

## **HUMAN BODY EFFECTS ON IMPLANTABLE ANTENNAS FOR ISM BANDS APPLICATIONS: MODELS COMPARISON AND PROPAGATION LOSSES STUDY**

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**Abstract**—In this paper propagation losses of body implanted antennas are studied at the ISM bands of 433 MHz, 915 MHz, 2450 MHz and 5800 MHz. Two body models are used, one based on a single equivalent layer and the other based on a three layer structure, showing the advantages and limitations of each one. Firstly, the antenna pair gain at different implanted antenna depths is analyzed. Next, we show the effects of the thickness of the different body tissue layers. Finally, we discuss the consequences of using a coating layer to isolate the antenna from the harsh environment of the human body.

### **1. INTRODUCTION**

During the second half of the past century an important effort was put in the design of different implantable biomedical devices for the treatment of various illness [1]. In 1952, Dr. P. Zoll reported the first external pacemaker [2], and some years later, the first implantable pacemaker was presented. As time went by, these primitive devices evolved to the actual ones, with better performance and longer lifetime. Other examples of applications where implantable devices can be found are monitoring systems, drug delivery systems and defibrillators [1].

In implantable devices a wireless link with an external receiver is desirable. It can be used to monitor the battery level of the device and the clinical parameters of the patient. For example, an implantable sensor with a wireless link could be used in a glucose monitoring system [3], automatically alerting the emergency systems

when a problem is detected. These implanted sensors with wireless communication links will be one of the key points for the future e-health systems.

The evaluation of the implanted antenna performance is difficult because it is almost impossible to make antenna measurements in the real operating scenario (inside the human body). For this reason, simulation models and physical models (phantoms) are extremely important to predict the behavior of the antenna and the whole system performance.

In measurements, the most widespread solution is the use of body tissue simulating liquids that fill a container with a regular or an anatomical shape [4]. The antenna is sunk into the liquid and measurements are carried out [5–9]. The main advantage of this method is that it is easy and practical to implement. Recently, Karacolak [10, 11] has been working in the use of tissue simulating gels trying to obtain a multilayered structure. Other authors have carried out measurements with real tissues [12, 13].

In simulations, the option that is simplest and fastest, but less accurate, is that which uses a single layer structure (equivalent to measurements made with tissue simulating liquids). Other options are the use of multilayered structures, with finite or infinite dimensions, or the use of 3D anatomical models [14–21]. These realistic anatomical models offer more accurate results, but the computational requirements are higher. For this reason, the aforementioned one layer and multilayer models are still very popular.

In this paper propagation losses of body implanted antennas are studied. Firstly, we will use the one layer and three layer models to evaluate the effects of introducing the antenna inside the human body. We will show the system performance as a function of different parameters: external antenna distance, implanted antenna depth and operating frequency. Next, we will use the three layer model to study the effects of the thickness of the different body tissue layers. Finally, we will discuss the consequences of adding a coating layer to the antenna, which is necessary for biocompatibility issues.

## 2. FREE SPACE WIRELESS LINK

In this section, a free space wireless link will be described. The system under study is based on two antennas. One of the main parameters that defines the performance of a wireless system is the antenna pair gain ( $G_a$ ) [22]. It can be calculated using the scattering parameters of

the system as

$$Ga = \frac{|S_{21}|^2}{(1 - |S_{11}|^2)(1 - |S_{22}|^2)} \quad (1)$$

where the term in the denominator is used to subtract the mismatch losses of the transmitting and receiving antennas.

The antenna pair gain is mainly related to the propagation losses and the antennas gain. In a free space scenario, where both antennas are outside the body and far field conditions are assumed, the antenna pair gain can be computed as

$$Ga_{(fs)} = G_T G_{Air} G_R \quad (2)$$

where  $G_T$  is the gain of the transmitting antenna,  $G_R$  is the gain of the receiving antenna and  $G_{Air}$  is the air propagation gain or free space propagation gain defined as

$$G_{Air} = \left( \frac{\lambda}{4\pi r} \right)^2 \quad (3)$$

where  $\lambda$  is the free space wavelength and  $r$  is the distance between both antennas.

