Joint Mutual Coupling Characterization and Swarm Optimization for Efficient Base Station Antenna Beamforming

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***Abstract*- In this work, practical beamforming technique is proposed for improving directional radiation properties of base station antennas operating at 1710-2690MHz. Firstly, we characterize the mutual coupling between antenna elements using Rohde & Schwartz multi-ports network analyzer. And with the active radiation parameters (from High Frequency Simulation Software), the real excitation coefficients of the different array elements' field are outputted by developing a MATLAB algorithm. Next, we use these excitation coefficients as inputs and then develop a swarm algorithm to compute the optimum phases of the array elements for a given sidelobes level requirement and beam steered angle. Experimental results are provided to confirm the analytical approach and the advantage of using mutual coupling characterization and swarm technique in base station antenna design process. Interestingly, results show that the analytical model approach can help to predict even the statistical performances of the antenna before testing it as minimum gap between analytical and experiment results has been observed.**

Keywords: Mutual Coupling Characterization, Particle swarm, Base station antenna

I. INTRODUCTION

Wireless communications have seen remarkable progress with an aim to satisfy the requirements for current and future wireless networks [1]-[7]. Radio access demands will continue to increase and spectrum will become more crowded leading to more focus on reviewing current technical specifications and to design new concepts putting them in the context of Long Term Evolution (LTE) systems and beyond[5], [6]. Accordingly, numerous challenges are generated on the antenna systems design as new frequency bands should be fully covered to meet the demands for various application levels impacting so the radio network design involving for example the propagation mechanism and the cell planning methods. Base station antennas (BSAs) are capable of converting energy between electricity and electromagnetic waves and are mainly composed of several radiating elements (called also dipoles or elements) useful for transmitting/receiving information throughout a communication system. Such disposition of set of dipoles also known as array architecture should be given more attention with an aim to provide desirable radiation performances. The number of dipoles and their physical distribution (size, spacing) introduce an array factor that has significant impacts on the global radiation performance of an antenna [8]-[10]. More specifically, undesired lobes with high level may appear when defining an inappropriate spacing factor resulting on affecting the electrical performance negatively. In [8] and [10], analysis assumed input impedance and radiation pattern of single element to be the same as single antenna model. However, such assumption seems not natural even being considered by most of antenna designers to simplify the analysis. In reality, every single element's radiation characteristics depend on the array structure and the effects from other elements. Therefore, it is recommended to take into account the active radiation pattern of all the elements as in [9], [11] and [12]. Most of these works focused on Minimum Scattering Antennas (MSA) where coupling is significant or consider quasi wide frequency application. If coupling can be modelled practically to get the physical array excitation parameters, one interesting task is to investigate using these parameters as inputs to compute more accurate beamforming coefficients for BSA based on robust method such as swarm [12]. The present study is the design of a framework based on mutual coupling characterization and swarm method for BSA operating at 1710-2690MHz for a given steered angle. An N-elements array is designed using HFSS software so that active radiation characteristic of each element can be obtained along with the full array S-parameters. The feeding networks is composed of N outputs with S-parameters that can be practically measured using Rohde & Schwartz multi-ports network analyzer. By making use of the network S-parameters, the full array S-parameters and each element's radiation pattern, we then characterize a mutual coupling matrix to output the complex excitation coefficients of the array elements. In addition, we make use of these coefficients to develop a particle swarm algorithm for beamforming purpose to control sidelobe level (SLL) over the entire operating frequencies for a given specified level. Furthermore, the antenna is fabricated and tested within an anechoic chamber and experimental results demonstrate the design analysis and the significant advantages of using mutual coupling characterization and swarm method in the antenna development process. Interestingly, results show that the analytical model approach can help to predict even the statistical performances of the antenna before testing it as minimum gap between analytical and experiment results has been observed.

The rest of the paper is organized as follows. Section II describes the mutual coupling characterization system model. Section III presents the beamforming analysis algorithm based on particle swarm method. In section IV, the experimental results are presented while section V concludes this work.

