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SELF-CALIBRATION FOR FAULT OR OBSTACLE CORRECTION IN CONTINUALLY ROTATING ARRAY ANTENNAS

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Abstract—A novel self-calibration scheme for rotating array antennas is proposed. It is based on the acquisition of some near field samples using a static probe providing information about the actual behavior of the antenna. If any error, fault or obstacle modifies the desired behavior, the weights applied to the feedings of the array elements are modified so that specifications are fulfilled again. Additionally, coupling between the elements of the arrays is also accounted for. Different disciplines such as near field to far field transformation, antenna modeling, adaptive filtering or automatic learning are involved in this system. Some significant results are also presented.

1. INTRODUCTION

Continually rotating antennas are typically used in Secondary Surveillance Radar (SSR) systems that could be affected by errors, faults, obstacles, etc. that could modify the behavior of the antenna [1, 2]. In many applications, a modification of the antenna characteristics is not allowed and diagnostic tools are necessary to prevent it. In most cases, diagnostic tools [3–5] are limited to fault detection in the case of array antennas and cannot detect or correct the effect of obstacles in a near environment of the system, while existing calibration tools [6–8] are devoted to static environments and typically cannot be included in realistic environments.

In this paper, we propose a complete system able to detect any modification of the behavior of the antenna and to correct it by adapting the weights applied to the feedings of the elements

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of the array antenna. In general terms, this system acquires near field (NF) information with a single probe making use of the continuous movement of the antenna. Then, the system transforms NF into far field (FF) information, compares FF information with the specifications and, if these are not fulfilled, modifies the internal numerical model of the antenna to, eventually, recalculate the feeding values. The overall system is represented in Figure 1.

Different techniques are used to compose the whole calibration system: an accurate model of the behavior of the antenna able to account for element coupling is calculated using Support Vector Regression (SVR) [9], an automatic learning technique, to provide an accurate initial model of the system reducing the need of corrections when starting the system; NF-FF transformation [10, 11] is used to convert near field samples to the actual radiation pattern of the antenna and to compare it with the specifications; a modified version of the Least Mean Square (LMS) algorithm [17] is used to re-adapt the model of the antenna when any modification has taken place; and a simple synthesis algorithm [18] is used to calculate the new weights that must be applied to the elements of the array so that the specifications are fulfilled. Additionally, some practical aspects have been accounted for: the rotation of the antenna is necessary to provide NF samples at different aspect angles with a single probe; the number of iterations of the modified LMS algorithm used to adapt the antenna model may be reduced choosing a proper starting point, so SVR is used to provide such starting point; some obstacles can modify the model of the array so substantially that the specifications cannot be fulfilled, so oversized

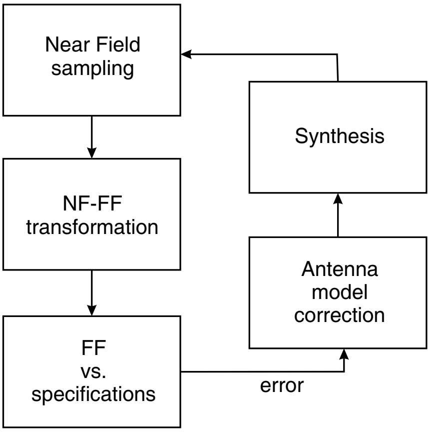

Figure 1. Self-calibration system overview.

antennas are considered.

This paper is organized as follows. In Section 2 the SVR-based modeling of the antenna is presented. In Section 3 the procedure for near field sampling and far field calculation and evaluation is described. Section 4 describes the model adaptation algorithm. Section 5 presents the final synthesis procedure. Finally, a general overview of the complete system, some significant results and our conclusions are presented.

2. SVR-MODELING OF THE ARRAY ANTENNA

Support Vector Regression is a powerful state-of-the-art technique able to obtain an accurate model of a system from the knowledge of the output provided by the system when different inputs are applied. In the case of linear systems, the obtained model is represented using a matrix [18]. The use of the Structural Risk Minimization (SRM) [9] principle guarantees improved learning properties.

