Research Networking Programmes

ESF Research Networking Programme NEWFOCUS

Final scientific report

Project title: **Focusing properties of elementary sources embedded in lossy multilayer spherical medium**

Applicant:
Zvonimir Sipus
Faculty of Electrical Engineering and Computing
University of Zagreb
Unska 3, 10000 Zagreb, Croatia
e-mail: zvonimir.sipus@fer.hr

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Host institution: Laboratory of Electromagnetics and Acoustics (LEMA), Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Host: Prof. Anja K. Skrivervik

Purpose of the visit

Various kinds of antennas are today used for sensing purposes or as parts of sensing systems that are installed inside some host medium. This implies that the antenna is often embedded inside a complex multilayered medium with losses that cannot be neglected. In such cases the antenna is enclosed in a shell which serves as a shield from the environment and also as the impedance matching medium. Due to the presence of the shell and the surrounding host medium the radiation properties of these antennas are quite different with respect to their behaviour in free space and they have been very marginally discussed in scientific literature. Elaborate studies don't exist because the problem is quite complex from a numerical point of view since it contains an antenna in a multilayered enclosure inside a larger lossy and possibly also multilayered medium.

In order to study the radiation and specially focusing properties of such antennas when placed at arbitrary position inside the host medium, we are developing a numerical algorithm suitable for solving these kinds of problems for spherical structures. It is based on separate spherical mode decomposition of waves inside the small spherical enclosure and inside the larger host sphere.

Within this short visit the aim is to collaborate with EPFL to investigate the problems related to the presence of different types of sources and their exact positioning inside the focusing shell to optimize their performance.

Description of the work carried out and main results obtained

During the exchange period at the EPFL the research was focused, as mentioned, on studying the complex propagation of waves due to sources in and on human body (modeled as multilayer spherical structure), in order to in a second step optimize antennas for Wireless Body Area Networks (WBANs). In this contribution we present results of a efficient numerical analysis tool developed to study the EM wave propagation inside human body. As it can be seen in Fig. 1 the structure of interest consists of two spherical structures - the spherical model of a body and the spherical model of an implanted antenna. Each spherical structure can be multilayered and can be separately analyzed using the spherical-wave modal expansion approach. Therefore, the main challenge in the analysis of the structure in Fig. 1 lies in connecting two spherical problems that have displaced centers of coordinate systems.

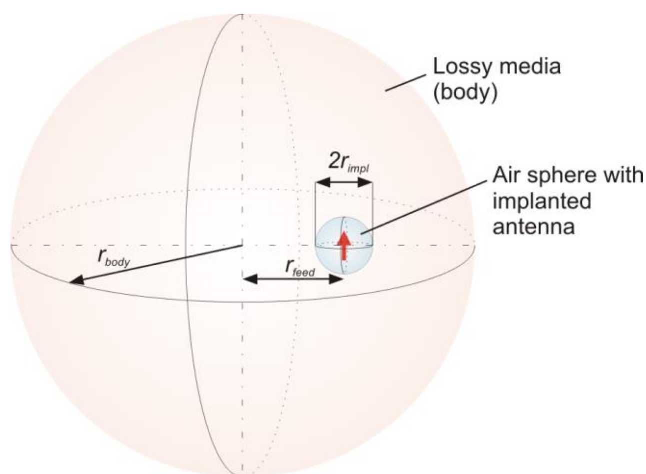

Figure 1. View of the analyzed structure with the excitation moved away from the center.

The EM fields in the implanted antenna sphere and in the outer sphere (human body) are “matched” using the equivalence theorem. In more details, using Love’s equivalence principle we have defined two equivalent problems: (a) the equivalent implanted antenna problem consisting of an implanted antenna surrounded with air, and (b) the equivalent spherical body problem in which the implanted antenna is replaced with a dielectric of permittivity equal to the one of implanted antenna surrounding material. Therefore, for the equivalent inside problem we consider the radiation of a dipole and of equivalent currents in the free-space, and for the equivalent outside problem we consider equivalent currents radiating in the homogeneous space with the permittivity equal to the permittivity of the layer that surrounds the small sphere (i.e. implanted antenna). The spherical harmonics representations of two equivalent problems should fulfill the boundary condition that the tangential EM-field is continuous at the boundary of the small sphere (containing the implanted antenna).

