High frequency ElectroMagnetic field sensors and small, integrated antennas: challenges for the future

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Abstract – In this educational overview paper it is shown that the traditional distinction between on the one hand ElectroMagnetic (EM) field sensors and on the other hand "antennas" is slowly disappearing at higher frequencies. First a definition of both components is given. Second, the fundamental difference between both components is discussed. Third, it is shown that at very high frequencies, both definitions actually "merge", resulting in a single component. The fact that in practise, higher and higher frequencies are indeed used in many applications should invoke an intense cooperation between the two research communities, the one involved in the analysis and design of EM sensors, and the one involved in the analysis and design of antennas. Also, the modeling tools used in both communities are based on the same fundamental principles. Cooperation there is also of mutual interest. The current trends and challenges for the future are discussed briefly. During the presentation, they will be addressed extensively.

Keywords: electric field sensors, magnetic field sensors, small antennas, high frequencies.

1. INTRODUCTION AND DEFINITIONS

An ***electric field sensor*** is a component measuring the electric field at a certain position in space. Actually, this is done by transforming the electric field present at that position into either 1. a voltage in between two terminals of an electronic circuit, or 2. a current flowing inside an electronic circuit. Applying duality, the same holds for a magnetic field sensor. Since in most cases these sensors are used in the normal range of frequencies (DC – a few 100 MHz or maximum 1 GHz), at normal frequencies they are (very) small compared to the wavelength. Spatial resolution may be an important issue. The basic electric field sensor is based on the capacitor topology. A commonly used magnetic field sensor topology is the simple loop, in many cases with multiple turns. Ideal EM field sensors show a flat response in the frequency domain, in order to be able to work in the time domain. Many topologies can be found in [1]. A traditional application area is the study of ElectroMagnetic Compatibility (EMC).

At a very general level, a receiving antenna can be regarded as a sensor. It indeed generates a signal proportional to the incident electromagnetic field. However, in practise, the way the transformation is done is different from the case of a typical EM sensor. This is clear from the following definition.

A receiving ***antenna*** is a component transforming an electromagnetic wave travelling in free space into a "useful" amount of power in an electric circuit. In many cases, an intermediate step, using "guided electromagnetic waves" is present, for example in waveguides or transmission lines. A transmitting antenna performs the reverse power transformation. A traditional antenna works under far field conditions and is designed in such a way that, taking into account the nature of the application, the power extracted from the free space wave is maximal. In many cases, directional rather than spatial resolution is an issue. For example in the case of satellite communication, mostly this results in highly directive antennas. Traditionally, antennas work in a limited band in the frequency domain. The type of topology used to build the antenna determines the frequency bandwidth (bw) of this component. In case of resonant topologies, the bw is low (for example the microstrip patch) to moderate (for example the simple dipole). Non-resonant topologies may show a larger bw (for example horn antennas).

Since the two definitions are different in nature, it is not always clear to the non-specialist what the differences are between a field sensor and an antenna. The difference is clearly in one of the main requirements of both components: 1. A field sensor normally has to be small. It does not necessarily have to be power efficient. 2. From a power perspective, an antenna has to be as efficient as possible. It does not necessarily have to be small.

Typically, electric and magnetic field sensors are used in situations where the power budget does not pose any problem at all, for example at small distances from the "radiating" source. Antennas are mostly used at larger distances, where the power budget and thus the power extracted form the field becomes a crucial issue.

2. EQUIVALENT MODELS

The topology of a capacitive type electric field sensor and the corresponding circuit model is depicted in Fig. 1. Z_{out} is a complex impedance, depending on the measurement device. In case of measurement with a FET device, it is also a capacitor (capacitive measuring device), in case of measurement using a matched transmission line, it is a resistance, in many cases 50 Ohm (resistive measuring device).