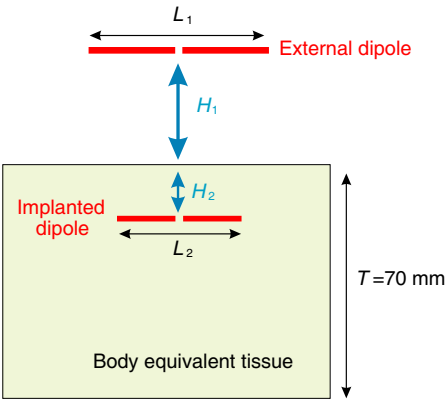
### 3. ONE LAYER MODEL

In this section we will use the one layer model to study the effects of having one of the antennas implanted in the human body. Firstly, we will define the simulation scenario, and next, the simulation results obtained with the FEKO MOM code [23] will be presented.

#### 3.1. Simulation Scenario

The system under study is based on two antennas, one implanted inside the human body, and the other external to the body. Taking into account that the aim of this paper is the study of the body effects and not the design of the antenna, simple straight dipoles will be used due to its simplicity. They are not the optimal solution, but they are typically used as reference antennas.

Half wavelength resonant dipoles will be used as transmitting and receiving antennas to avoid precision errors when subtracting the mismatch losses in (1). The frequency bands included in the analysis are the ISM (Industrial, Scientific, Medical) bands of 433 MHz, 915 MHz, 2450 MHz and 5800 MHz. The results of the 433 MHz band can be also considered valid for the 402–405 MHz MICS (Medical Implant Communication Service) band.



**Figure 1.** One layer simulation scenario. Half wavelength resonant dipoles are used as transmitting and receiving antennas. The body equivalent tissue properties are shown in Table 1.

**Table 1.** Electrical properties of the body tissues at the different frequency bands included in this study [24–26].

Frequency (MHz)	Relative Permittivity $\varepsilon_r$				Conductivity $\sigma$ (S/m)			
	433	915	2450	5800	433	915	2450	5800
Body equivalent tissue	56.7	55	52.7	48.2	0.94	1.05	1.95	6.0
Skin	46.08	41.33	38.01	35.11	0.70	0.87	1.46	3.72
Fat	5.57	5.46	5.28	4.95	0.04	0.05	0.10	0.29
Muscle	56.87	54.99	52.73	48.48	0.80	0.95	1.74	4.96

The simulation scenario and the definition of the different parameters are shown in Fig. 1. In order to reduce the simulation computational requirements an infinite dielectric structure has been used to model the body.

In the one layer model there is an additional question that must be answered: Which are the properties of the equivalent material to model the overall behavior of the real human body dielectric structure?

In literature different solutions can be found. For instance [5] and [6] use a material called “2/3 muscle”, that is, the electrical properties of the muscle tissue multiplied by 2/3. We believe that

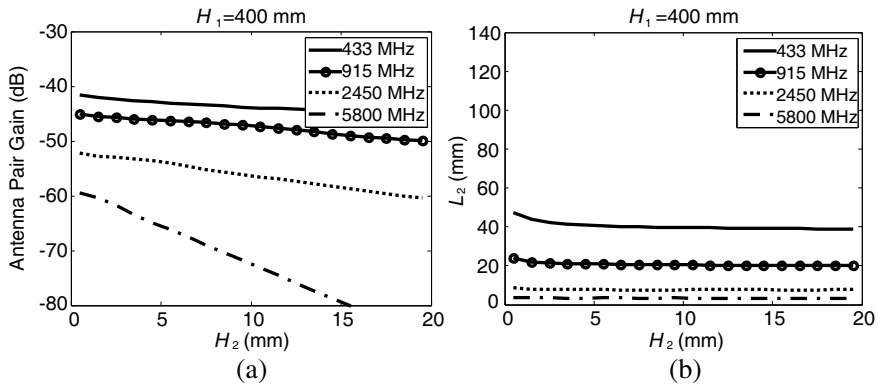
these values are not realistic, for this reason, we will use the properties of Table 1, defined by the Office of Engineering and Technology (OET Bulletin 65 supplement C [25]) of the Federal Communications Commission (FCC). The same values are also used in some commercial tissue simulating liquids (SPEAG [26]). The conductivity of this equivalent material is slightly higher than the conductivity of the muscle and the other body tissues, therefore, the propagation losses simulated by this equivalent material will be overestimated.

