# Electrically small antenna design: from mobile phones to implanted sensors

Anja K. Skrivervik[1], Marko Bosiljevac[2], Zvonimir Sipus[3],
[1] Microwave and Antenna Group (MAG), Ecole Polytechnique Fédérale de Lausanne, Switzerland, Anja Skrivervik@epfl.ch
[2]Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia
marko.bosiljevac@fer.hr, zvonimir.sipus@fer.hr

***Abstract*—In this review, intended to introduce the convened session on electrically small antennas, we describe the evolution of electrically small antennas from the early nineties, when the boom of mobile phones triggered an intense research activity on the, to our days, where virtually everything has a wireless connection. A special emphasis will be set on antennas for wearables and implants, as in those cases the strategies and limitations derived for electrically small antennas radiating into free space do not hold anymore. We will present the design strategies based on fundamental limitations and the special care that should be taken to measure and simulate such antennas.**

***Index Terms*—Miniature antennas, antennas for implants, wearable antennas, fundamental limitations.**

## I. Introduction

Electrically small antennas (ESAs) are as old as radio communications. Indeed, the antennas in the early days of wireless telegraphy operated in the range of hundreds of kilohertz. Thus, even the very large antennas used were electrically very small. The research on ESAs started in the forties, with the pioneering contributions of Wheeler [1] and Chu [2]. These early works recognized that there were some fundamental limitations on the radiation characteristics of ESAs, and that these limits could be directly derived from the laws of physics. This work continued in the fifties and sixties, with the work of Harrington [3] and Collin and Rothschild [4].

The interest for ESAs underwent a renewal in the late eighties and the nineties, with the democratization of mobile phones. In this decade, the size of the handsets underwent a drastic reduction and the same was true for the antennas thereon. This resulted in a rediscovery of the fundamental limitations derived earlier, and a refinement thereof [5, 6]. The boom on wireless mobile communication triggered an intense activity in the design of new antennas suited for mobile terminals, see for instance [7-11]. New generations of mobile phones and new services like Bluetooth, GPS, WiFi or WLAN required the ability to handle multiple frequency bands in volumes becoming smaller and smaller. At the beginning of this millennium, wireless services not connected to mobile appeared and started to grow, like RF-IDs, wireless sensors, remote controls, the Internet of Things (IoT) and finally the Internet of Everything (IoE).

Along this, a new field of applications emerged requiring wireless communication or powering: implantables or wearables. This new family of wireless nodes represented a change of paradigm for antenna designers: instead of radiating into free space, or at least a lossless medium, the antennas in this case radiate into a potentially very lossy medium made of biological tissues. This meant that new fundamental limits and design strategies, taking into account this fact have to be developed, and initial results are given in [12].

This paper is structured as follows. First, in section II, an overview of the fundamental limits for ESAs is given. The ESA Key Performance Indicators (KPIs) for different wireless applications and contexts are given, as it is for these KPIs that fundamental limits are the most useful. Section III presents different design strategies for ESAs, considering the classic ESAs radiating into free space and the case of implantable and wearable antennas. Measurement and simulation issues of ESAs are presented in Section IV, and the conclusions in Section V.

## II. Fundamental Limitations

As mentioned in the introduction, the interest for the fundamental limitations on ESAs started in the first half of last century already [1]. It was soon recognized that achieving a reasonable bandwidth was very difficult for an antenna small compared to the wavelength. The quality factor was established as one of the most relevant KPI for such antennas, as for small antennas it can be linked to the bandwidth if we assume that the antenna is tuned to resonance or antiresonance using a reactive lossless circuit element and that there is only one resonance in the considered frequency band [12, 13]. The first method to obtain a lower bound on the quality factor of ESA's was based on considering an elementary antenna, a short dipole and use a spherical wave expansion of the fields radiated by this antenna. From this expansion, Chu used an equivalent circuit model to compute the mean stored energy and the radiated power and thus the quality factor of the antenna [2], while others [4-7, 14] arrived to similar results directly from the fields. The result of these studies is that a lossless electrically small antenna circumscribed by a sphere of radius $a$ and radiating only the first TE or TM mode cannot have a quality factor smaller than