As an example, we have considered a simplified model of a human head consisting of a sphere with 9 cm radius and permittivity 43.50 – j34.75 at the working frequency of 403.5 MHz [IEEE Head model]. The air sphere around the source dipole has the radius of 0.1 cm, and both the electric and magnetic dipole excitations are considered. The E-field variation inside the body as a function of the implanted antenna position is given in Fig. 2 (the observation point is on the same axis as the source). As expected the decaying tendency is approximately the same for all positions of the source. However, the total radiated power, defined as the EM power leaving the spherical lossy body normalized with the power entering the host dielectric body (i.e. with the power leaving the small shell containing the dipole), almost does not depend on the position of the excitation dipole inside the model (see Fig 3.). This is a slightly non-intuitive result since the E-field magnitude increases with decreasing the distance between the source and the outer sphere interface. The reason for that is that the radiated field is more directive in such a case (see Fig. 4.a in which the angular dependency of the E-field magnitude is presented at the radial distance 10 cm from the center of spherical body). In other words, the body acts as a focusing device with a more dominant focusing effect when the implanted antenna is located closer to the body interface. Therefore, although locally the power density is increased, the total radiated power is almost constant. However, in the far field the difference between all three cases is not big (see Figure 4.b; the whole structure is quite small in terms of a wavelength).

In Fig. 3 the comparison between electric and magnetic excitations is also given. It can be seen that the magnetic dipole emits much higher level of total power. This is mostly due to the fact that magnetic dipole excites much stronger magnetic field in the vicinity of the dipole, which does not dissipate in the body since there are no magnetic losses present in human tissues. Furthermore, the comparison with the results obtained with a general EM solver (CST Microwave Studio) is also given in Figs. 2 and 3 to verify the results obtained using spherical modes expansion program. One should however note that the developed program based on spherical modes expansion is four orders of magnitude faster compared to the general solver.

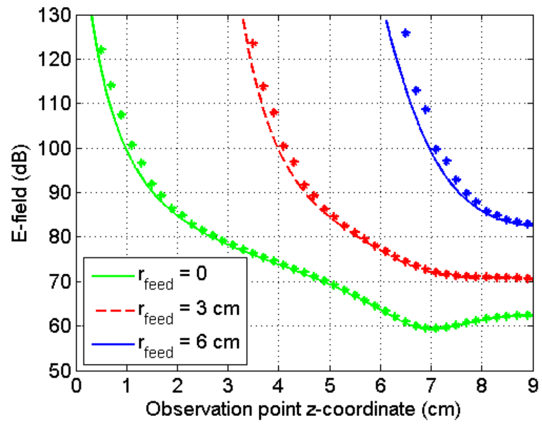

Figure 2. The E-field magnitude as a function of source and observation point positions. The source is located at the z-axis. Star-shaped dots represent the results obtained using CST Microwave Studio.

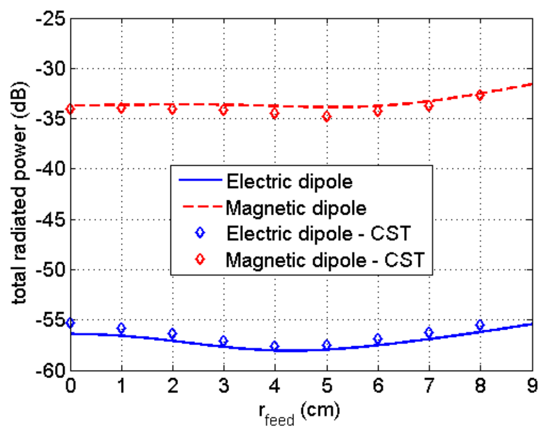

Figure 3. Total radiated power as a function of the source position.

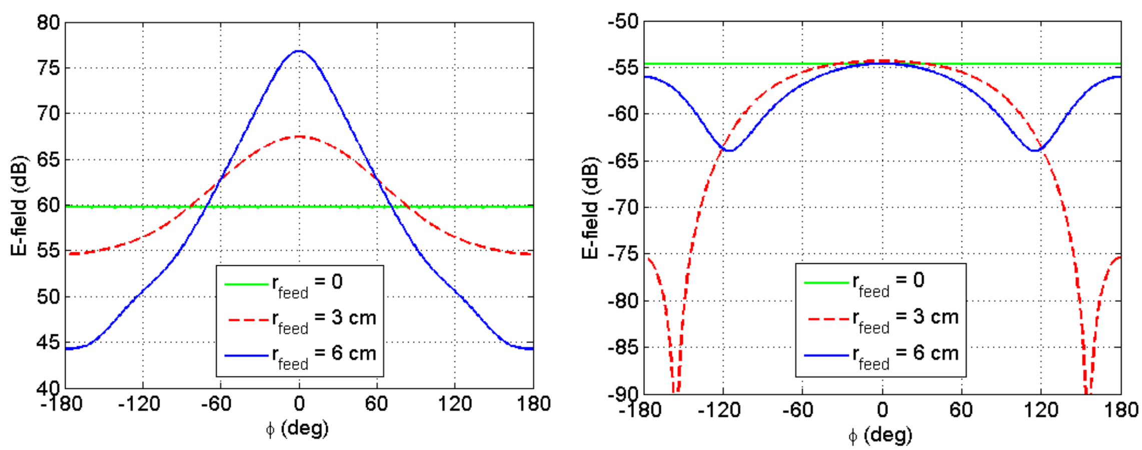

Figure 4. The angular dependency of the E-field magnitude as a function of source position. The x-oriented source is located at the z-axis and the angular dependency is taken in yz plane (a) just outside the dielectric sphere; (b) the far-field radiation pattern.

