Design of antenna arrays for near-field focusing requirements using optimisation

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An optimisation framework is proposed to properly focus on near-field locations using antenna arrays. This method is able to overcome the traditional problems of near-field focused antennas, obtaining some appropriate weights to be applied at the elements of the array so that the secondary lobes are reduced and the maximum level of the field is placed at the desired point. An illustrative example using simulated antennas is addressed to evaluate the capabilities of this framework.

Introduction: Near-field (NF) focused antenna arrays have been used in many applications, such as biomedical systems [1] or RFID [2]. These antennas are able to hold the radiated field on a certain position (in the near field) where a target is placed. The basic idea is to control the phase of the weights applied at each element of the array in such a way that all their individual contributions sum in-phase at the focal point.

The characteristics of this traditional approach have been analysed as functions of the array size, the inter-element distance and the focal distance [3, 4], finding some limitations. First, there is a focal shift which makes the peak of the radiated power density occur before the focal point, between that position and the aperture of the antenna, due to the field-spreading factor $1/R$ (R being the distance between the focal point and the antenna). On the other hand, the phases which provide the focusing on a certain target might generate important lobes at other regions. Although many systems focus on targets along the transversal axis of the array [3] where this problem is minimised, some applications need a focusing on other near-field points [2] in which the phase contributions of the array elements lead to interference lobes.

This Letter proposes a new method for the design of NF focused antennas arrays that overcomes those limitations, using an optimisation framework. The proposed technique is able to find the phase of the weights that provides the desired focus, minimising the lobes in other near-field regions and reducing the focal shift. Despite the fact that demanding results can be obtained synthesising only the phase terms, this method also allows the optimisation of the magnitude of the weights, increasing the accuracy of the technique and dealing with the problems of lobes caused by tapered distributions [4]. Although there are different optimisation algorithms able to solve this problem, the proposed optimisation framework is based on the Levenberg-Marquardt algorithm [5] as a robust solution for nonlinear problems.

Cost function and optimisation process: To obtain a near-field distribution which fulfils the focusing requirements, a cost function F must be properly defined, using a pair of templates to define the limits allowed for each position of the near field:

$$F = \sum_{n=0}^{N-1} [(G_n^2 - \overline{|E_n|^2})(g_n^2 - \overline{|E_n|^2}) + |G_n^2 - \overline{|E_n|^2}||g_n^2 - \overline{|E_n|^2}|]^2 \quad (1)$$

where $n \times 0 \ldots N-1$ is a discrete value to represent the nth point of the N considered positions; G_n, g_n identify the maximum and minimum bounds for the radiated field E_n at the nth point and $\bar{X} = X/max(X)$. Note that $|E_n|^2 = |E_{x,n}|^2 + |E_{y,n}|^2 + |E_{z,n}|^2$, where the spatial components of an antenna array with T elements are expressed as:

$$E_{x,n} = \sum_{z_t'}^{T_z}\sum_{y_t'}^{T_y}\sum_{x_t'}^{T_x} [(z_n - z_t')\omega_{y,t} - (y_n - y_t')\omega_{z,t}] \frac{1 + j\beta R_{n,t}}{R_{n,t}^3} e^{-j\beta R_{n,t}}$$
$$E_{y,n} = \sum_{z_t'}^{T_z}\sum_{y_t'}^{T_y}\sum_{x_t'}^{T_x} [(x_n - x_t')\omega_{z,t} - (z_n - z_t')\omega_{x,t}] \frac{1 + j\beta R_{n,t}}{R_{n,t}^3} e^{-j\beta R_{n,t}} \quad (2)$$
$$E_{z,n} = \sum_{z_t'}^{T_z}\sum_{y_t'}^{T_y}\sum_{x_t'}^{T_x} [(y_n - y_t')\omega_{x,t} - (x_n - x_t')\omega_{y,t}] \frac{1 + j\beta R_{n,t}}{R_{n,t}^3} e^{-j\beta R_{n,t}}$$

where $t = 0 \ldots T-1$ identifies the tth element of the array, T_x, T_y, T_z represent the number of elements in directions x, y, z, respectively, with $T = T_x \times T_y \times T_z$, and $\{x_n, y_n, z_n\}$ describes the spatial components of the nth space position. The feeding weights applied to the tth radiating element (placed at $\{x_t', y_t', z_t'\}$) are represented by their spatial components $\omega_{x,t}, \omega_{y,t}, \omega_{z,t}$. $R_{n,t}$ represents the distance between the tth element and nth position, $\beta = 2\pi/\lambda$ and λ is the wavelength.

The objective of the cost function defined in (1) is the minimisation according to the required unknowns, i.e. the spatial weighting coefficients $\alpha = \{\omega_{x,t}, \omega_{y,t}, \omega_{z,t}\}$, $\forall t$. The proposed method is flexible enough to optimise either the phase or both phase and magnitude of each feeding weight in order to obtain the desired near field.

