2

Omnidirectional Antennas:

the truth about GAIN vs SIZE.

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In this Technical E-Paper we aim to investigate about a well-known dilemma:

for a given omnidirectional antenna, how can we estimate its real gain starting from the mechanical dimensions?

Please find here some hints and tips that should be helpful to protect yourself from antennas that are a little bit too short respect to the manufacturer's claimed gain.

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1. Simple omnidirectional antennas.

In general, an antenna is defined *omnidirectional* when it radiates evenly in all directions of the horizontal plane. In this case, the corresponding radiation pattern is almost constant as the azimuth angle ϕ varies, which means that the gap between the two direction of maximum and minimum radiation is less than 3 dB (typically less than 1 dB).

Most omnidirectional antennas use radiating elements with rotational symmetry around the vertical axis (***Z*** axis). In addition, these structures are properly fed to ensure a current distribution as uniform as possible in each section of the element that is perpendicular to the ***Z*** axis.

Actually, in some designs a ϕ-independent current symmetry can be difficult to achieve, as you can guess from the ***Figure 1***, which shows a full-wave thick coaxial dipole operating at 5.6 GHz.

Figure 1
Full-wave coaxial dipole element.

In the event that the cross section of the conductor is much smaller than its length (and the operating wavelength), the radiating element can be considered as a ***thin-wire antenna*** and described accordingly from an electromagnetic point of view. In this case the RF current on the conductor can be simply modelled as ***I=I(z)***, i.e. by means of a single-variable function where ***z*** is the coordinate along the wire axis.

In ***simple omnidirectional antennas***, consisting of a single radiating element, the current distribution remains in phase over the entire length of the conductor itself, which then takes on dimensions between 0.5λ and 1λ.

For these two resonant lengths the theoretical gain values are known from the literature, being respectively:

$$G_{\frac{\lambda}{2}} = 1.64 \quad \Rightarrow \quad 2.15 \;\; dBi \qquad [1]$$

$$G_{\lambda} = 2.41 \quad \Rightarrow \quad 3.82 \;\; dBi \qquad [2]$$

So, in the case of a simple antenna, with a maximum size equal to a wavelength λ, real gain values are easily estimated.

2. Omnidirectional collinear antennas.

To achieve greater gain values, more complex omnidirectional antennas are designed by aligning on the same axis a given number of simple radiating elements (typically dipoles in λ/2 or λ) to form a mono-dimensional array, which is a composite antenna whose total size (height) can extend even for several wavelengths. This kind of radiating systems are referred as ***omnidirectional collinear antennas***, consisting of ***N*** elementary sources, usually dipoles, fed in phase (*Figure 2*).

The gain improvement is achieved by shrinking the radiation pattern, i.e. the main lobe, in the vertical plane. In the elevation plane, the radiation diagram of the composite antenna $f(\theta)$ is therefore given by the product of the single dipole radiation pattern $f_{el}(\theta)$ multiplied by the ***array factor*** $f_g(\theta)$:

$$f(\theta) = f_{el}(\theta) \cdot f_g(\theta) \qquad [3]$$

For our aim it's enough to say that, in the case of uniformly and in-phase fed arrays, the $f_g(\theta)$ function depends solely on the mutual position of the equispaced elementary sources (i.e. on the spacing value ***S***) as well as on the total number ***N*** of the array elements. In addition the array factor introduces a constraint on the maximum value of ***S***, which is found to be between 0.5λ And λ: in fact, being the group factor a periodic function, for ***S*** greater than λ there is a rapid growth of the side lobes (and a consequent decrease in the gain of the array) due to the increasing weight of the so-called *grating lobes* of $f_g(\theta)$ in equation [3].

3. Maximum gain.

Without delving into the array theory of electromagnetic, here we can follow a simpler approach with the purpose of estimating the theoretical gain of a ***N*** dipoles evenly spaced ***S*** collinear array, like the one represented in *Figure 2*.

The size of the array (or ***height***, since it is a vertical, omnidirectional antenna) L_a is given by:

$$L_a = (N-1) \cdot S + L_{el} \quad [\mathrm{m}] \qquad [4]$$

while the gain ***G*** is calculated as:

$$G = G_{el} + 10 \cdot \log_{10} N \quad [\mathrm{dBi}] \qquad [5]$$

in which, however, the individual dipoles are supposed to be totally decoupled with each other, this means that the distance ***S*** between two adjacent sources must be large enough to apply the [5].