### 3.2. Simulation Results

The insertion of the antenna inside the human body will have two main effects: A decrease in the implanted resonant antenna dimensions due to the high dielectric permittivity of the body tissues and a degradation of the gain due to the high conductivity of these tissues.

Figure 2(a) shows the antenna pair gain ( $G_a$ ) as a function of the internal antenna depth when the external antenna is 400 mm away from the body surface. The simulation reference impedance is  $50\ \Omega$ . Although the mismatch losses are subtracted from the antenna pair gain (Equation (1)) it must be said that good matching levels are usually obtained for both antennas.

Figure 2(a) shows as the antenna pair gain decreases when the frequency is increased. For instance, if the the implanted antenna depth is equal to 10 mm, the antenna pair gain decreases almost 20 dB when the frequency is changed from 2.45 GHz to 5.8 GHz. This degradation is due to the increase of the free space propagation losses



**Figure 2.** Simulation results for the one layer model (Fig. 1). (a) Antenna pair gain. (b) Implanted dipole length to keep the antenna resonant.

(the frequency is multiplied by 2, therefore 6 dB are added to the free space propagation losses) and the increase of the body conductivity (Table 1) that introduces approximately 14 dB of additional losses.

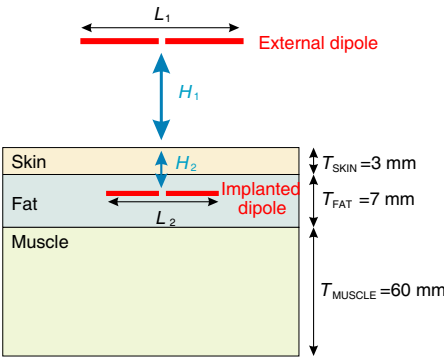
Figure 2(b) shows the required implanted dipole length to keep the structure resonant at different depths. It has been obtained empirically through an iterative simulation process.

This length is inversely proportional to the frequency. It is significantly smaller than one half of the free space wavelength because of the high permittivity of the body tissues. In Fig. 2(b) it can be also observed that, with the one layer model, the dipole length does not change significantly with the depth.

According to these results, a clear tradeoff between antenna dimensions and performance exists. When frequency is increased, antenna dimensions are reduced, but the antenna pair gain decreases degrading the system performance. Similar results and tendencies have been obtained with finite dielectric structures (higher computational requirements).

4. THREE LAYER MODEL

In the previous section, propagation losses have been studied using a simple one layer model. In this section we will repeat the study using a three layer model in order to represent more accurately the real scenario. Both studies will be compared to establish the one layer model limitations.



**Figure 3.** Three layer (Skin-Fat-Muscle) simulation scenario. Half wavelength resonant dipoles are used as transmitting and receiving antennas. The body tissues properties are shown in Table 1.

#### 4.1. Simulation Scenario

In this section, the three layer model shown in Fig. 3 (Skin-Fat-Muscle) will be used to model the body effects. Depending on the body area where the antenna is implanted the thickness of each layer can be different. For this reason thickness values used in literature may vary from author to author [3, 8, 10, 27, 28]. As average values, the thickness shown in Fig. 3 will be used. The electrical properties of the body tissues can be found in Table 1.

