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Impact of the human body in wireless propagation of medical implants for tumor detection☆

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ABSTRACT

This paper analyses the feasibility of using implantable antennas to detect and monitor tumors. We analyze this setting according to the wireless propagation loss and signal fading produced by human bodies and their environment in an indoor scenario. The study is based on the ITU-R propagation recommendations and prediction models for the planning of indoor radio communication systems and radio local area networks in the frequency range of 300 MHz to 100 GHz. We conduct primary estimations on 915 MHz and 2.4 GHz operating frequencies. The path loss presented in most short-range wireless implant devices does not take into account the human body as a channel itself, which causes additional losses to wireless designs. In this paper, we examine the propagation through the human body, including losses taken from bones, muscles, fat, and clothes, which results in a more accurate characterization and estimation of the channel. The results obtained from our simulation indicates a variation of the return loss of the spiral antenna when a tumor is located near the implant. This knowledge can be applied in medical detection, and monitoring of early tumors, by analyzing the electromagnetic field behavior of the implant. The tumor was modeled under CST Microwave Studio, using Wisconsin Diagnosis Breast Cancer Dataset. Features like the radius, texture, perimeter, area, and smoothness of the tumor are included along with their label data to determine whether the external shape has malignant or benign physiognomies. An explanation of the feasibility of the system deployment and technical recommendations to avoid interference is also described.

☞ keywords: Body area networks, wireless implants, indoor propagation, fading estimation, human tissue modeling, tumor detection.

1. Introduction

Medical implants have become an increasing trend among medical technologies due to the practicality of having an embedded system to measure and monitor the changes of human body tissues [1], [2], [3]. Safety concerns regarding electromagnetic radiation from implantable antennas have been addressed by efficiently controlling the delivery of power [4], [5], and the selection of the frequency of operation [6]. Further considerations have been taken to the fact that an implantable antenna might be viewed as invasive inside a patient's organism under certain insertion depths [7], [8]. According to the authors, a depth of 1cm in fat or muscle tissue can be considered safe if it does not compromise any vital organ. Improvements in antenna hardware [9], [10], [11], and miniaturization [12], [13] have boosted research on electronic implants. Spiral planar antennas have been proposed to study the presence of cancer cells on human breast [14], [15]. However, they have not considered the effects of the human body as a wireless channel. Human models that include fat, skin, and muscle have been used to simulate the effects of these tissues in wireless signals [16]. The authors studied the antenna performance in terms of gain, and bandwidth. Nonetheless, the return loss of the antennas has not been investigated. The coverage requirement of these short-range wireless communications has led to increasing demand for a proper and accurate model for propagation losses, in special for indoor areas in sensitive and complex wireless communication applications (i.e., hospitals, and patient residences). Technical advances and developments had been conducted in different areas that involve specific fragments of the whole wireless-implant structure, such as network topology

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and power control [17]. Nonetheless, they lack to considerate the fading and losses existent in a real-world scenario, where the human body acts as a channel that attenuates wireless signals.

In this paper, we study the feasibility of using antennas implanted in the human body to detect and monitor tumors. Specifically, we analyze how the wireless propagation loss and signal fading in an implant are affected by a human body as a channel. We conduct primary estimations on 915 MHz and 2.4 GHz operating frequencies. We include the losses taken from bones, muscles, fat, and clothes, to estimate and characterize the channel more accurately. We show the variation of the return loss of the antenna when a tumor is brought closer to the implant.

2. Propagation loss through the human body

2.1 Indoor non-LOS propagation estimation for in-body antennas

We design our system to operate at a frequency of 915 MHz and 2.4 GHz, with a minimum coverage range of 10m. To guarantee the minimum coverage range, the system must be able to transmit across obstructions (i.e., walls, furniture, etc.) between the transmitter and receiver. Furthermore, the fact that we consider an implant with 1cm depth in the human body makes all line-of-sight (LOS) formulation useless. The estimation of propagation losses for this specific application cannot be described with an outdoor model scheme since these mathematical approaches are not accurate for indoor scenarios where changes in the environment of the wireless path have a considerable response on the propagation characteristics. In this case, the extent of coverage is defined by the minimum distance, the frequency limited to the ITU Region 2 ISM radio band, and the geometry of the building under study [18], [19].