An estimate of the minimum spacing value ***S*** can be conducted considering an array of two half-wave dipoles (L_{El}=λ/2): for this simple arrangement (***N=2***), equation [5] provides a theoretical maximum gain of *5.16 dBi* which, incidentally, is the claimed gain value reported in many omnidirectional VHF/UHF antennas.

So, adopting a brute force method, i.e. by means of an electromagnetic software tool, the theoretical gain values of a two λ/2 dipole array have been computed across the spacing interval 0.5λ ≤ ***S*** ≤ 1.5λ. The results are shown in the *Figure 3*.

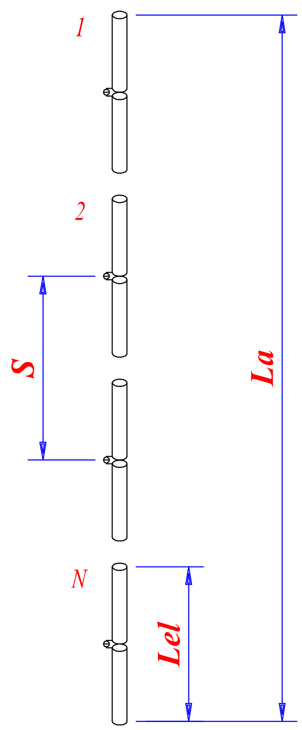

Figure 2
Array of *N* dipoles.

This figure shows that the maximum gain value, given by [5], is obtained for spacing values of about 0.9λ÷1λ, even if actually smaller values of ***S*** are often adopted.

As a reference, with ***S*** ≈ 0.75λ a theoretical gain value is reached within 0.5 dB of the maximum achievable figure. As a result, in order for the [5] to be valid within a tolerance of about 0.5 dB, the array spacing ***S*** must be kept in the range of:

$$0.75\lambda \le S \le \lambda \qquad [6]$$

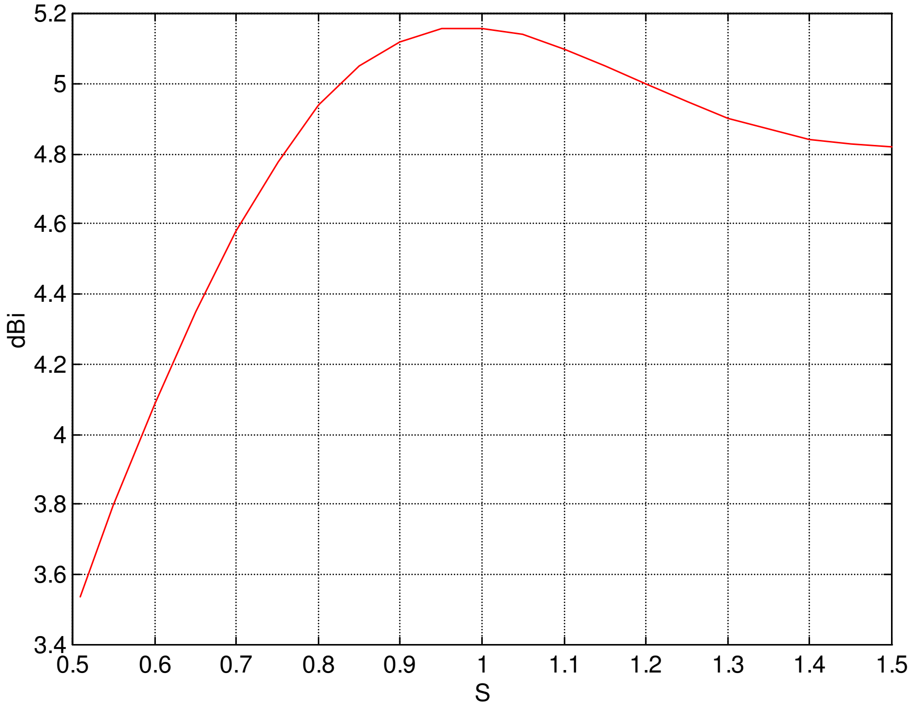

Figure 3

Computed gain of a two λ/2 dipole array vs elements spacing *S*/λ.

