Antenna diagnostics using near-field measurements with coupling reduction

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Abstract

Determination of antenna errors, either in the design or the manufacturing process, is required when the antenna measurements do not correspond with the simulated or ideal results. The easiest way to perform this error detection consists in obtaining the equivalent currents on a surface close to the antenna. A major problem arises due to the fact that these currents cannot be directly measured. Consequently, they must be computed from radiated field measurements. This paper explains the different ways this computation may be performed from spherical near-field measurements. It also shows the results that are obtained when real measurements, taken in the available facility at the Institute of telecommunications and multimedia applications, are used. Furthermore, in order to overcome the coupling on inputs of network analyzers, a interference reduction procedure is proposed and applied to a real case.

Keywords: Antenna diagnostics, near-field measurements, equivalent currents reconstruction, inverse problem.

1. Introduction

The development process of an antenna has several steps. First, the technical characteristics that are required for the application in which the antenna will be used are clearly defined. Then, considering these parameters, the antenna is designed and optimized to be later manufactured. Finally the antenna is measured in order to verify whether the resulting antenna fulfills the desired specifications. If they are not met, the error source must be located, either in the design or in the manufacture, and corrected. This last part, known as antenna diagnostics, is of main interest since it may be the only way the error can be located and, if possible, eliminated to achieve the desired result.

The most important source of information that is required for the antenna diagnostics is the equivalent currents on a surface close to the antenna. Unfortunately, these currents are hard to be directly measured [1], hence, they must be computed from radiated field measurements [2]. Several techniques have been proposed with this aim, which can be divided into two main groups: numerical techniques (e.g. the method of moments (MoM) [3]-[4], the finite element method (FEM) [5] or the finite difference time domain method (FDTD) [6]) and modal expansion techniques [7]-[8]. Several studies have been done to compare both types of techniques [9], and it may be concluded that each technique has its own advantages and drawbacks. However, in practice, because of their simplicity and accuracy, modal expansion techniques have become widely used for any kind of measurement system and, particularly for the spherical coordinate system.

Modal expansion techniques are based on the computation of wave coefficients from field measurements. By applying these coefficients, the field can be computed on the desired points, except in the inner points of the minimum canonical surface of the coordinate system that encloses the antenna, in which coefficients have been determined (which is normally the same as the one of the measurement system). This limitation is an important drawback when a spherical measurement system is employed, because the field cannot be obtained on a plane surface close to the antenna, but just outside the minimum sphere enclosing the antenna. Therefore, equivalent currents, which are determined from field using the equivalent principle [10], cannot be known.

A proper definition of the problem requires to determine the field measurement scan geometry and the surface where it is desired to reconstruct the currents. Specifically for this paper, a spherical measurement system is employed and the equivalent currents are desired on a flat surface close

The so-called microwave holographic technique is applied to obtain the field on the desired surface by means of the plane wave spectrum.

to the antenna. In addition, for the sake of generality, near-field measurements are considered.

Under this scenario, the easiest way [11] to achieve the currents reconstruction consists of computing the field in the far-field (FF) region from the near-field (NF) measurements [12]. Later, the so-called microwave holographic technique [13]-[14], is applied to obtain the field on the desired surface by means of the plane wave spectrum [15]. The main drawback of this technique is the loss of information in the near-field to far-field transformation. To overcome this problem, a method [8] has been proposed for directly computing the plane wave spectrum from the near-field measurements. Since far field is not used as an intermediate step, no loss of information is produced and, hence, better results are obtained.

In this paper, both algorithms are reviewed and some keys for the election of one of them are detailed. Moreover, some results for the selected technique are shown.

Finally, the effect of the coupling between the inputs in a network analyzer is studied. This effect, which is especially present at high frequencies and when measuring low gain antennas, causes great errors in the reconstructed equivalent currents. This paper proposes some procedures to reduce this effect.

The paper is organized as follows. First, the spherical wave expansion and the way the spherical coefficients are computed are briefly reviewed. Then, modal techniques for the currents reconstruction are explained and some results are shown. Finally, the effect of coupling is discussed and several ways to reduce it are proposed.