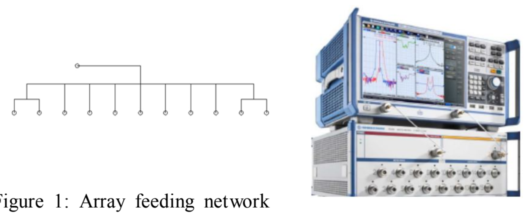

Figure 1: Array feeding network and multi-port network analyzer

II. COUPLING CHARACTERIZATION SYSTEM MODEL

The feeding network is composed of one input voltage (antenna port In) and a set of N outputs (Out1… Out$N$) as shown in fig.1a. The N outputs are physical terminals and the corresponding S-parameters can be measured using Rohde & Schwartz multi-port network analyzer as pictured in fig.1b.To obtain the complex excitation coefficients, a matrix model derived from the above inputs-outputs and different S-parameters should be established. Let's denote a_0 the incident wave to the antenna input (corresponds also to the feeding network input) and r_0 the corresponding reflected wave. We model also a_i as the i^{th} incident wave to the i^{th} output of the feeding network, r_i being the i^{th} reflected wave from the i^{th} antenna element to the i^{th} output of the feeding network. Thus, by denoting S as the scattering matrix, the parameter relation for the feeding network can be derived as:

$$\begin{bmatrix} r_0 \\ r_i \end{bmatrix} = S \begin{bmatrix} a_0 \\ a_i \end{bmatrix} \quad (1)$$

The matrix S can be easily decomposed as:

$$S = \begin{bmatrix} S_{00} & S_{0i} \\ S_{i0} & S_{ii} \end{bmatrix} \quad (2)$$

Where S_{00} is the reflection coefficient of the feeding network, $S_{0i} = S_{i0}$ is a $1xN$ sub-matrix characterizing the power transfer vector to the feeding network outputs and S_{ii} a NxN sub-matrix characterizing the coupling relation of the feeding network outputs. The array structure is designed and optimized using HFSS. In this experiment an 11-elements is considered as can be seen from fig.2. And the corresponding array S-parameters S_{arr} and each element's pattern P_i can be obtained. Since the feeding network has to be connected to the array element to build a complete BSA layout, we can derive the following relation:

$$a_i = S_{arr} r_i \quad (3)$$

Hence, by combining relations (1), (2) and (3) we can deduce that:

$$r_i = S_{arr}^{-1} \left(S_{arr}^{-1} - S_{ii} \right)^{-1} S_{i0} a_0 \quad (4)$$

We can realize that equation (4) determines the complex excitation coefficient relation of different array elements based on which we can obtain the physical radiation

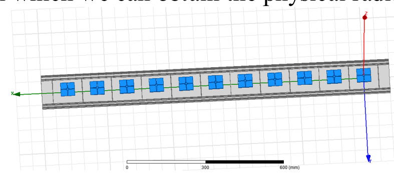

Figure 2: Antenna array structure from HFSS

characteristic by multiplying each element's coefficient by its corresponding pattern P_i. Consequently, it is interesting to use these coefficients as inputs for an optimization algorithm aiming to have better pattern beam control design as presented in next section.

III. BEAMFORMING ANALYSIS

This section addresses the vertical pattern performances regarding to the SLL constraint for a given steered angle θ_0. From the array theory, the far-field pattern of an N-elements antenna can be obtained by summing the active pattern of the different element with respective weight [11]. Let denote A_i the complex excitation coefficient of the i^{th} element as analyzed in above section (element being numerated from 1 to N with the first element located at the edge of the array) based on which the array field can be expressed as element-by-element sum as

$$F(\theta) = \sum_{i=1}^{N} A_i P_i(\theta) \quad (5)$$

Where θ is the elevation angle generally chosen between $-\pi$ and π.

Note that the far-field expression in (5) represents a pattern steered at 0°. However, to steer the pattern at a specified angle θ_0, the free space phase shift

$$\phi_0 = kd \sin(\theta_0) \quad (6)$$

and the position $p_i, i = 1 \ldots N$ of each element (according to a carefully chosen reference) should be considered as well. Roughly speaking, for the N-elements with a given referenced element carefully chosen (can be also a set of elements connected via appropriate power splitting element) resulting on

$$p_i = f_N(i) \quad (7)$$

Where $f_N(i)$ is the value of a function expressing the position of the i^{th} element from a given referenced position i_r ($f_N(i_r) = 0$).Thus, combining (5), (6) and (7) we can express the far-field array factor for a given steered angle as

$$F_{\theta_0}(\theta)=\sum_{i=1}^{N} A_i P_i e^{j\left[B_i+f_N(i)kd\sin(\theta_0)\right]} \quad (8)$$

