

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



# An Overview on Synthesis Techniques for Near-Field Focused Antennas

*Marcos R. Pino, Rafael G. Ayestarán, Paolo Nepa and Giuliano Manara*

## Abstract

Microwave and millimeter-wave antennas focused in their radiative near-field (NF) region, which are usually named as near-field focused (NFF) antennas, are becoming increasingly popular. Indeed, when compared to conventional far-field focused antennas, they can guarantee performance improvement at a relatively limited implementation cost, in short-range communication systems, wireless power transfer arrangements, remote nondestructive sensing setups, and radio-frequency identification apparatus, among many others. In this chapter, application fields and metrics for NFF antennas will be briefly summarized. Most of the chapter is then devoted to the description, classification, and critical review of the many synthesis techniques that go beyond the simple, yet effective and with a clear physical insight, conjugate-phase approach.

**Keywords:** near-field focusing, focused antennas, focused arrays, near-field shaping, near-field synthesis, focused array synthesis, antenna focusing, phase conjugate technique

## 1. Introduction

Many wireless systems require directive antennas for proper operation. These are antennas that are able to radiate most of their input power into a limited angular sector. Indeed, above feature can improve either the spatial resolution of a localization system or the sensitivity of a remote measurement system, reduce the interference level with other wireless systems, and increase either the transfer efficiency of wireless power transfer systems or the signal-to-noise ratio in radio communication links. As it is well known to antenna designers, antenna directivity can be increased at the expense of electrically larger antennas, namely antennas that are large in terms of the free-space wavelength. Indeed, electrically large antenna arrays are becoming popular in several industrial applications, indoor wireless communication systems, and even in consumer electronic goods.

Let us consider a specific wireless system whose frequency band is assigned, as well as the typical expected distance between the transmitting antenna and the target (transponder, receiving antenna, material sample under analysis, scatterer,

etc.). Then, when enlarging the transmitting antenna size to increase its directivity, it must be considered that the boundary of the antenna far-field region moves far from the antenna itself and the target may end up with belonging to the antenna radiative near-field region, where conventional antenna far-field parameters, as radiation pattern, array factor, half-power beamwidth and gain, all become meaningless. Therefore, different design criteria must be considered when synthesizing the excitations of a large array or the layout of a large aperture antenna. It is worth noting that above phenomenon may not be rare in real-world short-range wireless systems with operating frequencies larger than a few GHz (microwave frequencies and beyond).

In above situations, the most evident design criterion consists in exploiting the well-known optical focusing concept. Indeed, by simply controlling the phase of the array element currents (or equivalent currents on the antenna aperture), it is possible to achieve a constructive combination, namely an in-phase summation, of the fields radiated by the array basic radiators at an assigned point in the antenna radiative near-field region, i.e., the focal point, where the target may be located. It is worth noting that when the assigned focal point moves far from the antenna, beyond the boundary of the far-field region, the above phase profile smoothly converges to that of a conventional far-field focused antenna (simply named as unfocused antenna in the following), i.e., a constant phase profile for a broadside antenna or a linear phase profile for a phased array, as expected.

At the focal region, the power density radiated by an NFF antenna is larger than that radiated by an unfocused antenna with equal size and input power. Equivalently, the NFF antenna can guarantee at the targeted focal point an assigned power density as for the unfocused antenna, but with a lower far-field radiation, thereby limiting the coupling with nearby wireless systems. In the following section, a planar array of printed patches operating at the 2.4 GHz ISM band will be used to quantify above advantages as well as to introduce the parameters that can be used to characterize NFF antennas.

The usefulness of an NFF antenna has been demonstrated in several applications [1]: remote sensing of material sample properties with high sensitivity and high spatial resolution, wireless power transfer at distances larger than those achieved with magnetic coupling, reliable radio-frequency identification systems, effective biomedical devices, dedicated short-range communication (DSRC) systems, among many others.

Almost any antenna technology can be used to realize NFF antennas, as it is just required to modify the layout of a conventional unfocused antenna to get the proper phase profile of the radiation currents on the array/aperture surface. An overview of the different technologies that have been applied to prototype NFF antennas can be found in [2]. Among them, it is worth mentioning reflectarrays and transmitarrays, linear and planar arrays (made of dipoles, patches, dielectric resonator antennas), planar slotted waveguide antennas, lens antennas, dielectrically loaded horn antennas, elliptical reflectors, substrate integrated waveguide (SIW) antennas, leaky wave antennas, and Fresnel Zone Plate Lens antennas. A number of more recent papers deal with the design of focused metasurface antennas [3, 4]. With respect to the layouts of conventional unfocused antennas, the implementation of the focusing phase profile for the array currents only requires small layout modifications, as the adjustment of the feeding network in microstrip arrays, or the tuning of the geometrical parameters of the quasi-periodic cells in reflectarrays/transmitarrays, or the tapering of the guiding structure in leaky-wave antennas. The required array excitation profile can be derived by either the basic phase-conjugate approach or *ad hoc* synthesis techniques.

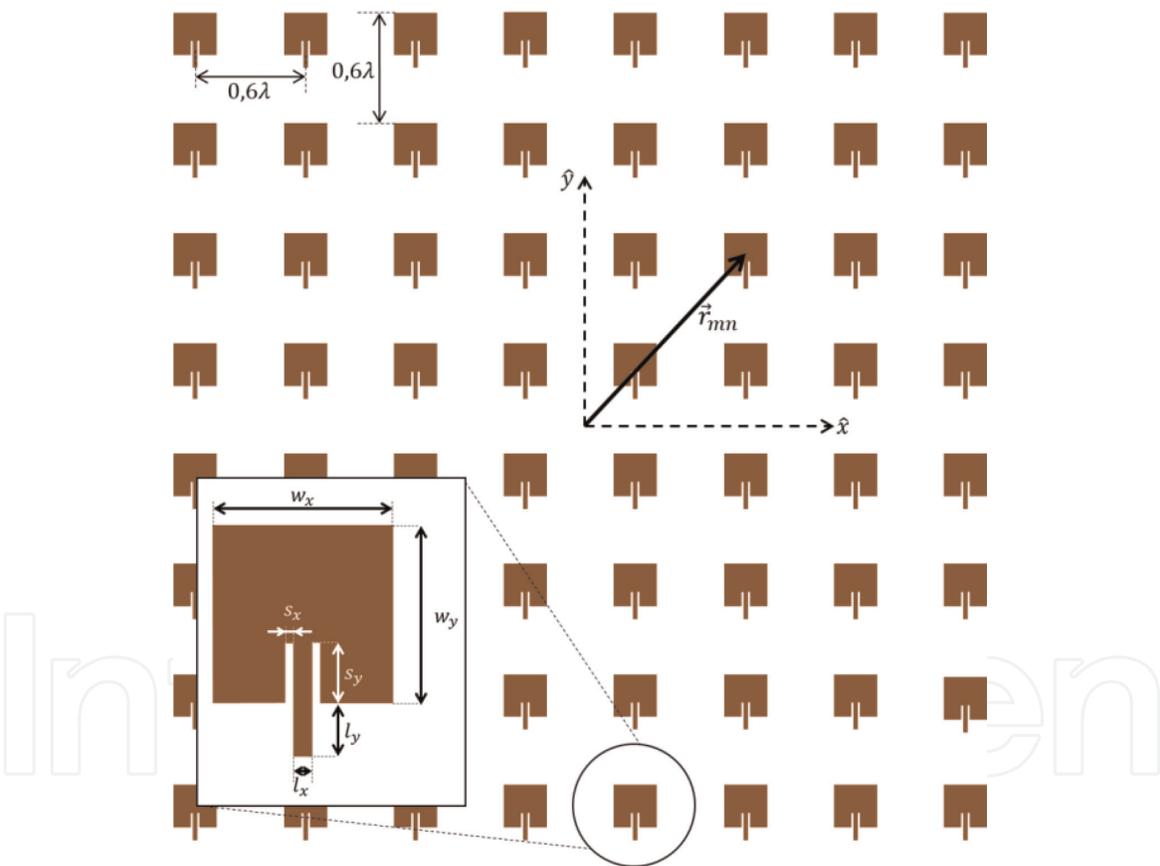
## 2. Near-field focused antennas: design criteria and metrics

Let us consider a planar array of  $8 \times 8$  linearly polarized inset-fed patches resonating at 2.4 GHz, which are realized on a thin grounded dielectric layer (FR-4 substrate with a relative dielectric constant of  $\epsilon_r = 4.4$ , loss tangent  $\tan \delta = 0.02$  and thickness of 1.52 mm). The array layout is shown in **Figure 1** and its geometrical parameters are listed in **Table 1**. The array surface coincides with the  $z$ -plane of a rectangular coordinate system, and the assigned focal point is at  $\vec{r}_{focal} = z_f \hat{z}$ .