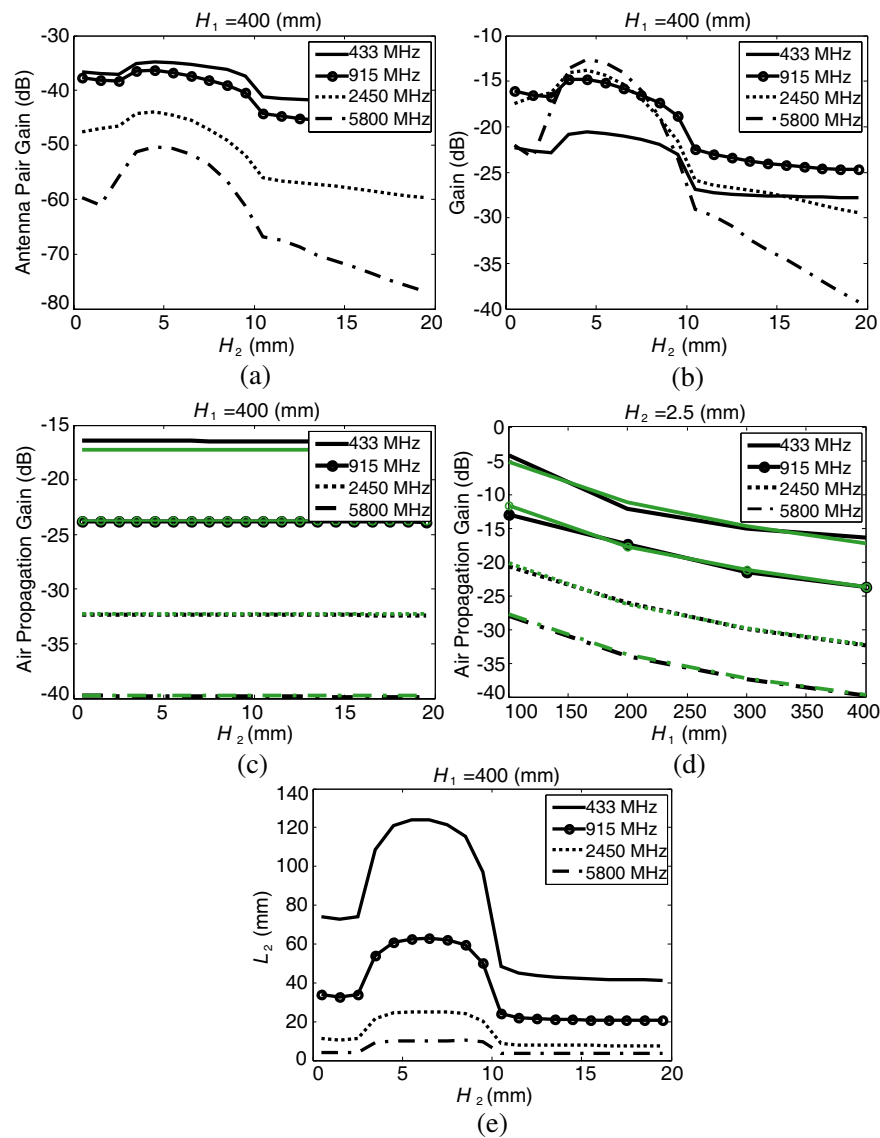
#### 4.2. Simulation Results

Figure 4 shows the simulation results when the three layer model is used. It can be seen as the antenna pair gain (Fig. 4(a)) depends significantly on the layer where the antenna is positioned. In the implanted antenna gain plot (Fig. 4(b)), the effects of the three layers can be clearly distinguished. According to Table 1, skin and muscle tissues have higher conductivity values, therefore, the implanted antenna gain is lower in these layers. Fat tissue has lower conductivity, consequently, the gain in this layer is higher. It must be noted that for the higher bands, where the fat layer is electrically thicker, more than 10 dB of improvement can be obtained.

Figures 4(c) and (d) show the air propagation gain ( $G_{air}$ ). Simulated air propagation gain has been obtained subtracting the internal and external antenna gains from the antenna pair gain ( $G_a$ ). The theoretical results obtained using a free space propagation model have been plot with a green thin line (Equation (3)). When the depth of the implanted antenna ( $H_2$ ) is changed, flat plots are obtained, proving that with typical antenna depths of some millimeters, the air propagation gain does not significantly depend on this parameter. When the distance to the external antenna ( $H_1$ ) is changed, an inversely proportional quadratic dependence is observed, showing a good agreement with the theoretical model.