SVR has been successfully used in different applications including antenna array modeling [18] and synthesis [19] and other electromagnetic problems [20]. In this case, the radiation pattern generated by an antenna array with N elements in a certain direction of the space $\{\theta, \phi\}$ is assumed to be expressed as

$$E(\theta, \phi) = \mathbf{v^T} \cdot \mathbf{g}(\theta, \phi) \tag{1}$$

where $\mathbf{v} = [v_1, v_2, \ldots, v_N]^T$ is a vector containing the N feeding values applied to the array, $\mathbf{g}(\theta, \phi) = [g_1(\theta, \phi), g_2(\theta, \phi), \ldots, g_N(\theta, \phi)]^T$; $(.)^T$ denotes the transpose, and $g_i(\theta, \phi)$ is a term that indicates the influence of the i-th radiating element in the direction $\{\theta, \phi\}$. We can also define a vector $\mathbf{e} = [E(\{\theta, \phi\}_1), E(\{\theta, \phi\}_2), \ldots, E(\{\theta, \phi\}_M)]^T$ containing the value of the radiation pattern in the M directions of interest. The SVR approach states that a matrix model $\mathbf{G}$ of the antenna can be defined as $\mathbf{G} = [\mathbf{g}(\{\theta, \phi\}_1), \mathbf{g}(\{\theta, \phi\}_2), \ldots, \mathbf{g}(\{\theta, \phi\}_M)]$ so that (1) becomes

$$\mathbf{e}^T = \mathbf{v}^T \cdot \mathbf{G} \tag{2}$$

The matrix model $\mathbf{G}$ represents the global behavior of the antenna relating the voltages applied to its ports and the samples of the resulting radiation pattern. When the behavior of the radiating structure is modified by the presence of passive elements in a near environment or a fault in the structure, this matrix should also be modified to accurately represent the behavior of the antenna.

As it was shown in [18], the matrix model can be calculated taking into account all the real properties of the structure and its environment. Let us consider that P voltage sets and their corresponding radiation patterns $\{\mathbf{v}_n, E_n(\{\theta,\phi\})\}$, $n = 1,\ldots,P$, are available for training purposes (for example, measured in an anechoic chamber). If we focus on a certain direction of the space $\{\theta,\phi\}_i$, the SRM principle establishes that $\mathbf{g}(\{\theta,\phi\}_i)$ can be obtained through the minimization of the following cost function [9]:

$$J(\mathbf{g}(\{\theta,\phi\}_i))=\frac{1}{2}||\mathbf{g}(\{\theta,\phi\}_i)||^2+C\sum_{n=1}^{P}|E_n(\{\theta,\phi\}_i)-\mathbf{v}_n^T\cdot\mathbf{g}(\{\theta,\phi\}_i)|_\varepsilon \quad (3)$$

where

$$|\gamma|_\varepsilon = \max(0,|\gamma|-\varepsilon) \quad (4)$$

is the so-called Vapnik's ε-insensitive loss function, and $C > 0$ is a penalty value which establishes a tradeoff between the model complexity and the cost of deviations larger than ε.

The P training patterns are used for the regression introducing a set of positive slack variables ζ and $\tilde{\zeta}$ in order to deal with the fact that the function considered for the regression could not be feasible. Then, the minimization of (3) can be rewritten as the constrained optimization problem of minimizing

$$J(\mathbf{g}(\{\theta,\phi\}_i),\zeta,\tilde{\zeta}) = \frac{1}{2}||\mathbf{g}(\{\theta,\phi\}_i)||^2 + C\sum_{n=1}^{P}\left(\zeta_n+\tilde{\zeta}_n\right) \quad (5)$$

subject to

$$\begin{aligned}\mathbf{v}_n^T\cdot\mathbf{g}(\{\theta,\phi\}_i) - E_n(\{\theta,\phi\}_i) &\leq \varepsilon+\zeta_n\\ E_n(\{\theta,\phi\}_i) - \mathbf{v}_n^T\cdot\mathbf{g}(\{\theta,\phi\}_i) &\leq \varepsilon+\tilde{\zeta}_n\\ \zeta_n,\tilde{\zeta}_n &\geq 0\end{aligned}$$

for all $n = 1,\ldots,P$. This problem can be solved through Lagrange's method and the definition of a Lagrangian function [9]. This method establishes that the first derivative of this Lagrangian function with respect to all the variables of interest mush vanish, what leads to an equivalent dual problem given by the maximization of

