Application of Hilbert Transform for Phased Antenna Array Calibration

Anwendung der Hilbert-Transfomation zum Kalibrieren von phasengesteuerten Gruppenantennen

Daniel Hristov

Technical University of Sofia, Faculty of German Engineering and Economics Education
Kliment Ohridski blvd. 8 1756 Sofia, Bulgaria, e-mail: danielh@gilat.com

Abstract — The paper presents a procedure for phase errors estimation across an aperture of phased antenna array applying Hilbert transform on the measured data. The measurement principle, signal processing and the error compensation are described. The procedure is validated on receiving phased antenna array for Ku band, composed of 16x16 V- and H-polarized circular elements. The pattern of calibrated antenna is presented and compared with the pattern of uncalibrated antenna.

Zusammenfassung — Die Arbeit stellt ein Verfahren zur Ermittlung von Phasenfehlern entlang der Apertur einer phasengesteuerten Gruppenantenne unter Anwendung der Hilbert-Transformation auf den gemessenen Daten vor. Das Messprinzip, die Signalverarbeitung und die Fehlerkompensation sind beschrieben. Das Prinzip wurde an einer Emphangsantenne für Ku-Band validiert, die aus 16x16 V- und H- polarizierten Patchelemente besteht. Das Antennendiagramm der kalibrierten Antenne ist dargestellt und mit dessem unkalibrierter Antenne verglichen.

I. Introduction

Phased antenna arrays consist of multiple radiating elements, whose phase and amplitude can be individually controlled in order to dynamically modify the radiation pattern of the antenna. Due to technological limitations each phase and amplitude control element introduces an error, or a difference between the optimal and the obtained feeding signal, which leads to a radiation pattern, different from the desired one. The phased antenna array calibration is process of error correction. In order to be efficient, a calibration technique for serial antenna production has to be both fast and precise and must take into account both the features of measurement equipment and the behavior of antenna circuitry, as well as their dynamic characteristics.

The calibration procedure is divided into three steps - field measurement, data processing and error compensation. The measurement is arranged in accordance with the widely used Rotating Electric-Field Vector (REV-) Method.

The data processing relies on conversion of measured sequence to analytical signal using the Hilbert transform and subsequent calculation of correlation with a referent complex sine-function.

II. Measurement Principle and Test Setup

The measurement principle is based on Rotating Electric-Field Vector Method, described in [1, 2, 3] and illustrated on Fig. 1. The block diagram of the test setup is shown on Fig. 2.

The coordinates on Fig. 1 represent the orientation of incident V- or H- polarized waves, emitted by every single radiating element, towards a sensing antenna - with orientation corresponding to the polarization. A spectral analyzer detects the superposition of the incident waves into the sensing aperture.

The measurement is carried out inside of an anechoic chamber in order to minimize errors, caused by interference. The power level is chosen according to the maximal dynamic range of the measured antenna in order to obtain maximal possible signal-to-noise ratio (SNR).

If the feed signal of a particular/individual radiating element is sequentially phase shifted from 0 to 2π radians, the level received by the sensing antenna will describe a sine wave in euclidean plane or a circle in the polar plane. The center of this circle coincide with the level caused by the field of the remaining elements and the radius corresponds to the level, emitted by the analyzed element.

In the classical REV-Algorithm the information about the relative phase is retrieved correlating the measured sequence with a sine and cosine function. This approach delivers correct values only if the shape if the received power sequence is tightly close to an ideal circle and if the shape-deviation is normally distributed along all phase states [4, 5]. If these conditions are not met, the phase-estimation will be biased by the curve shape imperfections.

The phase control circuitry is a typical source of shape distortion. Another source of shape distortion in the case of microstrip antenna arrays is the mutual coupling between the radiating elements. If distortion occurs, the underly-

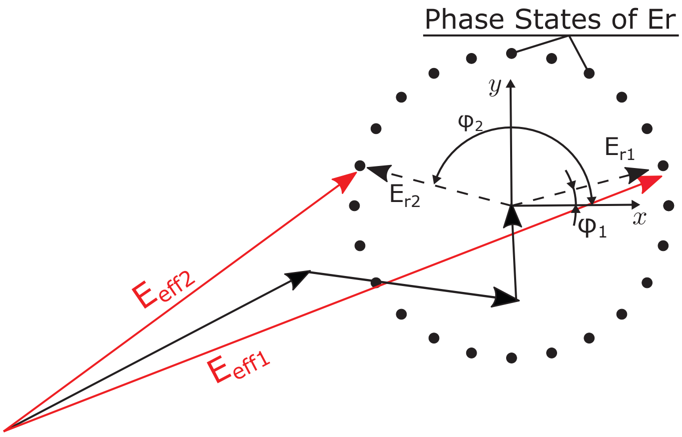

Fig. 1. REV- Principle of superposition.