The comparison of total radiated power between electrical dipoles parallel and perpendicular to the outer surface is given in Fig. 5. It can be seen that a much higher level of radiated power can be obtained if the dipole is oriented parallel to the nearest boundary of the sphere, mostly because the dipole has a zero in the far field in the axial direction. Similar results are obtained for the magnetic dipole. The comparison of total radiated power of single-layer and multilayer shell model of lossy body (i.e. of spherical head model) is also given in Fig. 5. The multilayer model contains a 4mm thick layer of bones (ε_r = 13.139 - j4.083) and a 2 mm thick layer of skin (ε_r = 46.70 - j30.72). The outer sphere radius is kept the same (r_{body} = 9 cm). It can be seen that the presence of several layers at the outer boundary only slightly affects the radiated power. Therefore, we can also conclude that in this basic research it is not critically important to analyze the accurate model of the human body and of the implanted antenna.

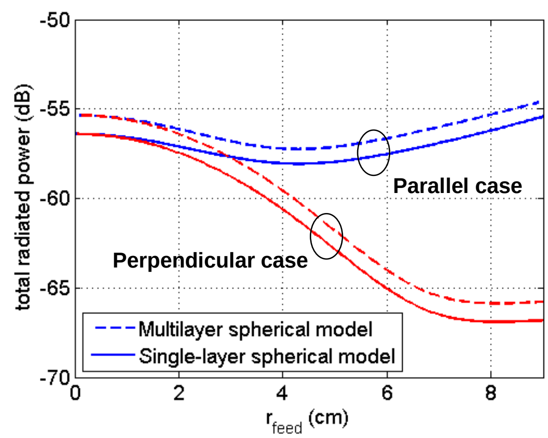

Figure 5. Comparison of the total radiated power of electrical dipoles directed orthogonal (perpendicular) and parallel to the nearest spherical boundary. Solid lines represent single-layer spherical model, dashed lines represent multilayer spherical model.

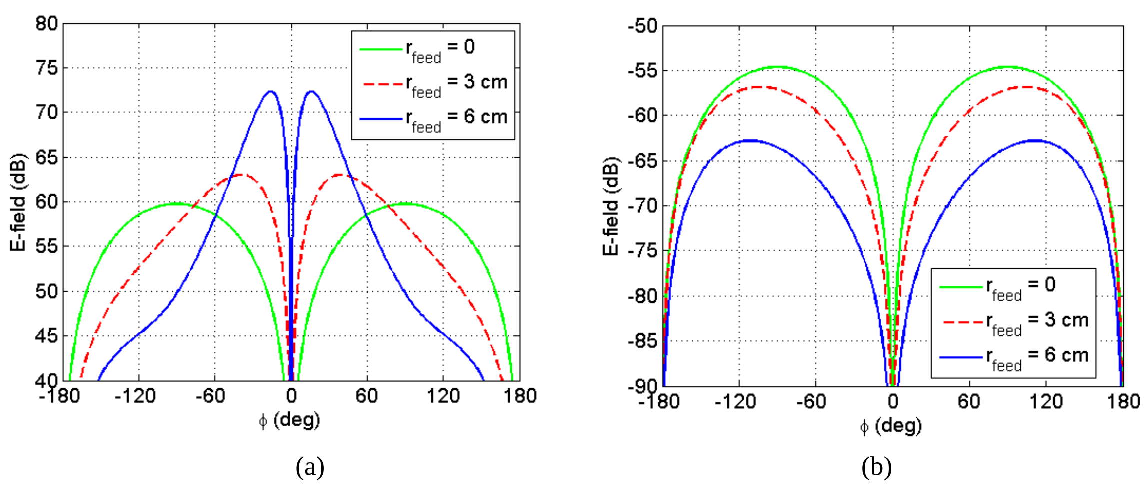

Figure 6. The angular dependency of the E-field magnitude as a function of source position. The z-oriented source is located at the z-axis and the angular dependency is taken in yz plane (a) just outside the dielectric sphere; (b) the far-field radiation pattern.

