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Realistic Modeling of the Biological Channel for the Design of Implantable Wireless UWB Communication Systems

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Abstract— **Several emerging medical applications require that a miniature data acquisition device be implanted into the head to extract and wirelessly communicate brain activity to other devices. Designing a reliable communication link for such an application requires a realistic model of the surrounding biological tissues. This paper exploits a realistic model of the biological channel to design a suitable wireless ultra wideband communication link in a brain monitoring application. Two scenarios for positioning the implanted transmitting antenna are considered. The 1st scenario places the antenna under the skull, whereas the 2nd scenario places the antenna under the skin, above the skull. The propagation characteristics of the signal through the tissues of the human head have been determined with full-wave electromagnetic simulation based on Finite Element Method. The implantable antenna and the external antenna are key components to establish an electromagnetic link between an implanted transmitter and an external receiver. The average specific absorption rate (ASAR) of the implantable antennas are evaluated and compared for the two proposed scenarios. Moreover, the maximum available power from the implanted antenna is evaluated to characterize the performance of the communication link established between the implantable antenna and the external antenna, with respect to spectrum and safety regulations. We show how sensitive the receiver must be in order to implement a reliable telemetry link based on the proposed model of the channel.**

I. INTRODUCTION

There is growing interest in using implantable transmitters for extracting the raw electrophysiological data gathered from miniature implanted systems. These emerging devices are crucial components in the development of new medical applications targeting the diagnostic of neurological diseases or the control of prosthetic devices [1]-[3]. Transmitting ultra-wideband (UWB) signals in the unlicensed Federal Communications Commission (FCC) approved frequency range (3.1-10.6 GHz) is attractive because it enables higher bit rates than narrowband systems, like in the Medical Implant Communications Service (MICS), due to its wideband [2], [3]. Moreover, standard integrated circuit technology, such as complementary metal–oxide–semiconductor (CMOS), yields simplified, small in size, low-power, and low cost UWB transmitters that are necessary in the implementation of implantable devices [3]. Wireless UWB systems require antennas as key component of transmitters and receivers, which must feature simple geometry, small size and wide bandwidth, rendering planar monopole antennas extremely attractive [4]. Designing planar monopole UWB antennas in the context of a miniature wireless implantable device is particularly challenging compared to free space applications [5]. The presence of surrounding biological tissues has a drastic influence on the performance of the antenna. These effects must be taken into account in the design and optimization of implantable communications systems. UWB transmitters have been previously designed to transmit from a wireless data acquisition system implanted into the human head, but did not take into account the characteristics of the channel or the average specific absorption rate (ASAR). Instead, previous implantable UWB antennas were optimized for radiation in free space [2], [3]. To date, the properties of the human head as a wireless propagation channel into the UWB frequency band have been poorly considered [6]. Recent research calculated the path loss for the human head in the 100 MHz to 6 GHz band [6]. In that case, an mm-size antenna was employed without specific consideration on the bandwidth of the antenna and on the effect of biological tissues on its performance. The characteristics of the channel must be taken into account in the design of implantable transmitters and receivers as their performances are significantly affected by surrounding biological tissues. Channel knowledge also permits calculation of bit error rate and required transmit power [6].

This paper discusses two scenarios for the location of the wireless implantable transmitter in the frequency range of 3.1 to 10.6 GHz for brain monitoring. In the first scenario, the transmitter is located under the skull, whereas in the second scenario, the transmitter is located above the skull, under the skin. We model the biological tissues as a dispersive dielectric in a homogeneous medium. A simulation-based modeling strategy of a realistic UWB radio link is employed using HFSS and a finite element method to design three implantable UWB antennas: two transmitting antenna designs (under/above skull), and one common receiving antenna design. Best and worst cases tissue compositions, with respect to absorption, are considered. As absorption in tissues increases with frequency, analyses show that lower frequency should be exploited to improve transfer efficiency [6]. We evaluate the safety of transmission (to avoid tissue damage) via 1-gram ASAR distributions via the model in HFSS and contrast results for our two antenna link designs. We perform the ASAR calculation and compute the maximum power that can be safely delivered according to ANSI/IEEE regulation [11] from an implanted transmitter to a receiver antenna within a separation of a few cm, into the UWB frequency band. Finally, the maximum available powers at the different proposed transmitter locations are obtained to analyze the reliability of the communication link and to estimate the minimum sensitivity of the receiver with respect to FCC and ANSI regulations.

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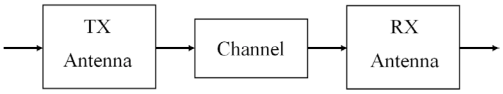


Figure 1. Channel model for in-body wireless UWB communications.