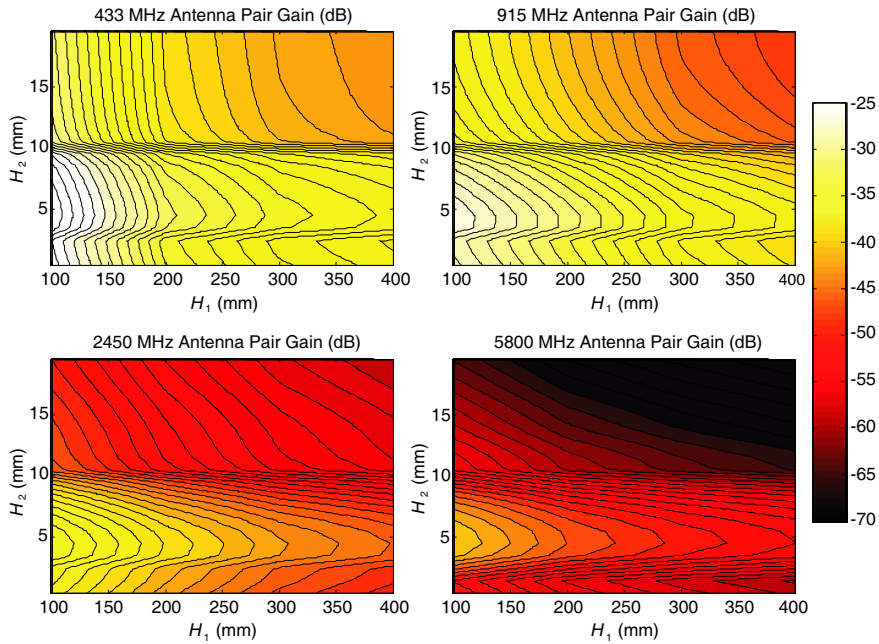
These results prove that when far field conditions are fulfilled, body losses can be included in the gain of the implanted antenna and assume a simple propagation model to evaluate the system link budget.

Finally, Fig. 4(e) shows the dipole length ( $L_2$ ) required to keep the internal dipole resonant. When the antenna is in the fat layer, the effective permittivity is significantly lower and the dipole length has to be increased by approximately a factor of 2 in order to keep the same resonant frequency. As it was aforementioned, we can see a tradeoff between antenna dimensions and performance. When the antenna is in the fat layer, its gain is higher (Fig. 4(b)), but it has to be longer to keep the same operating frequency (Fig. 4(e)).



**Figure 4.** Simulation results with the three layer model (Fig. 3). Thick black lines show simulated results, thin green lines show theoretical results. (a) Antenna pair gain. (b) Implanted antenna gain. (c) Air propagation gain as a function of the implanted antenna depth. (d) Air propagation gain as a function of the external antenna distance. (e) Implanted dipole length to keep the antenna resonant.





**Figure 5.** Coverage maps showing the antenna pair gain ( $G_a$ ) at the different frequency bands as a function of the depth of the implanted antenna and the distance to the external antenna. Coverage maps are useful to quickly predict the performance of the system depending on the frequency band and the antennas position.

Figure 5 shows the coverage maps at the different frequency bands. In these coverage maps the antenna pair gain is plotted as a function of the depth of the implanted antenna ( $H_2$ ) and the distance to the external receiver ( $H_1$ ). These maps can be used in the system design process. From the system specifications, the required antenna pair gain is computed, and through Fig. 5, the range of the system can be easily predicted for a given frequency band and an implanted antenna depth. As an example, if the antenna pair gain has to be higher than  $-35$  dB to assure the properly system operation, we can predict that it will be impossible to have the system operating at  $5.8$  GHz.

#### 4.3. One Layer Model vs Three Layer Model

This section shows a comparison between the results obtained with the one layer model and the three layer model. Our objective is to point out the limitations of the one layer model, which are similar to the

limitations existing in the measurements made using phantoms filled with a uniform equivalent tissue simulating liquid.

With reference to the antenna pair gain, it is lower in the one layer model (Fig. 2(a)) than in the three layer model (Fig. 4(a)). This fact was predictable since the conductivity values used in the one layer model are slightly higher than the values used in the three layer model. However, it must be noted that the one layer model does not take into account the gain improvement when the antenna is in the fat layer. Therefore, the one layer model tends to overestimate losses so it can be accepted as a conservative approach from the point of view of antenna pair gain.

Figures 2(b) and 4(e) show the implanted dipole length as a function of the depth ( $H_2$ ). In the three layer structure differences in length are important (more than a factor of 2) depending on the tissue in which the antenna is implanted. This effect is not considered in the one layer model, where the length of the internal dipole is kept almost constant.