2. Spherical wave expansion (SWE)

The electric field radiated by an antenna can be expressed in spherical coordinates *(r,Θ,ϕ)* by means of the spherical wave expansion (SWE) as follows:

$$\vec{E}(r,\theta,\phi) = \frac{k}{\sqrt{\eta}} \sum_{smn} v T_{smn} \vec{F}^{(3)}_{smn}(r,\theta,\phi), \qquad for\ r > r_0$$

[1]

where k is the wavenumber, η is the admittance of the of the medium, v is the amplitude of the incoming wave to the local port of the antenna under test, T_{smn} are the wave coefficients characterizing the antenna in transmission, the so-called transmitting coefficients, and $\vec{F}^{(3)}_{smn}(r,\theta,\phi)$ are the spherical basis functions (whose complete expressions can be found in [17]).

In (1) all parts are known except of the transmitting coefficients, which must be determined by means of the transmission formula [17]. This probe-corrected expression relates the transmitting coefficients and the AUT spherical near-field measurement in the following way:

$$w(A,\chi,\theta,\phi) = \frac{v}{2} \sum_{\substack{smn \\ \mu}} T_{smn} e^{jm\phi} d^{n}_{\mu m}(\theta) e^{j\mu\chi} P_{s\mu n}(kA)$$

[2]

where $w(A,\chi,\theta,\phi)$ is the signal received by the probe at a distance A , with two different polarizations (x = 0 and x = $\pi/2$) and on the spherical grid (θ,ϕ); $d^{n}_{\mu m}(\theta)$; are the rotation coefficients [17]; and $P_{s\mu n}(kA)$ are the so-called probe response constants [17], which are responsible of the probe correction. The way expression (2) is solved is beyond the scope of this paper. A detailed explanation on this issue can be found in [17] for first-order probe correction, i.e. $\mu = \pm 1$, (the one applied in this paper).

Hence, in order to compute the radiated field by an antenna at any point, first a spherical field measurement is taken, then the transmitting coefficients are computed with (2) and, finally, the radiated field is obtained on the desired points with (1) (except of the inner points to the minimum sphere enclosing the antenna, where (1) is not valid). Although the measurement may be taken in either the near-field or the far-field region, in this paper, for the sake of generality, near-field measurements are considered and,

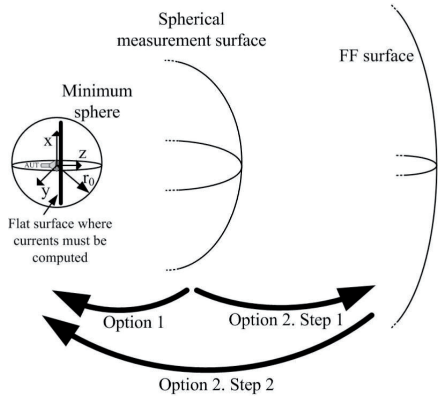

Figure 1. *Inverse problem diagram and solution by means of two different options: NF to currents, or NF to FF to currents*

hence, a near-field to far-field transformation is performed as depicted above when the radiated field in the far-field region is required.

3. Antenna diagnostics: inverse problem

The diagnostics of flat antennas requires the knowledge of the equivalent currents on a plane surface close to them. These currents, from the equivalence principle [10], are computed using the tangential field to the desired surface. Hence, measured field must be backpropagated from the measurement points to the surface of interest, what is normally known as inverse problem. Depending on the measurement surface and on the surface where currents must be computed, the solution to this problem is different. Fig 1 depicts the situation considered in this paper where, as can be observed, the measurement surface is a sphere and surface where currents are desired is a plane close to the AUT.

Two problems arise from the set-up of Fig 1. The first one is due to the fact that, since spherical measurements are considered and the spherical wave expansion explained above is used, the radiated field can just be computed outside the minimum sphere, of radius r_0, enclosing the AUT. Therefore, as depicted in Fig 1, the closest points to the antenna where the radiated field (and, hence, the equivalent currents) can be computed are far from the AUT, what leads to not obtaining useful currents to carry out the antenna diagnostic.

The second problem is consequence of the first one. Since the spherical wave expansion does not allow radiated field on close points to the AUT to be computed, a coordinate system change is required. The aim of this change is to express the field in a coordinate system in which the minimum canonical surface enclosing the antenna allows the radiated field on a close surface to the AUT to be computed. In this paper the coordinate system that has been chosen is the Cartesian coordinate system. Thus, the radiated field can be obtained on a flat surface close to the antenna.

