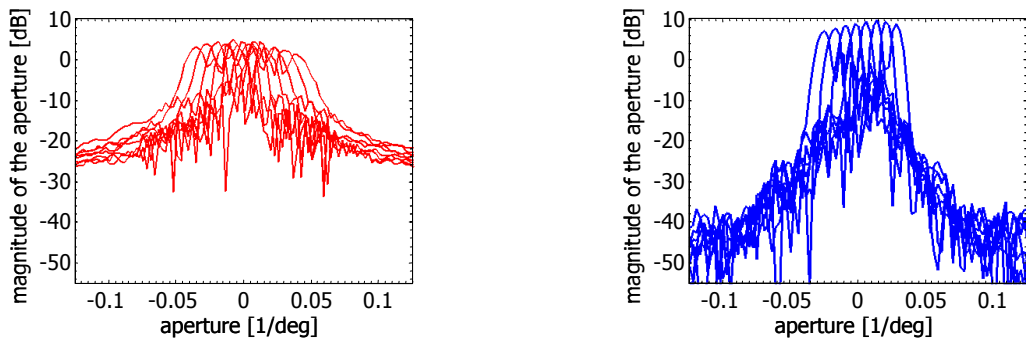


Fig. 3 Equivalent aperture distribution function (EADF) calculated from the eight element beam patterns of the ULA by DFT w/ (left) and w/o the phase drift corrected (right)

Investigations on the performance of the ULA exploiting the CRLB

The procedure for determining the CRLB as described in the first part of this paper is now applied using the reduced EADF as shown in Fig. 3 (right). The CRLB represents the variances and co-

variances of the estimated parameters dependent on a given signal-to-noise-ratio (SNR). Since we are considering an ULA, the variance of the azimuth and of the complex path weight (separated into real and imaginary parts) will be considered. At first the achievable accuracy of the investigated ULA will be demonstrated assuming a single source in the far field over the whole azimuth range.

Single path scenario

This scenario is described by one LOS path. The CRLB-results are depicted in Fig. 4, dependent on the DoAs in azimuth. The figure shows the standard deviations of estimated path parameters for different SNRs which only change the CRLB on a logarithmic scale. It can be seen clearly that the ULA operates very well within a DoA range of ± 60 degree. For a very good SNR of 35dB a maximum standard deviation of the angle in azimuth below 0.5 degree and a relative standard deviation of the complex path weight (for both components) below -42dB results. The following examples are calculated for a moderate SNR of 15dB. As mentioned, the results can be scaled for other SNR.

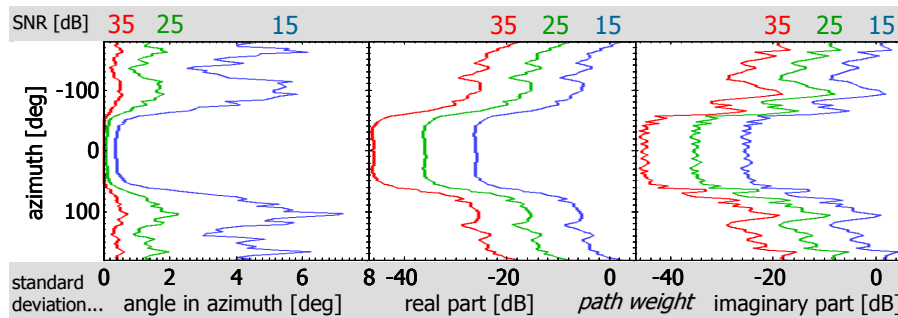


Fig. 4 CRLBs of the angle in azimuth and the path weight (split up in real and imaginary part) for a single path scenario basing on the ULA apertures

Coherent two path scenario

Two paths are said to be coherent if their weights have the same frequency and if they have an almost constant phase difference during the available observation window. Because of the superposition of the two wave-fronts, a static spatial pattern results with areas of constructive and destructive interference. The spatial periodicity of this interference pattern depends on the angular separation of the paths. The size of these areas of maxima and minima is, in general, larger than the array size if we are considering high-resolution (sometimes also called super-resolution) as opposed to Fourier resolution.