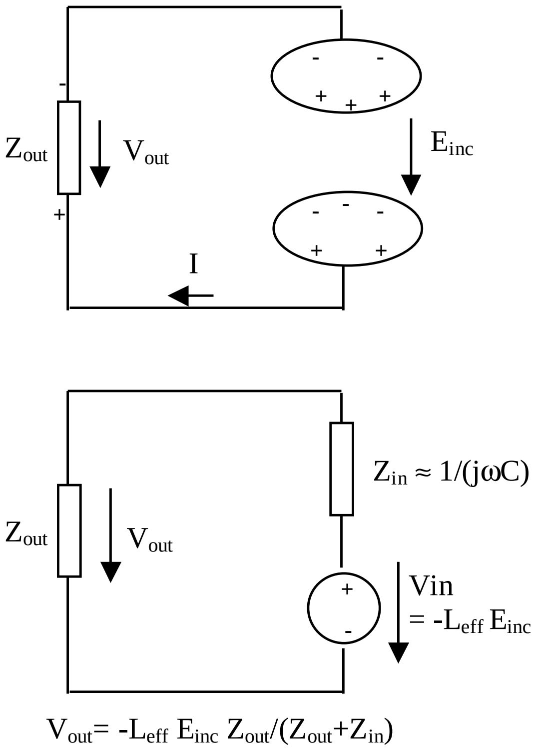

Fig. 1. a. Topology and b. circuit model of a capacitive type electric field sensor.

Z_{in} is the complex impedance of the sensor topology itself. In the case of low frequencies, where the size of the sensor is much smaller than a wavelength, quasi-static approximations can be used, which yield $Z_{in} \approx 1/(j\omega C)$. C is the capacity between the two conductors. This model is important because important considerations concerning sensitivity and power transfer can be derived from it.
In case of a capacitive measuring device

$$V_{out}/E_{inc} = -L_{eff}/(1+C_{out}/C) \quad (1)$$

which means that the sensitivity is constant in the low frequency band. Ideally no power, and in practise very little power is extracted from the incident electromagnetic field and transferred to the measuring device. In practice normally $C_{out} << C$.
In case of a resistive measuring device

$$V_{out}/E_{inc} = -j\omega\, L_{eff}\, R_{out}\, C/(1+ j\omega\, R_{out}\, C) \quad (2)$$

which means that the sensitivity is proportional to the frequency in the low frequency band, thus zero at DC. In practice normally $(\omega\, R_{out}\, C) << 1$. This results in a very low sensitivity, compared to (1). The fundamental reason is the presence of a current path, through which the opposite charges at both sides of Z_{out}, as indicated in Fig. 1a, can flow and annihilate each other. However, power is extracted from the incident electromagnetic field and transferred to the measuring device. This power transfer can be characterised by the ratio: power dissipated in the measuring device over incident power density. In "far field" conditions this power density is proportional to the square of the incident electric field. The result is

$$P_t/p_{inc} \sim (\omega\, L_{eff}\, C)^2\, R_{out} \,/\, (1 + (\omega\, R_{out}\, C)^2) \quad (3)$$

which yields extremely low values.
Since the equivalent circuit model is based on fundamental electromagnetic considerations, in case of an electric field measurement using an antenna the equivalent model is basically the same (Fig. 1). The key differences are that
1. Z_{in} is now the input impedance of the antenna, which ideally is mainly resistive in the working band of the antenna,
2. in most cases a resistive measuring device is used.
This yields

$$V_{out}/E_{inc} = -L_{eff}/(1+R_{ant}/R_{out}) \quad (4)$$

which results in a constant sensitivity in the working band of the antenna. In most cases $R_{ant} = R_{out} = 50$ Ohm. Outside the working band of the antenna, its impedance can be very different from R_{out}, which may reduce the sensitivity considerably. The power extracted from the incident electromagnetic field is characterized by

$$P_t/p_{inc} \sim L_{eff}^{\;2} \,/\, (1 + R_{ant}/R_{out})^2 \,/\, R_{out} \quad (5)$$

which yields much larger values than (3).
If one would work with an antenna in combination with a capacitive measuring device, the result is

$$V_{out}/E_{inc} = -L_{eff}/(1+ j\omega\, R_{ant}\, C_{out}) \quad (6)$$

Since the frequency is always large (enough) in this case, $\omega\, R_{ant}\, C_{out}$ is not necessarily small, which results in a reduced sensitivity. Also, no power or very little power is extracted from the incident electromagnetic field.
For magnetic field sensors, and their comparison with antennas in magnetic field measurements, a similar line of reasoning can be used, but based on the loop topology.
The conclusion of this section is that the only set-up yielding both a good sensitivity and a reasonable extraction of power from the incident electromagnetic field is using an antenna in combination with a resistive measuring device. Real sensors, in the traditional meaning of the word, may show a good sensitivity, but extract only a minor amount of power from the incident electromagnetic wave. This means that in applications where this power is important, for example in telecommunications, the antenna set-up is preferable. In other cases, both antennas and sensors may be used.

