Array factor measurements towards array antennas characterization

T. ZERVOS[1,2], A.A. ALEXANDRIDIS[1], F. LAZARAKIS[1], K. DANGAKIS[1], C. SORAS[2]

[1] National Centre for Scientific Research "Demokritos", Institute of Informatics and Telecommunications, Athens, GREECE

[2] University of Patras, Department of Electrical & Computer Engineering, Patras, GREECE

Abstract: - The huge expansion of mobile terminal users and the high data rate services has lead the networks to their limits. During last years there is intent research in how to increase the capacity in networks. The base stations have mainly antennas with omnidirectional or sectored patterns. There is a need for adaptive radiation pattern in order to save power and to have larger capacity that means an increased number of users. To this direction, phased array antennas are commonly used. Phased arrays have the advantage that controlling the phase angle of each array element it is feasible to control the radiation pattern of the array and to steer the lobe in a desirable direction. In the design and evaluation of communications systems, there is a growing need for array antenna characterization. The main parameter that characterizes such an antenna is the Array Factor (AF). In this work, a methodology for the measurement of AF is presented. This methodology is applied on a reference array prototype made for the evaluation of the proposed measurement procedure. The results of the measurements are compared to those obtained both from theory and EM model simulation.

Key-Words: - Phased array, array factor, antenna characterization measurements

1. Introduction

An array of antenna elements is a spatially extended collection of a number of elements that have the same polar radiation patterns, orientated in the same direction in the 3D space. It is not necessary for the elements to be placed on a regular grid, neither to have the same terminal voltages, but it is assumed that they are all fed with the same frequency and that one can define a fixed amplitude and phase angle for the drive voltage of each element. Phased arrays have the advantage that controlling the phase angle of each array element it is feasible to control the radiation pattern of the array and to steer the lobe in a desirable direction.

A number of array geometries have been proposed in the literature [1]-[4] such as linear, circular, and two or three dimensional grid arrays. One of the simplest array geometries is a linear equidistant array where all elements are placed along a line with equal distance between them.

In this paper measurement results conducted with a linear array with four monopoles are presented. This array has been constructed in order to be used for the organization of a generalized measurement methodology for array antennas characterization. The four elements were placed above a ground plane and the distance between them was equal to one wavelength. The specific array has been designed to operate at the frequency of 2.45 GHz (i.e. in the ISM band). First, a model of the antenna was developed by means of EM simulation software and the 3D radiation diagram of the array was calculated using that model. Then, a prototype of the antenna was constructed and measurements of the Array Factor (AF) were taken using the proposed measurement methodology. The results of the measurements were compared to theoretical ones as well as to simulation results where the proposed methodology is applied to the EM simulation model.

2. Array model

In order to analyze theoretically the EM radiation of the antenna array, we have used the electromagnetic field simulation software "CST Microwave Studio" that is based on the Finite Integration Technique (FIT). In this general approach Maxwell's equations are rewritten in the integral form on a grid space, maintaining the physical properties of the electromagnetic fields. FIT can be employed in both the time domain and the frequency domain. The time domain allows the broadband calculation of far fields where with a single simulation run multiple resonances in the entire frequency band can be examined.

The model of the array consists of the ground plane and the four elements and can be seen in Fig. 1. The ground plane is an aluminum rectangular

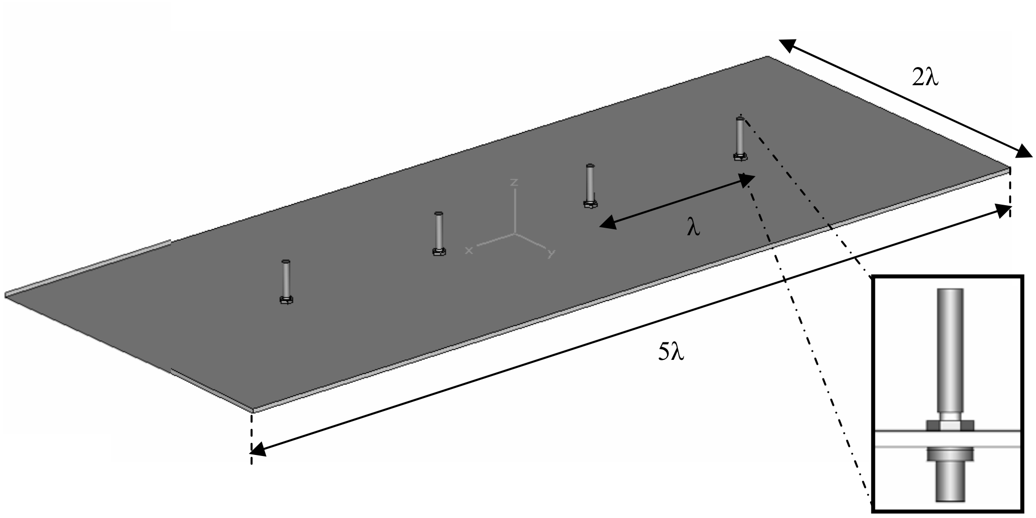

Fig. 1. The array model.

