Technical E-Paper

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Integrated antennas:

electrical specifications on datasheet and measurements.

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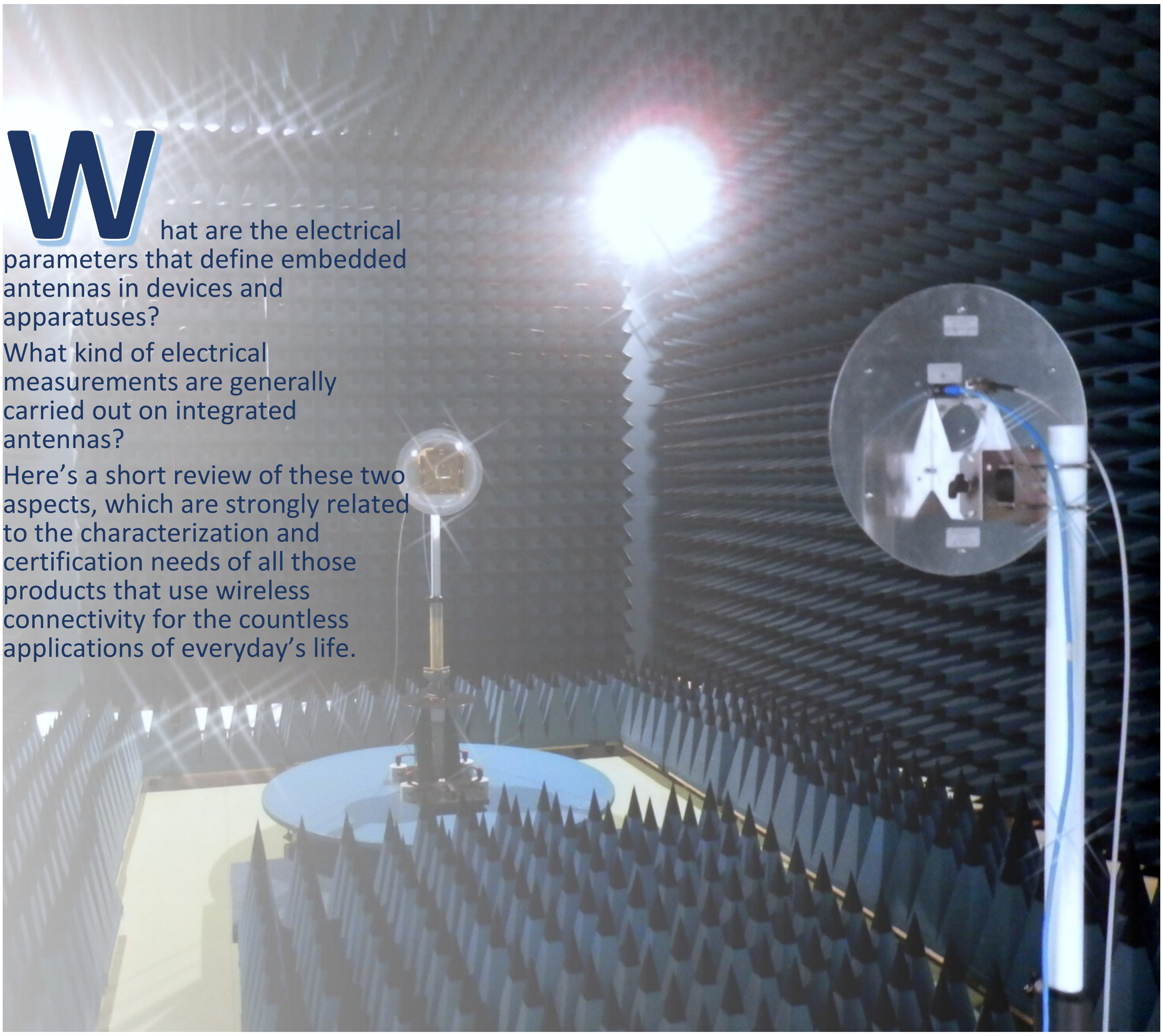

What are the electrical parameters that define embedded antennas in devices and apparatuses?

What kind of electrical measurements are generally carried out on integrated antennas?

Here's a short review of these two aspects, which are strongly related to the characterization and certification needs of all those products that use wireless connectivity for the countless applications of everyday's life.

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1. Introduction.

An antenna is defined ***integrated*** when it is inserted into an electronic device or apparatus and it is therefore optimized to work in such environment.