To focus the field radiated by the patches at the assigned focal point, the phase of the array element excitations can be simply derived by imposing a phase shift that compensates for the distance between the assigned focal point  $\vec{r}_{focal}$  and each array element position  $\vec{r}_{mn}$  (conjugate-phase – CP – approach):

$$\phi_{mn} = \frac{2\pi}{\lambda} \left\| \vec{r}_{focal} - \vec{r}_{mn} \right\|_2, \quad (1)$$

where  $\lambda$  is the free-space wavelength and  $\|\cdot\|_2$  stands for the Euclidean distance.



**Figure 1.**  $8 \times 8$  planar array layout. The inset shows the dimensions of the array elements separated at  $0.6\lambda$  in both directions ( $0.6\lambda = 7.5$  cm at 2.4 GHz).

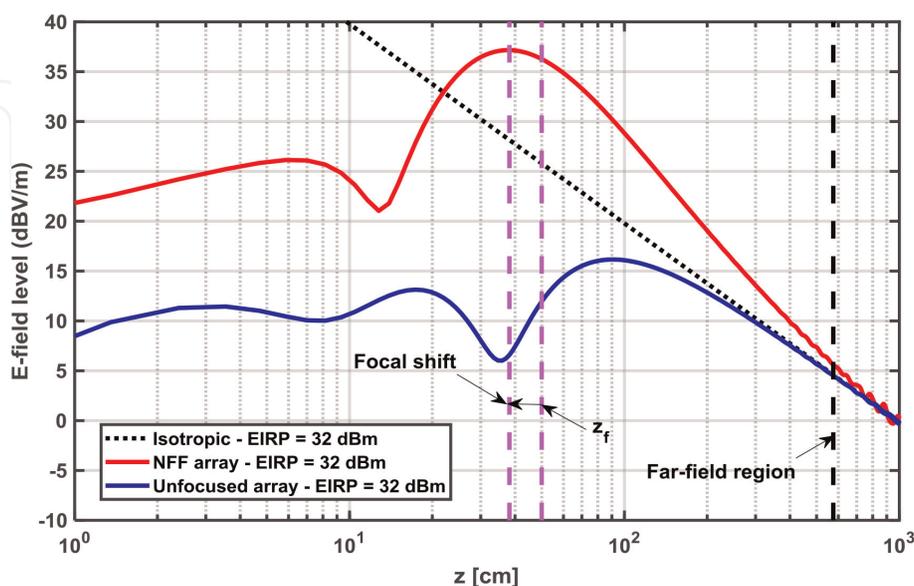
Dimensions of the array element (mm)			
$w_x$	30	$w_y$	29.5
$s_x$	1.5	$s_y$	10
$l_x$	3.0	$l_y$	9.0

**Table 1.** Array element geometrical parameters.

If the focal point is assumed at  $z_f = 4\lambda = 50$  cm, all the ports are fed with a voltage of  $A_{mn} = A_0 e^{j\phi_{mn}}$  and the obtained E-field distribution radiated by the NFF array along the  $z$ -axis is shown in **Figure 2**. In the same figure, the field amplitude radiated by a similar unfocused array ( $A_{mn} = A_0$ ) is also plotted. As a reference, the electric field amplitude radiated by an ideal isotropic antenna has been added in the same figure. All three antennas radiate with an equal effective isotropic radiated power (EIRP) level, which is here assumed of 32 dBm. It is worth noting that the far-field region of the arrays starts at around  $46\lambda = 5.75$  m, as confirmed by the fact that all three curves become parallel after around 6 m. The realized gain of the unfocused array is 20.1 dB; meanwhile, the gain of the NFF array is only 8.1 dB. Due to its lower gain, the maximum power transmitted by the NFF can be higher than the one transmitted by the unfocused array, for an assigned EIRP level. This fact, together with the near-field focusing effect, causes that the NFF antenna generates in the neighborhood of the focal region, a field level that is up to 21 dB larger than that achieved by the conventional unfocused array.

As verified in many NFF antennas whose synthesis uses the CP approach [1], the field amplitude peak does not coincide with the assigned focal point, it being located between the focal point and the antenna aperture. Indeed, for an assigned focal point, the CP is the approach that maximizes the field amplitude at that point, although it does not correspond to the field peak in the antenna near-field region. This well-known phenomenon (focal shift) is simply due to the fact that the field radiated by each array element increases as the observation point moves close to the antenna surface. For the planar array considered here, the focal shift is around 12 cm. It is apparent that it is possible to increase the focal distance needed to evaluate the phase profile in Eq. (1) until the field amplitude peak moves at the desired location.

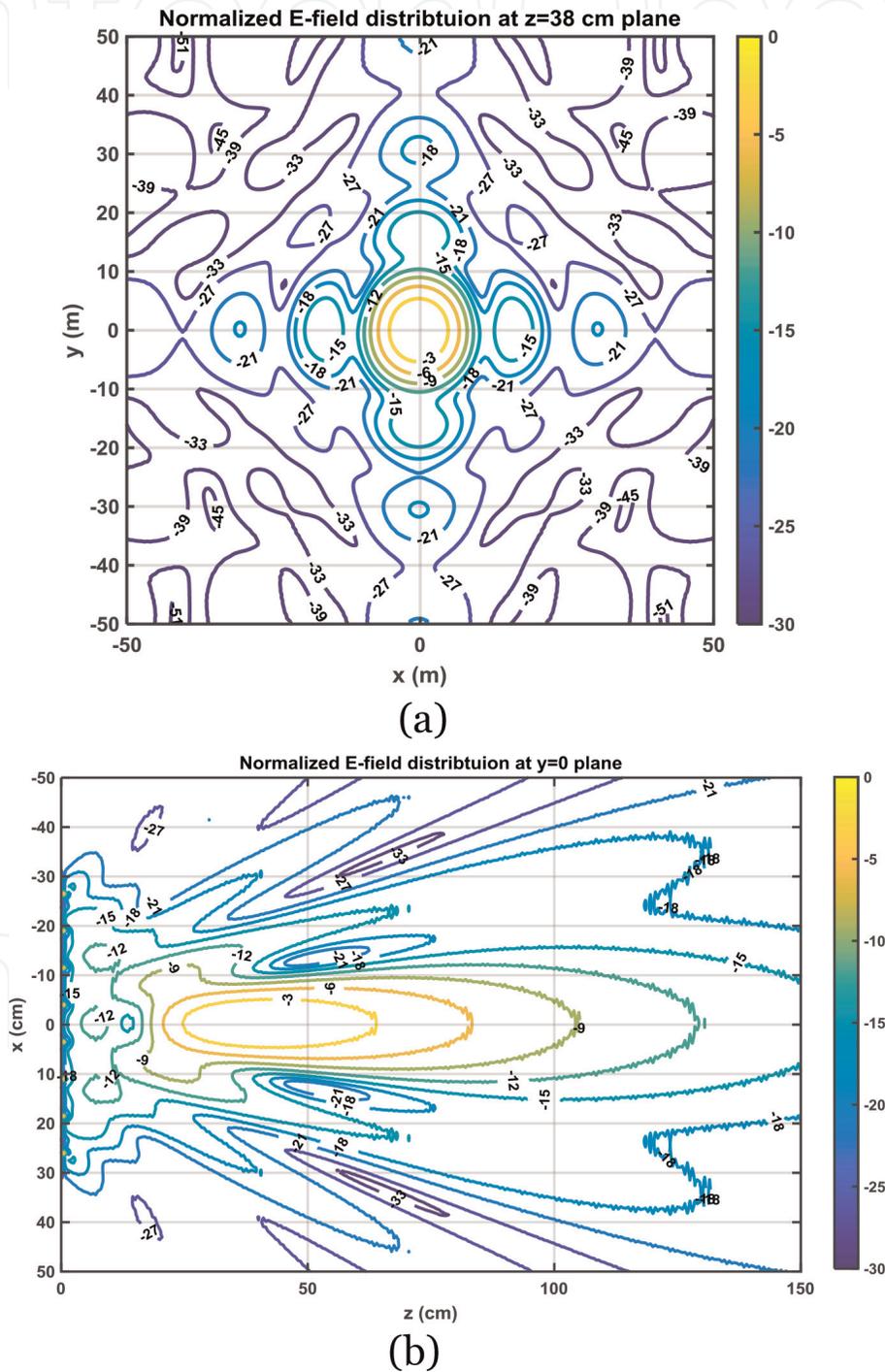
The field focusing boosts a focal spot around a field amplitude peak, whose  $-3$  dB size along three orthogonal axes is used to quantify the achieved focusing effect [1]: the  $-3$  dB width along the focal point direction (depth of focus, DoF); the  $-3$  dB width of the focal spot along two orthogonal axes perpendicular to the focal point direction (width of focus, WoF). For the NFF planar array considered here, a



**Figure 2.** E-field distribution along  $z$ -axis comparing the  $8 \times 8$  NFF array (red) with a broadside unfocused array (blue). The dot line represents the radiated field amplitude for an ideal isotropic radiator transmitting 32 dBm.