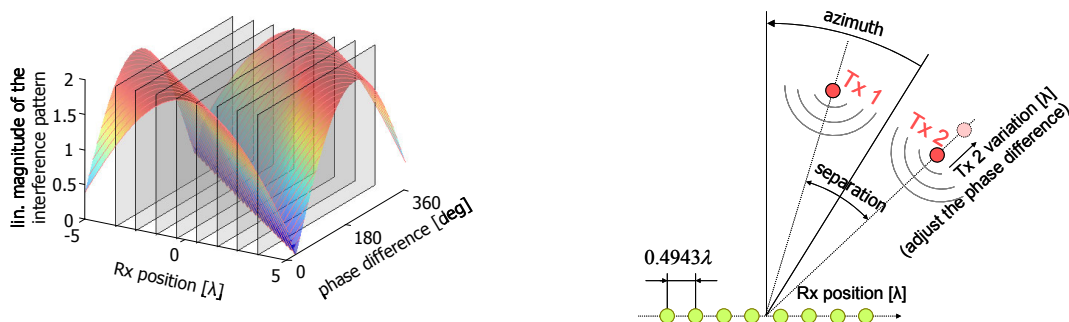


Fig. 5 Simulated interference pattern (magnitude) as it results from two equal-magnitude coherent paths with a separation angle of 5 degree for impinging from broadside azimuth direction (left) and the simulation scheme (right)

So in this high-resolution case the array cannot observe the complete spatial information which will deliver only a reduced knowledge about the field distribution. Dependent on the phase difference between the impinging paths, the array samples the interference pattern at different positions (cf. left part of Fig. 5). This probably leads to an ill-posed parameter estimation problem since it can easily be observed that the resulting degradation depends on the (unknown but fixed) phase difference between the path weights. This scenario was measured as described already in [7], [8]. Here it will be used for

CRLB calculation. From the structure of the Fisher information matrix it can be seen that in the described case of closely spaced paths non-diagonal co-variance coefficients arise which indicate variance increase and correlation between the estimates of both path parameters.

The following example shows in Fig. 6 the correlation (normalized co-variances) between the estimates of the two angular parameters for the considered ULA in the coherent two path scenario. The results are then used to calculate the CRLB of the path's parameters in the same scenario. Actually the data model (see equation (2.2) in [3]) for this scenario has been constructed by a superposition of two single path responses from the stored data model which gives us a maximum of flexibility when changing the parameters.

In Fig. 6 (left and middle) it can be seen clearly that phase differences around 90 and 270 degree show a low correlation whereas at 0 and 180 degree the correlation is significant higher which indicates the worst case regarding to the phase constellation. Of course, as closer the paths are in their DOA, as higher the correlation.

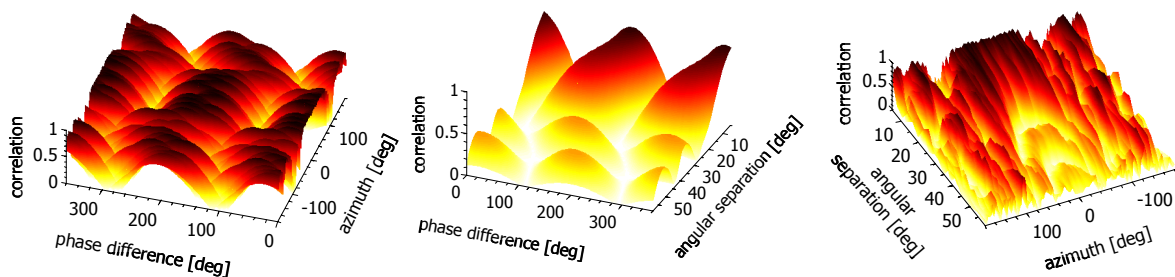


Fig. 6 Magnitude of the correlation between the two DoA parameters dependent on the phase difference, shown for the whole DoA range and an angular separation of 5 degree (left) and in dependency of the path weight phase difference and for different angular separations for impinging from broadside azimuth direction (middle) and for different angular separations for a path weight phase difference of 180 degree (right)