$$\begin{aligned}W(\alpha,\tilde{\alpha}) = &-\sum_{n=1}^{P}\varepsilon(\tilde{\alpha}_n+\alpha_n)+\sum_{n=1}^{P}E_n(\{\theta,\phi\}_i)(\tilde{\alpha}_n+\alpha_n)\\ &-\frac{1}{2}\sum_{n,m=1}^{P}(\tilde{\alpha}_n+\alpha_n)(\tilde{\alpha}_m+\alpha_m)\mathbf{v}_n^T\cdot\mathbf{v}_m \quad (6)\end{aligned}$$

subject to $0 \leq \tilde{\alpha}_n,\alpha_n \leq C$ for all $n = 1,\ldots,P$. This is a convex quadratic programming (QP) problem and, therefore, has a globally optimal solution that can be efficiently found. Then, the optimal regressor can be calculated, according to the conditions obtained through the derivatives of the Lagrangian function, as:

$$\mathbf{g}(\{\theta, \phi\}_i) = \sum_{n=1}^{P} (\tilde{\alpha}_n - \alpha_n)\mathbf{v}_n \tag{7}$$

According to support vector theory, only the input patterns (feeding sets) whose corresponding output lays out of the ε-tube defined by the Vapnik's loss function have Lagrange multipliers greater than zero and, consequently, appear in the expansion (7). These input patterns (typically less than P) are called *support vectors*.

Repeating this regression for all the M directions of the space, the columns of the matrix model $\mathbf{G}$ are obtained.

For the proposed calibration system, the SVR scheme can be used to obtain an initial model of the antenna free of obstacles or faults, so that it can be included in the system. As it will be mentioned later, an accurate initial point for the model adaptation algorithm may reduce the number of iterations required to compensate an obstacle or a fault when it arises.

3. NEAR FIELD SAMPLING AND FAR FIELD CALCULATION

One of the key points to implement a self-calibration procedure for an array antenna is to determine what the antenna is actually radiating and to compare it with the specified radiation pattern. It is straightforward that a direct far field-sampling of the radiation pattern cannot be implemented in any real system, so only near field-based solutions can be considered. In the particular case of continually rotating antennas, a near field probe can be placed at a predefined distance of the center of the antenna and can be used to sample the field at its position. The movement of the antenna will lead to a characterization of the near field distribution in a circular domain. It is important to notice that static antennas would require a number of NF probes equal to the number of NF samples required to characterize the actual behavior of the antenna, what typically is not possible in practical applications. However, in the case of rotating antennas a single probe is enough to obtain samples at different aspect angles, what represents an important advantage and enables easier implementation of the system. Figure 2 illustrates the advantage of rotating antennas requiring only one probe to sample M aspect angles.

Once the near field distribution has been observed, it can be transformed into the corresponding far field distribution in order to

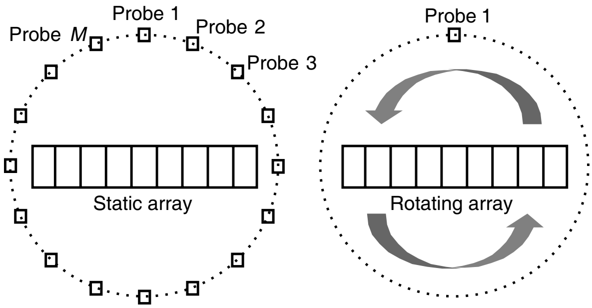

Figure 2. Static antenna and rotating antenna NF probe geometry.

compare it with the far field specifications. There are many different techniques to perform this NF-FF transformation, including spherical wave expansion [12, 13], equivalent current reconstruction [10, 16] or even neural networks [11]. In this paper we propose the use of the matrix model indicated in (2). Such model can be used to represent the behavior of the antenna in FF or in NF by simply using different training sets for the regression. Let us assume that we have obtained both a FF and a NF model for the antenna, $\mathbf{G}_{FF}$ and $\mathbf{G}_{NF}$ respectively, using SVR for the initial point of the system or through adaptation during operation. The field distributions corresponding to a set of feeding values are