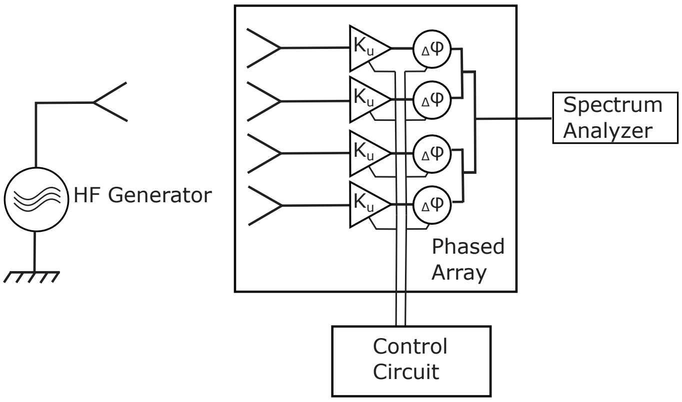

Fig. 2. Test Setup - Block Diagram.

ing waveform could be restored deploying different signal processing algorithms - e.g. point-to-point interpolation, low-pass filtering and least-square-error algorithms , but they require enough sample points around the fault one.

All this motivates the search for a phase estimation approach, providing sufficient accuracy with reduced count of samples. “Sufficient accuracy” is understood as less then a half phase step, if a digital phase shifters are used.

A. Experimental Setup Description

The test setup is arranged as shown on Fig. 2. The chosen low gain sensing antenna is placed in the boresight of the measured antenna and the distance between them meets the far-field criterion.

The measured antenna contains 256 patch elements, arranged into 16x16 regular planar array. The phase and amplitude of every element’s feed power is controlled by 64 four-channel MMICs, as shown on Fig. 3. The gain of every channel is controlled by a 3-bit digital attenuator with 1 dB step. The phase shift is controlled by a 5-bit digital phase shifter, providing a phase step of $2\pi/32$ radians.

For the purpose specifically to verify the approach usability to extract phase information from measured sequence, the power difference ζ across all elements was reduced down to ± 1.5 dB, prior the main REV-measurement.

The feed-signal of every particular patch-element is sequentially shifted through all possible 32 phase states and the received signal—Fig. 4—is placed into an 256x32 matrix. One can recognize the underlying sinusoidal wave and the non-linear signal distortions.

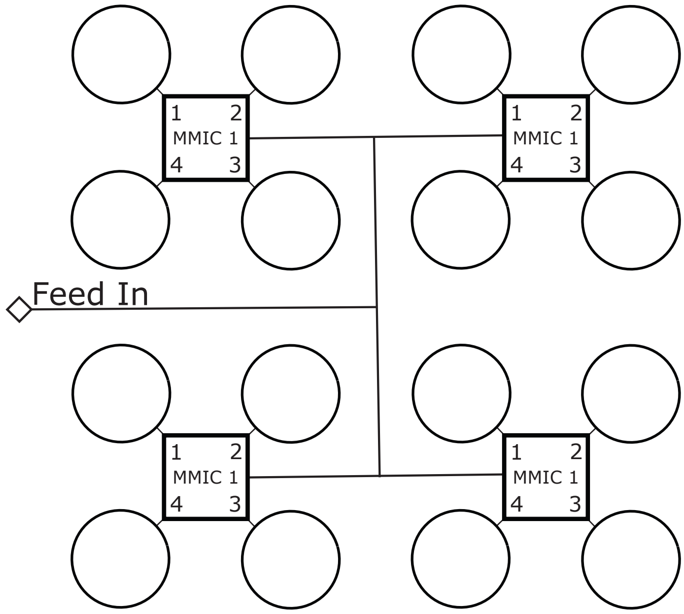

Fig. 3. Simplified antenna layout.