plate 3 mm thick with dimensions: 5λ x 2λ (about 611 x 244 mm). Each element is a λ/4 brass monopole (30.6 mm height at 2.45 GHz) with 2.5 mm radius. The array model is very detailed since the SMA connectors of the elements are also modeled for more accurate results. Four discrete ports with reference impedance of 50 ohms were applied at the bottom of the monopoles.

3. Theoretical Array Factor

Generally, for the case where all the array elements have the same radiation diagram, the total radiation diagram can be found from the product of the AF with the diagram of the single element. The knowledge of the AF is very useful for the characterization and the evaluation of a phased array antenna because it reflects the behavior of the antenna in terms of the phases and the amplitudes of the signals that drive the elements while the AF is independent from the radiation diagrams of the elements. Specifically, the array factor is the sum of the phases of the E fields radiated by the array elements.

An arbitrary three-dimensional array of N elements has an array factor given of [5],[6]:

$$AF(\theta,\varphi) = \sum_{n=1}^{N} I_n e^{j(\zeta_n + \delta_n)} \tag{1}$$

where I_n is the magnitude and δ_n is the phase of the weighting of the nth element and ζ_n is the relative phase of the incident wave at the element given by:

$$\zeta_n = \frac{2\pi}{\lambda}(x_n \sin\theta\cos\varphi + y_n \sin\theta\sin\varphi + z_n \cos\theta)$$

where x_n, y_n, z_n are the coordinates of the nth element in the 3D space. The normalized array factor is given by:

$$AF_{norm}(\theta,\varphi) = \frac{AF(\theta,\varphi)}{\max\{|AF(\theta,\varphi)|\}} \tag{2}$$

In the case of a linear array with four elements placed along the x-axis and by setting the phase $\delta_n = 0$, the normalized array factor for the azimuth plane can be written as:

$$|AF_{norm}(\varphi)| = \left|\frac{1}{4}\sum_{n=1}^{4} e^{j\left(\frac{2\pi}{\lambda}x_n \cos\varphi\right)}\right| \tag{3}$$

The above formula can be written in different form as:

$$|AF_{norm}(\varphi)| = \left|\frac{\sin\left(4\dfrac{\pi}{\lambda}d\cos\varphi\right)}{4\sin\left(\dfrac{\pi}{\lambda}d\cos\varphi\right)}\right| \tag{4}$$

where d is the distance between two adjacent elements. Therefore, the normalized array factor of the antenna under test (where d=λ) is given by:

$$|AF_{norm}(\varphi)| = \frac{|\sin(4\pi\cos\varphi)|}{|4\sin(\pi\cos\varphi)|} \tag{5}$$

4. Array Prototype and AF measurements

A real antenna array with the four elements has been constructed in order to measure the array factor and to compare it with the simulated one. The array elements and the ground plane have the same dimensions with the simulated model. A photo of the prototype in measurement environment can be seen in Fig. 2. The ground plane has a number of holes at the axis of the array elements in order to change the distance between the elements as required for future study.

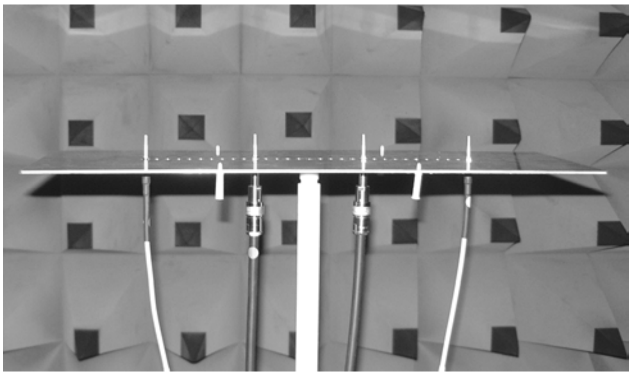

Fig. 2. The array inside the anechoic chamber.