DoF of 40 cm and a WoF of 10 cm are obtained, as shown in **Figure 3** where the field distribution over different planes is given. In **Figure 3(a)**, the field distribution at a plane parallel to the array,  $z = 38$  cm, is shown and the WoF = 10 cm along  $x$ - and  $y$ -axes can be verified. In **Figure 3(b)**, the field distribution is plotted over the  $y = 0$  plane and the DoF = 40 cm is shown along the  $z$ -axis.

As shown in [1], DoF and WoF are related to the normalized geometrical parameters  $z_f/\lambda$  and  $D/\lambda$ , where  $D$  is the array size, and they can be used as the design requirements for the NFF antenna, depending on the specific short-range radio links at hand.



**Figure 3.**  $8 \times 8$  NFF array normalized field distribution over different planes: (a) XY plane with  $z = 38$  cm, (b) XZ plane with  $y = 0$ . In case of multifocus NFF antennas, the CP approach can still be applied by a simple superposition of the excitations as derived from Eq. (1) for each single focus, as long as the foci are not too close to each other.

### 3. Power transfer efficiency optimization

In the previous section, the CP approach has been introduced, where a simple closed-form expression for the phase profile allows to obtain a limited focal spot by in-phase addition of all array-element contributions at a given point located in the array NF region. One issue inherent to the CP approach is that no coupling between array elements is taken into account. Indeed, the geometrical distribution of the array elements and the focal point position determine on their own the feeding phase of each array element (see Eq. (1)).

The mutual coupling between the array elements is included if a synthesis method based on the optimization of the power transmission efficiency (PTE) between the transmitting array antenna and a test receiving antenna is adopted [5]. When the testing antenna is located into the radiative NF region or far-field region of the transmitting array, the above optimization problem naturally yields to an NFF array or a conventional unfocused array, respectively. The technique is based on using the scattering matrix  $\mathbf{S}$  of the  $(N + 1)$ -port network defined by the  $N$ -ports of the NFF transmitting array and the port of the testing antenna:

$$\begin{bmatrix} \mathbf{b}_{\text{tx}} \\ \mathbf{b}_{\text{rx}} \end{bmatrix} = \mathbf{S}_{(N+1) \times (N+1)} \begin{bmatrix} \mathbf{a}_{\text{tx}} \\ \mathbf{a}_{\text{rx}} \end{bmatrix} \quad (2)$$

where  $\mathbf{a}_{\text{tx}}$  and  $\mathbf{b}_{\text{tx}}$  are the incident and reflected waves, respectively, at the transmitting array ports (1 port for each array element), and  $\mathbf{a}_{\text{rx}}$  and  $\mathbf{b}_{\text{rx}}$  are the incident and reflected waves, respectively, at the testing/receiving antenna port. The complete scattering matrix can be obtained with full-wave electromagnetic software in order to consider a proper electromagnetic analysis of the radiation of each array element, including the mutual coupling between them. Any obstacle nearby the two antennas can be considered too.

The optimization parameter PTE is defined as the ratio between the power delivered to the load connected to the testing antenna and the power transmitted by the array:

$$\text{PTE} = \frac{|\mathbf{b}_{\text{rx}}|^2 - |\mathbf{a}_{\text{rx}}|^2}{|\mathbf{a}_{\text{tx}}|^2 - |\mathbf{b}_{\text{tx}}|^2}. \quad (3)$$

Expressing the vectors  $\mathbf{b}_{\text{tx}}$  and  $\mathbf{b}_{\text{rx}}$  as functions of  $\mathbf{S}$  and  $\mathbf{a}_{\text{tx}}$  and assuming that the whole system is well matched, a matrix equation can be derived to obtain the incident waves at each NFF array port:

$$\mathbf{A} \mathbf{a}_{\text{tx}} = \text{PTE} \mathbf{a}_{\text{tx}} \quad (4)$$

where  $\mathbf{A} = \mathbf{S}_{\text{rt}}^T \mathbf{S}_{\text{rt}}$ ,  $\mathbf{S}_{\text{rt}}$  being the scattering matrix taking into account the coupling between all receiving and transmitting ports. Eq. (4) corresponds to an eigenvalue problem for getting the optimal solution of the array excitation. Applying the obtained solution to a  $4 \times 4$  array working at 2.45 GHz, an optimal PTE close to 30% is achieved, with a maximum E-field spot located at 10 cm from the array surface (less than one wavelength) [5].

It is also possible to apply the proposed technique to a circularly polarized (C-Pol) array by considering a C-Pol single-port microstrip patch as an array element, to obtain the scattering matrix as presented in [6]. Here, a pin-fed rectangular patch with two squares cutting off two opposite corners is used to obtain a C-Pol near field. The authors have also presented an in-line-fed patch with an L-shape slot

and cutoff corners to obtain a single-port C-Pol patch. These two different elements have been used to implement two different  $4 \times 4$  NFF array prototypes. After applying the PTE technique, the corresponding excitations generate an NFF spot with an axial ratio below 1 dB.

The PTE approach can be generalized to consider multiple receiving ports when the receiving antenna is an array. In [7], the authors extend the application of the technique to optimize the PTE between two linearly polarized arrays. The mutual coupling between the two arrays is included through the above matrix  $\mathbf{A}$ . Using two arrays (for both transmitting and receiving antennas) allows to increase the transmission efficiency, reaching up to a maximum of 42% for a system of a  $6 \times 6$  transmitting antenna and a  $4 \times 4$  receiving antenna, which are 40 cm separated, at 5.8 GHz. For the same frequency band and using two equal  $8 \times 8$  arrays that are 100 cm separated, the measured PTE reaches up to 46.9%.

Another interesting feature of the PTE technique is that it is able to determine the optimal feeding values of a transmitting array even when the testing antenna radiates in presence of an unknown medium. This medium can be around the testing antenna in its nearby scenario, or the antenna can be inside the unknown medium. This application is presented in [8], where a dielectric slab is placed between the transmitting and receiving antennas. In this case, the scattering matrix  $\mathbf{S}$  is obtained from the measurements of the S-parameters for the  $N + 1$  ports, by using a vector network analyzer (VNA). Using measurements may substitute the full-wave electromagnetic analysis when the latter cannot be used since the electromagnetic parameters of the surrounding media are unknown.

In all previous examples, the optimal feeding excitation of the transmitting antenna leads to a single focal spot in the NF region. Recently, in [9], the authors have proposed this technique to get a flat-top radiation pattern, for both NF and far-field (FF) applications. In particular, for the NF application, it is necessary to define a number of testing ports and their location in order to impose the flat-top E-field distribution in the targeted zone. The flat-top distribution is obtained by imposing equal values for the power of the outgoing waves at all testing ports; under this, Eq. (3) cannot be solved as an eigenvalue problem, as yielding to an optimization problem in which both the objective function and the constraints are quadratic functions (quadratically constrained quadratic program). By imposing some simplifications under FF assumptions and using weighting coefficients to reduce the ripple presented in the NF region, the authors are able to derive linearly constrained quadratic programming:

$$\begin{aligned} & \text{maximize}_{\mathbf{x}} \mathbf{x}^H \mathbf{A} \mathbf{x} \\ & \text{subject to } \mathbf{S}_t \mathbf{x} = \mathbf{W} \mathbf{y} \end{aligned} \quad (5)$$

where the vector  $\mathbf{x}$  will provide the optimal excitations and  $\mathbf{W} \mathbf{y}$  stands for the weighting coefficients at the testing ports. The authors have applied this technique to obtain a uniform field distribution along a bookshelf for an RFID detection application. Using a five-element transmitting antenna for the RFID reader and 11 testing points along the bookshelf, an almost flat-top distribution (ripple  $< 3$  dB) is obtained at 22 cm from the reader antenna. The flat-top distribution is imposed in a 73-cm long area in the direction parallel to the transmitting antenna.

As the PTE maximization approach is based on the S matrix evaluation, it works for any value of the focal distance. When the array is in free space and the receiving antenna lies in the array radiative near-field region, it is expected that the PTE solution approaches that predicted by the CP technique.

More recently, Cicchetti et al. [10, 11] presented an interesting and flexible NF synthesis procedure based on the eigenfields of the radiation matrix of the antenna array. Once a surface close to the antenna has been assigned, the active power passing through that surface can be optimized or a specific field pattern can be synthesized. The synthesis surface can be either opened or closed and surrounding the antenna; the field synthesis can be based on both the electric and magnetic fields, or the electric field only. In [11], a set of different complex NF distributions have been considered for a numerical validation of the proposed synthesis procedure: tilted Bessel beams, orbital angular momentum (OAM) Bessel beams and Airy beams.