The apparatus that contains the embedded antenna, which we could define *host apparatus*, is designed and sized to cope with a particular use: if we think of a *Smartphone*, of a *Smart-Metering* wireless unit installed on a gas-meter or of a tiny GPS-tracker covert into a vehicle, it is clear to us that the applications, and consequently the way the antenna can be conceived, can be widely different from each other.

Looking at the myriad of radio devices we usually find in everyday life, it is clear that an integrated antenna cannot be considered as an element in its own right, i.e. like a so-called "normal" antenna, such as the television aerial.

As such it must therefore be developed and characterized.

2. Traditional antennas Vs integrated antennas.

We already know from theory the rigorous definition of an antenna, i.e. it is a *transducer* that converts the electromagnetic energy from a *ducted* state to a *radiated* one and vice versa.

Generally, to accomplish a measurement, we can consider the antenna as transmitting and proceed as follows:

a) We define ***a reference section*** at the antenna input port, such as a coaxial connector or a waveguide flange, through which electromagnetic energy enters into the antenna in a ducted state, i.e. constrained into a defined region of space that is delimited by precise boundary conditions (the transmission line conductors). In this way it is possible to define and measure all those electrical parameters that are derived from the definition of *input port*, such as the characteristic impedance, the reflection coefficient, the *VSWR* or *return loss*, the input impedance, and so on.

b) We define ***a unique observation criterion for the radiated field***, which is not dependent on the antenna you are considering. This can be accomplished by choosing the observation point so that it belongs to the far field region, i.e. the space where the following constraints on the distance ***R*** from the source (antenna) are met:

$$R > \frac{2 \cdot D^2}{\lambda} \qquad [\mathrm{m}] \qquad [1]$$

$$R >> \lambda \qquad [\mathrm{m}]$$

where ***D*** is the antenna size and λ the wavelength. When equations [1] are met we can assess all those parameters that involve antenna radiation, such as *gain*, *polarization*, *radiation patterns* and so on.

Of course, ***integrated antennas*** fall into the general definition just provided, a definition that can be found written on each manual of electromagnetics. However, in the specific case of embedded antennas, it is important to make the following observations, related to the practical aspect of electrical parameters and their measurements.

It is not always easy to identify the reference section, for two main reasons.

- In most cases there is a direct connection between the radiating element and the feed line (microstrip) without a real connector or well-defined antenna feed-point. In addition, it is often necessary to include a matching network and then locate the input section including this RF circuit.
- The feed-point and the transmission line, (for example, a microstrip on its ground plane), is not decoupled from the radiating system. This can be critical when carrying out measurements, due to the stray currents on the external conductor of the coaxial cable that connects the antenna to the network analyser.

It is not always easy to identify the antenna size D, to apply equations [1] or to properly identify what actually contributes to the radiation of the whole system, i.e. "*antenna + apparatus*". In the case of an integrated antenna, it is important to distinguish between *radiating element* and *radiating system*, the latter consisting of the radiating element and all the surrounding parts that are also involved in radiation as they are run by RF currents. Most of the times the *radiating system* coincides with the whole metallic mass of the apparatus.

This is an important point in the comprehension of the radiation mechanism of an integrated antenna. There can be *very tiny radiators* but, to provide satisfactory performance, they must always be embedded into a customized structure, which is far larger than the elements alone, so as to constitute a *radiating system* optimized in the particular device or apparatus in which it is built-in.

So, a bare *radiating element* is not sufficient to develop an integrated antenna that works properly.

3. Electrical characteristics of an embedded antenna.

The electrical parameters, both regarding radiation and impedance matching, which generally characterize antennas are obviously applicable also to integrated ones, even if the actual assessment and measurements regard necessarily the whole "*antenna + apparatus*" system.

Therefore, as a first approximation, an integrated antenna shall be considered as a *short antenna* that is mounted in close proximity of conducting, dielectric and resistive objects that affect, even harshly, its radiation performance.

Let us review the main parameters that, in the particular case of a built-in antenna, can represent antenna specifications.

Input impedance and matching.

The impedance matching specification depends on the characteristics of the radio module that is connected to the antenna: the *RF chip* manufacturer indicates a maximum VSWR value (typically 2) for which a given power value delivered to the load and a maximum current drain are guaranteed. In devices that are battery operated (e.g. IoT or *tele-metering* sensors), a poor antenna VSWR can limit the operational autonomy of the wireless product as well as its radiated power.