3. HIGH FREQUENCIES

At 1 GHz the wavelength is about 30 cm. This means that in order to be power efficient, an antenna should be around a quarter (7.5 cm) to half this size or larger. Antennas on or in a mobile are indeed smaller, a few cm, but the price paid is … indeed … a lower efficiency, partially compensated by the larger antenna gain in the base station antennas of the system. When the distance is too large, the communication fails.

For sensors, 7.5 cm is very large. Among others, it would result in a poor spatial resolution. In applications where this resolution is needed, smaller sensor topologies will be used.

At 10 GHz, a wavelength is about 3 cm, and at 100 GHz, it is 3 mm. This changes things drastically. At these frequencies, components can be built that are both power efficient *and* small, thanks to the smaller wavelength.

Also, the higher the frequency, the more coupled the electric and magnetic fields present themselves. This means that the distinction between electric field sensors and magnetic field sensors disappears. Whereas for low frequency sensors, different topologies have to be used to measure either the electric or magnetic field, at higher frequencies, this is not the case, just as for antennas.

It is evident, at higher frequencies, the clear separation between on the one hand sensors, and on the other hand, antennas fades away.

3. CHALLENGES

There are several challenges that are currently being addressed in the antenna research community. They may prove to be important also for the people involved in EM sensors.

A first trend, invoked by demanding applications in between 1 GHz and 10 GHz, is to make antennas as ***small*** as possible. This is necessary for many hand-held devices and also for devices being equipped with wireless technology. The antenna has to fit within the laptop, the mobile, even the chips used (Fig. 2), or in some future applications, even near or within the human body (integration of the antenna in clothing for example). Since an antenna is a device that inherently works based on the wave behaviour of electromagnetic fields, miniaturization is a challenge flirting with the fundamental boundaries of physics. From an overall perspective, including both antennas *and* sensors, one could say that the challenge is to combine the power efficiency of a traditional antenna with the size of a traditional sensor, for frequencies as low as possible.

It is important to understand that real miniaturization actually means that the antenna is made as small as possible relative to the wavelength at the working frequency considered. Designing at higher frequencies, with smaller wavelengths, and thus smaller antenna dimensions for the same topology and functionality, is not really miniaturization, but it does open the possibility to have small efficient antennas/sensors. There is a wealth of information and papers on this topic. A good starting point is [2], or the websites on

1. the current COST project on antennas: www.cost284.com,
2. the European Network of Excellence on antennas (ACE = Antenna Centre of Excellence): www.ist-ace.org and www.antennasvce.org

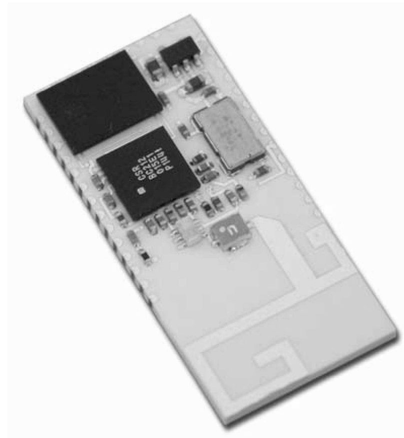

Fig. 2. Bluetooth Module on a 6 layer LTCC (Low Temperature Cofired Ceramic) substrate of size 15 x 32 mm with a printed planar inverted F antenna (lower right), and surface mounted packaged IC's (upper left) containing the radio and baseband signal processing chips and flash memory chip with stored software.

A second trend is the ***integration*** of the component as part of the peripheral electronics and/or overall package, preferably with existing fabrication technology. In Fig. 3 a possible topology for the integration of (small !!!) antennas in the package of IC's is depicted [6]. The topology was conceived taking into account the existing size of the package, the materials used, and the test and measurement set-up for the type of chip considered. It is evident that this trend is also based on the first trend, miniaturization. But whereas pure miniaturization may use new materials and fancy topologies, integration has to take into account existing manufacturing technology, which means for example the use of materials that are not common in the antenna community, and only slightly modified topologies.