Measurements were taken in an RF shielded anechoic chamber with dimensions: 10 m x 5 m x 5 m, fully lined with absorbing pyramids. The measurements setup is presented in Fig. 3. The antenna array was placed on a tripod at the one side of the chamber. A calibrated reference horn antenna (EMCO-3115) was sited at the opposite side of the chamber. Generally, in antenna measurements the array is mainly in receiving mode. Due to reciprocity inside the anechoic chamber the array of the antennas was set to transmitting mode without changing the expecting result. Each monopole of the array was connected to a signal generator with central frequency at 2450 MHz, while the horn antenna was connected to a spectrum analyzer. All the devices were controlled by a PC using a standard IEEE bus for the interconnections.

Assuming that the four monopoles have similar radiation patterns in the azimuth plane, we can measure the array factor by changing the phase difference, $\Delta\psi$, between the adjacent elements according to the properly selected formula: $\Delta\psi = \frac{2\pi}{\lambda} d \cos\varphi$ where d is the distance between two adjacent elements. The phases of the signals feeding the antenna elements can be seen in Fig. 4. The proposed method of measurements requires precise synchronization of the used signal generators and accurate control of their phase.

Following the previous described procedure we

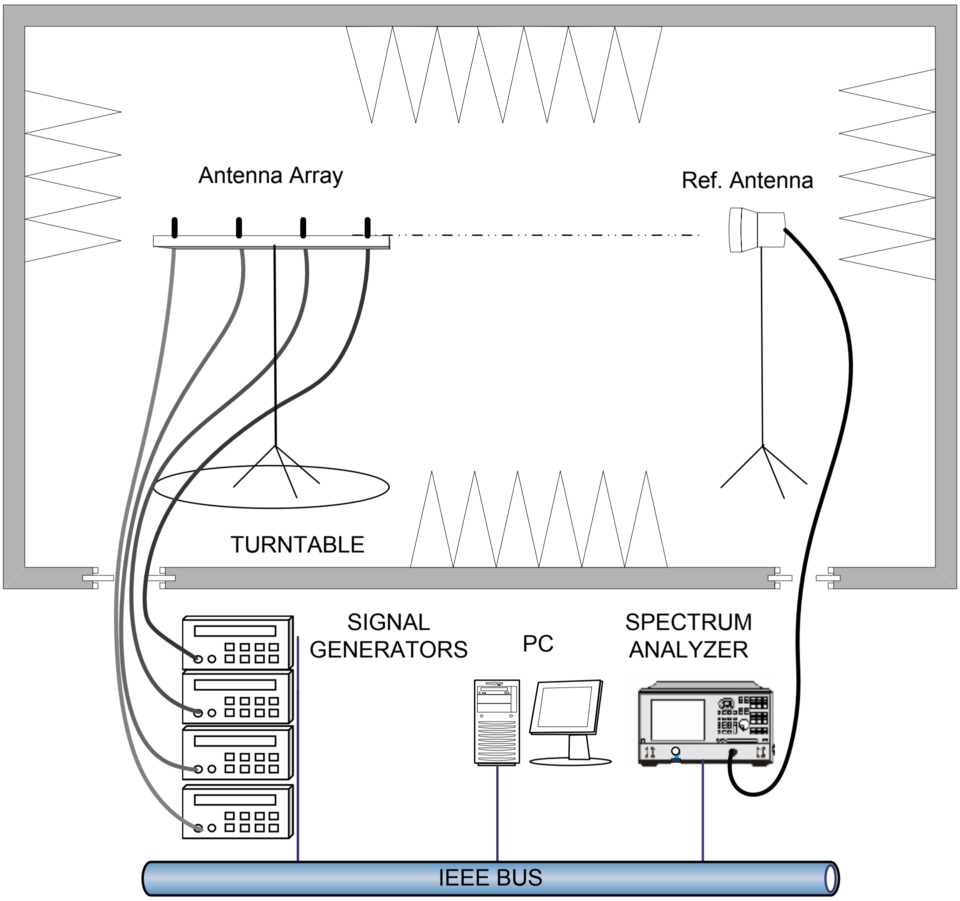

Fig. 3. Measurement setup.