#### 4. Synthesis algorithms for an assigned NF distribution

The most popular approaches to the design of NFF antennas are based on assigning a required field distribution in the antenna NF region, and not only the targeted focal point positions. In some cases, such field distribution is completely assigned (it is usually referred to as a shaped field distribution or a 3D field distribution), while it is only partially specified in other cases (as for example at certain locations, such as the assigned focal points or volumes). Moreover, in some cases, a realistic field distribution is required, while some schematic values suffice for the algorithms to converge for other cases.

By specifying a target field distribution, some of the limitations of previous methods are overcome, as far as any requirement may be included for the field: multiple focal spots, arbitrary focusing volumes, a vanishing field at certain positions, a complete 3D field distribution. This fact leads to a wider range of potential applications and scenarios where NFF antennas might be useful, or even considered as a subset of NF problems. The price to pay is the complexity of the algorithms, usually associated to higher computational costs too.

The way in which specifications are given or treated differs from one method to another. However, the most significant differences between the methodologies are given by the type of algorithms used to get a solution, and not by the potential applications for each method. Most of the methods make use of different optimization schemes in order to minimize a cost function designed according to the requirements, which accounts for the distance between the targeted field distribution and that associated to a given array excitation vector. In some of the methods, additional constraints are included in the optimization in order to deal with different types of requirements, in many cases related to technological issues such as implementation or manufacturing simplifications.

Although this is a general framework, differences in the statement of the problem arise between methods solving different implementation problems or facing with different applications.

Direct optimization is not the only way to deal with NF focusing based on a given field distribution. Other techniques have been proposed to achieve the desired distribution through iterative methods using intersection approach (IA), machine learning, genetic algorithms (GA), or compressive sensing frameworks, among others. Although all of them include the minimization of the distance between target and achieved distributions, the statement of the problem is different from direct optimization, so they are studied separately in the following.

##### 4.1 Optimization algorithms based on cost function minimization

In a general optimization problem, a cost function is designed and minimized so that the resulting solution fulfills the specifications. This means that the key point is

the definition of a proper cost function that must account for the requirements. In case of NFF antennas, different sets of requirements may lead to different procedures. For example, the number of assigned focal points might vary depending on the method, or even a complete 3D field distribution might be specified. Even more, other requirements might be accounted for, as those regarding manufacturing issues, radiation properties, etc.

As a pioneer work, [12] presented a method intended to synthesize an assigned shaped NF distribution. Although it is not strictly a focusing method, it is based on ideas that became the bases for next NFF optimization-based methods. In particular, a certain NF distribution is assigned through a set of field samples, and the relation between these samples and the excitation weights to be applied to the elements of the array is represented in a matrix formulation, then solving the optimization least-squares problem given by

$$\operatorname{argmin}_{\mathbf{w}} \|E_{ref} - E_{NF}(\mathbf{w})\|_2 \quad (6)$$

where  $E_{ref}$  is the target or reference field distribution, and  $E_{NF}(\mathbf{w})$  is the achieved distribution, which is a function of the set of weights  $\mathbf{w}$  applied to the elements of the array. This is a well-known problem in the scientific literature that can be efficiently solved through a direct derivation (as it is in that paper) or using any iterative scheme. This is not a strict NFF method, but it may be considered the original approach for the following methods.

Let us consider first those methods aimed at getting a single focal spot. A direct optimization of the aperture field of an antenna to obtain a targeted focal spot is proposed in [13, 14], where the scalar case is considered. A focal point in the antenna broadside direction ( $z$ -axis) is assigned, at a given distance  $z_f$ , and the real part of the radiated field is maximized at that point. The formulation relates the near-field distribution at the plane  $\vec{r}_{focal} = z_f \hat{z}$  and the aperture field (field at  $z = 0$ ) through a plane-wave decomposition based on the Fourier transform (FT). In [13], the result of the optimization is the required aperture field, and the optimization includes a constraint to keep the field level below a bound outside the region of interest (the side lobe level, SLL). This problem can be formulated as:

$$\begin{aligned} & \operatorname{maximize}_{E_{AP}} \Re \left\{ E_{NF}(\vec{r}_{focal}) \right\} \\ & \text{subject to } |E_{NF}(\vec{r})| \leq \text{SLL}, \forall \vec{r} \in R_{SLL} \end{aligned} \quad (7)$$

where it is stated that the aperture field,  $E_{AP}$ , is the expected result; the real part of the field is maximized at the assigned focal point; and the field level is bounded by the SLL value at any other position in the region  $R_{SLL}$ . This is a convex optimization problem that may be efficiently solved, for example, using the proposed toolbox CVX [15], which is a very popular choice specifically developed to deal with this type of problems [16]. The main feature in convex problems relies on the existence of a unique solution, with improved convergence avoiding local minima. Although it is not strictly a requirement for optimization problems, it is an interesting property as far as it simplifies implementation and reduces computational costs.

In [14], the focal spot is allowed to be designed in positions out of the broadside axis, and a further cost function to be minimized is defined as the infinite norm of the field samples in each aperture zone, where  $N$  zones are defined, which enforces the field at each zone to have a constant amplitude. It is formulated as:

$$\begin{aligned}
& \text{minimize}_{E_{AP}} \sum_{n=1}^N \|E_{AP}(R_{AP}^n)\|_{\infty} \\
& \text{subject to} \\
& \Re\{E_{NF}(\vec{r}_{focal})\} \geq 1 \\
& |E_{NF}(\vec{r})| \leq SLL, \forall \vec{r} \in R_{SLL}
\end{aligned} \tag{8}$$

plus other constraints in the aperture.

The field at the focal point  $\vec{r}_{focal}$  is included as a constraint enforcing it to be greater than or equal to 1 (normalized value), while additional constraints are included to limit the field level below an assigned SLL at any other position (recall that it is enforced to be constant by the cost function), and to deal with lossy stratified media and the geometric properties of the aperture. The resulting problem is still convex and may be solved making use of CVX tool [15].

An interesting example is presented in [17], where a complete set of techniques are combined to obtain the weights to be applied to an array so that a designed focal spot is achieved with a minimum number of elements. This method may be included in the general class of *compressive sensing* (CS) techniques [18], where sparse information (the array elements in this case, resulting in a *sparse array*) is linearly related to a compressed set of data. The recovery of the sparse information from the compressed data is done through an optimization problem where the cost function is the  $l_0$  norm of the solution (i.e., the number of non-null elements). It is this recovery that is used to perform NFF synthesis in this work. The core of the method is the optimization scheme, although the distance between the target field distribution and the achieved one is considered a constraint and limited by an assigned tolerance. The minimized function is, interestingly, the  $l_0$  norm of the weights (i.e., the number of non-null weights, and hence the number of active radiating elements) so that the resulting set of weights represents an array with a minimum number of elements. It represents a good example of how to modify the optimization formulation to account for technological/implementation issues, and making use of other existing approaches such as CS. The schematic formulation of the resulting problem is:

$$\begin{aligned}
& \text{minimize}_{\mathbf{w}} \|\mathbf{w}\|_0 \\
& \text{subject to } E_{ref}(\vec{r}) - E_{NF}(\vec{r}) < e, \forall \vec{r}
\end{aligned} \tag{9}$$

where the parameter  $e$  is related to the pattern matching tolerance. The optimization itself takes advantage of the CS general framework, based on convex formulation, and hence resulting in a convex problem that might be efficiently solved. In [17], the popular toolbox CVX is used together with some probabilistic estimation methods.

Additionally, an important effort is made both in defining the target field distribution that better suits the given radiating structure, and taking into account the desired control over SLL. Also, in postprocessing, the results are checked to avoid *clusters* of elements concentrated at certain locations (a secondary effect of the proposed formulation, which established a grid of possible element locations closely spaced). To complete the formulation, mutual coupling between array elements may also be included in the formulation via an FEKO-computed impedance matrix that may be used to relate the weights for the coupling and noncoupling cases.

Once the optimization framework is developed to deal with a single focal spot problem, the straightforward extension is using it to include other requirements

such as multiple focal spots (*multifocusing*) or a combination of spots and radiation nulls. A cost function based on a template or mask for the field distribution in the NF region is used in [19] to calculate the weights that must be applied to an antenna array for multifocusing applications. The idea behind the method is relatively simple: a set of bounds for maximum and minimum field levels at each position is specified, so that higher values are required in the focal spots, and lower levels are requested at any other position. A typical cost function used for FF synthesis is adapted to the NFF case:

$$\begin{aligned} \text{minimize}_{\mathbf{w}} \sum_{p=1}^P & \left[ \left( G^2(\vec{r}_p) - |E_{NF}(\vec{r}_p)|^2 \right) \left( g^2(\vec{r}_p) - |E_{NF}(\vec{r}_p)|^2 \right) \right. \\ & \left. + \left| G^2(\vec{r}_p) - |E_{NF}(\vec{r}_p)|^2 \right| \left| g^2(\vec{r}_p) - |E_{NF}(\vec{r}_p)|^2 \right| \right] \end{aligned} \quad (10)$$

where  $G(\vec{r}_p)$  and  $g(\vec{r}_p)$  are the maximum and minimum field levels at the  $p$ -th position of the NF region defined by  $\vec{r}_p$ . This cost function penalizes field values  $E_{NF}(\vec{r}_p)$  out of the specified limits. The Levenberg-Marquardt algorithm (LMA) is used to reach the solution, although any other minimization algorithm might be used by adapting the formulation in [20]. The same formulation, also using the LMA, may be found in [21] for the case of reflectarray antennas and the design of an antenna for generating an assigned quiet radiation zone.