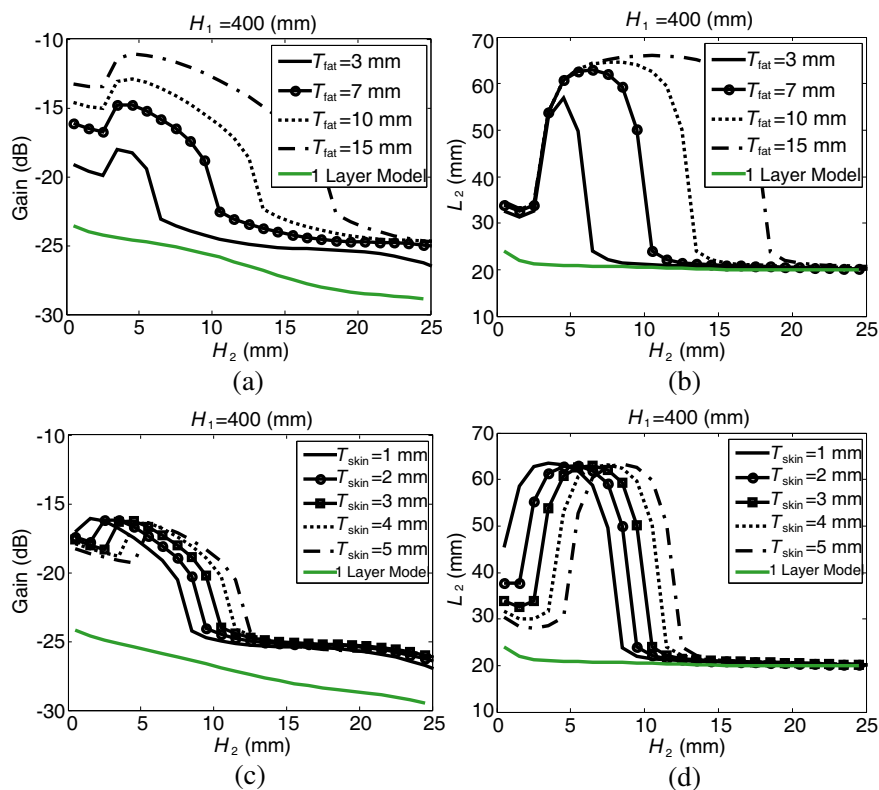
This is an important limitation of the one layer model and the measurements made using an homogeneous body tissue simulating liquid. If the antenna design is carried out taking into account the single layer model, the phantom measurements can agree with simulations. However, if the antenna is implanted in the fat layer, it will be detuned and the system might not work properly. The conclusion is that a three layer model should be used in the antenna design process, especially if the antenna has to be implanted in the fat layer.

## 5. EFFECTS OF THE LAYERS THICKNESS

In this section the effects of modifying the thickness of the skin and fat layers will be shown. The skin layer can change from 1 mm to 5 mm depending on the part of the body, and the fat layer from 3 mm to 15 mm. Furthermore, we will continue with the comparison of the one layer and the three layer models.

Figure 6(a) shows the antenna gain at 915 MHz as a function of the fat layer thickness. The thicker is this layer, the wider is the depth range where the gain is maximum and the higher is the maximum value of this gain. This is due to the fact that the antenna is more separated from muscle and skin so the losses introduced by these tissues are reduced.

Figure 6(b) shows the length of the resonant dipole for different fat layer thickness. When the thickness of this layer increases, the depth range where the dipole has to be longer is wider. Comparing



**Figure 6.** Effects of the skin and fat layers thickness. The solid green line shows the results obtained with the one layer model. Operating frequency 915 MHz. (a) and (c) Implanted antenna gain. (b) and (d) Implanted dipole length to keep the antenna resonant.

the one layer model and the three layer model, the differences between both models become more important when the fat layer is thicker.

When the thickness of the skin layer is increased (Figs. 6(c) and (d)), the depth range where the antenna gain is higher changes accordingly to the fat layer depth. The same conclusion can be drawn for the depth range where the antenna is longer.