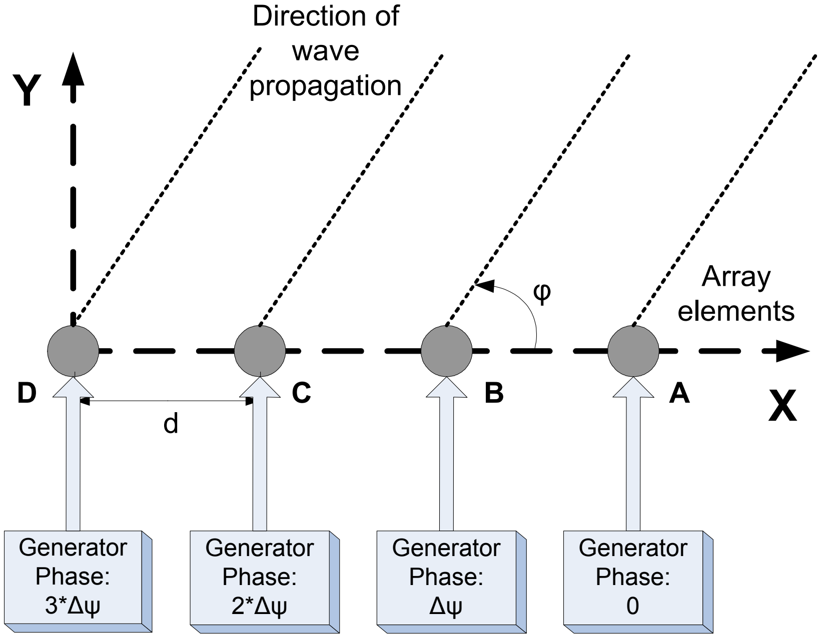

Fig. 4. The array elements and generator phases.

have taken measurements corresponding to the AF in the azimuth plane from 0 to 180 degrees with step of 1 degree by changing respectively the phase difference $\Delta\psi = 2\pi\cos\varphi$.

5. Results

From the measurements and the numerical simulations that have been performed the normalized Array Factor can be drawn. The polar diagrams of both the theoretical AF and the one

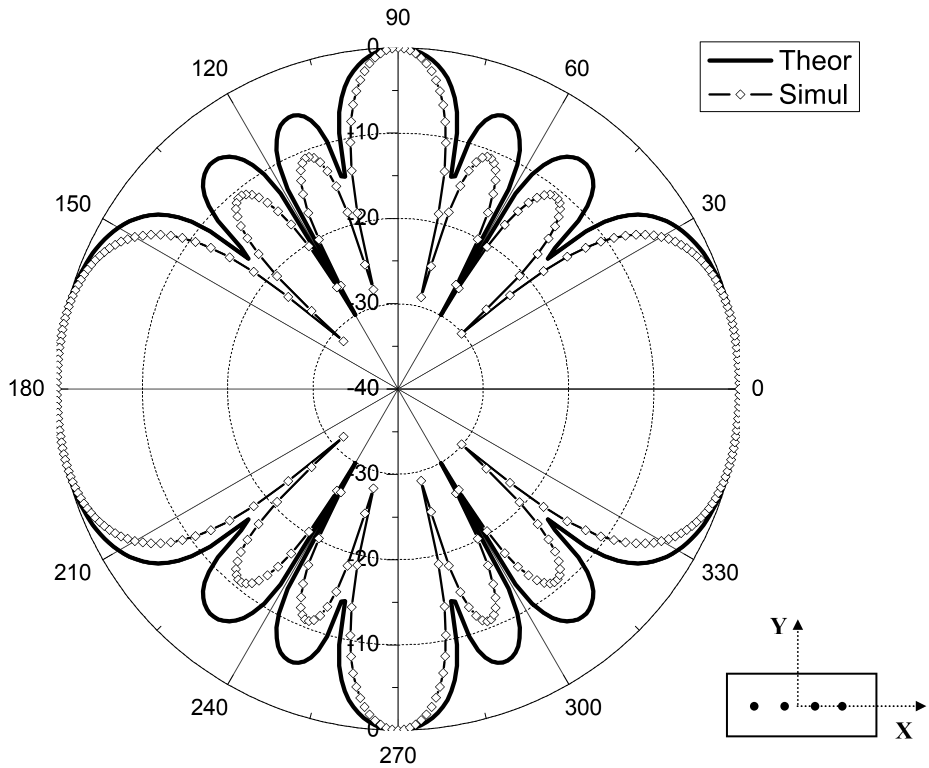

Fig. 5. Theoretical and simulated AF (normalized) in the xy plane.