The wave expansion in a Cartesian coordinate system is known as plane wave expansion (PWE). It is the solution of the wave equation in a source-free region in this coordinate system [10], and can be expressed by means of a double integral of a spectral signal over the transformed domain (k_x, k_y) as follows:

$$\vec{E}(x,y,z)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\vec{A}_E(k_x,k_y)e^{jk_xx}e^{jk_yy}e^{jk_zz}dk_xdk_y \quad [3]$$

where $\vec{A}_E(k_x,k_y)$ is the plane wave spectrum and, as can be observed, the transformation is just an inverse Fourier transform provided that it has been assumed the time convention $e^{-j\omega t}$ for field variation with regard to time.

Therefore, from the set-up depicted in Fig 1, where the plane of interest is a plane with z component constant, it may be concluded that, by just setting to that of the plane of interest, (3) may be used to compute the field on the plane of interest. The problem at this point is how the plane wave spectrum $\vec{A}_E(k_x,k_y)$ is computed from the spherical near-field measurement. With this aim, Fig 1 depicts two possibilities. Next subsections explain both solutions assuming that the transmitting coefficients have been previously computed from the spherical near-field measurement.

Option 1: Direct computation from NF measurement
In this option, the plane wave spectrum is directly computed from the spherical coefficients by applying the direct transformation proposed in [8]. The specific way in which this transformation is carried out is beyond the scope of this paper; however it must be pointed out that its main advantage lies in the possibility of determining the plane wave spectrum at spectral points (k_x,k_y) outside the circle of radius, i.e., the weights that correspond to the evanescent waves. The reason for this possibility is the fact that the near-field measurement (which includes the information of the evanescent waves because these waves have not been completely attenuated at the short distance where the near-field measurement is taken) is directly applied for computing the plane wave spectrum. The consequence of this advantage is the high accuracy that is obtained in the reconstructed currents

The main drawback of this option is the way points near the circle of radius k, i.e., points where $\sqrt{k_x^2+k_y^2}\approx k$, must be avoided. The reason for this restriction is a singularity of the basis functions applied for this transformation [8] at these points. This fact leads to unstable solutions if the exclusion of the suitable margin is not conveniently carried out at both sides of the circle of radius k.

Furthermore, though in this option the plane wave spectrum can be computed at points beyond the circle of radius k, it must be taken into account that it is not possible to determine the complete spectrum. This is because the size of the region beyond the circle of radius k that can be computed depends on the measurement distance: the shorter the measurement distance, the greater the region is. In addition, it must be considered that the evanescent waves are heavily attenuated at short distances and, hence, though the spherical measurement is taken close to the antenna, a strong attenuation takes place, what leads to be able to just obtain a small region beyond the circle of radius k. Therefore, though certain gain with regard to considering far-field measurements exists, depending on the

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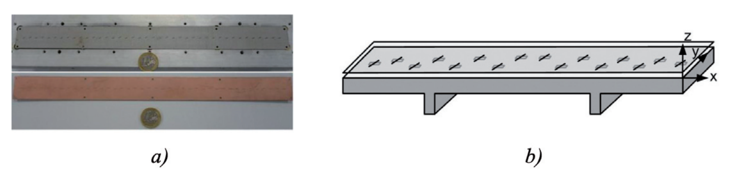
situation, this option may not be the most suitable option and the second one must also be considered.

Option 2: Computation using FF as an intermediate step: MHT.
This second option determines the plane wave spectrum in two steps. The first step computes the field in the far-field region from the spherical coefficients by means of (1) (or other simpler expression particularized at large distances [17]). The second step is the so-called Microwave holography technique (MHT) [14] which, by using the computed far field ($\vec{E}_{FF}(\theta,\phi)$), computes the plane wave spectrum in the following way:

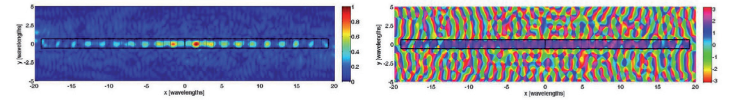
$$\vec{A}_E(k_x,k_y) = \vec{E}_{FF}(\theta,\phi)\frac{R}{jk\cos\theta e^{jkR}} \quad [4]$$

where R is the distance at which far field has been computed.



a) b)

■ **Figure 2.** *Measured antenna: a) Pictures of bottom and upper side, and b) Antenna diagram for dipole position with regard to slots*