The use of different constraints or the optimization of different parameters present in the formulation as arguments to be calculated allow accounting for technological issues: considering both the amplitude and phase of the weights or only the phase [22], accounting for coupling effects between the elements of the array through an impedance matrix [23], or allowing for nonuniform structures where the location of the elements of the array may also be optimized [20].

Another direct optimization approach is presented in [24, 25]. Although [24] is intended for a scalar case in multifocusing applications and [25] is presented as a method for a complete optimization of the radiated field, accounting for its three components, both methods are based on the maximization of the real part of the field radiated at the focal points with additional constraints to vanish the imaginary part of the field and to control the field level at positions apart from the focal points. The choice of a real value field at the focal point does not reduce the degrees of freedom of the problem as far as it represents a simple change of the overall phase reference. For the single-spot focusing problem, the maximization problem becomes:

$$\begin{aligned} & \text{maximize}_{\mathbf{w}} \Re \left\{ E_{NF}(\vec{r}_{focal}) \right\} \\ & \text{subject to} \\ & \Im \left\{ E_{NF}(\vec{r}_{focal}) \right\} = 0 \\ & |E_{NF}(\vec{r})|^2 \leq B, \forall \vec{r} \neq \vec{r}_{focal} \end{aligned} \quad (11)$$

where  $B$  is a non-negative function that represents a field-level bound at positions outside the focal spot (i.e., a mask for the field level). Notice that this problem is quite similar to that in Eq. (7). This approach is referred to as focusing via optimal constrained power (FOCO). The main contribution of this work is its extension to multiple targets. This extension results in an NP-hard problem that is interestingly

transformed into several different convex problems, allowing a much easier implementation. For example, for two targets, the problem is formulated as:

$$\begin{aligned}
& \text{maximize}_{\mathbf{w}} \Re\{E_{NF}(\vec{r}_{focal\_1})\} \\
& \text{subject to} \\
& \Im\{E_{NF}(\vec{r}_{focal\_1})\} = 0 \\
& \Re\{E_{NF}(\vec{r}_{focal\_2})\} = \Re\{E_{NF}(\vec{r}_{focal\_1})\} \cos \phi \\
& \Im\{E_{NF}(\vec{r}_{focal\_2})\} = \Re\{E_{NF}(\vec{r}_{focal\_1})\} \sin \phi \\
& |E_{NF}(\vec{r})|^2 \leq B, \forall \vec{r} \neq \vec{r}_{focal\_1}, \vec{r}_{focal\_2}
\end{aligned} \tag{12}$$

with  $\phi \in [-\pi, \pi]$  being an auxiliary value that represents the phase shift between the fields at the two target positions. The resulting formulation corresponds to a convex problem, where the phase shift has to be also explored to get a convenient value. The price to pay is, obviously, computational complexity, as the problem has to be repeated several times, depending on the number of targets and sampling points of the auxiliary variable  $\phi$ .

In case of the methods presented in [24, 25], it is also important to point out the differences between the scalar and vector cases, as the scalar case seems to represent a simplified formulation perfectly suitable for focusing applications, while the vector case fits a complete shaping of the 3D NF distribution, accounting for the three components of the radiated field.

Both multifocusing and 3D field shaping are addressed in [26], where multitarget time reversal is proposed as the foundation of a method also involving optimization. This interesting work shows how multifocusing and 3D NF shaping are closely linked, so that the statement of the problem in both cases is equivalent, simply selecting a different number of specified positions in the near-field region. Another example is presented in [27], where the cost function is minimized by resorting to the Steepest-Descent method, with two particularities: only the phase of the excitations is calculated, and the CP approach is used to establish an initial guess of the solution in the iterative procedure, thereby improving the speed of convergence.

A step beyond is given by [28, 29], where both near- and far-field specifications are considered, simultaneously. Although synthesizing an FF pattern with NF constraints is not a novel topic, considering simultaneous synthesis for both regions is an interesting improvement from the NFF perspective, as in this case, some applications such as wireless power transfer, may benefit from constraints in the FF region, while it is actually the NF region that represents the main subject of interest. Optimization is again the basis of the proposed methodology, which begins with the definition of a cost function balancing near- and far-field requirements. The NF term is based on the same principles as in the previous methods, while the FF term is defined as in typical FF synthesis algorithms. A trade-off between both terms is controlled using a multiplier that properly balances both requirements. The general formulation proposed in this work is:

$$\text{minimize}_{\mathbf{w}} f_{NF}(\mathbf{w}) + \gamma f_{FF}(\mathbf{w}) \tag{13}$$

where  $f_{NF}(\mathbf{w})$  and  $f_{FF}(\mathbf{w})$  are functions of the weight vector  $\mathbf{w}$  accounting for NF and FF requirements, balanced by the trade-off parameter  $\gamma$ . Depending on the

application, different functions may be specified in Eq. (13). For example, for given NF and FF distributions, the problem becomes:

$$\operatorname{argmin}_{\mathbf{w}} \sum_{p=1}^P \left| E_{NF_{ref}}(\vec{r}_p) - E_{NF}(\vec{r}_p) \right|^2 + \gamma \sum_{q=1}^Q \left| E_{FF_{ref}}(\vec{r}_q) - E_{FF}(\vec{r}_q) \right|^2 \quad (14)$$

minimizing the distance between the target or specified distributions and the achieved ones in  $P$ -assigned positions of the NF region and  $Q$ -assigned directions of the FF region. Other examples are given for other problems. For example, if minimum transmitted power is required, the NF term is defined as

$$f_{NF}(\mathbf{w}) = \|\mathbf{w}\|^2 + \sum_{p=1}^P \left| E_{NF_{ref}}(\vec{r}_p) - E_{NF}(\vec{r}_p) \right|^2 \quad (15)$$

so that the applied excitations are reduced.

By using all the previously mentioned ideas, multifocusing combined with any type of FF requirement may be addressed, resulting in a set of weights to be applied to the array so that the resulting radiated field distribution fulfills all the specifications at one time.

## 4.2 Iterative algorithms using IA

Iterative algorithms represent an alternative method to obtain a field distribution  $E_{AP}$  over an antenna aperture that generates a given  $E_{ref}$  field distribution (or some given field specifications) inside a focusing area. Iterative algorithms seek to obtain an  $E_{NF}^{(n)}$  over the focusing area at the  $n$ -th iteration complying with the given specification or with a controlled error-level respect to the given reference field  $E_{ref}$ . Above approach is usually referred as IA where a set  $\mathcal{R}$  of the fields that can be generated by the antenna aperture must present an intersection with the set  $\mathcal{M}$  that includes the fields complying with the specifications or the field  $E_{ref}$  plus the tolerable errors. At each iteration, two operations known as projectors are performed, to obtain the final solution  $E_{AP}$  that radiates an  $E_{NF}$  field that belongs simultaneously to both sets  $\mathcal{R}$  and  $\mathcal{M}$ .

The algorithms are initialized establishing a starting solution, generally an initial guess of  $E_{AP}^{(0)}$  is used. Then, the  $i$ -th iteration can be resumed in four main steps: in the first step,  $E_{NF}^{(i)}$  is calculated as a forward propagation of  $E_{AP}^{(i)}$ . In general,  $E_{NF}^{(i)}$  will not belong to  $\mathcal{M}$  so different constrains are imposed on the field to adapt it to  $\mathcal{M}$  obtaining  $\tilde{E}_{NF}^{(i)}$  (known as *forward projection* of  $E_{NF}^{(i)}$  on set  $\mathcal{M}$ ) and to gradually converge to the desired solution. As a third step, the constrained  $\tilde{E}_{NF}^{(i)}$  is backward propagated to obtain a new field at the aperture  $\tilde{E}_{AP}^{(i)}$ . In this situation, additional constrains may be imposed on  $\tilde{E}_{AP}^{(i)}$  to obtain  $E_{AP}^{(i+1)}$  to adapt it to the possible fields at the aperture before proceeding with the forward propagation in the next iteration. The combination of these last three steps (backward propagation, applied constrains on  $\tilde{E}_{AP}^{(i)}$ , and forward propagation) can be seen as *backward projection* of  $\tilde{E}_{NF}^{(i)}$  on set  $\mathcal{R}$ . Once the computed  $E_{NF}^{(n)}$  belongs to  $\mathcal{M}$  with no need to apply a new *forward projection*, it is considered that it complies with the desired specifications and a solution is met.