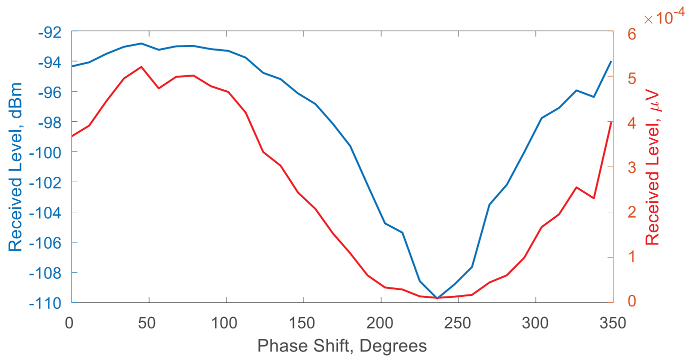

Fig. 4. Received Level as function of phase shift.

III. Analytical Signals and the Hilbert Transform

The use of analytical signals is justifiable in situations, where the signal processing in the complex space is preferable, compared to the simple time-space processing - e.g. single side band modulation and demodulation, speech processing and direction-of-arrivial measurements.

An analytical signal $S_a[t]$ is defined as a complex valued function with no negative spectral components:

$$S_a[t] = S_r[t] + j\widehat{S}_r[t] = S_r[t] + H\left\{S_r[t]\right\}, \qquad (1)$$

where $S_a[t]$ represents real valued original sequence and the $H\{S_a\}$ - it’s Hilbert transform, also real valued but in quadratature with the original one [6, 7].

The analytical signals reveal their advantages in polar form:

$$\begin{aligned} S_a[t] &= S_m[t]e^{j\phi[t]} \\ S_m[t] &= |S_a[t]| \\ \phi[t] &= \arg[S_a[t]] \\ f[t] &= \frac{1}{2\pi}\frac{\delta\phi(t)}{\delta t}, \end{aligned} \qquad (2)$$

where $S_m[t]$, $\varphi[t]$ and f(t) represent the so called *”local features”* - *”instantaneous amplitude, phase”* and *” frequency”* of the analytical signal.

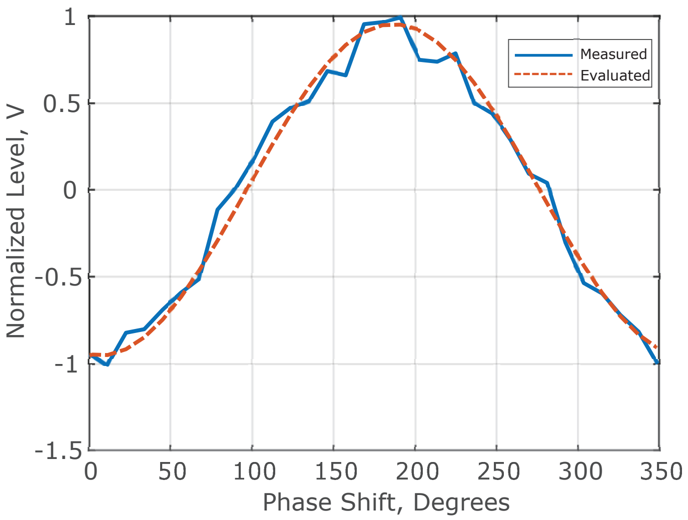

Fig. 5. $[A_j]_{center}$ and Approximated sine-wave

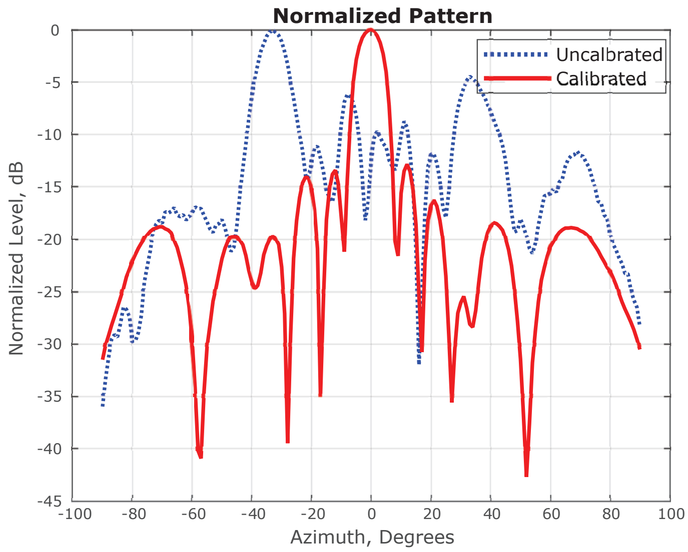

Fig. 6. Patterns before and after calibration

The work assumption is that the "local features" - can be directly implemented for deriving the parameters of the underlying harmonic wave.