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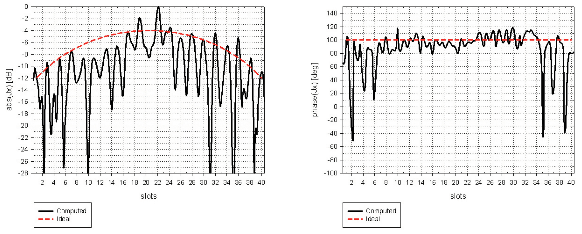
■ **Figure 3.** *Computed equivalent electric currents on z=0 plane: a) absolute value in lineal scale and b) phase in radians of the x component (Jx).*



a) b)

■ **Figure 4.** *Cross section of the computed and ideal equivalent currents at y=0 on z=0 plane: a) absolute value in dB and b) phase in degrees of x component (Jx).*

The advantages of this technique are, firstly, the computation of the basis functions, which have to be just computed on real angles (the first option requires the computation of the basis functions at complex angles); and, secondly, the possibility of directly applying the field measurement in (4) if the measurement is taken in the far-field region (without requiring the computation of the spherical coefficients).

The main drawback is the low resolution of this option. Since the far field is used, either as an intermediate step or directly in (4), evanescent modes (and the information they include) are not considered in the plane wave spectrum computation. This fact becomes apparent when just the visible part of the spectrum, i.e., the spectral points that carry out the condition $\sqrt{k_x^2+k_y^2}<k$, can be computed. As a result, the reconstructed currents have just a resolution of λ / 2, where λ is the wavelength. This limited resolution, however, is enough for some applications and, hence, this second option may reconstruct useful currents for the antenna diagnostics.

To illustrate this second option, the antenna of Fig 2 working at 36.85 GHz was measured for its diagnostics at 1.825 m on a complete sphere around the antenna. Then, the spherical coefficients were computed by solving the transmission formula (2) and the field in the far-field region was obtained with (1). Finally, the plane wave spectrum was computed by applying (4) and the field on a surface close to the antenna was determined with (3). Once the field on the points of interest was known, the equivalent principle [10] was used in order to obtain the equivalent currents of the antenna.

Fig 3 shows both, the absolute value and the phase of the x component of the equivalent electrical current on a flat surface close to the antenna, as well as some lines to indicate where the radiating elements are placed. As can be observed, currents are confined within the region of the antenna and a certain alternating behavior around the y axis is observed, which corresponds to the oscillatory position of elements around the y axis depicted in Fig 3 b).

In order to improve the antenna diagnostics, the cross sections depicted in Fig 4 must be considered. Here it can be observed that, though the behavior of currents looks like the ideal one, just half of the elements are excited and, hence, just these elements contribute to the radiation. Therefore, this diagnostics allows the wrong position of the slots on the guide to be determined and, hence, to take corrective action on this issue in order to achieve the desired result.

4. Coupling reduction

When measuring the radiated field of an antenna a major problem can be found: the signals in the input of the network analyzer receiver (one coming from the signal generator and another one coming from the probe) may couple. This situation becomes common when dealing with measurements at high frequencies since the attenuation of waves is extremely high and, hence, the signal transmitted by the AUT does not reach the probe. The first solution consists in reducing the distance between both, AUT and probe; however this solution is not always possible because of the difficulty to move the anechoic chamber positioners. Hence, considering that the power supplied to the AUT cannot be enhanced, other solutions must be carried out.

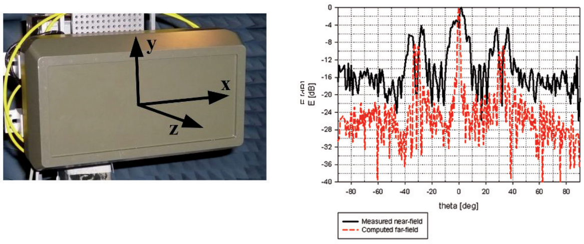
The easiest solution may be the use of an amplifier just after the probe. Thus, the signal coming from the probe, and measured by the receiver, is strong enough to not be coupled with the other input signal. The major drawback of this solution is the high cost of amplifiers, especially at high frequencies. This makes this solution not possible in many cases and, hence, another solution must be adopted.