$$\mathbf{e}_{FF}^T = \mathbf{v}^T \cdot \mathbf{G}_{FF} \tag{8}$$

$$\mathbf{e}_{NF}^T = \mathbf{v}^T \cdot \mathbf{G}_{NF} \tag{9}$$

The far field distribution can be obtained from the near field values as

$$\mathbf{e}_{FF}^T = \mathbf{e}_{NF}^T \cdot \mathbf{G}_{NF}^{+} \cdot \mathbf{G}_{FF} \tag{10}$$

where $(.)^+$ denotes the Moore-Penrose pseudoinverse matrix. The use of both matrix models allows taking into account all the real properties of the antenna. However, any other accurate NF-FF transformation technique ([14, 15]) could be used.

4. MODEL ADAPTATION ALGORITHM

Once the actual radiation pattern is calculated, it can be compared with the specified one obtaining the error due to the presence of an obstacle, a fault in the structure, or even a miscalculation of the feeding values in the design of the antenna. The error can be easily calculated as

$$\underline{\epsilon} = \mathbf{e}_0 - \mathbf{e}_{FF} \tag{11}$$

where $\mathbf{e}_0 = [E_0(\{\theta,\phi\}_1), E_0(\{\theta,\phi\}_2), \ldots, E_0(\{\theta,\phi\}_M)]^T$ is a vector containing samples of the specified radiation pattern, and $\underline{\epsilon} = [\epsilon(\{\theta,\phi\}_1), \epsilon(\{\theta,\phi\}_2), \ldots, \epsilon(\{\theta,\phi\}_M)]^T = [\epsilon_1, \epsilon_2, \ldots, \epsilon_M]^T$ is a column vector containing the error at each aspect angle.

The calculated error can be used to modify the matrix model of the antenna so that it actually corresponds to the behavior of the antenna under the current conditions. A modified version of the Least Mean Square (LMS) [17] iterative algorithm is proposed in this paper. It has been adapted to deal with the fact that a complete matrix must be adapted, and not only a vector as in the case of the standard LMS. This Matrix-LMS (MLMS) algorithm can be formulated as

$$\mathbf{G}_{i+1} = \mathbf{G}_i + \mu \cdot \mathbf{v} \cdot \underline{\epsilon} \tag{12}$$

where i indicates the number of iteration (typically each iteration is associated with each sampling instant), $\mu > 0$ is a parameter to control the convergence of the algorithm, and $\mathbf{v}$ is the vector of feeding values that currently are being applied. The error $\underline{\epsilon}$ must be updated at each iteration as

$$\underline{\epsilon} = \mathbf{e}_0 - \mathbf{G}_i \cdot \mathbf{v} \tag{13}$$

For the sake of simplicity, typically only one iteration of the algorithm is performed at each NF-sampling instant. It has been found that the overall calibration system guarantees an adequate convergence towards the appropriated model.

It is important to notice that the actual far field distribution $\mathbf{e}_{FF}$ has been calculated making use of Equation (10), where the NF model of the antenna is considered. This fact implies that it is necessary to adapt in parallel both the FF and the NF model of the antenna. To adapt the NF model, Equation (11) must be considered again for NF values as

$$\underline{\epsilon}_{NF} = \mathbf{e}_{0NF} - \mathbf{e}_{NF} \tag{14}$$

where $\mathbf{e}_{0NF}$ is the NF distribution corresponding to the specified radiation pattern and must be calculated when designing the system, and $\mathbf{e}_{NF}$ was defined in Equation (9). The adaptation algorithm for the NF model can be expressed as:

$$\mathbf{G}_{NF,i+1} = \mathbf{G}_{NF,i} + \mu \cdot \mathbf{v} \cdot \underline{\epsilon}_{NF} \tag{15}$$

5. SYNTHESIS OF CORRECTED FEEDING VALUES

The final goal of the calibration system is to obtain a set of feeding values so that when they are applied to the antenna under the current conditions (obstacles, faults, etc.) the corresponding radiation pattern fulfills the specifications. This problem is referred to as *synthesis* [22].