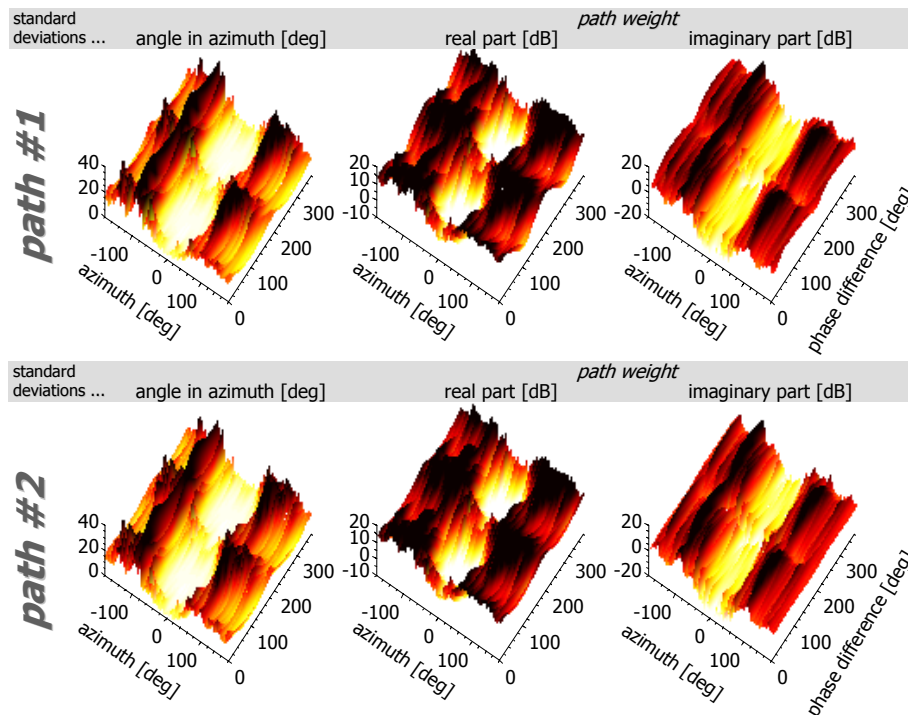


Fig. 7 Standard deviations of all estimated path parameters in the coherent two path scenario in dependent on the phase difference and the whole DoA range (angular separation of 5 degree; SNR @15dB)

The corresponding standard deviations of all six parameters for a close angular separation of only 5 degree are depicted in Fig. 7. Highest standard deviations result for the *worst case* path weight phase constellation – as already seen in Fig. 6. Solely the imaginary part of the path weight behaves different. But the deviation of the imaginary part is always below the deviation of the real part.

An interesting question is now, how does the presence of the second source degrade the performance of the ULA compared to the single source scenario? The answer will be given in Fig. 8. For the worst case phase difference of 180 degree between the sources and a close angular separation of 5 degree the deviation of the angular parameter is more than 30 times larger than in the absence of the second source. The path weight shows a similar characteristic (not depicted; real part approx. 120 times larger, imaginary part approx. 20 times larger).

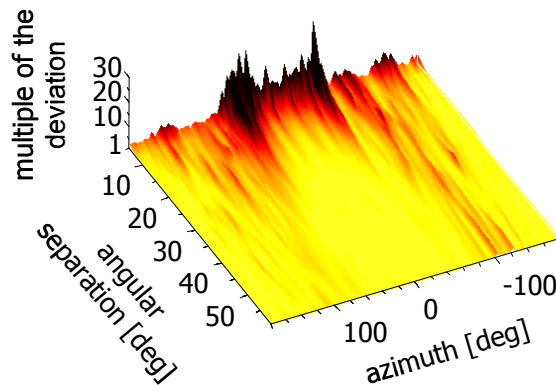


Fig. 8 Multiple of the standard deviation of the angle in azimuth of the coherent two path scenario respective to the single source scenario dependent on the angular separation and the whole DoA range

SUMMARY

Based on the method described in the first part of this paper we have demonstrated experimental results on the CRLBS of an example ULA array in a single path and a coherent two path propagation scenario. In the latter case remarkable performance degradation can be observed because of a correlation between the estimates of the two paths.

As the described method relies only on complex beam-pattern measurement in an anechoic chamber and as it gives performance limits independent on any specific parameter estimation procedure, it can be seen as a method for performance evaluation and comparison of real antenna arrays.

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