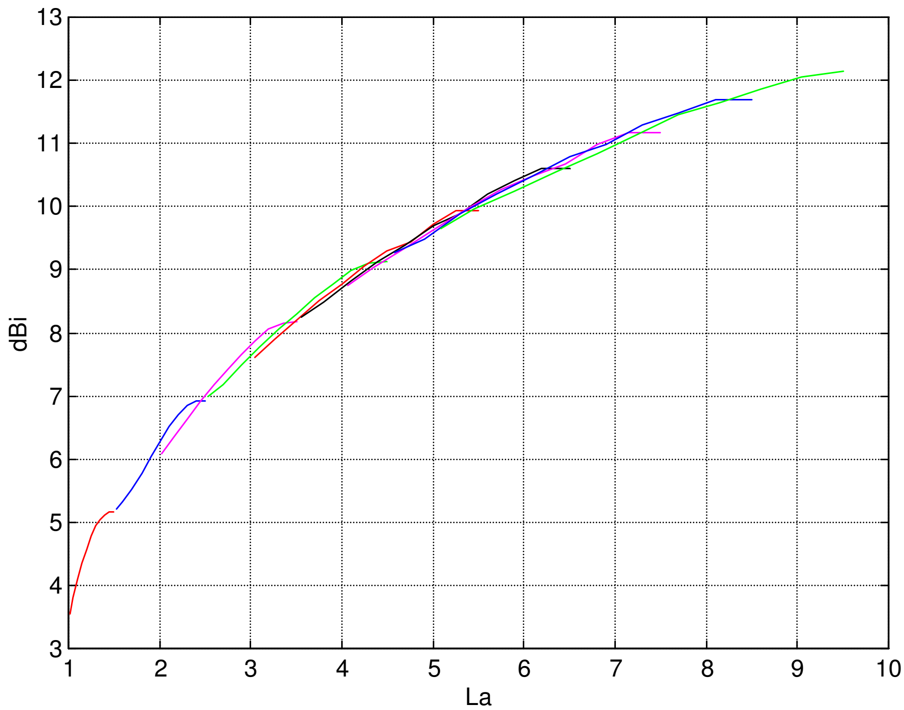

Figure 4

Gain curves of a ***N*** λ/2-dipole array vs total length of the array L_a/λ.
Each coloured curve is computed into spacing interval 0.5λ ≤ ***S*** ≤ λ, and nine plots are superimposed on the same graphic, considering the values of ***N*** between 2 and 10 (N=2, N=3, N=4, N=5, N=6, N=7, N=8, N=9, N=10).

Now, let's repeat the same calculation of *Figure 3* for some collinear arrays of different sizes, i.e. considering $2 \leq \boldsymbol{N} \leq 10$, and for spacing ranges that can be practically adopted ($0.5\lambda < \boldsymbol{S} \leq \lambda$). Then, instead of taking **S** as a reference, let's report in the horizontal scale the total length of the array $\boldsymbol{L_a}$., also normalized to wavelength λ. All these new results are summarized in *Figure 4.*

From this figure it is clear that, for a given value of **N**, the gain of the collinear antenna increases as the spacing increases **S** from its minimum value ($\approx 0.5\lambda$) to the actual maximum value (λ). The adjacent curves, as **N** increases, partially overlap more and more markedly. In this empirical way an important property of the collinear arrays has been assessed, and we can summarize it as follows.

The maximum gain that can be obtained from a collinear antenna does not depend on the number of radiating sources used (e.g. half-wave dipoles), but on the total array length $\boldsymbol{L_a}$.

Of course, this principle is valid as long as the spacing **S** is no greater than λ and no grating lobes occur.

4. The quick method for estimating the gain of an omni-antenna.

The *Figure 4* can be already taken as a reference for assessing the maximum gain that can be obtained from an omnidirectional collinear antenna of total height $\boldsymbol{L_a}$.

A good approximation of the curves shown in the *Figure 4* is given by the following equation, taken from [4] and [5] by placing: $\boldsymbol{L_{a\lambda}=L_a/\lambda}$ And $\boldsymbol{S_\lambda=S/\lambda}$:

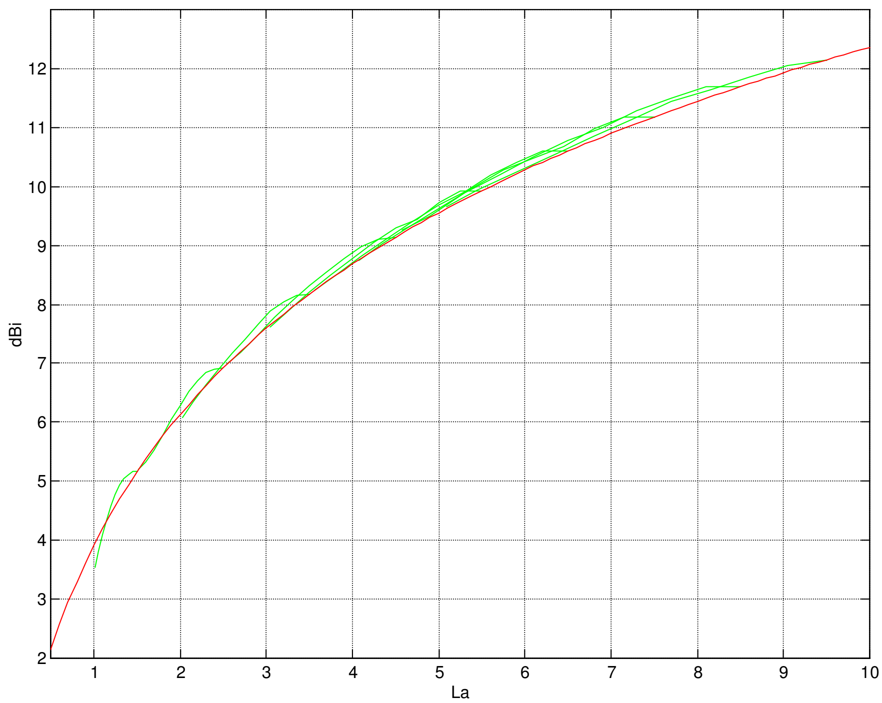

Figure 5

Gain of a collinear omnidirectional antenna vs its total length $\boldsymbol{L_a}$, normalized to λ.
The red curve is equation [7] and it is compared to the simulations results of *Figure 4* (green traces).

$$G = 2.15 + 10 \cdot \log_{10}(L_{a\lambda} + 0.5) \quad \text{[dBi]} \qquad [7]$$

Using equation [7], it is possible to make an easy calculation of the maximum gain we can expect from a given omnidirectional collinear antenna, thus managing to establish the correctness of a specification.

In *Figure 5* the above equation is plotted, indicating the gain values *G* (dBi) vs the normalized array size $L_{a\lambda}$.

The simulations results already shown in *Figure 4* have been added in *Figure 5*, shown here in light green.

Now let's apply this method to real-world cases, i.e. to antennas currently available on the market for which it is necessary to make a preliminary assessment of the reliability of the manufacturer's datasheet, starting from gain and size values, both reported in the technical specifications.

After a short search on the internet it was easy to come across three actual data sheets of omnidirectional antennas, very significant for the following examples.

Obviously, I will omit antennas brand and model of the following case histories.

- **Example 1.**

The datasheet of an omnidirectional XXXX-branded antenna reports: operating band 165÷174 MHz, gain 7.4 dBi, total length 228 in (i.e. 5,791 m).

Let's refer to the operating band center frequency f_0=169.5 MHz, which corresponds to a wavelength equal to:

$$\lambda = \frac{300}{169.5\ MHz} \cong 1.770 \quad \text{[m]} \qquad [8]$$

If you take into account the portion at the antenna base occupied by the mast mounting bracket, which does not radiate, the actual antenna length is L_a 5.2 m. This can be inferred directly from a mechanical drawing or from the product image, carrying out simple proportion. Since this information was derived from a real datasheet, taken as an example, for obvious reasons no image of the antenna is reported.

Applying equation [7] with the above figures:

$$L_{a\lambda} = \frac{5.2\ m}{1.770\ m} \cong 2.94 \qquad [9]$$

you get an estimated gain value ***G*** = 7.51 dBi, which in this case can be consistent with the manufacturer's specified value, which is 7.4 dBi.

- **Example 2.**

From the datasheet of an omnidirectional antenna built by YYYY we can read: operating band 430÷440 MHz, gain 11.5 dBi, total length 5.15 m.

In this case, the bandwidth frequency is f_0=435 MHz, which corresponds to a wavelength equal to:

$$\lambda = \frac{300}{435\ MHz} \cong 0.69 \quad \text{[m]} \qquad [10]$$

Since the antenna uses radials at the base, we as L_a the total antenna height reported by the manufacturer, which is 5.15 m.

Again, we cannot provide an image of the product.

Always from equation [7]:

$$L_{a\lambda} = \frac{5.15\,m}{0.69\,m} \cong 7.46 \qquad [11]$$

You get an estimated gain value ***G***=11.1 dBi, which in this case we can say to be a little less consistent with what the manufacturer says, since the value of 11.5 dBi is still higher than our estimate.