The different versions using this technique mainly differ in the following aspects: the regions where  $E_{ref}$  is imposed, the applied constraints to  $E_{NF}$  in order to get a convergent solution, and the expressions and techniques used to relate  $E_{AP}$  and  $E_{NF}$  in the forward and backward propagation (direct integral evaluation, physical optics – PO, etc.). Some contributions also may apply constraints on  $E_{AP}$  once it is updated from the backward propagation of  $E_{NF}$  when considering additional restrictions mainly related to the antenna physics.

One common characteristic of these techniques is that all of them relate  $E_{AP}$  with  $E_{NF}$  in terms of an FT, in order to apply the fast FT (FFT) to accelerate the numerical computation.

In this context, [30] applies above iterative procedure to obtain an NFF antenna with a radial line slot array (RLSA). In this case, both the forward and backward propagations are performed in terms of plane wave spectrum (PWS) propagation and the FT is used to compute the PWS from each field distribution and vice versa. The field spectra at the two planes ( $\mathbb{E}_{NF}$  and  $\mathbb{E}_{AP}$ ) can be related using:

$$\mathbb{E}_{NF}(k_x, k_y, d) = \mathbb{E}_{AP}(k_x, k_y, 0)e^{-jk_z d} \quad (16)$$

where  $k = \sqrt{k_x^2 + k_y^2 + k_z^2}$  is the free-space propagation constant and  $d$  is the distance between the aperture and focusing planes (supposing them parallel oriented). The algorithm requires four FFTs evaluations: two of them to compute  $E_{NF}$  in the forward propagation of the field and other two to compute  $E_{AP}$  in the backward propagation.

Once  $E_{NF}$  is computed at each iteration, the mask defining  $E_{ref}$  is applied to trim the field amplitude  $|E_{NF}|$  to keep it within the mask values. Specifically, Etorre et al. [30] propose limiting the minimum field value in the focal spot area and define a maximum value for the rest of the region, to keep a low SLL. After convergence, the radial component of  $E_{AP}$  is used to synthesize an RLSA antenna compliant with the  $E_{ref}$  desired distribution.

More recently, [31] applies a similar procedure to the synthesis of a millimeter-wave reflector antenna. In this case, PO is used to calculate the  $E_{NF}$  along the axis perpendicular to the antenna aperture ( $z$ -axis). Exploiting radial symmetries together with a Taylor expansion of the field and proper mathematical transformations, the authors come to an FT-like expression to relate  $E_{AP}$  and  $E_{NF}$  so the FFT and inverse FFT can be used to speed up the synthesis algorithm.

In this case, the proposed technique just considers a phase-only synthesis (POS) so that the computed  $E_{NF}$  along the  $z$ -axis is constrained to maintain the phase variation while the amplitude is replaced by  $|E_{ref}|$ . In the *backward projection*, the  $E_{AP}$  is updated with the new phase calculated keeping the original amplitude distribution at the aperture.

The previous contributions have presented results to obtain a focal spot at a given distance along the aperture broadside direction. In [32], a 3D shaping of the NF distribution is presented, which can be seen as a generalization of the previous techniques when defining a different mask at multiple planes along  $z$ -direction. These multiple masks allow to maintain the focal spot along the transversal planes generating a 3D spot along the  $z$ -axis. The technique requires the definition of  $m$  masks along  $z$ , the computation of  $E_{m,NF}$  at all the  $z$ -planes where the masks have been defined, trimming them considering each mask and then individually perform the backward projection to obtain  $E_{m,AP}$  related to  $E_{m,NF}$ . Considering that the iterative procedure requires only one  $E_{AP}$ , the multiple  $E_{m,AP}$  obtained are averaged as:

$$E_{AP} = \frac{1}{N} \sum_{i=1}^m E_{i,AP} \quad (17)$$

An RLSA of 12 cm radius working at 30 GHz is synthesized and prototyped, obtaining a uniform spot along  $z$  between 6 and 18 cm away from the antenna.

### 4.3 IA combined with optimization techniques

In [33], the use of optimization techniques is proposed to perform one of the above-mentioned projectors inside an iterative algorithm of IA. The combination of an optimization technique inside the IA iterative algorithm can be seen as a generalization of the IA to the problem of antenna FF radiation pattern synthesis, by taking advantage of the optimization technique properties applied to given steps of the iterative procedure. In particular, in [34], the LMA is proposed as an optimization technique to perform the *backward projector* of the IA to synthesize the far-field radiation pattern of a reflectarray antenna. At each iteration of the IA, only a few iterations of LMA are performed to get the new distribution  $E_{AP}^{(i+1)}$  from the constrained far-field radiation pattern (through a local search around  $E_{AP}^{(i)}$ ) to gradually achieve the convergence of the IA algorithm.

The application of this generalized IA to an NF focusing problem has been presented in [35] to synthesize a reflectarray antenna with a quite zone in its NF region ( $5.3 \times 5.3 \lambda^2$  zone at  $20 \lambda$  from the reflector aperture). The LMA is used inside each iteration of IA algorithm as part of the *backward projector* to obtain a new field distribution  $E_{NF}^{(i+1)}$  from the constrained  $\tilde{E}_{NF}^{(i)}$ . At the  $i$ -th iteration of the IA, the LMA starts from  $E_{AP,LMA}^{(0)} = E_{AP}^{(i)}$  and performs a local search through  $l$  iterations to get  $E_{AP,LMA}^{(l)}$  that minimizes the defined cost function. The cost function is usually defined in terms of the field distribution over the NF focusing region  $E_{NF,LMA}^{(l)}$  trying to minimize its distance to the constrained  $\tilde{E}_{NF}^{(i)}$ :

$$\text{minimize} \sum_{p=1}^P \left[ \left( \left| \tilde{E}_{NF}^{(i)}(\vec{r}_p) \right|^2 - \left| E_{NF,LMA}^{(l)}(\vec{r}_p) \right|^2 \right)^2 \right] \quad (18)$$

noticing that  $E_{NF,LMA}^{(l)}$  is obtained from  $E_{AP,LMA}^{(l)}$  at the  $l$ -th iteration of the LMA applying the forward propagation used in the IA operations. After a few iterations of the LMA, the  $(i+1)$ -th iteration of the IA starts using the solution obtained with LMA, that is  $E_{AP}^{(i+1)} = E_{AP,LMA}^{(l)}$  that generates  $E_{NF}^{(i+1)} = E_{NF,LMA}^{(l)}$  to be forward projected on the set  $\mathcal{M}$ .

The results achieved with this hybrid technique clearly improves those presented in [21] where only the LMA is directly applied as optimization technique using Eq. (10) without considering the IA iterative algorithm. The quite zone achieved using IA with LMA is  $7.3 \times 7.3 \lambda^2$  fulfilling the specifications of a maximum amplitude ripple of 1.5 dB and the phase distribution at the aperture presents a smoother variation, which leads a physical realizable antenna in comparison with the results obtained by direct application of LMA where an almost random phase distribution is achieved.

The main drawback of this technique is the high computational cost required by the LMA to evaluate the gradient, as far as it performs multiple evaluations of the

NF at the focusing region from the known field at the aperture. This drawback can be overcome by applying the differential technique presented in [36] where the new  $E_{NF,LMA}$  evaluations are calculated in terms of the differential variations produced at each iteration without requiring the whole evaluation of the field in the NF region. This gradient evaluation in terms of differential contributions (DFC) is faster than using FFT for the FF problems. The application of the DFC to speed up the NF computation inside the IA-LMA has been presented in [37] where a reflectarray has been designed to generate a uniform coverage area of  $100 \times 30 \text{ cm}^2$  at a distance of 2.2 m in its NF region using an aperture of  $15 \times 15 \text{ cm}^2$  at a central frequency of 28 GHz, for 5G applications.

#### 4.4 Further techniques

Additional methods have been proposed to solve NF problems from an assigned field distribution but by using approaches that cannot be considered into previous categories.

As a first example, in the pioneer work presented in [38], a unified approach for the synthesis of an assigned NF distribution is based on the decomposition of both the amplitude and phase reference patterns in terms of the coefficients of spherical vector wave functions. This formulation leads to a set of linear equations that may be solved to calculate the complex excitations to be applied to certain array structures. This method is intended for NF synthesis problems, but it is also the background for the already cited work [12], which tries to overcome the limitations of this method by becoming also the pioneer method in optimization through the specification of a reference NF distribution.

