On the Evaluation of the Available Power for Antennas in Reception

Andrea Neto*, *Fellow, IEEE*, Nuria Llombart, *Senior Member*, *IEEE*, Angelo Freni, *Senior Member*, *IEEE,* Arturo Fiorellini Bernardis

***Abstract*—In this paper we provide a simple and accurate physical picture of the antenna reception mechanism. Specifically we introduce the concept of the *observable field*. This is the portion of the incident field that can be received by a lossless antenna located in a given region of space. The observable field is composed by two complementary inward and outward propagating spherical waves whose amplitude can be calculated via the equivalence theorem.**

***Index Terms*—Antennas, reception, equivalent circuit**

I. INTRODUCTION

In the cornerstone article [1], Kwon and Pozar introduced the concept of available power. This power represents the maximum power that an ideal (lossless) antenna, with a maximum volume occupation, can extract from the incident field. Specifically [1] uses a field representation in terms of spherical vector modes to represent the incident field. In [1], it was shown that only a finite number of spherical waves should be used to evaluate the *available power*. Such number would depend on the volume of sphere enclosing the volume allocated to the antenna. The retention in [1] of a finite number of spherical modes for the representation of the interacting field corresponds to extracting from the incident field the portion that interacts with the antenna itself. However, the estimation of the observable field proposed in [1] is quantized, via the number of selected modes, and thus approximate. Consequently also the proposed available power is approximate. Especially for antennas with radius in the order of a fraction of a wavelength, the available power according to [1] is an inadequate approximation, when compared with experiments [2],[3].

In this paper we propose an alternative representation for the observable field, that does not introduce quantization errors. The procedure is based on an integral representation of the field scattered by the ideal antenna via the equivalence theorem currents. We refer to this method to estimate the observable field as the *ideal antenna currents method*. Using this methodology we also derive the available power. When the methodology is applied to estimate the maximum effective area of antennas in reception, the maximum effective area provided for small antennas by the ideal antenna currents method is much closer to the experimental data available in the open literature, while it converges to the values provided by the procedure in [1] for very large or very small antennas (in terms of the wavelength).

II THE OBSERVABLE FIELD AND IDEAL ANTENNA

The spherical modes procedure cannot be used to obtain a useful estimation of the available power for 90% of all antennas (that are in the order of few tenths of the wavelength). The antenna community has responded to this difficulty heuristically: the effective area curve predicted by the spherical modes procedure in Fig. 1, has been interpolated to rendering it continue [2]. This technique has been shown to be fairly accurate when compared to experiments for single plane wave incidence. However it cannot be extended to treat generalized incidence cases, where the superposition of different planes waves needs to be accounted for rather than the superposition of powers.

A field with similar role can be introduced, *the observable* field, that well approximates the spherical modes interacting field far from the antenna, for very small and large antennas, provides effective areas very comparable to the heuristic interpolation for medium antennas, and it is much simpler to evaluate. In this section we introduce the observable field for a plane wave incident from broad side $\theta_{inc} = 0$.

The observable field, $\vec{e}_{obs}^{\,outw}(\vec{r}_\infty)$ is defined as the electric field radiated in free space and in the far zone by a couple of electric and magnetic distributions, $\vec{m}_{eq}, \vec{j}_{eq}$, extended over a finite circular surface of physical area $A_{phys} = \pi a^2$, on the central portion of a plane in the cross section of a sphere of radius a representing the antenna domain.

$$\vec{e}_{obs}^{\,outw}(\vec{r}) = \iint_{A_{phys}} \left[\bar{\bar{g}}^{ej}(\vec{r},\vec{r}')\vec{j}_{eq}(\vec{r}') + \bar{\bar{g}}^{em}(\vec{r},\vec{r}')\vec{m}_{eq}(\vec{r}')\right] d\vec{r}' \quad (1)$$

where $\bar{\bar{g}}^{ej}$, $\bar{\bar{g}}^{em}$ represents the Green's function providing the electric field radiated in free space by equivalent electric and magnetic currents

$$\begin{aligned} \vec{m}_{eq}(\vec{\rho}') &= \frac{A_{id}^{eff}}{A_{phys}}\left[\hat{z} \times \vec{e}_{inc}^{\,pw}(\vec{\rho}')\right] \\ \vec{j}_{eq}(\vec{\rho}') &= \frac{A_{id}^{eff}}{A_{phys}}\left[-\hat{z} \times \vec{h}_{inc}^{\,pw}(\vec{\rho}')\right] \end{aligned} \quad \forall\ \vec{\rho}' < a \quad (2)$$

In (2), A_{id}^{eff} represent the effective area associated to the far field radiated in (1). The incident field can be arbitrarily represented as the superposition of an *observable* component and a remaining component:

$$\vec{e}_{inc}(\vec{r}) = \vec{e}_{obs}(\vec{r}) + \vec{e}_{rem}(\vec{r}) \quad (3)$$

The introduction of the observable fields clarifies the mechanism of the antennas in reception. An incident plane wave is represented as a wave that first converges toward the origin and then diverges from the origin (the observable field) plus a remaining field (that does not interact with the antenna). The *ideal antenna* is the one that captures (transforms into guided waves) all the fields associated to the converging observable field, and cancels the diverging waves. The available power can be calculated by integrating the angular distribution of the incident observable field

RESULTS AND INTERPRETATION

In this section a comparison between the power available to an ideal antenna calculated using different procedures is presented. Fig. 1 shows, the effective area of such ideal antennas as function of the cross physical area of increasing spheres normalized with respect to the squared wavelength. The three different curves correspond to the results obtained using the canonical quantized spherical modes representation, [1], the Heuristic interpolation proposed in [2], and the present ideal currents procedure to derive the observable field representation. The logarithmic scale in both axis allows one to appreciate that, for small domains in terms of the wavelength, the quantization error intrinsic in the spherical modes is very pronounced, while the Heuristic model proposed in [2] provides results very close to those provided by the present observable fields.