If, in the case of narrowband radio systems (i.e. 433 MHz, 868 MHz, etc.), the VSWR requirement can be straightforwardly achieved, a satisfactorily matching over a larger frequency interval (e.g. 850÷960 MHz) can be much more critical to meet, even taking into account the other electrical parameters that have to be considered in the required band portion.

Sometimes integrated antennas are actually designed to comply with less stringent VSWR values, such as 2.5 or 3, and this choice can be satisfactory as well.

As happens when dealing with short antennas, the input impedance of the radiating element shows impedance values lower than 50Ω, and often the constrained antenna layout adds some extra reactance due to other components disposition (metal parts, wiring, etc.): this situation can narrow the actual bandwidth for a given VSWR limit.

There may also be cases where the proximity of dissipative elements, such as batteries or the presence of a resistive plastic moulded casing (used in explosive environments to comply with *ATEX* regulations), lead to a lower antenna Q which, even if it provides a lower VSWR, can lead to a severe gain degradation.

Isolation.

In the case of multiple integrated antennas, both operating on the same or different frequency bands, a specification about ports isolation may be required, i.e. attenuation $|S_{ij}|$ that exists between the different inputs (port $\boldsymbol{i}$ and port $\boldsymbol{j}$) of the antennas. The electromagnetic problem of obtaining the highest isolation between different antennas placed in close proximity is not trivial at all, and can also be solved by brute force, that is, by inserting SMD SAW filters in the microstrip lines that connect antennas to their respective RF sources.

Efficiency, directivity and gain.

As we know, the *radiation efficiency* $\boldsymbol{\eta}$ of an antenna is given by:

$$\eta = \frac{P_r}{P_{tot}} = \frac{P_r}{P_r + P_p} = \frac{R_r}{R_r + R_p} \qquad [2]$$

where $\boldsymbol{P_r}$ is the *radiated power* and $\boldsymbol{P_{tot}}$ is the total input power coming through the reference antenna input section, i.e. the sum of the radiated power and the power $\boldsymbol{P_p}$, lost in heat into conductors and dielectrics with which the antenna is built and/or are present in its near field region.

Efficiency can also be calculated in terms of *radiation resistance* and *loss resistance*, respectively $\boldsymbol{R_R}$ and $\boldsymbol{R_P}$.

In the case of integrated antennas, the losses due to the radiating element itself are added to other losses due to the presence of lossy nearby elements that are necessary for operation and/or homologation of the whole wireless device.

Another factor that impairs the efficiency of an embedded antenna is the size of its ground plane that most of the times is greatly reduced respect to its optimal size because of aesthetic or operating constraints.

The measurement of the overall antenna efficiency is not so straightforward and cannot be deduced from eq. [2], instead it is generally derived from the ratio between directivity $\boldsymbol{D}$ and gain $\boldsymbol{G}$:

$$\eta = \frac{G}{D} \qquad [3]$$

If gain measurement can be accomplished quite easily, the estimate of directivity $\boldsymbol{D}$ has to be computed from the following equation:

$$D = \frac{4\pi}{\iint_{\Omega} f(\theta,\phi)\, d\Omega} \quad \text{[dBi]} \qquad [4]$$

by giving an approximation of the *directivity function* $f(\theta,\phi)$, across the whole solid angle Ω. So, in this case, an accurate 3-D radiation pattern acquisition has to be carried out to get a good approximation of $f(\theta,\phi)$. Upon this topic we will come back later, talking about integrated antennas measurements.

Anyway, from a practical point of view, the most important measurement consists on the gain G, that gives also an indirect estimate of antenna overall efficiency.

Radiation patterns.

An estimate of the directivity function can be deduced from the radiation patterns, that represent the intersection of $f(\theta,\phi)$ with the principal planes, that in this case are the planes taken as a reference for the whole "*antenna + apparatus*" system. These planes can be either the horizontal (azimuthal) or vertical (elevation) plane, if there is a defined operating position. In the case the product has no fixed installation, such as a bare PCB board or a mobile phone, it is more convenient to adopt as a reference orthogonal planes XY, XZ, YZ directly related to the device under measurement.

Most of the times, for an integrated antenna the design constraints and relative degrees of freedom available are not sufficient to provide a true radiation patterns optimization, both in shape and direction of maximum radiation.