$$Q = \frac{1}{ka} + \left(\frac{1}{ka}\right)^3 \quad (1)$$

The second KPI of interest for ESAs is the achievable directivity. Harrington showed in [3] that if there is no fundamental limitation on the directivity of an ESA (as is indeed demonstrated by superdirective antennas), there is indeed such a limit for the ratio of the directivity over the quality factor, D/Q. From this observation, he proposed his well-known upper limit for the directivity for an ESA with a reasonable bandwidth:

$$D_{\max} = (ka)^2 + (ka) \quad (2)$$

where $k$ is the wavenumber and $a$ the radius of the smallest sphere circumscribing the antenna. This result was obtained through the observation that modes having order higher than the electric size of the antenna ($ka$) contributed highly to the mean stored energy close to the antenna and thus increased drastically the quality factor. The idea is thus to limit the number of radiated modes to $N<(ka)$. All these classic results were derived considering ESAs radiating only in linear polarization, but are easily extendable to circular polarization [2, 15-18]. In [15], Pozar gives a very clear overview on the different possible combinations of limitations on Gain and Quality factors for a system composed of two elementary dipoles (electric and electric or electric and magnetic) on Gain and quality factor depending on the polarization the system radiates.

The fundamental limitations derived using the spherical wave approach were very useful to understand the way ESAs worked. However, as they are based on a sphere circumscribing the antenna, the limit they give is quite far from what an antenna with a form factor different from a sphere would achieve. With the increased demand for electrically small antennas induced by the boom in wireless communications, these limitations were revisited starting in the early nineties. Several aims were pursued: refine the limitations by taking into account the antenna's shape factor [19], extend the work to take into account dispersive materials [20], losses in the antenna materials [21]**Error! Reference source not found.** and materials having negative permittivity or permeability [22].

In 2007, Gustafsson et al. introduced a change in paradigm by introducing fundamental limits for antennas of arbitrary shape [23, 24], based not on wave expansions but on the polarizability dyadic of the antenna, thus on a static field value.

One thing is common for all these works on fundamental limits for electrically small antennas: The KPIs for such antennas are the quality factor (which can be linked to the bandwidth) and the Directivity over quality factor ratio.

Things change drastically when ESAs radiating (partially) into lossy media are considered, as for instance implantable or wearable antennas. Indeed, in this case the KPIs change, as the quality factor of such an antenna is difficult to define: what is the mean stored energy in a lossy medium? Even the bandwidth, in the sense of the reflection coefficient bandwidth loses its importance, as the lossy environment of the antenna will broaden this band by reducing the reflected power by absorption. Moreover, other classic antenna characteristics as the radiation pattern do not exist anymore for antennas radiating into a lossy medium, as there is no far field reason anymore [25]. KPIs for these antennas need to be defined and agreed upon by the community, but could be linked to the total power reaching outside the lossy host body for the case of an implant for instance, or to the power density outside the lossy medium in the direction of maximal radiation. Preliminary work based on the study of elementary sources in a spherical phantom representing a multilayered lossy medium, for instance these KPI, will depend mainly on the depth of the implant, the size of the implant (represented by a lossless encapsulation), the type of the source and the materials making up the phantom [26, 27]. Similarly, new KPIs are requested for wearable antennas [28]. From these KPIs, new fundamental limitations are needed to help the design process of antennas radiating (partially) in lossy media, and the research is at its beginning in this topic. A preliminary result for the case of implantable antenna gives the maximal power density at the phantom-air interface, as a function of the electrical size of the implant, the depth of the implant and the characteristics of the tissues of the host body. This result is obtained using a spherical wave decomposition, very similar to the pioneering work of Chu and Harrington, but considering a spherical multilayered model for the lossy host medium [29].