Where d is the spacing factor, $k=2\pi\lambda^{-1}$ represents the wave number and B_i is the additional phase of the i^{th} element outputting a given sidelobe level target. Therefore, the side lobes defined for values of θ out of the main beam range can be controlled by carefully analyzing expression (8). In fact, we can realize that the problem becomes now to find the vector phase $B=(B_i)_{i=1...N}$ of the array elements subject to a required maximum SLL for a given steered angle θ_0. Consequently, by formulating an optimization algorithm, the problem can be analyzed and solved through numerical methods.

a. Concept of PSO algorithm

Computational technique introduced in 1995 by Kennedy and Eberhart [13]. It is not only simple compared to Genetic Algorithm (GA) [14] and Simulated Annealing (SA) [15], but efficient as well [12]. PSO is generally based on the coordination of particles (swarms) moving towards a target within a solution space. Each particle can be represented by its position and velocity (initialized randomly) in the solution space. And their movement can be coordinated easily if each of them knows always its best position (named personal best position) and the best position among all the particles (generally called global best position). The position and velocity of the ith particle can be denoted respectively as $X_i=(x_1,x_2,x_3,...)$ and $V_i=(v_1,v_2,v_3,...)$. Through a test function (called also fitness function) [12], each particle's position and velocity can be regularly updated using the following equations:

$$v_i = wv_i + c_1 rand()(p_i^{best}-x_i)+c_2 rand()(g^{best}-x_i) \quad (9)$$

$$x_i = x_i + v_i \quad (10)$$

Where p_i^{best} and g^{best} represents the i^{th} particle's personal best position the global best position among all the particles respectively. w is the inertia weight, c_1 and c_2 represent the acceleration constants and $rand()$ denotes a pre-defined function that generates a number in [0, 1] in a random fashion.

b. Beamforming analysis using PSO

Based on the above points, we can define the different parameters of the different elements based on which a PSO algorithm is developed with 11 elements forming a particle (analysis is suitable for an N-order element as well). It follows that the i^{th} particle within the solution space can be defined as:

$$X_i=(B_1,B_2,B_3,B_4,B_5,B_6,B_7,B_8,B_9,B_{10},B_{11}) \quad (11)$$

The validity of a particle being optimal can be guaranteed by carefully defining a test function (fitness function as already mentioned above). As we can notice, the main parameter to be optimized for a given maximum SLL and a steered angle is the vector phase of the different elements within the operating frequency band. So, for a given number

Table 1: Vector phase of the 11-elements array

B_i	150	157	158	100	99	97	97	97	95	97	104

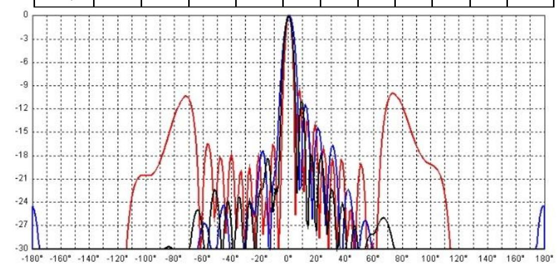

Figure 4: Simulation results of the mutual-coupling PSO analysis framework (Blue for 1.7GHz, Black for 2.2GHz and Red for 2.7GHz)

of frequency points, defining a function taking into account the maximum side lobe value at steered angle θ_0 seems to be a suitable candidate. Consequently, we can define a fitness function as:

$$f(\theta)=\max\{SLL(\theta_{SL0})\} \quad (12)$$

Where θ_{SL0} represents the region of the side lobes (region out of the main beam).

Therefore the optimization problem can be formulated as:

$$\begin{cases} Min\ F_{\theta_0}(\theta) \\ \max\{SLL(\theta_{SL0})\}-SL_T \le 0 \end{cases} \quad (13)$$

Where SL_T is the SLL target. Now, we set up a model to be computed by making use of MATLAB and the above mentioned equations (8), (9), (10) and (13) to compute the vector phase of the different element for a given SLL requirement at a steered angle. As an example of simulation, 11- elements array is used for boresight pattern ($\theta_0=0^o$), a number of 10 particles are initialized within their corresponding velocities. In (9), the inertia weight is set to 0.7, the acceleration constants are set to 1.5. At each iteration step, the pattern is computed for 3 frequencies (1.7, 2.2 and 2.7GHz), and the personal best position of each particle was obtained with the global best position. After processing, the best output regarding to the desired requirements (SLL not greater than -16 dB) is the particle with elements shown in table 1 with the corresponding pattern as shown in fig.4. From fig.4, we can observe that the SLL is below the required target.