IV. Data Processing

The data processing is split into five different steps:

- Conversion from dBm to µV
- Centering
- Conversion to analytical form
- Correlation calculation and Phase extraction
- Compensation.

A. Conversion to μV and Centering

The array [A] consists 256 columns $[A_j]$, each with the 32 values of received power for every phase state. [A] has to converted from dBm to µV and in order to avoid value-induced biasing, a column-wise normalization to value of 2 is performed in accordance with:

$$[A]_{\mu V} = 10^{[A]_{\mathrm{dBm}}/20}$$
$$\overline{[A_j]} = 2 * \frac{[A_j] - \min([A_j])}{\max([A_j]) - \min([A_j])} \qquad (3)$$

The centering of every level vector A_j(columns in $[A]\mu V$) is performed calculating vector's zero-frequency component:

$$[A_j]_{center} = \overline{[A_j]} - |FFT_0\overline{[A_j]}| \qquad (4)$$

B. Conversion to analytical form

The conversion of $[A]_{\mathrm{center}}$ to analytical form $[A]_H$ is performed using the built in MATLAB function `hilbert()`.

In the same way an additional "reference" sine wave is generated and transformed to analytical form:

$$S_{ref} = \sin([n\pi]), \text{ where } n = 0 : 0.1963 : 2$$
$$S_H = H\{S_{ref}\} \qquad (5)$$

C. Correlation calculation and phase extraction

The correlation between the measured sequence $[A_j]_H$ and the reference signal S_H is calculated using the inner-product of both compex sequences: per-element multiplication of $[A_j]_H$ with the conjugate of S_H:

$$\Lambda_j = \frac{1}{32} \sum [A_j]_H \bullet S_H^* \qquad (6)$$

The phase shift of $[A_j]$ in relation to the reference sinusoidal sequence $[S_H]$ can be derived as mean of the local phases of Λ_j

$$\Phi_j = \overline{\angle \{\Lambda_j\}} \qquad (7)$$

D. Compensation

A binary configuration, corresponding to the correction phase shift Ω_j

$$\Omega_j = -\Phi_j \qquad (8)$$

is loaded into the phase shifter for the particular MMIC's channel. An example of measured sequence and approximated sine-wave $\sin(\omega t + \Omega_j)$ is presented on Fig. 5.

The Antenna Pattern with the loaded correction phase shifts is presented in red on Fig. 6. For the sake of comparability, the antenna pattern before the phase correction is shown in blue on the same figure.

V. Conclusion

It was presented the conversion of measurement sequence to analytical signals provides a convenient way to make a correct estimation of phase errors from every single radiation element. The pattern of the calibrated antenna exhibits close to the theoretical maximum -13dB Peak to the first side lobe and well defined lobes and zeros.

Future work will be dedicated to reduction of measurement samples used for phase estimation and to its comparision with other phase estimation techniques like the Pisarenko Harmonic Decomposition, MUSIC, ESPRIT and others using the same count of input samples.

References

[1] Katagi,T., Mano, S., "A Method for Measuring Amplitude and Phase of Each Radiating Element of a PhasedArray Antenna", *Electronics and Communications in Japan*, 1982, Vol. 65-B, No. 5, 58 - 64

[2] Yonezava, R., Konishi, Y., et. al. "Beam-Shape Correction in Deployable Phased Array", *IEEE Transactions on Antennas and Propagation*, 1999, MARCH, VOL. 47, NO. 3, 482 - 486

[3] Sorace, R., "Phased Array Calibration", *IEEE Transactions on Antennas and Propagation*, 2001, Apr, Vol. 49 , Issue: 4, 517 - 525

[4] Hazewijk, J., "Fast Determination of Element Excitation of Active Phased Array Antennas", *Antennas and Propagation Society International Symposium*, 1991, Digest, 1478 - 1481

[5] Takahashi, T., Miyashita, H., et. al., "Theoretical Study on Measurement Accuracy of Rotating Element Electric Field Vector (REV) Method" *Electronics and Communications in Japan*, 2006, Part 1, Vol. 89, No. 1, 22 - 33

[6] Oppenheim, A., Schafner, R., *Discrete-Time Signal Processing, 3-th ed.*, 2010, Prentice Hall Press Upper Saddle River, NJ, USA

[7] Hahn, S., *Hilbert Transforms in Signal Processing*, 1996, Artech House, Michigan, USA