Another approach, based on machine learning, was proposed in [39], where a trained neural network (NN) is used to relate a targeted near-field distribution to the corresponding radiating element excitations. In an NN, a mapping between input and output data is established through a previous training process where the system *learns* from previously known data (the so-called *training patterns*). The internal weights in the synapsis between the neurons are optimized so that the overall behavior of the network approximates the unknown function relating inputs and outputs. To use an NN approach in NFF antenna design, different sets of excitations are applied to determine the resulting NF distribution for a given radiating structure (through electromagnetic analysis or numerical simulations). During the training process, the NN discovers the relation between excitations and NF so that it may provide the array excitations required to achieve certain field distributions, typically with a minimum square error criterion. Once the NN is trained and ready for operation, a distribution consisting on constant real values at the focal points and zero-values at any other position is presented to the network to get the corresponding weights. It is interesting to point out that this approach allows for specifying any shaped 3D near-field distribution, taking advantage of the specification of field values at the assigned positions of the specified NF region. One of the main advantages of this approach is given by the fast computation time of the trained NN, which may be considered a real-time process. Exhaustive computation is required during the training process, but it is done only once.

That in [39] is not the first technique making use of machine learning methods. In [23], support vector machines (SVMs), and in particular, the so-called support vector regression framework is used together with the previously mentioned optimization scheme. However, it is not used to solve the NF synthesis problem but to calculate a model of the radiating system accounting for coupling effects, individual radiation patterns of the array elements, nonuniformities, nonidealities or any realistic effect that might affect the global behavior of the antenna. SVMs are able to

extract such model from known patterns consisting on effective feedings applied to the array and samples of the resulting field distribution. These patterns may be obtained through measurements or simulations, provided that they are able to account for all above effects. The obtained model is incorporated into the optimization so that it becomes much more accurate and realistic.

It is interesting to relate [39] with [40]. At first glance, the two methods appear as being completely different. However, the internal structure of an NN is an approximation of the represented function as a combination of local or global basis functions, just as it is proposed in [40] to represent the field distribution for multiple focusing points. In [40], the field close to the antenna aperture is calculated from the expansion of the field distribution in these basis functions, although through analytical formulation instead of training data.

Although it is related to optimization, the approach in [41, 42] is based in a least-squares calculation, to generate a quiet zone, i.e., a local plane-wave field generated in an assigned volume of the NF region. The oscillation of the amplitude and phase of the field distribution in such volume is minimized, as well as the field outside the quiet zone in order to reduce multipath interferences. The proposed formulation of the problem is a quite standard LS case whose solution is well known and directly applied.

In [43], an unconventional approach combining NF-FF transformation and a GA is proposed. A desired NF distribution is assigned and its corresponding FF distribution is calculated. Then, an FF synthesis method based on a GA approach is used to determine the excitations of an array of short dipoles. GAs are known to be excellent global optimizers, as they are based on the so-called *random search* principle. Although inspired by biological evolution, any GA is actually composed of different stages that perform an exhaustive search on the space of solutions with different mechanisms to avoid local minima. Their performance is usually excellent provided that a proper *fitness function* is defined (a function playing a role equivalent to the cost function in direct optimization), although the computation time is typically larger than using other techniques. In [43], the proposed method takes advantage of the maturity of FF synthesis methods based on GA, which have been proven to be successful, although a direct application to the NF distribution might have been explored.

Although most of the papers here referenced present simulation and experimental results for planar arrays, it is worth mentioning that in many cases, the proposed synthesis technique can be easily extended to conformal arrays. Indeed, the phase compensation required to focus the near-field radiated by an antenna array can also be obtained by controlling the physical distance between each array element and the assigned focal point, namely using a conformal array. In this context, Otera [44] showed that a curved slotted waveguide array is effective to get a focusing effect if the phase variation along the guiding structure is properly combined with the waveguide curve shape. More recently, a detailed analysis of an NFF leaky wave array antenna based on a curved slotted SIW has been presented in [45]. In that paper, the authors use the further degree-of-freedom represented by the array linear shape (namely, the spatial location of each slot) to improve the control of the array focus steering when the latter is achieved through frequency variation. The shape of the linear slotted SIW is approximated with an  $m$ -order polynomial, whose  $m + 1$  coefficients are synthesized through a conventional least-squares method that minimizes the discrepancy between the achieved position of the field amplitude peak and the its assigned position, for a number of frequency values of the frequency scanning range. In the field evaluation, for each hypothetical shape, the slot position along the SIW is derived by using the CP-based approach.

As already introduced through [45], another interesting aspect when designing NFF antennas is the analysis of the synthesized near-field pattern vs. frequency, especially when such a dependence is exploited on purpose to implement a low-cost focus steering. The frequency dependence of the involved traveling wave phase constant (as in series-fed arrays, leaky wave antennas, etc.) and free-space phase constant can be easily introduced in most of the previous synthesis techniques, if the higher computational costs can be tolerated. Not surprisingly, most of the papers presenting NFF antennas with frequency focus steering use a CP-based synthesis approach. In this context, a NFF planar array is proposed in [46] to implement a two-dimensional microwave imaging system, where the focal point steering is obtained by using frequency scan (from 8.5 to 11.5 GHz) and phase shift between 8 series-fed parallel linear arrays, in the two planes orthogonal to the array surface, respectively. The details of the array design process are given in [47], where the phase synthesis is based on the quadratic approximation of the phase profile calculated by the robust and valuable CP approach. The quadratic phase approximation helps to control the focus steering independently along the two principal planes, as far as the required focus displacement from the broadside direction is relatively small.

Finally, it is worth noting some recent investigations on focused antennas implementation for wireless power transfer by exploiting frequency-diverse arrays or time-modulated arrays [48].

## **5. Conclusions**

Focusing and shaping the field radiated by an antenna in its radiative near-field region may be important to improve the performance of several wireless systems based on short-range radio links at microwave and millimeter-wave frequency bands, as for instance radio links for effective wireless power (and data) transfer. In this chapter, it has been shown that the large number of available synthesis techniques can efficiently solve many real-world focusing problems, when different requirements on the antenna near field are assigned.

Future work could deal with comparing and merging the presented synthesis techniques with the well-known focusing techniques developed at the optical region, as well as with those techniques usually applied when the target is closer to the antenna, in its reactive near-field region. Interest is also devoted to potential radio link architectures where both the transmitting and receiving antennas are relatively large with respect to their separation distance, and a simultaneous synthesis of the coupled NFF antennas is required.

Finally, a larger and larger utilization of near-field focused antennas in practical scenarios is desirable, as they can improve the performance of the short-range wireless systems with a very limited increase of the antenna layout complexity and realization costs.

## **Acknowledgements**

This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under project TEC2017-86619-R (ARTEINE) and by the Gobierno del Principado de Asturias/FEDER under project GRUPIN-IDI/2018/000191.

IntechOpen

### **Author details**

Marcos R. Pino<sup>1</sup>, Rafael G. Ayestarán<sup>1</sup>, Paolo Nepa<sup>2\*</sup> and Giuliano Manara<sup>2</sup>

1 Department of Electrical, Electronics, Computers and Systems Engineering,  
University of Oviedo, Gijón, Spain

2 Department of Information Engineering, University of Pisa, Pisa, Italy

\*Address all correspondence to: [paolo.nepa@unipi.it](mailto:paolo.nepa@unipi.it)