## 6. COATING LAYER EFFECTS

In previous sections the antenna was directly in contact with the human body. In real applications an insulation or coating layer of biocompatible material will be necessary to protect the antenna from

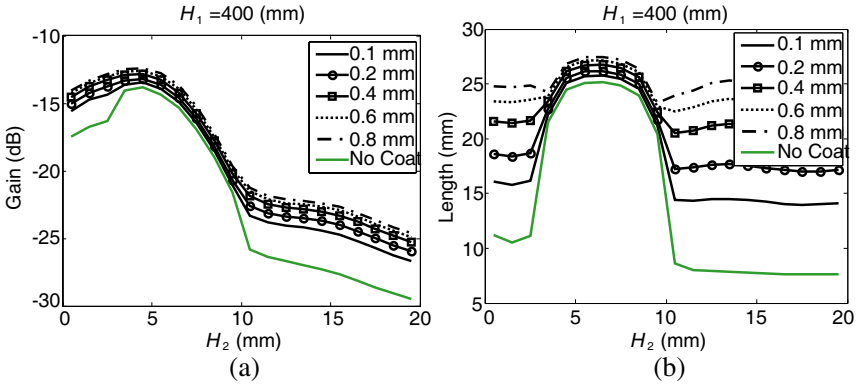
the body tissues. In this section the effects of this coating layer will be analyzed.

In [29] Merli et al. show a list of materials that can be used as insulation layers. In our study, a low loss coating layer with a relative permittivity equal to  $\varepsilon_r = 4$  will be considered. Fig. 7 shows the resonant dipole gain and length at the 2450 MHz band when the coating layer thickness varies from 0.1 mm to 0.8 mm. Results with no coating are also plotted.

With regard to the antenna gain, the presence of a coating layer is advantageous, especially if the antenna is in the muscle or skin layers where gain improvements around 5 dB can be observed with coating layers thinner than 1 mm. When the antenna is in the fat layer, the gain improvement is not so significant because losses are not so important in this layer.

Figure 7(b) shows the implanted dipole length to keep the antenna resonant. From this point of view the use of a coating layer has a positive and a negative aspect. The positive one is that, as the coating thickness increases, the antenna becomes less sensible to the surrounding material, and therefore, the antenna detuning in the different layers will be less significant.

The negative aspect is that when the coating layer is applied the effective permittivity decreases. Consequently, the miniaturization obtained by the high relative permittivity of body tissues is less important. Variations higher than a factor of 2 can be observed depending on the coating layer thickness.



**Figure 7.** Effects of a coating layer on the antenna performance. Operating frequency 2450 MHz. (a) Implanted antenna gain. (b) Implanted dipole length to keep the antenna resonant.

## 7. CONCLUSION

This paper has evaluated the propagation losses in a link between an implanted antenna inside the human body and an external antenna at the ISM bands of 433 MHz, 915 MHz, 2450 MHz and 5800 MHz.

The main effects of having the antenna implanted inside the human body are a reduction of its dimensions and an increase in the propagation losses. These effects are mainly due to the high permittivity and high conductivity of the human body tissues.

Simulation results prove that, when far field conditions are fulfilled, body losses can be included in the gain of the implanted antenna and assume a free space propagation model to evaluate the system link budget.

The most commonly used body models to predict the antenna behavior are the one layer model (measurements and simulations) and the three layer model (simulations). We have shown as the one layer model is a conservative approach that tends to underestimate the antenna pair gain and does not take into account the gain improvement observed with the three layer model when the antenna is in the fat layer. According to the three layer model, the resonant dipole has to be longer in the fat layer than in the muscle layer (a factor of 2 or higher). These variations are not considered in the one layer model. Therefore, when tissue simulating liquids are used in measurements, one have to be careful since, if the antenna is to be implanted in the fat layer, the measured input parameters can be quite different from the real ones.

When the frequency is doubled there exists a clear tradeoff between antenna dimensions and system performance. The antenna dimensions are reduced to one half. However, the free space propagation losses will be increased in 6 dB and the antenna pair gain will be further degraded due to the higher losses of the body tissues. A similar tradeoff is observed when the position of the antenna is changed from one layer to another.

We have generated some coverage maps. These coverage maps are useful for the system design. With the information of these plots, the system designer can obtain the antenna pair gain for a given frequency band and implanted antenna depth.

Finally, we have studied the effects of introducing a coating layer which is usually necessary for biocompatibility issues. The insulation layer decreases the losses, improving the gain of the antenna. Furthermore, the antenna properties are less dependent on the layer in which it is implanted. The main drawback is that the antenna dimensions have to be bigger because part of the miniaturization

obtained thanks to the high permittivity of the body tissues is lost.

## ACKNOWLEDGMENT

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