Generally, since the short antenna condition of eq. [1] is met, radiation patterns are not so directive, unless the whole system is wall mounted or near other shielding objects that prevent radiation toward some regions of space.

Just to give you an example, the embedded antenna of an IoT device installed on a domestic radiator for heat metering, sees a significative metallic mass behind that acts as the reflector of a panel antenna.

The components layout and wiring inside the host apparatus can also be home to currents, induced by the near-by radiating element, which also contribute to the radiation, as well as the presence of any metal mass, with arbitrary dimensions and shape, present inside the product's casing.

4. Integrated antennas measurements.

Both during the development and validation processes of an embedded antenna it is mandatory to reproduce as precisely as possible the real operating conditions of the whole "*antenna + apparatus*" system.

For this purpose, a reference configuration is assessed, i.e. a typical installation scenario that will be used for carrying out all the electrical measurements on the wireless product. An example is reported in *Figure 1* and *Figure 2*.

In a wireless device with an embedded antenna inside, the electrical measurements can be distinguished in two main families, as follows.

a) Measurements carried out directly on antennas.

The antenna, although embedded into the wireless device, is measured by defining an input port, or reference section, with a normalized impedance to 50Ω.

Generally, this port is identified with the RF module input pin, including the effects of the microstrip (transmission line) length and eventually the SMD matching network.

To this antenna input section, a tiny coaxial pigtail is soldered to allow connection to a measurement port of a vector network analyser (*VNA*).

b) Measures carried out on the whole apparatus.

In this case the whole product comprehensive of electronic boards, radio module and built-in antenna are considered as a single object, both for the transmitting and receiving operations. To accomplish these measurements a spectrum analyzer or other communication protocol analyzers are used, together with a reference antenna that is calibrated at the operating frequencies. So, let's start to give a short description of the main electrical measurements that are carried out on integrated antennas.

4.1. Measurements carried out directly on antennas.

- Input impedance and matching.

VSWR and input impedance are acquired by means of a measurement setup like the one pictured in *Figure 1*. Even if these measurements are considered quite simple to accomplish, when you have to deal with integrated antennas it is fundamental to pay maximum attention to the connection point to the microstrip on the electronic board, i.e. to the antenna input port.

The tiny coax pigtail itself, if not adequately routed and/or shielded, can be place of stray RF currents on its outer shield that introduce a "random" parallel reactance to the actual load.

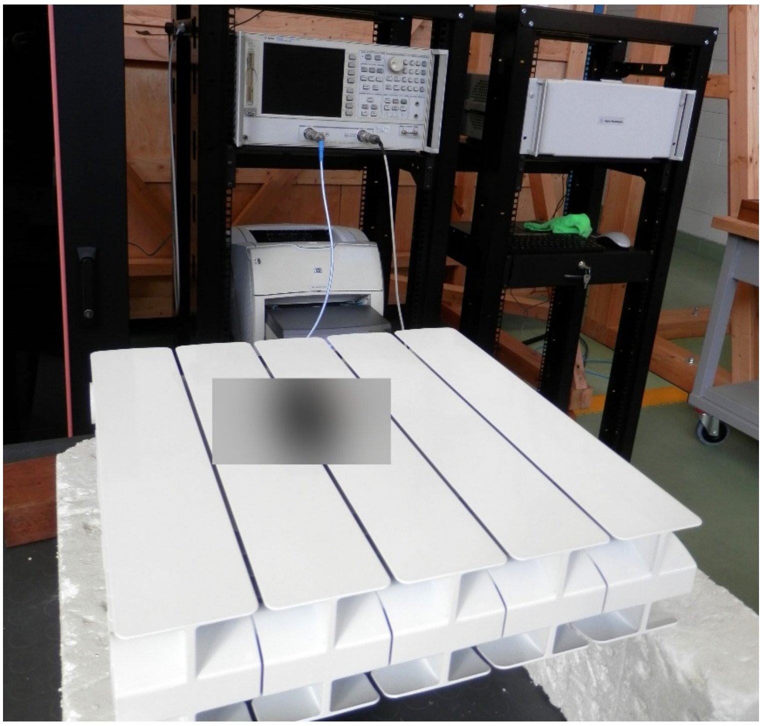

Figure 1

VSWR and impedance measurements using a VNA.
The DUT (Device Under Measurement), with a built-in antenna, is installed on its reference configuration, i.e. in this case it is mounted on a radiator. To observe a NDA agreement, the actual IoT device in the picture has been masked.