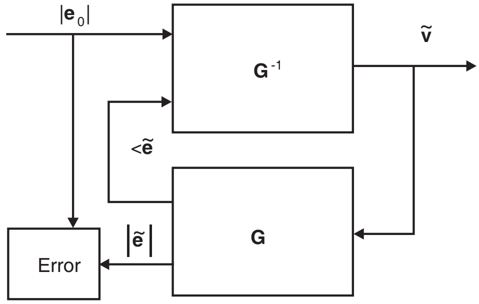

Figure 3. Iterative procedure for amplitude-only synthesis.

In our particular problem, the feeding values that are applied to the antenna before the adaptation could be no longer valid as they correspond to a non-valid model of the antenna that is being modified. Then, a simple synthesis problem must be solved to recalculate the feeding values that must be applied to the *modified* antenna.

Provided that a new adapted model of the radiating system $\mathbf{G}$ has just been calculated, it can be used to calculate the new feeding values as

$$\mathbf{v}^T = \mathbf{e}_0^T \cdot \mathbf{G}^+ \tag{16}$$

where $\mathbf{e}_0$ is the specified radiation pattern.

In Equation (16) it has been assumed that both amplitude and phase of the radiation pattern have been specified. If this is not true, other synthesis algorithms are available in the literature [18, 21, 23–30] and can be used, always paying attention to the use of the corrected model of the antenna. Provided that the matrix model $\mathbf{G}$ of the antenna has been properly calculated, when the phase distribution is not specified it can be initially set to zero and used to calculate a first approximation to the feeding values. These feeding values can also be used to calculate their corresponding radiated field distribution whose amplitude is compared with the specified pattern. If a certain error criterion is not fulfilled, the phase of the calculated distribution is used together with the specified amplitude to calculate a new approximation to the feeding values. This iterative process is represented in Figure 3.

6. OVERALL SYSTEM

All the different procedures presented in previous sections compose a global calibration system that is represented in Figure 1.

In the first step, the near field probe acquires samples of the field distribution that the antenna is actually radiating. The rotation of the antenna allows using only one probe to achieve a complete near field information. Then, this NF information is transformed into a far field radiation pattern that is compared with the specifications. The obtained error is used to adapt the antenna matrix-model to the actual behavior of the radiating structure. Finally, the corrected model is used to calculate the feeding values that must be applied to the elements of the array so that the system radiates according to the specifications.

When any obstacle appears in a near environment of the antenna or any fault occurs, the model of the behavior of the antenna is no longer valid, and an important error is obtained when comparing the far field distribution, leading to a proportional correction of the model. If there is no obstacle neither fault the error is null and the adaptation of the model is not carried out.

The use of a SVR-based model of the antenna provides the *starting point* of the system. If the initial model were not so accurate, a certain number of iterations would be required to correct it and a certain delay in reaching a stable operation point would be introduced. Additionally, the use of SVR techniques allows taking into account the presence of the near field probe in the environment of the antenna.

It is also interesting to recall the fact that the MLMS algorithm for matrix correction can be programmed to work with any number of iterations. In the examples presented in this paper, only one iteration has been considered. It has been found that the iterative nature of the overall calibration system is enough to get a good correction allowing an implementation with lower computational cost.

One important fact to take into consideration is that the subspace of possible radiation patterns given a certain radiating structure is limited. Although it has been considered that the array antenna has been designed to obtain the specified radiation pattern, once a fault has taken place or an obstacle has appeared in a near environment the resulting *complex radiating structure* could not be able to radiate according to the specifications with any set of feeding values. The proposed system can provide the best approximation to the specified radiation pattern in terms of minimum square error due to the use of the error (11) in the MLMS algorithm and the pseudoinversion (16), but it does not guarantee a perfect fit with the specified pattern. For this reason, it is recommended to oversize the number of elements of the array. A higher number of elements results in an increased subspace of possible radiation patterns and hence in an increased capability of fulfilling specifications under fault conditions.

In order to measure the accuracy of the synthesized radiation pattern, the relative square error is used in this work. The relative square error in the radiation pattern may be defined as follows:

$$\epsilon = \frac{||\underline{\epsilon}||^2}{||\mathbf{e}_0||^2} \tag{17}$$

where $\underline{\epsilon}$ and $\mathbf{e}_0$ have been defined in Equation (11), and $||.||$ represents the l-2 norm.