It can be easily noticed that the only null addends in F correspond to those positions in which the field is inbounds, so F can be expressed as:

$$F = \sum_{n=0}^{N-1} \begin{cases} 0, & \forall n | g_n^2 \le \overline{|E_n|^2} \le G_n^2 \\ [2(G_n^2 - \overline{|E_n|^2})(g_n^2 - \overline{|E_n|^2})]^2 = (d_n - f_n(\alpha))^2, & \text{otherwise} \end{cases} \quad (3)$$

where $f_n(\alpha) = 2\overline{|E_n|^2}(G_n^2 + g_n^2 - \overline{|E_n|^2})$ and $d_n = 2G_n^2 g_n^2$, which respectively represent the values that do depend and those that do not on the vector of unknowns α, for each n. The above expression responds to a well-known square error function, which can be minimised using an optimisation method, such as the Levenberg-Marquardt (LM) algorithm [5]. The LM algorithm is based on an iterative process which requires the calculation of a Jacobian matrix as a function of the different unknowns considering the N positions. The partial derivates that form this Jacobian matrix depend on the variables to obtain, i.e., only the phase or both magnitude and phase of $\{\omega_{x,t}, \omega_{y,t}, \omega_{z,t}, \forall t$. Thus, the actual vector of unknowns α corresponds to the phases of the weighting coefficients or their real and imaginary parts, respectively. Note that the phase-only optimisation is carried out through the inverse tangent of the phases, in order to avoid periodicity problems in the solutions.

Simulations and results: The traditional approach for near-field focused arrays has inherent problems proportional to the distance R between the focal point and the aperture of the antenna: the focal shift and depth of focus (DoF) increase, and the achieved gain at the focal point decreases as R increases [3, 4]. Some interesting results have been obtained after several simulations that demonstrate that the proposed focusing method is able to reduce those limitations.

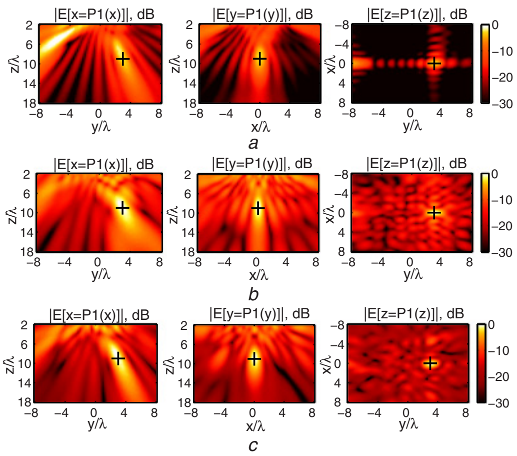

Fig. 1 *Normalised radiated field in x,y,z cuts of target point*

a Traditional NF-focused approach
b LM applied to magnitude and phase (MP) optimisation
c LM applied to phase-only (PO) optimisation

The proposed method is applied to achieve the proper weights so that an 8×8 uniform planar array focuses on a target $P = (0, 3, 9)\lambda$ in the near field, comparing the results with the traditional focusing method. The isotropic elements of the array are uniformly separated each λ, located at $z = 0$. Phase-only (PO) and magnitude-phase (MP) optimisations of the feeding weights of the array elements have been carried out. The pair of templates has been defined so that the realistic behaviour of the antenna can be respected avoiding divergence provided by too restrictive requirements. As a result, g_n^2, $G_n^2 = 0.1$ for all n except those positions around the target point where $d_n = [(-x_n)^2 + (3\lambda - y_n)^2 + (9\lambda - z_n)^2] \le 0.5\lambda^2$ in which $g_n^2 = 0.9d_n$, $G_n^2 = d_n$. The solutions have been reached at iterations 38 and 88 for the MP and PO cases, respectively, with an average error of $F_{MP}/N = 5.12 \times 10^{-4}$ and $F_{PO}/N = 8.45 \times 10^{-4}$, with $N = 35937$ (samples uniformly taken in $x, y \in [-8, 8]$, and $z \in [2, 18]\lambda$ each 0.5λ).

The radiated fields focused on P obtained with the traditional focusing method and LM optimisations are shown in Fig. 1. Each column represents the x, y, z cuts around the target position, i.e. $|E_n(0,\ y_n,\ z_n)|^2$, $|E_n(x_n,\ 3\lambda,\ z_n)|^2$, $|E(x_n,\ y_n,\ 9\lambda)|^2$. To make this comparison, a unit magnitude is considered for all the feeding weights (the mean of the magnitude is unitary in the MP case).

Some problems are found when the traditional method focuses on P. The phase contribution at the focal point leads to high field levels around $(0,\ -7,\ 6)\lambda$, as it appears in the x-cut (Fig. 1*a*), where the field is higher than the one achieved at P. The previous interfered lobe is reduced using the proposed optimisation framework (Figs. 1*b* and *c*), in both the MP and the PO cases. The MP case provides better results, since there are more variables (degrees of freedom) to optimise than in the phase-only option.

On the other hand, Fig. 2 shows the correction of the focal shift problem of the traditional approach, representing the normalised radiated fields along the direction of the target point defined as $\overrightarrow{z_P} = 3\hat{y} + 9\hat{z}$. The depth of focus is also minimised in both optimisation cases, especially in MP. However, the quotient between the levels at the target and at $10z_P$ is lower after optimisations, since the gain reduction is proportional to the location of the maximum. Nevertheless, the field is clearly concentrated at the target point and the inherent problems of traditional NF focused antennas are minimised.

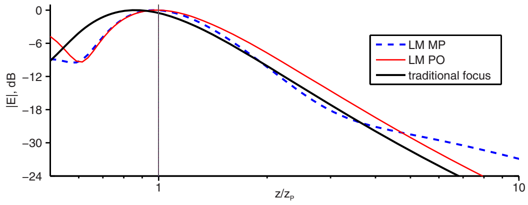

Fig. 2 *Normalised radiated field along target direction*

Conclusion: The proposed method allows the optimisation of the feeding weights (either magnitude and phase or only phase terms) of the elements of a near-field array antenna so that the radiated field is concentrated at a desired target point. A representative example is addressed, where the inherent problems related to the traditional near-field focused arrays are overcome thanks to the minimisation of a proper cost function.

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One or more of the Figures in this Letter are available in colour online.

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