We will be back on this topic on next paragraph.

- **Example 3.**

The datasheet of an omnidirectional antenna, produced by ZZZZ, shows: operating band 163÷173 MHz, gain 5 dBi, total length 1,550 m, radome diameter 20 mm.

From a first observation of the product datasheet we observe that the antenna is supplied with a coax pigtail of a given length (unspecified coax type and brand) which enters directly at the antenna's bottom flange by means of a cable gland. We therefore do not consider the extra attenuation introduced by this pigtail, which cannot be removed nor replaced with a low-loss cable.

Using radome diameter as a reference, scaling the antenna image we can deduce the length of the lower bracket that's about 80 mm.

As a result, the height of the radiating part L_a is 1,470 m.

At the operating band center frequency, f_0=168 MHz, the wavelength is now equal to:

$$\lambda = \frac{300}{168\,MHz} \cong 1.786 \quad [\mathrm{m}] \qquad [12]$$

from which a normalized value of L_a:

$$L_{a\lambda} = \frac{1.470\,m}{1.786\,m} \cong 0.823 \qquad [13]$$

From equation [13] it is interesting to note that the electric length of the antenna is less than λ, therefore it is straightforward to state that the gain will be less than the value G_λ given by [2], i.e. *3.8 dBi*.

Always applying the [7], we can predict a gain ***G*** of *3.36 dBi*, which does not correspond to the *5 dBi* claimed by the manufacturer.

To have a datasheet that is consistent with the so far exposed findings, from *Figure 5* we can deduce that the radiating section of the antenna should have a minimum length of about 1.5λ, and therefore the total length (including bracket) should be at least 2.75 m, so we are dealing about an omnidirectional collinear antenna that should be at least one meter longer.

5. Real omnidirectional antennas.

The equation [7] provides a gain estimate that is based on the following approximations, which are never found in a real antenna:

- Uniformly illuminated array, i.e. all dipoles are fed in phase and with the same input power;
- Total absence of losses, all the power delivered to the antenna connector is radiated;
- Perfect symmetry of current distribution on each dipole of the array, i.e. the directivity function of each source is not distorted.

In a real antenna, the actual measured gain value can also differ appreciably from what is estimated.

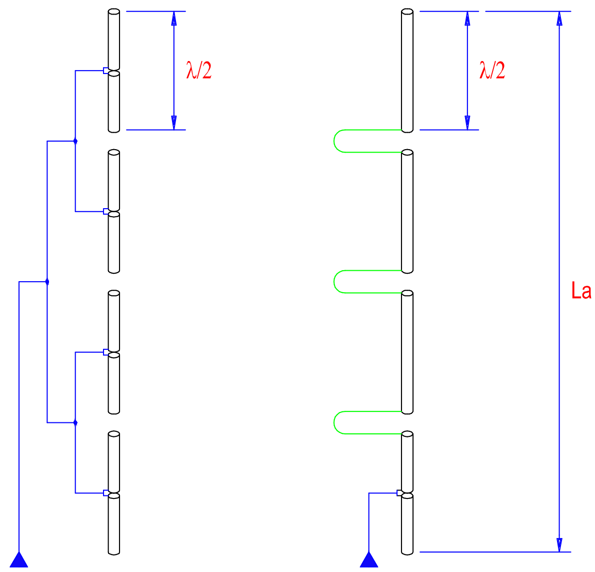

Figure 6

Collinear antennas types: (a) parallel-feed dipoles (corporate feed), (b) series-feed dipoles with 180° re-phasing sections (green coloured in the figure).

Without going into the design and construction details of a collinear antenna, *Figure 6* schematizes the two main types of antenna feeding network: the array consisting of parallel fed dipoles (*corporate feed array*) with transmission line sections and power dividers (***a***); the *series feed array* that uses re-phasing, not radiating sections (***b***).

In the case (***a***), the estimated gain of equation [7] should be modified taking into account of the loss α [dB/m] introduced by the feeding lines and power splitters (first approximation of length $\boldsymbol{L_a}$).

In this case, the [7] should be rewritten as follows (here as a function of $\boldsymbol{L_a}$ [m]):

$$G = 2.15 + 10 \cdot \log_{10}\left(\frac{L_a}{\lambda} + 0.5\right) - \alpha \cdot L_a \quad \text{[dBi]} \qquad [14]$$

An example of applying the [14] is shown in *Figure 7*.