In order to perform the analysis, an appropriate indoor non-LOS propagation model have to be selected. Our wireless implant design complies with the propagation characteristics within buildings at 915 MHz and 2.4 GHz. At these frequencies, the fading experienced by the human body is an acute issue, as well as the interference generated by multipath propagation and movement of people in the area of analysis. The ITU-R Indoor Site-General Model [20], obtained from the: “Propagation data and prediction methods for the planning of indoor radio communication systems and radio local area networks in the frequency range 300 MHz to 100 GHz”, provides guidance in order to perform the planning needed by the implant system, covering the required frequency range. The indoor planning used for this design requires general information referring to the building architecture in order to estimate a statistical model in static use, nevertheless, basic path loss estimation values can be defined from the ITU recommendation statistics [20]. The first part of the ITU-R basic model is constructed based on the path loss at a reference distance d_0 = 1 m, assuming free-space propagation. The model also accounts for an implicit budget for transmission through blocking to be encountered on a sole floor, this allowance is contained in the distance power loss coefficient (N). For the implant design, N is taken from the ITU-R recommendation for a 900 MHz frequency in an office environment and is equal to 33 [20]. The floor penetration factor (L_f) expressed in dB, can be obtained from the ITU-R recommendation. This factor depends on the number of floors (n) penetrated, and for the design purpose the value is 9 dB, obtained with a frequency of 900 MHz in an office environment considering n = 1 for a worst-case scenario [20]. The variable f represents the frequency of operation of the system in MHz, and d denotes the distance between the implant and the receiver unit (d = 10 m). The ITU-R Site-General Path Loss Model equation is presented below:

$$L_{total[dB]} = 20\log_{10} f - 28 + N\log_{10}\frac{d}{d_0} + L_f(n) \tag{1}$$

For the case of 900 MHz, a total loss

$$L_{total[dB]} = 20\log_{10}(900MHz) - 28 + 33\log_{10}\frac{10m}{1m} + 9 \tag{1.1}$$

equates 73.228 [dB].

2.2 Signal propagation with the human body as a wireless channel

Propagation of radio signals through the human body has been an issue of interest to several researchers that modelled and analysed the human body at deep [21], [22]. The correct estimation of the attenuation values in wireless body area networks, and personal area networks, are becoming a progressively important part of the mobile communications system. The specific absorption rate (SAR) is one of the most important variables in implant research.

2.2.1 Propagation through typical human tissues at 900 MHz

The basic path loss calculation values can be defined from the ITU recommendation model. For the proposed scheme, SAR attenuation estimations are considered based on research measurements of the human body parameters [23]. The permittivity of the skin is found to be ϵ = 46.7, with a conductivity of σ = 0.69 [S/m] and the mass density of human body tissues as ρ = 1.01×103 [Kg/m3]. Our design considers a skin penetration depth of ρ = 1×10-2 m. The following equation takes these variables into account to find the desired attenuation,

$$SAR = \frac{\sigma |E|^2}{\rho} \text{ [W/Kg]} \quad (2)$$

where $|E|$, indicates the induced electric field, and can de estimated as follows:

$$|E| = \frac{\sigma}{\epsilon} \text{ [V/m]} \quad (3)$$

Consequently, the following SAR value can be obtained from (2) as:

$$SAR = \frac{6.9\times10^{-1}|1.48\times10^{-2}|^2}{1\times10^{-2}} = 1.5\times10^{-2} \text{ [W/Kg]}, \quad (2.1)$$

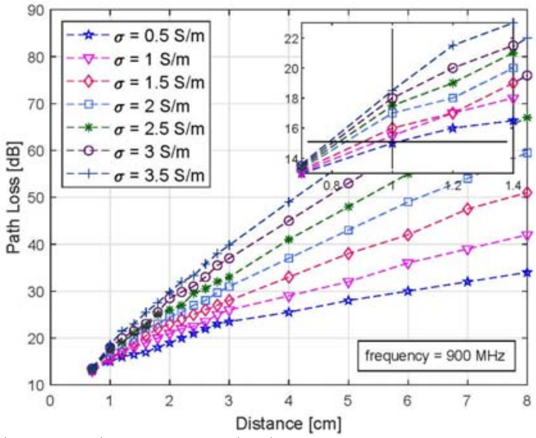
where the induced electric field is estimated from (3) as follows:

$$|E| = \frac{6.9\times10^{-1}}{46.7} = 1.48\times10^{-2} \text{ [V/m]}. \quad (3.1)$$

For the path loss estimation, fitted models as a function of separation for our frequency can be referred [24]. We have conducted our own simulations with the human Voxel model from The University of Texas, and for the conductivity of σ = 0.69×10-1 [S/m] at 1 cm of implant insertion, we obtained a path loss value of ≈ 15.1 dB (Figure 1). The total loss can be estimated as follows:

$$L_{total[dB]} = 20\log_{10}(915MHz) - 28 + 33\log_{10}\frac{10m}{1m} + 15.1 \quad (4)$$

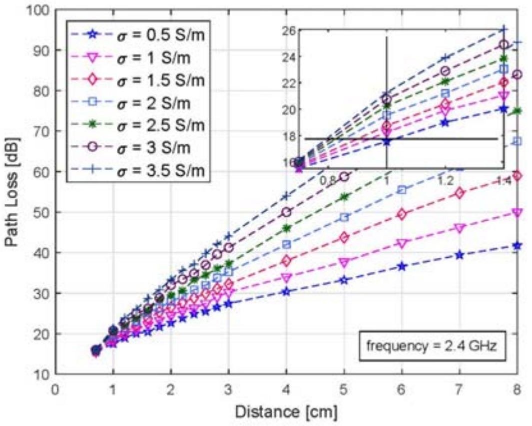
$$L_{total[dB]} = 79.328 \text{ [dB]} \quad (4.1)$$



(Figure 1) Path loss (dB) as a function distance (cm) for a range of between 0.5-3.5 S/m obtained from simulations on a human Voxel model at 900 MHz.