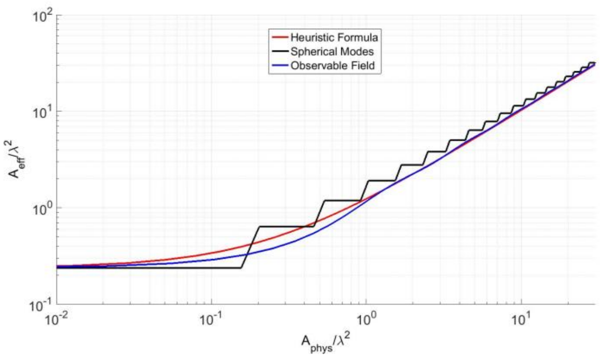

Fig.1 *Effective area of the different ideal antennas in reception realized using 3 different methods. The classical spherical mode expansion, the Heuristic formula from {Kildal- Best} and the present ideal currents method.*

The main result of this investigation is that one does not need the calculation of spherical wave mode coefficients from an incident fields to estimate the power available to the terminal of an antenna in reception. Actually it is sufficient and more accurate to extract from the incident field in the antenna region an observable field component.

A plot of the field associated to the interacting spherical modes in the surrounding of a one wavelength radius antenna, is shown in Fig. 2. The field associated to the typically adopted N=6 modes, is only roughly approximating the incident plane wave field in the antenna region. In the same graph it is highlighted that the ideal currents isolate the antenna domain much better. The observable field can be represented, in the far field as the superposition of an inward and outward propagating spherical wave. The outgoing portion of the observable field is canceled out by the scattered field generated by the antenna in reception, while the inward component of the observable field is entirely absorbed by the matched load connected to the ideal antenna. A comparison of the representation of the field via a finite number of spherical modes and the observable field, in the far region for the case of a one wavelength cross section sphere is presented in Fig. 3. The two fields are qualitatively similar in broadside directivity despite the shape difference.

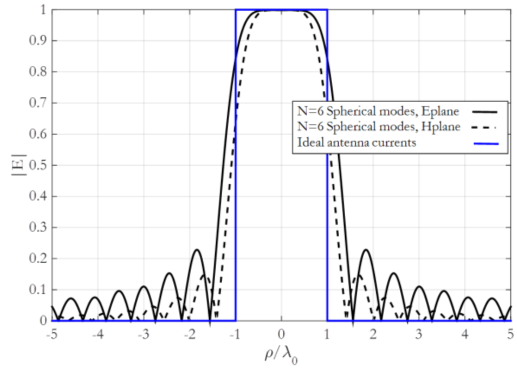

Fig.2 *Near field associated to the ideal antenna understood by the spherical mode expansion, compared with the support of the currents defining the observable field introduced in this article. Case pertinent to a sphere of radius of one wavelength.*

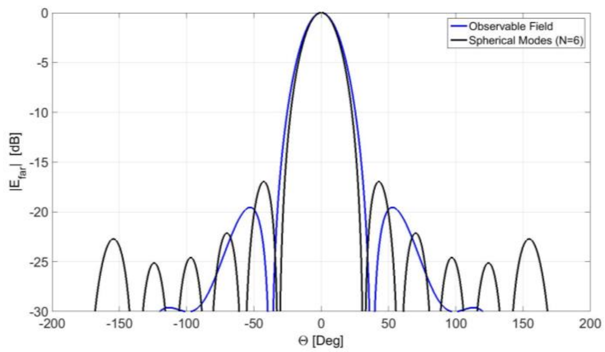

Fig.3 *Far fields associated to the ideal antenna understood by the spherical mode expansion, compared with the observable field introduced in this article. Case pertinent to a sphere of radius of one wavelength.*

The extension to fields composed by the superposition of multiple plane waves is straight forward, and will be discussed at the conference.

ACKNOWLEDGEMENT

The work of Andrea Neto was supported by European Research Council (ERC) Consolidator Grant-Advanced Antenna Architectures for THz Sensing Systems-(AAATSI, 278794). The work of Nuria Llombart is being supported by the ERC Starting Grant LAA-THz-CC (639749).

REFERENCES

[1] Do-Hoon Kwon; Pozar, David M., "Optimal Characteristics of an Arbitrary Receive Antenna," in Antennas and Propagation, IEEE Transactions on , vol.57, no.12, pp.3720-3727, Dec. 2009

[2] P.-S. Kildal and S. R. Best, "Further investigations of fundamental directivity limitations of small antennas with and without ground planes", IEEE International Symposium on Antennas and Propagation (IEEE AP-S), San Diego, July 2008

[3] E Martini, P-S Kildal, and S Maci "Degrees of Freedom of the Field and Maximum Directivity" 2016 URSI International Symposium on Electromagnetic Theory (EMTS)