In summary, we can say that the KPIs for ESAs radiating into a lossless medium are mainly the quality factor and the directivity over quality factor ratio, but that there is no consensus yet in the community about the KPIs for ESA's radiating (partially) into a lossy medium. However, it sees that the latter are linked to the total power or power density reaching out of the lossy host medium. In the same way, well-established and very useful fundamental limits have been derived for the KPIs of classic ESA's, while the research is still at its beginning when fundamental limits for ESA's in lossy media are considered.

## III. Design Strategies

Techniques to make antennas smaller have been known for a long time, and many of them are described in standard textbooks (see for instance [30, 31] or [32] for more exotic antennas). For ESAs used for mobile communications, the classic techniques used are linked to loading the antenna with lumped elements, high dielectric materials or with conductors, using ground-planes and short circuits, optimizing the geometry and using the antenna environment (like the casing) to reinforce the radiation [11].

The latter strategy finds a very neat illustration in the antenna design using the characteristics modes of the antennas elements, and more specifically the ground plane. Indeed, the latter is often the largest part of the antennas, and the idea is to use it to perform the radiation, by designing a clever structure allowing the excitation of these modes and the matching at the frequencies of interest for the application [33-35]. Characteristic modes allow also to design multi-frequency antennas, or MIMO antennas [35].

When designing ESAs, antenna engineers have relied upon optimization schemes to achieve antennas with the best possible characteristics. However, such optimizations are tricky, as the search spaces contain many variables, usually non-orthogonal, and many local minima and maxima. Genetic Algorithms (GA) very soon attracted the attention of the community, as they are adapted to these situations, and were used as early as the nineties for the optimization of mobile phone antennas [36-40]. In more recent years, optimization tools were developed to design antennas optimal with respect to the KPIs stated above [41-43].

In general, we see that the design procedures of ESAs have become more performant and mature over the years, building on the knowledge gained over time. Globally, a good design will try to minimize the mean stored energy in the structure in order to maximize the bandwidth, while providing the current distribution required achieving the sought for directivity.

The story is quite different for antennas radiating (partially) into lossy media. Even though many good designs have been presented in the literature, the design procedures are much less mature. Indeed, we are still in a phase where KPIs are being defined and fundamental limits looked for.

Looking at implantable antennas, which radiate into a lossy host medium before reaching free space, an interesting KPI is to maximize the power reaching outside the lossy host, or in other terms to minimize the losses inside it. Preliminary results [27-29] have illustrated that there are three mechanisms contributing to the losses inside the host medium where the antenna is implanted: The coupling of the near field to the body losses, the coupling of the propagating filed to the losses and the reflection at the interface between the host body and the free space. This is illustrated on Fig. 1 for the canonical case of a Hertzian dipole (electric or magnetic) implanted in a sphere of muscle and radiating at a frequency of 403 MHz (MedRadio band). The results show the total power reaching out of a sphere at a radial distance from the antenna (horizontal axis). The absorption of the propagating field in exp (-2αr) and the reflection at the outer boundary are inherently present due to the application and therefore unavoidable. Thus, in order to achieve a good design, the antenna engineer should strive to minimize the coupling of the near field of the antenna to the lossy host medium. One way to achieve this is to design the antenna in a way to confine most of the near field in the biocompatible encapsulation surrounding the antenna and electronics, as the latter is usually made od low loss material.