IV. EXPERIMENTAL RESULTS

Motivated by the results from the above analysis, we aim to implement and test the antenna. The antenna is fabricated as pictured in fig.5 and tested in Tongyu's anechoic chamber having dimensions of 11x11x55m. The pattern results are plotted in figure 6 at different frequency spots. The red curves represent the analytical results while the blue ones are for the measurements. As can be observed, the analytical results approach the ones from the field measurements at different frequency spots. It is important to note that the errors from the feeding networks due to cable lengths affect the phase of the signal of interest impacting on the vertical pattern as well causing deviations between analytical and measurement at some points. However, based on statistical point of view for more insights, we can realize that the analytical approach can be used to predict even the real pattern characteristic for a BSA.

V. CONCLUSION

Rigorous design process are needed to exploit more benefit about the advantages given from the access networks. In this work, we analyzed and developed a beamforming framework based on mutual-coupling and particle swarm techniques. We characterized BSA elements mutual coupling using Rohde & Schwartz multi-ports network analyzer and derived a closed form expression computing the physical excitation coefficients developing MATLAB algorithm. We used these excitation coefficients as inputs and then developed a particle swarm algorithm to compute the optimum phases of the N-elements array for a given sidelobes level requirement and beam steered angle. Experimental results are provided to confirm the analytical approach. As an important remark, results showed that the analytical model approach can help to predict even the statistical performances of the antenna before testing it as minimum gap between analytical and experiment results has been observed.

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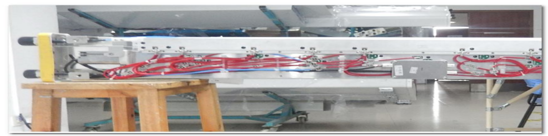
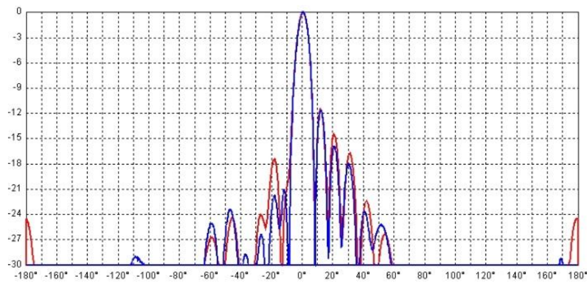
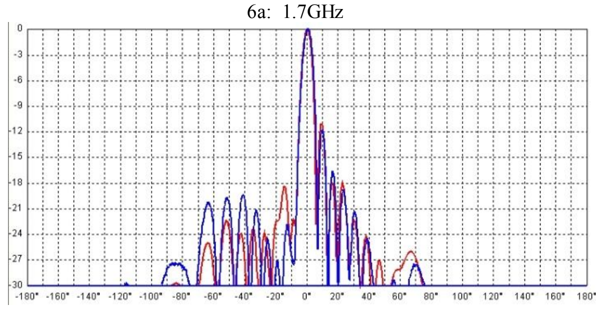


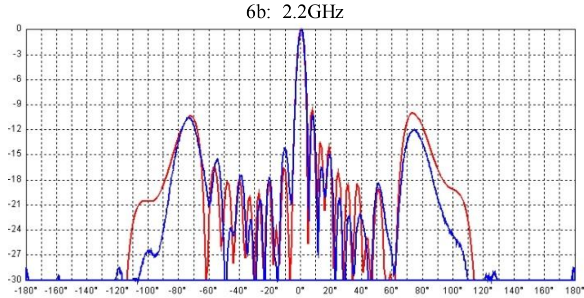
Figure 5: Manufactured BSA layout



6a: 1.7GHz



6b: 2.2GHz



6c: 2.7GHz

Figure 6: Representation of the measured (blue) and analytical (red) patterns according to the frequency