The reason why a much higher level of radiated power can be obtained if the dipole is oriented parallel to the nearest boundary of the sphere is illustrated in Figure 6. The main reason is the fact that the dipole has a zero in the far field in the axial direction. This is visible both in the near and far field regions (Figures 6.a and 6.b, respectively). The focusing effect is much stronger in the near-field region, just like in the case of parallel dipole (the whole structure is quite small in terms of a wavelength, therefore the far-field not so different comparing to the dipole in the free-space; however the field-level is much smaller due to absorption in the lossy dielectric body).

We still need to distinguish absorption losses and reflection from the outer boundary. The dominant factor (as seen in Figure 7) are losses in the dielectric of the body. To prove our statement let us investigate the case when the implanted antenna is located in the center of the sphere. We have calculated the total radiated power as a function of radial coordinate (i.e. we have investigated how the total radiated power is reduced with enlarging the distance from the implanted antenna). Note that for considered radial coordinate smaller than 9 cm we are still inside the dielectric body. Note also that outside the body (r > 9 cm) the total radiated power is constant since there are no losses outside the body. From Figure 7 it can be seen that we can distinguish three regions. First region is near-field region ($1/r^3$ region) in which there is a strong attenuation in the case of electric dipole (since in that case the electric field is much stronger in the vicinity of the dipole and we have assumed that all the losses are included in complex permittivity, i.e. we have assumed non-magnetic body material). Then we have a region in which the dominant absorption is from the factor $\exp(-jkr) = \exp(-\alpha r) \cdot \exp(-j\beta r)$ that is part of the spherical Hankel function. Finally, there is a loss from the reflection from the outer surface (in the planar approximation the predicted losses due to the discontinuity are -3.7 dB).

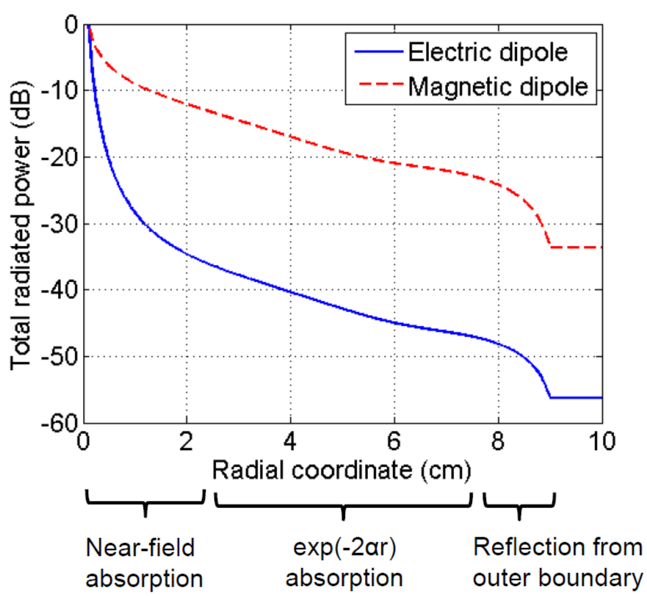

Figure 7. Total radiated power (out from the sphere of considered radius) as a function of radial coordinate.

Finally, we have investigated the dependence of the total radiated power on the working frequency (i.e. on the size of the dielectric body) as shown in Fig. 8, where electric excitation for the single-layer body model is considered. Note that the frequency variation of the permittivity is also taken into account (εr = 41.5 - j20.22 at 800 MHz, and εr = 40.0 - j12.58 at 2 GHz). It can be seen that although the size of the spherical body (in wavelengths) has changed, the amount of total radiated power did not change significantly (it is even larger for the electric dipole excitation), mostly due to reduced value of the imaginary part of permittivity.

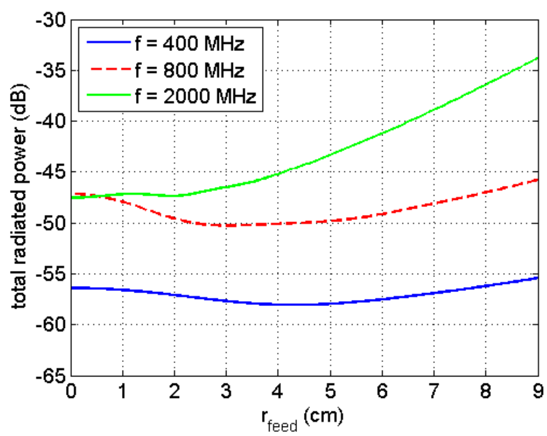

Figure 8. Total radiated power as a function of the frequency and of the source (electric dipole) position.