### **IntechOpen**

---

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

## References

- [1] Nepa P, Buffi A. Near-field focused microwave antennas. *IEEE Antennas and Propagation Magazine*. 2017;**59**(3): 42-53
- [2] Nepa P, Buffi A, Michel A, Manara G. Technologies for near-field focused microwave antennas. *International Journal of Antennas and Propagation*. 2017;**2017**:17
- [3] Yu S, Liu H, Li L. Design of near-field focused metasurface for high-efficient wireless power transfer with multifocus characteristics. *IEEE Transactions on Industrial Electronics*. 2019;**66**(5): 3993-4002
- [4] Yurduseven O, Smith DR, Fromenteze T. Design of a reconfigurable metasurface antenna for dynamic near-field focusing. In: 2018 IEEE International Symposium on Antennas and Propagation. Boston, MA, USA; 2018. pp. 8-13
- [5] Shan L, Geyi W. Optimal design of focused antenna arrays. *IEEE Transactions on Antennas and Propagation*. 2014;**62**(11):5565-5571
- [6] Jiang YH, Geyi W, Yang LS, Sun HC. Circularly-polarized focused microstrip antenna arrays. *IEEE Antennas and Wireless Propagation Letters*. 2016;**15**: 52-55
- [7] Yang XD, Geyi W, Sun H. Optimum design of wireless power transmission system using microstrip patch antenna arrays. *IEEE Antennas and Wireless Propagation Letters*. 2016;**16**:1824-1827
- [8] Sun HC, Geyi W. Optimum design of wireless power transmission systems in unknown electromagnetic environments. *IEEE Access*. 2017;**5**: 20198-20206
- [9] Cai X, Geyi W. An optimization method for the synthesis of flat-top radiation patterns in the near-field and far-field regions. *IEEE Transactions on Antennas and Propagation*. 2019;**67**(2): 980-987
- [10] Cicchetti R, Faraone A, Testa O. Energy-based representation of multipoint circuits and antennas suitable for near- and far-field synthesis. *IEEE Transactions on Antennas and Propagation*. 2019;**67**(1):85-98
- [11] Cicchetti R, Faraone A, Testa O. Near field synthesis based on multi-port antenna radiation matrix Eigenfields. *IEEE Access*. 2019;**7**:62184-62197
- [12] Narasimhan MS, Philips B. Synthesis of near-field patterns of arrays. *IEEE Transactions on Antennas and Propagation*. 1987;**35**(2):212-218
- [13] Iliopoulos I, Fuchs B, Sauleau R, Pouliguen P, Potier P, Ettorre M. On the use of convex optimization for electromagnetic near-field shaping. In: 2017 11th European Conference on Antennas and Propagation (EUCAP). Paris, France; 2017. pp. 1013-1016
- [14] Iliopoulos I, Fuchs B, Sauleau R, Pouliguen P, Potier P, Ettorre M. Scalar near-field focusing in lossy media. In: 2017 International Conference on Electromagnetics in Advanced Applications (ICEAA). Verona, Italy; 2017. pp. 718-721
- [15] Grant M, Boyd S. CVX: Matlab software for disciplined convex programming, version 2.1. 2014. Available from: <http://cvxr.com/cvx>
- [16] Boyd S, Vanderberghe L. *Convex Optimization*. Cambridge, UK: Cambridge University Press; 2004
- [17] Huang ZX, Cheng YJ. Near-field pattern synthesis for sparse focusing arrays based on Bayesian compressive sensing and convex optimization. *IEEE*

- Transactions on Antennas and Propagation. 2018;**66**(10):5249-5257
- [18] Candès E, Walkin MB. An introduction to compressive sampling. *IEEE Signal Processing Magazine*. 2008; **25**(2):21-30
- [19] Álvarez J, Ayestarán RG, Las Heras F. Design of antenna arrays for near-field focusing requirements using optimization. *Electronics Letters*. 2012; **48**:1323-1325
- [20] Ayestarán RG, Álvarez J, Las Heras F. Design of non-uniform antenna arrays for improved near-field multifocusing. *Sensors*. 2019;**19**(3):645
- [21] Prado DR, Vaquero AF, Arrebola M, Pino MR, Las-Heras F. General near field synthesis of reflectarray antennas for their use as probes in CATR. *Progress In Electromagnetics Research*. 2017;**160**:9-17
- [22] Álvarez J, Ayestarán RG, León G, Herrán LF, Arboleya A, López JA, et al. Near field multifocusing on antenna arrays via non-convex optimization. *IET Microwaves, Antennas and Propagation*. 2014;**8**(10):754-764
- [23] Muñiz JA, Ayestaran RG, Laviada J, Las Heras F. Support vector regression for near-field multifocused antenna arrays considering mutual coupling. *International Journal of Numerical Modelling: Electronic Networks Devices and Fields*. 2016;**29**(2):146-156
- [24] Bellizzi GG, Iero DAM, Crocco L, Isernia T. Three-dimensional field intensity shaping: The scalar case. *IEEE Antennas and Wireless Propagation Letters*. 2018;**17**(3):360-363
- [25] Iero DAM, Crocco L, Isernia T. Constrained power focusing of vector fields: An innovative globally optimal strategy. *Journal of Electromagnetic Waves and Applications*. 2015;**29**(13): 1708-1719
- [26] Bellizzi GG, Bevaqua MT, Crocco L, Isernia T. 3-D field intensity shaping via optimized multi-target time reversal. *IEEE Transactions on Antennas and Propagation*. 2018;**66**(8): 4380-4385
- [27] Chou H-T, Hung K-L, Chou H-H. Design of periodic antenna arrays with the excitation phases synthesized for optimum near-field patterns via steepest descent method. *IEEE Transactions on Antennas and Propagation*. 2011;**59**(11):4342-4345
- [28] Ayestarán RG, León G, Pino MR, Nepa P. Wireless power transfer through simultaneous near-field focusing and far-field synthesis. *IEEE Transactions on Antennas and Propagation*. 2019;**67**:5623-5633
- [29] Ayestarán RG, Pino MR, Nepa P. Synthesis of near field focused arrays including far-field constraints. In: 2017 International Applied Computational Electromagnetics Society Symposium (ACES). Florence, Italy; 2017. pp. 1-2
- [30] Ettorre M, Casaletti M, Valerio G, Sauleau R, Le Coq L, Pavone SC, et al. On the near-field shaping and focusing capability of a radial line slot array. *IEEE Transactions on Antennas and Propagation*. 2014;**62**(4):1991-1999
- [31] Xu G, Zeng R, Chen S, Shi M, Yu C. A novel synthesis method for millimeter-wave antenna with contoured-beam at near-field region. In: 2017 47th European Microwave Conference (EuMC). 2017. pp. 264-267
- [32] Iliopoulos I, Casaletti M, Sauleau R, Pouliguen P, Potier P, Ettorre M. 3-D shaping of a focused aperture in the near field. *IEEE Transactions on Antennas and Propagation*. 2016;**64**(12):5262-5271
- [33] Bucci OM, D'Elia G, Mazzarella G, Panariello G. Antenna pattern synthesis: A new general approach. *Proceedings of the IEEE*. 1994;**82**(3):358-371

- [34] Prado DR, Arrebola M, Pino MR, Florencio R, Boix RR, Encinar JA, et al. Efficient crosspolar optimization of shaped-beam dual-polarized reflectarrays using full-wave analysis for the antenna element characterization. *IEEE Transactions on Antennas and Propagation*. 2017;**65**(2):623-635
- [35] Vaquero AF, Prado DR, Arrebola M, Pino MR, Las-Heras F. Near field synthesis of reflectarrays using intersection approach. In: 2017 11th European Conference on Antennas and Propagation (EUCAP). 2017. pp. 3644-3648
- [36] Prado DR, Vaquero AF, Arrebola M, Pino MR, Las-Heras F. Acceleration of gradient-based algorithms for array antenna synthesis with far-field or near-field constraints. *IEEE Transactions on Antennas and Propagation*. 2018; **66**(10):5239-5248
- [37] Vaquero AF, Prado DR, Arrebola M, Pino MR. Reflectarray Antennas for 5-G Indoor Coverage. In: 2019 13th European Conference on Antennas and Propagation (EUCAP). Krakow, Poland; 2019
- [38] Narasimhan MS, Varadarangan K, Christopher S. A new technique of synthesis of the near- or far-field patterns of arrays. *IEEE Transactions on Antennas and Propagation*. 1986;**34**(6):773-778
- [39] Ayestarán RG. Fast near-field multifocusing of antenna arrays including element coupling using neural networks. *IEEE Antennas and Wireless Propagation Letters*. 2018;**17**(7): 1233-1237
- [40] Chou H-T, Wang N-N, Chou H-H, Qiu J-H. An effective synthesis of planar array antennas for producing near-field contoured patterns. *IEEE Transactions on Antennas and Propagation*. 2011; **59**(9):3224-3233
- [41] Hill DA. A numerical method for near-field array synthesis. *IEEE Transactions on Electromagnetic Compatibility*. 1985;**27**(4):201-211
- [42] Hill DA, Koepke GH. A near-field array of Yagi-Uda antennas for electromagnetic-susceptibility testing. *IEEE Transactions on Electromagnetic Compatibility*. 1986;**28**(4):170-178
- [43] Clauzier S, Mikki SM, Antar YMM. Design of near-field synthesis arrays through global optimization. *IEEE Transactions on Antennas and Propagation*. 2015;**63**(1):151-165
- [44] Othera I. Focusing properties of a microwave radiator utilizing a slotted rectangular waveguide. *IEEE Transactions on Antennas and Propagation*. 1990;**38**(1):121-124
- [45] Wu YF, Cheng YJ. Proactive conformal antenna array for near-field beam focusing and steering based on curved substrate integrated waveguide. *IEEE Transactions on Antennas and Propagation*. 2019;**67**(4):2354-2363
- [46] Li P-F, Qu S-W, Yang S. Two-dimensional imaging based on near-field focused array antenna. *IEEE Antennas and Wireless Propagation Letters*. 2019;**18**(2):274-278
- [47] Li P-F, Qu S-W, Yang S, Nie Z-P. Microstrip array antenna with 2-D steerable focus in near-field region. *IEEE Transactions on Antennas and Propagation*. 2017;**65**(9):4607-4617
- [48] Mani F, Masotti D, Costanzo A. Exploitation of time modulated arrays for multisine power transmission. In: *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. Bologna; 2018. pp. 9-12