- Isolation measurements.

This kind of measurements are strongly dependent on the reference configuration of the whole wireless device that, as previously stated, it has to be representative of product's final operating condition.

Even these measurements are carried out accordingly to a measurement setup similar to the one of *Figure 1*, but in this case both ports of the *VNA* are connected to the antennas inputs to get the $|S_{12}|$ or $|S_{21}|$ readout across the operating bands of both antennas.

Isolation measurements is also strongly affected by antennas VSWR.

- *Anechoic chamber measurements.*

For integrated antennas, gain and radiation pattern measurements are carried out in anechoic chamber, taking care to isolate the outer conductor of the connection cable to the measuring equipment to prevent unwanted radiation.

Since these kind of radiating systems do not present a well defined characteristic polarization, radiation measurements are carried out for each linear orthogonal polarisation, generally referred to the normal versors $\vec{\phi}$ and $\vec{\theta}$, by means of a reference antenna like the one depicted in *Figure 3* that has been expressly designed for the 750÷1050 MHz band.

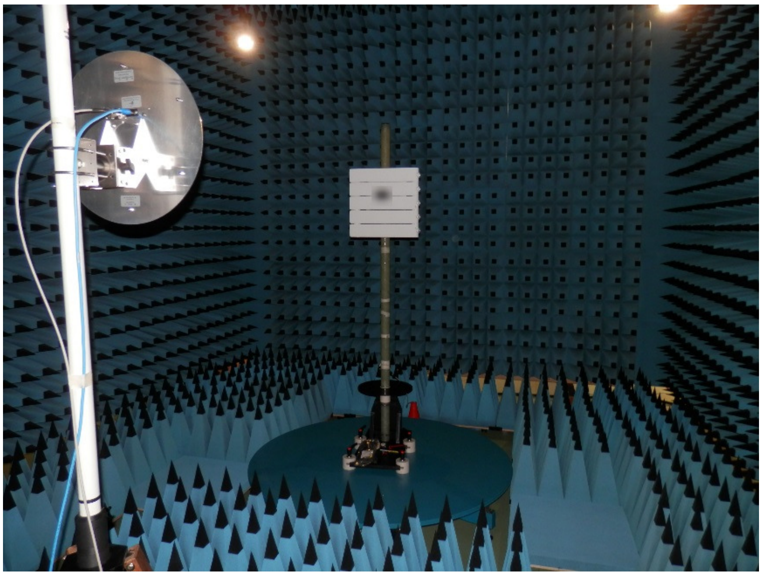

Figure 2

Gain and radiation pattern measurements carried out into an anechoic chamber.

The DUT is mounted on its reference (operating) position, i.e. on a radiator. On the left side of the picture the reference antenna is shown.

Often it is not clear a priori what will be the direction of maximum radiation, so it is preferred to plot the directive gain curves across the principal planes, i.e. the product between the *gain value* ***G*** and the *directivity function* ***f(θ,ϕ)***:

$$G(\theta,\phi) = G \cdot f(\theta,\phi) =$$

$$= G_\theta \cdot f_\theta(\theta,\phi) + G_\phi \cdot f_\phi(\theta,\phi) \quad [4]$$

Here shown in non-logarithmic units.

The *total directive gain* ***G(θ,ϕ)*** is then computed as composition of the two orthogonal components, obtaining a result similar to the plots reported in *Figure 4*, from which it is possible to identify the gain ***G*** as the peak value of the ***G(θ,ϕ)*** trace.