2.2.2 Propagation through typical human tissues at 2.4 GHz

Wide-ranging measurements and statistical analysis have revealed that propagation loss and fading in on-body communications channels at 2.4 GHz are not a stationary process [25]. To find the conductivity of the human body at an insertion depth of 1cm at 2.4GHz, we have plotted the simulation results from CST Microwave Studio on the human Voxel model from The University of Texas (Figure 2). We found a path loss value of ≈ 17.8 dB for the conductivity of σ = 6.9×10-1 S/m.



(Figure 2) Path loss (dB) as a function distance (cm) for a range of between 0.5-3.5 S/m obtained from simulations on a human Voxel model at 2.4 GHz.

The path loss at 2.4 GHz from the implant to the receiver located at 10 m, can be estimated as shown below:

$$L_{total[dB]} = 20\log_{10}(2400MHz) - 28 + 33\log_{10}\frac{10m}{1m} + 17.8 \quad (5)$$

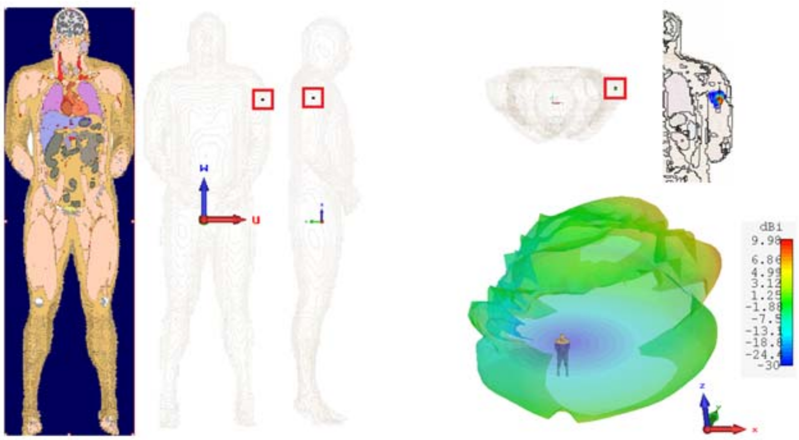
$$L_{total[dB]} = 90.404\,[dB] \quad (5.1)$$

According to [26], [27], the attenuation attributed to factors such as the body, head, and clothing are 19.2, 13.0, and 1.7 dB, respectively, from measurements performed in an anechoic chamber. These values are very accurate and similar to numerous subsequent investigations for this particular frequency and help us to corroborate of losses (17.8 dB) of the implant at approximately 1cm body depth.

3. Simulation results and performance evaluation for tumor detection

The human body has a significant influence on the electromagnetic field distribution and needs to be considered for the design o fany in-body antenna. Since an experimental campaign in a real living organism can be harmful and complex, simulation offers the only opportunity to investigate the behavior of electromagnetic fields in a human body. Our simulations are established with a digitalized Voxel human model used for medical research from the University of Texas at Austin. The model has a resolution of 1 mm3 and is based on a dissected male corpse sliced into several thousand layers. A spiral planar antenna is used to simulate the implant on a human arm using CST Microwave Studio through the human Voxel model (Figure 3). The implanted antenna is built using a Rogers 4350 substrate with 1.524 mm of height, a loss tangent of 0.04 S/m, and a relative permittivity of 3.66. The tumor was modeled under CST Microwave Studio, using Wisconsin Diagnosis Breast Cancer Dataset. Features like the radius, texture, perimeter, area, and smoothness of the tumor are included. Since the antenna operates in a particularly challenging environment, its performance is affected by deformation due to the geometrical complexity of the body, the high permittivity, and the dispersive material properties of living tissue. A linear relation between the adjustment in the frequency of operation of the system and the variability of the path loss coefficient in the proposed environment is hard to find. A reduction of path loss coefficient when increasing the frequency is predictable, however increasing the frequency, reduces the attenuation since the waves are reflected from objects and multipath components contribute to the total received signal. Operation at higher frequencies, means a clearer Fresnel zone, decreasing the total loss. To attain a long LOS, the location of the base station should be as high as possible to avoid attenuation due to blocking.