The relative square error is a quantitative measurement of the error and, therefore, it may not provide an optimal solution from a practical point of view. Nonetheless, it is useful to evaluate the performance of the proposed system in terms of the relative square error as it is the error criterion used both in the MLMS algorithm and in the synthesis scheme. As it has been succinctly mentioned before, a perfect fit with the specifications cannot be expected as the presence of an obstacle or a fault might modify dramatically the capability of pattern generation of the radiating system, and the specified radiation pattern might not be feasible in general. However, the use of this self-calibration guarantees the best possible fit in terms of relative square error as defined in (17) under obstacle or fault conditions.

7. RESULTS

In order to evaluate the performance of the proposed system, some simulated experiments have been performed. A radiating structure consisting of 8 collinear half-wavelength dipoles with centers separated 0.7λ and a frequency of 10 GHz have been considered. The parameters for the calculation of the model of the antenna using SVR are $C = 1$ and $\varepsilon = 0$, and 100 training patterns have been used.

In experiment #1, an obstacle consisting on a metallic grid has been placed in front of the antenna during its regular operation. The

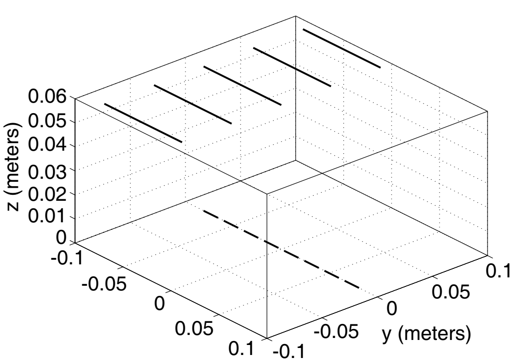

Figure 4. Geometry of the antenna and obstacle, example #1.

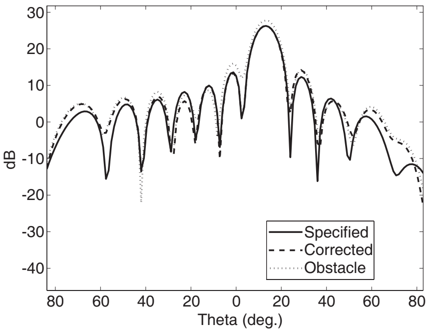

Figure 5. Specified, distorted and corrected radiation patterns, example #1, part 1.

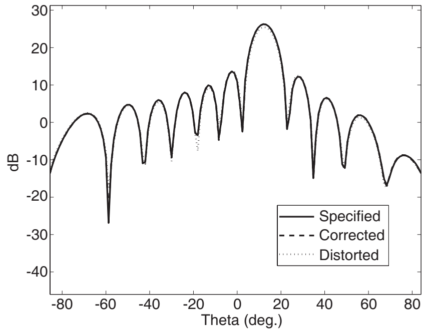

Figure 6. Specified, distorted and corrected radiation patterns, example #1, part 2.

obstacle consists of five parallel metallic bars, also parallel to the array, placed in front of the antenna and covering exactly one half of it. Each bar has a length of 2.95λ. The bars are separated 1.5λ and the grid is separated 2λ from the array. The geometry of the obstacle and the array is plotted in Figure 4.

Figure 5 shows the specified radiation pattern together with the pattern obtained when the obstacle is inserted and the corrected pattern provided by the calibration system. A parameter $\mu = 0.001$ has been considered in the MLMS algorithm, and 200 iterations of the calibration system have been performed. A set of 30 NF samples (directions of the space) placed at 5λ from the center of the array are considered. It can be noticed the improvement of the accuracy obtained by means of the correction which is specially clear for aspect angles near the broadside. The resulting relative error in the radiation pattern when the obstacle is inserted is 5.5%, meanwhile the calibration system reduces this error to 0.66%.

Once the adaptation has taken place, we have simulated a modification in the position of the obstacle. The obstacle is moved away from the radiating system to a new distance of 5λ, so the model of the antenna and the feeding values are no longer valid and a new adaptation takes place. After 40 iterations of the system a new radiation pattern is obtained and represented in Figure 6 together with the specified pattern and the new distorted pattern (obtained when the obstacle is moved and before adaptation takes place).