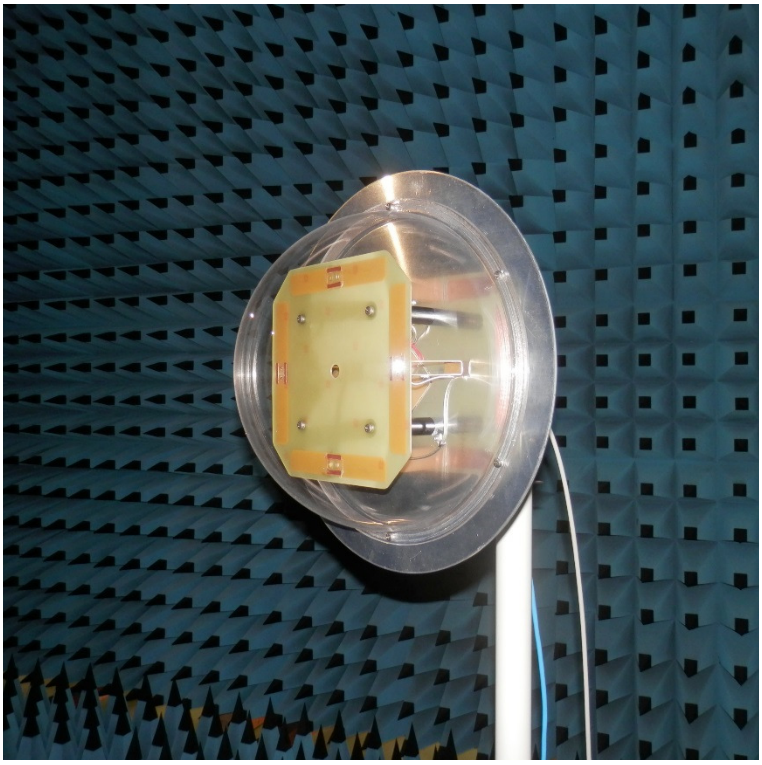

Figure 3

Calibrated reference antenna with two switchable linear polarisations H and V, that operates across the 750÷1050 MHz frequency band

Just to give another example, *Figure 5* reports the radiation patterns of the three field components $\vec{\phi}$, $\vec{\theta}$ and total.

4.2. Measures carried out on the whole apparatus.

Let's now mention the electrical measurements carried out on the whole wireless apparatus, i.e. with the built-in antenna in its true operating conditions with the radio module directly connected to it. These measurements, that involve the control and feeding subsystems of the product, concern both the transmitting and receiving behaviour of the wireless system.

- EIRP and EIS measurements.

EIRP (*Effective Isotropic Radiated Power*) measurement consists on the effective transmitted power by the *DUT* (*Device Under Test*), acquired by means of a calibrated receiving system, consisting of a reference antenna and a spectrum analyzer connected together via a length of coaxial cable with a given attenuation. The *EIRP*, given in *dBm*, is the radiated power level of an isotropic radiator that produces, at receiver end, a signal of the same intensity as the *DUT* actually produces.

Vice versa, *EIS* measurement describes the performance of the apparatus receiver side, and represents the overall sensitivity of the system.

This parameter is also expressed in dBm with the minus sign (since it is a quantity far less than 1 mW). The lowest is this figure the better.

The *EIS* parameter is the sensitivity of a theoretical isotropic receiver when it is illuminated by a plane wave sent by a reference transmitter, whose input power is gradually lowered down to a threshold level that corresponds to a given *BER* (*Bit Error Rate*) value, measured at the data output of the *DUT*.

Both *EIRP* and *EIS* values are acquired for both orthogonal polarizations and then combined, in natural units, accordingly to the following equations:

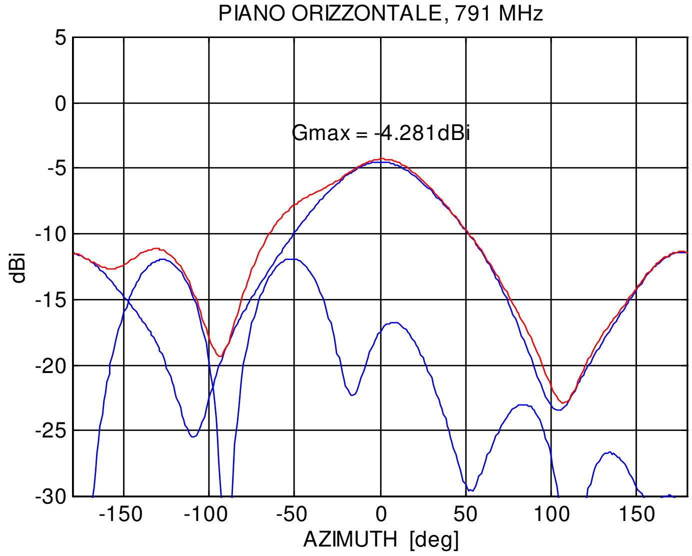

Figure 4

Directive gain curves of an integrated antenna.

Here shown the vertical polarised component trace (bleu coloured), the horizontal component (dashed bleu trace) and the total directive gain (red trace).