In other to investigate other solutions, the effect of the coupling on the reconstructed equivalent currents must be observed. With this aim, the antenna of Fig 5 a) working at 36.85 GHz was measured at 0.84 m, i.e., in the near-field region since the antenna diameter is 40 λ. Fig 5.b shows both, the measured radiated field at 0.84 m and the computed far field, in the XZ plane.

As can be observed in Fig 5 b), the measurement and the computed far field is heavily affected by thermal noise, which appears because of the low gain of the AUT. However, the major problem arises when computing the equivalent currents on a surface close to the antenna. Fig 6 a) shows these currents with a square to indicate where the antenna is located on the plane. As can be observed, the obtained currents are affected by a great singularity in the centre which does not allow the currents to be seen.

The reason for this singularity is not the thermal noise present in the measurement, but the coupling between the inputs of the receiver, which effect is a constant interference in all the measurements with a low level. To explain why the constant interference causes the observed singularity, it must be taken into account that the interference in the near-field measurements is propagated to the computed far field, which is related to the currents by means of a Fourier transform. Thus, the constant interference is also present in the far field and, hence, a singularity in the centre of the currents appears since the Fourier transform of a constant signal is a delta function. As a consequence, the resulting signal is the one shown in Fig 6 a).

Therefore, in order to remove the singularity in the reconstructed currents, the coupling, i.e., the constant interference, must be reduced to zero. The first option consists in applying a filter, like a Hamming window. As a result smoother currents are obtained, with the interference partly eliminated, but with a extremely low resolution. This last consequence is a strong drawback and, hence, this option, as long as it is possible, must be avoided.

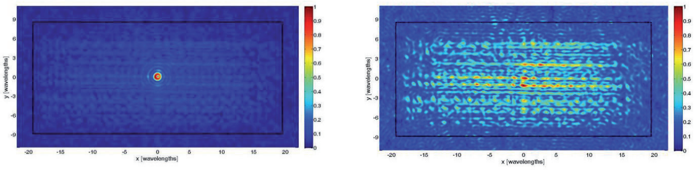


a) b)

Figure 5. *2D array Antenna measured at 36.85 GHz: a) picture and b) measured near field at 0.84 m and computed far field from measurements.*

Another option is to just concentrate on the interference and to try to eliminate its effect. To do this, it may be considered that measurements far from the directive zone of the radiation pattern have a low level and, hence, they are just a measurement of the interference. Therefore, the average of these points is the value of the interference itself and, therefore, its computation is as easy as the mean of the measurements at these points. Later, the computed average is extracted from measurements, what leads to have the measurement with just noise (without the constant interference) and, hence, to be able to compute useful currents for the antenna diagnostics.

Fig 6 b) shows the equivalent currents computed by applying this procedure to the measurement of the antenna of Fig 5 a). As can be observed, now the singularity has been completely removed and currents, though affected by noise, can be used to carry out the diagnostics of the antenna. For instance, now it can be seen how the different elements of the antenna are fed. By comparing this information with the desired weights, it can be justified the strange behavior in the measured pattern.



a) b)

Figure 6. *Reconstructed equivalent currents of the 2D array antenna measured at 36.85 GHz: a) considering noise and interference in the measurement and b) extracting the interference from measurements.*

5. Conclusion

When the manufacturing process of an antenna finishes, it must be verified the radiating characteristic of the resulting antenna. If they do not fulfill the desired parameters, it must be carried out a diagnostics procedure in order to locate the source of the error. This paper reviews seve-

This paper shows the effect of the coupling in the inputs of the network analyzer receiver.

ral techniques to do this antenna diagnostic and, specifically, those involving a modal expansion, which are simple and accurate.

For the case of spherical near-field measurements and currents on a flat surface, two modal expansion techniques have been explained. Both obtain the plane wave spectrum and their main difference is the resolution that can be achieved. In this paper, several examples are shown for the option that makes use of the far-field pattern as an intermediate step and it has been observed that, though a low resolution is obtained, good results are obtained to perform a correct antenna diagnostics.
Furthermore, this paper shows the effect of the coupling in the inputs of the network analyzer receiver. This effect consists in a constant interference which causes great errors on the reconstructed equivalent currents. It has been proposed an easy computation in order to remove this effect from measurements, what offers very good results which, though still affected by noise, allow the currents to be examined and, hence, decisions about their shape or value to be taken.

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