The modification of the position of the obstacle increases the relative square error to 1.5%, while the adaptation algorithm reduces it to 0.00001%. It is interesting to notice that the new position of the

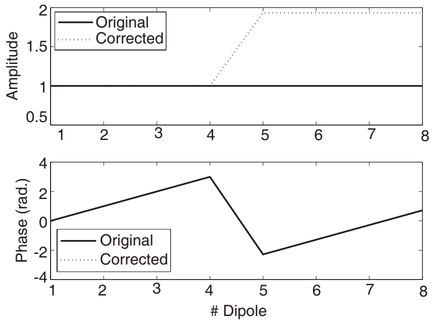

Figure 7. Feeding values, example #2.

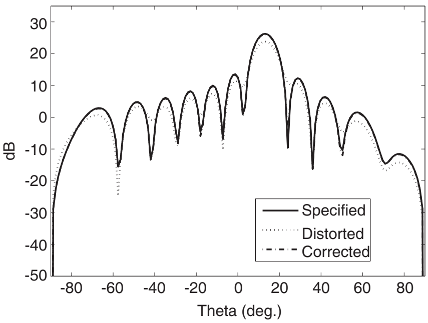

Figure 8. Specified, distorted and corrected radiation patterns, example #2.

obstacle allows a better fit with the specified radiation pattern because the obstacle has been moved towards the far field, reducing its influence in the radiating structure. The resulting complex structure is closer to the case free of obstacles for which the specified radiation pattern was originally defined.

In experiment #2, a fault in the elements of the array has been simulated by considering that half of the elements of the array are affected by a feeding problem and only receive half of the current. A uniform feeding has been considered, so in the resulting faulty system half of the dipoles receive a feeding value of 1 while the others receive a feeding value of 0.5. The resulting relative error in the radiation patterns when this problem arises is 12.7%. After 300 iterations of the calibration system the error is reduced to 0.006%. Figure 7 shows the original and corrected feeding distribution for the elements of the array. It can be observed how the feeding values to be applied are modified to provide a real uniform current distribution in the elements. Figure 8 shows the specified, distorted and corrected radiation patterns. Once more, the calibration system considerably reduces the relative square error in the radiation pattern due to faults in the array.

8. CONCLUSIONS

A novel and efficient self-calibration system for continually rotating array antennas has been presented. It is based on near field sensing, the adaptation of the model of the antenna once an obstacle is present in the near environment or a fault in the elements of the array arises, and the calculation of the required set of feeding values to be applied to the elements of the array. The near field information can be obtained with a single probe making use of the rotation of the antenna, what allows sampling at different aspect angles. The NF information is transformed into FF information so that it can be used to compare the actual behavior of the antenna and the specified one. The error is used to correct both the FF model and the NF model of the antenna and hence to recalculate the feeding values that must be applied to each element of the array.

Although in many practical antenna applications quantitative evaluation might lead to suboptimal solutions, a relative square error criterion has been used to evaluate the performance of the proposed system. Such relative quare error has been found appropriate as it is used both in the Matrix-LMS algorithm (MLMS) proposed for model adaptation and the pseudoinverse approach used in the synthesis of new feeding values. The use of these two techniques allows guaranteeing that the system converges towards the best possible solution in terms of relative square error, what represents an improvement of the behavior of the radiating system when an obstacle appears or a fault arises, as it has been shown in some significant results. However, the influence of obstacles or faults might modify the capability of pattern generation of the radiating system so that the specified radiation pattern might not be feasible. For this reason, when the system is being designed it is recommended to overdimension the number of elements in the array resulting in an increased capability of radiation pattern generation.

Some of the algorithms that have been used in the paper can be substituted for equivalent state-of-the-art techniques. For example, more sophisticated NF to FF transformation schemes can be used, allowing phaseless NF sensing and hence a simpler hardware implementation of the system. Another interesting topic subject of further work is the selection of the initial model of the radiating system. Although it has been calculated making use of an innovative technique (SVR), more adequate models could be found by including in the model the presence of the NF probe. Finally, the synthesis method can be substituted by any other technique existing in the literature, specially in applications where the specifications are not given as a target radiation pattern but as a set of parameters to be accounted for. In such cases, a new application-dependent error criterion must be specified for the synthesis step and for the evaluation of the performance of the system. All these changes might be carried out without affecting the overall concept of self-calibration, and will be subject of future work by the authors.

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