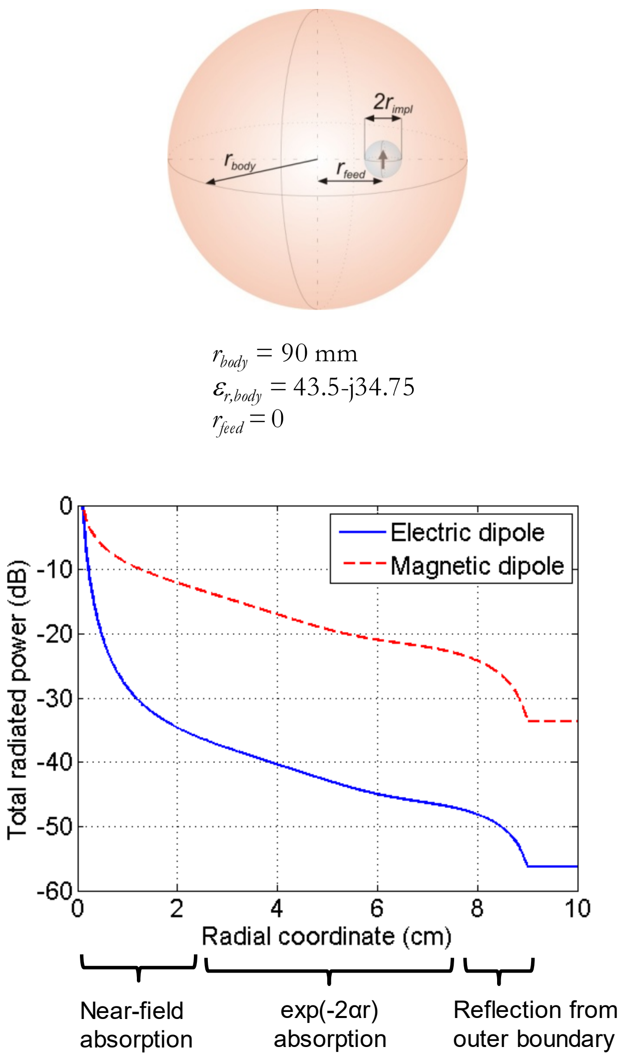


Fig. 1. Total radiated power as a function of the radial coordinate, for an elementary source implanted in the centre of a lossy host medium.

Thus, the design procedure is in principle very different form the design procedure of classic ESAs.

## IV. MEASUREMENT ISSUES

It is well known that the measurement of ESA's can be very tricky, due to the so-called cable effects [44, 45]. What happens is that as the antenna is small, the ground plane is usually too small to be a real ground plane, but becomes rather a radiating part of the antenna. Which means, that the excitation point to which the coaxial measuring cable is connected is not a port in the circuit sense anymore, but just a point where the signal is injected into the antenna. This does not have any consequences for the ESA in its final setup, as it will usually be connected by a very short printed line to the PA or the LNA. But when the antenna is measured it will generate a spurious current on the external conductor of the coaxial cable connecting the antenna to the measurement equipment. This current will induce spurious radiation, and thus strongly affect the measured results. Several means exist to alleviate this problem, and alternative measurement procedures have been developed to overcome the issue [46-49]. They are based on methods avoiding completely the cable by connecting the antenna directly to a source [46], the Wheeler cap method [47, 48] or the reverberation chamber method [49].

Implanted antennas encounter exactly the same problem, as in their case also the ground plane is too small to avoid cable currents. Moreover, the problem is exacerbated by the fact that the cable will be in contact with the lossy host medium, which, due to the losses, will strongly affect the current [50], leading to strong discrepancies between simulation and measurement not only on the radiated fields but also on the input impedance. Thus, the same precautions should be taken for the measurements of implanted antennas as that for classic ESAs.

In addition to the problem described above, the measurement of implantable or wearable antennas has to be performed on phantoms modelling the medium in or on which the antenna will be placed. These phantoms have to mimic the dielectric characteristics of these lossy media which are frequency dependent. Different phantoms are thus required for different frequency bands, which makes the overall measurement procedure quite costly.

Finally, The characterization of antennas radiating in or on living biological host bodies require the measurements of field and Specific Absorption Rate (SAR) levels, in order to ensure that the maximal levels specified by the regulator are not breached.

## V. Summary

In this contribution, we have presented the similarities and differences between antennas designed to be implanted or placed on a lossy host medium and classic electrically small antennas radiating into free space. We have seen that the Key Performance indicators (KPIs) differ significantly for the two families, as do the design procedures. The study of antennas radiating into (partially) lossy media is less advanced than in the case of ESAs, and more knowledge is required in order to derive efficient design and optimization procedures for the latter. Finally, the measurement issues are identical for both antenna families, making the experimental characterization of such antennas far from trivial.

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