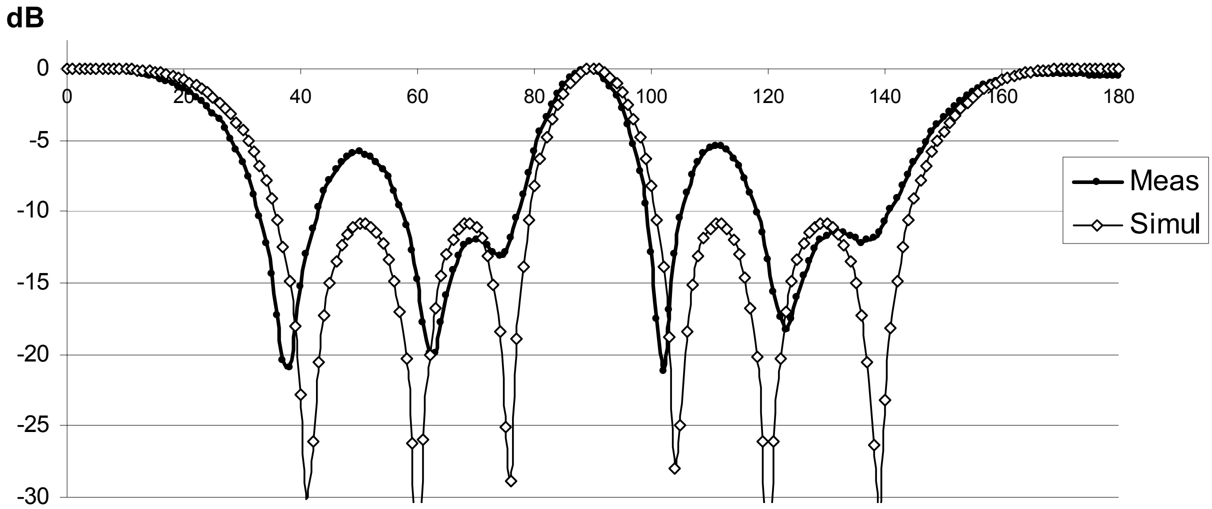

Fig. 6. Measured and simulated AF (normalized) in the azimuth sector 0 to 180 deg.

resulting from the EM model simulation are shown in Fig. 5, where differences of approximately 5 dB appear in the side lobes. The reason for this can be the fact that the matching of elements is not perfect, causing delays of the radiated signals not taken into account during the theoretical estimation.

In the diagram of Fig. 6, the measured values of AF are compared to those derived from simulation, for the azimuthal sector ranging from 0 to 180 degrees. A quite good agreement between the simulated and the experimental results can be noticed. It can also be observed that the main lobes of the pattern are in the same direction for simulation and measurements: Wide lobes at 0 (180) degrees and narrower ones at 90 (270) degrees. On the other hand, there is a 5dB deviation between simulation and measurements of the first side lobe that follows both main lobes in 0 (180) degree and 90 (270) degrees respectively. That deviation can be explained by the observed differences between the EM model and the prototype, which result to deviations between real and simulated input impedances of the array elements. These deviations cause certain variations at the delays between radiated signals with a direct influence to the AF.

6. Conclusions

A measurement methodology for the Array Factor (AF) estimation has been introduced. Using the proposed measurement procedure we can compensate the problem of deviation between theoretical and/or numerical simulation results in comparison with the real ones referring to the estimation of the AF of a linear phased array antenna. This methodology has been applied on a reference array prototype that consists of four monopole elements. The experimental results are compared to those obtained from both theory and EM model simulation. Measurement of the AF has been performed in the azimuth plane without rotating the array but by changing the generator phase of each element using a specific formula to obtain appropriate phase differences between the array elements that correspond to all possible directions at the azimuth plane.

References:

[1] K. Fujimoto, J.R. James, *Mobile Antenna Systems Handbook*, Artech House 2nd edition, 2001

[2] P.H. Lehne and M. Pettersen, *An overview of smart antenna technology for mobile communications systems,* IEEE Communications Surveys, Vol. 2, No. 4, 1999, pp. 2-13

[3] M.T. Ma, *Theory and Application of Antenna Arrays,* Wiley, 1974

[4] Jeng Shiann-Shiun, G.T. Okamoto, Xu Guanghan, Lin Hsin-Piao, W.J. Vogel, *Experimental evaluation of smart antenna system performance for wireless communications,* IEEE Trans. Antennas and Propagation, Vol. 46, No. 6, June 1998, pp.749-757

[5] L.C. Shen, J.A. Kong, *Applied Electromagnetism,* PWS Publishing Company 3rd edition, 1995

[6] C.Balanis, *Antenna Theory Analysis and Design,* John Wiley& Sons 2nd edition, 1996