Classic electrically small antennas versus In/ On-Body antennas: similarities and differences

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***Abstract*— Electrically small antennas (ESAs) have been discussed since the early radio days, when all antennas were small compared to the wavelength. The boom of mobile phones triggered a second wave of intense research activity on these devices, which continues today where virtually everything has a wireless connection. This intense research activity has produced interesting and usefully results on the physical limitations of such antennas, design rules and optimal designs. Since the beginning of the century, the number of medical, sports, or security applications (to name just some of them) requiring implantable or wearable communication devices has grown at a high speed, launching the interest for wearable or implantable ESAs. Many interesting designs have been published to this date, but we only start understanding the fundamentals of such antennas. Neither physical bounds on their radiation characteristics nor optimal designs or design rules are yet available. In this contribution, I will highlight the main similarities and differences between classic ESAs and antennas for wearables and implants, illustrated by practical examples..**

***Index Terms*—miniature antennas. Implantable antennas**

I. INTRODUCTION

The story of electrically small antennas (ESAs) started with the early days of radio communications, as due to the low frequencies used, the first wireless telegraph antennas were physically huge, but electrically very small. This fact triggered the first series of studies on the characteristics of such antennas, their physical limitations and on how to design them [1-4]. A second wave of interest for ESAs appeared in the eighties and nineties, due to the apparition of digital mobile phones and the huge interest for the public for such devices. This lead to new studies on fundamental limits of ESAs [5,6], or their design [7,11]. New services lie Bluetooth, GPS, WiFI, WLAN, RF-IDs, wireless sensors, the Internet of Things (IoT) increased the demand antenna miniaturization and multifreqeuncy small antennas, while the request for larger wireless capacity lead to diversity antennas, smart antennas and MIMO.

At the turn of the millennium, as new family of wireless devices appeared, namely devices to be worn On or implanted In a living wearer, human or animal. Applications for these devices range from medical to sport, over security and fashion. It soon appeared that the knowledge gain on the classic ESA studies were not always applicable to antennas for wearable or implantable sensors, even if the latter are in general electrically small. Indeed all classic ESA studies presuppose that the antennas radiate into a free space, thus a lossless environment, which is not the case for antennas placed in or on a biological medium. Thus new studies on the fundamental characteristics of such antennas are requested, with some initial results available for instance in [11].

In this contribution, similarities and differences between classic ESAs and miniature antennas for wearables and implantables will be highlighted. Initial fundamental limits for implantable antennas will be presented, and a first set of design rules proposed.

II. SIMILARITIES AND DIFFERENCES

It was soon recognized that the main difficulty in realizing ESA was achieving a reasonable bandwidth and a high directivity. The antenna quality factor soon emerged as one of the most relevant figure of merit, as it is linked to the bandwidth for ESAs [12-13]. This lead to the classic first limit on the quality factor for a linearly polarized ESA, namely [2-7, 14]

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

The second figure of merit for ESAs was defined as he achievable directivity. However, there is no fundamental limit on the directivity of an antenna, as superdirectivity has shown. There is however a limit on the ration of the directivity over the quality factor. In the same idea, Harrington [3] proposed the limit for the directivity of an antenna with a reasonable bandwidth, again for linearly polarized antennas:

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

where k is the wavenumber and a the radius of the smallest sphere circumscribing the antenna. These results are easily extendable to circular polarization. polarization, but are easily extendable to circular polarization [2, 15-18].

These studies were in later years refined in order to take into account the antenna's shape factor [19], dispersive materials [20], losses in the antenna materials [21], 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. The figures of merit concerned were again the quality factor and the directivity.

In the case of wearable or implantable antennas, these figures of merit do not apply anymore, as for instance the bandwidth is more influenced by the losses surrounding the antenna than by the latter's design. Moreover, as the directivity is defined in the far field [25], it depends more on the host body than on the antenna. The actual figure of merit for wearable or implantable antennas is the total power reaching outside the host body. Thus new figures of merit need to be defined both for wearable or implantable antennas. A potential candidate is the Total Power Radiated outside the (lossy) host body. In order to gain insight on limitations on antenna radiating into a lossy medium, a canonical model based a spherical wave decomposition of an elementary was proposed for implants [26.27] and wearables [28], always considering a spherical phantom for the host body. Initial results on the limitations of implantable antennas are presented in [29].

Optimal classic ESAs are designed by optimizating the geometry of the antenna in order to minimize the structure's stored energy. Optimal implantable antennas on the other hand are designed by minimizing the power dissipated in the lossy host body [29].

Finally, both classic ESA's [30-33] and small antennas for wearables or implants [24] are notoriously difficult to measure, due to the spurious mode induced on cable of the measurement setup. This mode is due to the fact that an antenna which is small as compared to the wavelength does not have a well defined port.

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