Alterations of up to 8% of the return loss are observed when cylindrical figures of ϵ_r = 60, and σ = 0.1 are located adjacent to the antenna (Figure 4). The important characteristic to notice here, is that when the simulated tumor (independent variable) is moved next to the antenna, the return loss (dependant variable) fluctuates proportionally to the distance and features of the external body. The result shows the potential of implant antennas for early tumor tissue detection in humans. The same pattern is repeated for an implant antenna designed to operate at a frequency of 2.4 GHz. Consequently, the existence of an external figure in the human body and the Return Loss (S1,1) are strongly correlated. The propagation model also should consider the fundamental peculiarity of a real environment, taking into account the uncertainties like the unknown delay, phase, shifts of frequency, noise, etc. The maximum delay time



(a) (b)

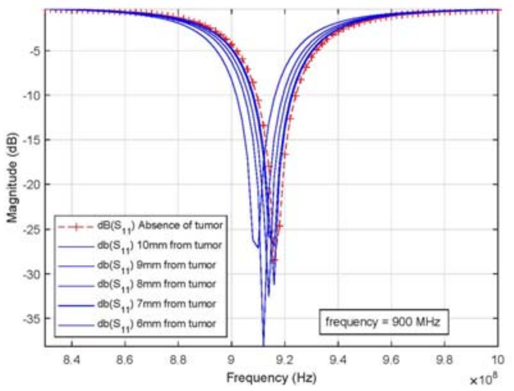
(Figure 3) Simulation results showing (a) the implant placement and electromagnetic measurements in the Voxel human model, and (b) the radiation pattern of the wireless implant.

in the environment is approximately 3.3d ns; this is obtained from [20], where a guaranteed link distance is 10 m.

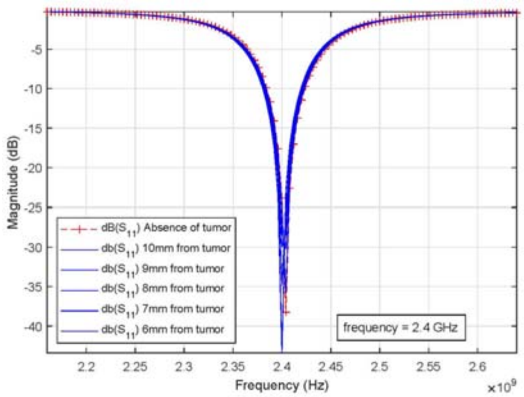
4. Conclusions and future work

We have seen how the simulation data supports our initial hypothesis. Among the most important discoveries, we noticed that a linear relationship between the frequency of operation and the path loss coefficient in the planned environment is not always predictable. On one hand, a reduction of path losses due to frequency decrease could be expected, nevertheless, increasing the frequency will reduce the attenuation since the waves are reflected from objects, and multipath components contribute to the total received signal. Also, working at 915 MHz requires a larger antenna to achieve the same gain that higher frequencies, where a clearer Fresnel zone is obtained lessening the total loss for this global frequency. Therefore, the analysis has to be relative to these two contraptions. The isolation through multiple floors, known as floor penetration factor, has a limit when increasing the number of floors n in the basic path loss model, given that the signal may find alternative paths to spread and complete the wireless link with a reduced amount of losses. Losses caused by human skin propagation has revealed 15.1 dB and 17.8 dB, for 900 MHz and 2.4 GHz, respectively. Fading on this communications channel design is not a stationary process, uncertainties of a random person blocking the path link, as well as walls and multipath should be considered in future research. A temporal motion of objects in the patient room causes Ricean, and Nakagami-Rice fading distributions that could be used to analyse the probability density of the system.

To sum up, the feasibility of the system design is compromised by the transmit power, implant depth, link distance, interference from supplementary transmitters and the size of the implant resonator. Therefore, an in-depth research needs to be undertaken in these areas. Body Area Networks is a motivating field of study by itself, but the most fascinating part is yet to come to this research area. With the increasing number of datasets and images being labelled by doctors across the world. The next step is to train an automated model to do the inference using deep learning to fight the shortage of doctors or pathologists in countries that do not have access to medical services, using the tumor labelled data to determine whether the external shape has malignant or benign physiognomies. The problem of detecting cancer from a tumor can be easily answered by a supervised learning task, such as binary classification, logistic regression, neural networks, etc. This notion will not replace medical doctors by any mean,



(a)



(b)

(Figure 4) Fluctuations in the return loss S1,1 caused by the approximation of the simulated tumor shape to the placement of the implanted antenna. Results obtained at an operating frequency of (a) 900 MHz, and (b) 2.4 GHz.

although this method can be used to support and help doctors to make a more accurate diagnose. We believe that the presented awareness can help to identify early stages of tumors in humans, a disease, that for being to an extent preventable; must be categorized as unacceptable.

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