In the case (***b***), characterized by an asymmetric feeding point (not in the center but at the base), the currents on each dipole are not actually the same but tend to decrease as you move away from the base of the array. Moreover, the phase error is zero only at the center frequency $\boldsymbol{f_0}$ for which all the re-phasing sections are designed: so, a linear phase error (that adds or subtracts) occurs as you move away from the center frequency and produces a beam tilt upwards ($f>f_0$) or downwards ($f<f_0$).

In both cases (***a***) and (***b***), as the size of the array $\boldsymbol{L_a}$ increases, the actual gain improvement becomes more and more smaller, so it becomes not convenient to raise further the antenna size, even if a huge array can achieve high directivity values.

We could furtherly discuss about the excessive narrowing of the beam in the vertical radiation diagram, although here would open a very long and complex topic that comes out from the aim of this paper.

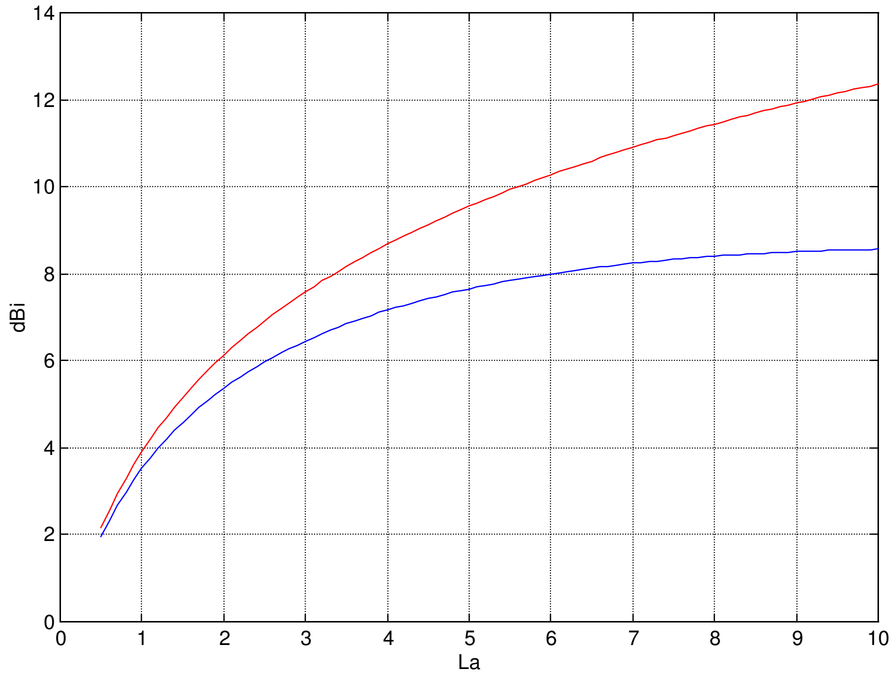

Figure 7

*Gain of a collinear antenna vs total array height **L_{α}**, operating at 300 MHz (λ=1 m).*

*The **red curve** is the gain of the array without losses due to the feeding lines (Eq. [7]).*

*The **blue curve** is the gain of the array with a corporate feed network that use a SM-86 coaxial cable, with α=0.38 dB/m @ 300 MHz (Eq.[14]).*

6. Conclusions.

We hope that this short paper has provided you with a practical method to estimate the actual gain of an omnidirectional collinear antenna, since a correct evaluation of the electrical parameters taken from a manufacturer's datasheet is the first step to find out the right product-antenna for your application.

The examples reported in *paragraph 4* were all taken from real antenna datasheets, which can be easily found in the web.

About the *Example 3*, it really happened that a big company takes the datasheet of this antenna (…with a claimed gain of *5 dBi* and a total height of about 1.5m @169 MHz) as an internal technical reference that's valid both for radio link dimensioning, quote requests or tenders.

From the point of view of a serious antenna manufacturer, it is clear that it is technically impossible to meet these specifications, since a true *5 dBi* antenna should be at least one meter longer, since from a 1,5 m tall omnidirectional you can get about *2 dBi* gain.

Since in many applications in the 169 MHz ISM band, the 1.5 m antenna "*Zzzz*" can still give satisfactory performance in field tests, it is essential that the technical specifications taken as reference are correctly assessed.

Only in this way it is possible to speak the same language with all potential suppliers, as well as to know what kind of stuff you are actually buying and using for your products, systems or installations.

This is for everyone's benefit.

For any needs and/or question fell free to contact us at:

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