At the same time, the antenna has to be ***broadband*** or multi-band, in order to cover several standards simultaneously. Indeed, manufacturers want to avoid putting numerous antennas to cover all applications. Since there is a fundamental limit (Wheeler's limit [7]) stating that the product of bandwidth and efficiency is proportional to the electrical size, one of the main problems is efficiency. It is extremely hard to design very small, broadband, and at the same time power efficient antennas (and thus sensors). The term power efficiency is related to the power considerations made in section 2. It means the capability to extract power from the incident electromagnetic wave and transfer it to the measuring device.

Although for immediate implementation, using existing fabrication technology with existing materials is preferable, .a possible solution in the longer term is to allow antenna, electronics and package to operate together by making optimal use of the presence of new materials. But these have to be introduced then in the fabrication process, something that takes time and money.

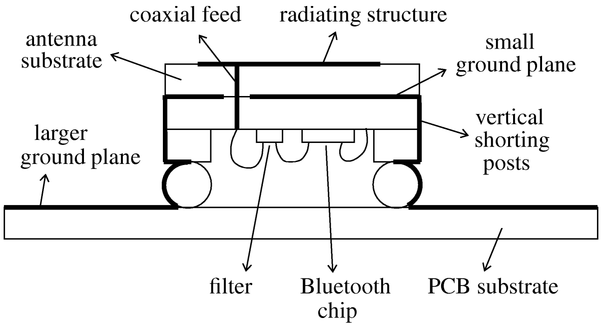

Fig. 3. Conceptual topology to integrate antennas/sensors in chip packages to be mounted on PCB's.

Another trend is the introduction of the Ultra Wide Band (UWB) concept. In this type if systems, the antenna actually has to be considered in the time domain, rather than in the frequency domain, For this a flat frequency response is necessary, just as in the case of many traditional EM field sensors. The difference is that this flat response has to be reached now in high bandwidths at rather high frequencies.

Apart from the purely electrical and mechanical evolutions that such systems have brought along, biological and environmental aspects have to be taken into account. One needs to think of not only the recent anxiety about possible adverse effects of GSM radiation on human health, but also of the development of systems where the components of the wireless communication system are embedded and distributed within textile clothing, located upon (WBAN, Wireless Body Area Network) or even implanted inside the human body, for example for medical purposes. In the future, there is thus an emerging need not just to study the mutual effect of human biological and technological electrical systems, but to consider them more as a whole. Actually, the concept of a WBAN is a typical example where the traditional differences between "sensors" and "antennas" completely disappear.

All these trends have been made possible because in the last decade, numerous electromagnetic solvers have become available in the software market, some of them especially for antennas. Cruising through literature, it is obvious, by far most recent antenna designs (and this is especially through for miniaturized designs) are performed by using general or dedicated CAD tools, based on a full wave solution of Maxwell's equations. At the moment, several numerical techniques are actually competing in the market, depending on the antenna topology and specifications considered:

- FE (Finite Elements): HFSS (www.ansoft.com), AI*EMAX (www.ansys.com),
- FDTD (Finite Difference Time Domain) and related techniques: Microwave Studio (www.cst.de), Micro-stripes (www.micro-stripes.com), Fidelity (www.zeland.com), concerto (www.vectorfields.com),
- Integral Equations: Sonnet em (www.sonnetusa.com), Momentum (www.agilent.com), Ensemble (www.ansoft.com), IE3D (www.zeland.com), FEKO (www.feko.co.za).

Besides this, there is an overwhelming amount of software developed at universities and in research institutes. Within the framework of ACE, the European Network of Excellence on Antennas [4, 5], this type of software (dedicated to antennas) has been inventoried and reported. Moreover, within ACE, an integrating activity was set-up, aiming at integrating the European research community in this field. It is important to emphasize that most of these solvers are applicable in all fields of research where electromagnetic field distributions within a certain topology of materials is of concern. They are certainly applicable and in some cases probably are already used in the sensor research field. This is why the Antenna Software Initiative within ACE is inviting other research communities in Europe to cooperate towards a general open software framework for electromagnetic field problems.

4. CONCLUSIONS

In this paper, it is shown that as a consequence of the quest for higher frequencies, the classical (topological and other) differences that characterize the separation between EM sensors and antennas are bound to disappear. The design of both components will be performed along similar design rules. The key challenges to the research communities involved concern the integration of existing and new modeling tools, and the optimization of the compromise between size, power efficiency, and bandwidth, and the use of new materials.

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