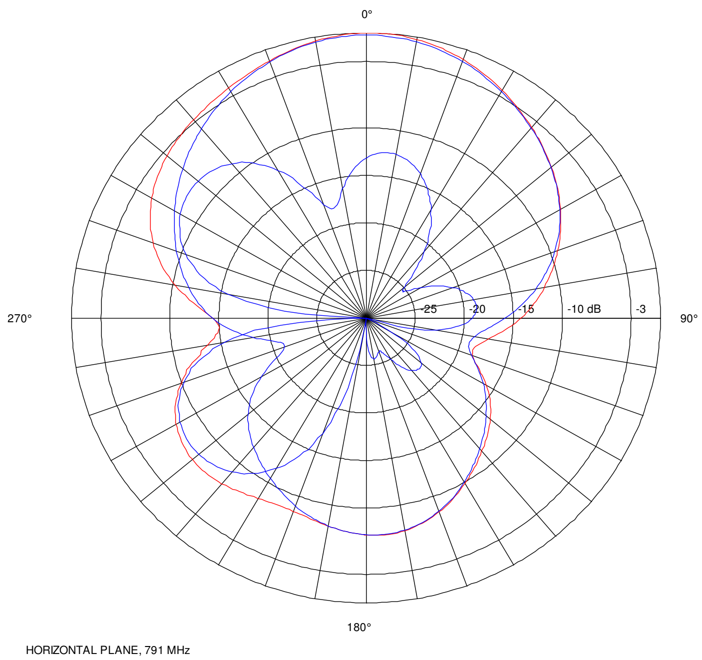

Figure 5

*Radiation patterns polar plot of the three field components reported in Figure 4.: vertical polarised (**bleu** trace), horizontal polarised (**dotted trace**) and total (red trace).*

$$EIRP_{tot}(\theta,\phi) = EIRP_{\theta}(\theta,\phi) + EIRP_{\phi}(\theta,\phi) \qquad \text{[mW]} \qquad [5]$$

$$EIS_{tot}(\theta,\phi) = \frac{1}{\frac{1}{EIS_{\theta}(\theta,\phi)} + \frac{1}{EIS_{\phi}(\theta,\phi)}} \qquad \text{[mW]} \qquad [6]$$

Please note that in eq. [6] the contributions of *EIS* are inverse, since the lower sensitivity values are the better ones.

From *EIRP(θ,ϕ)* and *EIS(θ,ϕ)* data, measured across all directions in the entire solid angle it is possible to find either the maximum *EIRP* value and minimum *EIS*, that correspond to the best values of these two parameters.

- *TRP and TRS measurements.*

As these measurements depend on direction *(θ,ϕ)*, both parameters are derived by summing a series of data collected upon a given number of directions, uniformly sampled over the whole solid angle. In this way it is possible to compute the *TRP* (*Total Radiated Power*) and the *TRS* (*Total Radiated Sensitivity*).

So, if we consider ***N*** equally spaced measurement points in the elevation plane ($0° \le \theta_n \le 180°$) and ***M*** points in the azimuthal plane ($0° \le \phi_m \le 360°$), by applying the following sum

$$Y = \frac{\pi}{2NM} \cdot \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} X(\theta_n,\phi_m) \cdot \sin\theta_n \qquad [7]$$

it is possible to get the *TRP* and *EIS* values, indicated with *Y* in eq. [7], where with $X(\theta_n,\phi_m)$ we mean the correspondent total values acquired for each of the ***N·M*** measurement points (θ_n,ϕ_m), respectively given by eq. [5] and eq. [6].

Thanks to these two numbers it is possible to assess the global transmitting and receiving performance of the system, taking into account the antenna behaviour and the way it is interfaced to the radio module, together with other device parameters that can indirectly affect wireless performance (e.g. power foldback due to high VSWR or power supply fluctuations), both in transmission and reception.

5. Conclusions.

Even if we do not have any claim to have exhausted the wide argument of antenna measurements, in this article we tried to give an idea about the more critical parameters that identify the antennas integrated into devices and wireless products.

In the same way a brief description of the measurements that can be carried out on these apparatuses has been given, both for antennas only and the whole system.

For all those who may be interested on devices with integrated antennas in their professional activity and/or plan to develop a custom product that’s radio connected, it’s fundamental to acquire a certain knowledge of the problem so as not to incur errors or underestimations about the electromagnetic aspect of any project of this type.

In fact, even if an integrated antenna remains "hidden" into the apparatus, it should never be forgotten that it represents the bottleneck of any wireless performance.

For any need and/or question, please send an email to:

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