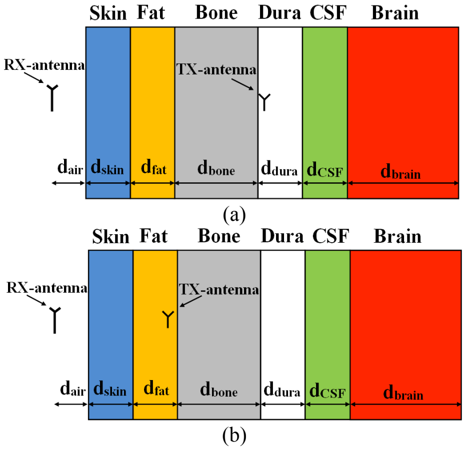
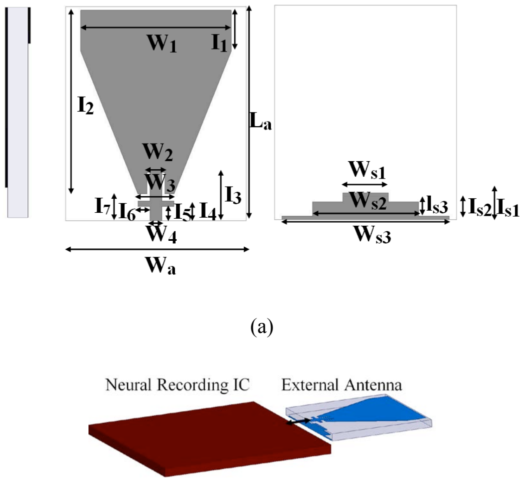


Figure 2. Multi-layer model of the biological tissues for two different link configurations (a) the transmitter antenna is under the skull (b) the transmitter antenna is above the skull.



(b)

Figure 3. (a) geometric parameters of the implanted antenna (b) connection antenna to neural recording chip.

II. CHANNEL MODELING AND SIMULATION

A. *Multi-Layer Model of tissues*

The traditional definition of path loss is a transmission loss in the channel which is independent of antennas. For a brain monitoring wireless link, we do not operate in the far field as conventional systems do, thus the channel cannot be investigated separately from the antennas [6-7]. Therefore, our definition of the path loss includes the responses of the transmitting and receiving antennas. We carried out 2-port simulations of the entire link, including the antennas (transmitting and receiving) to characterize the link (Figure 1). The two potential transmitter antenna locations (under or above of the skull) are modeled as shown in Figure 2. Unlike free space communications, the various biological tissues have unique conductivity and dielectric constants offering different effects of RF interaction. The specific dielectric properties of the tissues must be taken into account in the design of the implantable antenna because they will strongly influence its electrical features. We first characterize and model the biological medium as a communication channel in the UWB frequency band. The complex permittivity for several different human tissues is provided in [8]. We used these electrical parameters to define each layer as a specific dielectric material in a multi-layer model implemented in HFSS. The model is used to simulate the implantable antennas in a medium where they are surrounded by several strata of tissues illustrated in Figure 2. The implemented multi-layer model consists of brain matter, cerebro-spinal fluid (CSF), dura, bone (skull), fat, and skin with respective thicknesses, the thicknesses of which are shown in Table I. Table I gives the lower and upper bounds for the thicknesses encountered in the heads of adults [9].

TABLE I. LAYER THICKNESS

Type of Tissues	***Best Case (mm)***	***Worst Case (mm)***
Skin	.5	1.0
Fat	0	2.0
Bone	2.0	7.0
Dura	.5	1.0
CSF	0	2.0
Brain	40.0	40.0

B. *Antenna Design*

The implantable UWB antenna is subject to specific requirements that render its design particularly challenging: 1) it is restricted to small dimensions, 2) it must be biocompatible, and 3) it needs to be electrically insulated from the body [5]. Planar monopole antennas are attractive for wireless UWB systems because they have simple geometry, small size and wide bandwidth. We propose two implanted monopole microstrip antennas as transmitter antennas (for different locations in Figure 2a and 2b) combining an Euclidean figure approach with a truncated ground plane to cover the UWB band. The monopole microstrip antennas are covered with a biocompatible material (AlO_2O_3 ceramic substrate with relative permittivity 9.8) having a thickness of 1 mm [4-5]. A common external receiver antenna is also designed with the same topology as the implanted transmitter antenna, but without any insulating layer. The receiver antenna is located outside the body, very close to the implanted area. Since this antenna is for external use only, we cannot define the gain of the antenna inside the body, and therefore only the return loss is considered, which must be below -10 dB [10]. Both monopole antennas are designed to match a 50-Ω microstrip transmission line with a Euclidean figure. Thus, specific matching shapes are required to cover the whole UWB band (Fig. 3 a). The antenna and the neural recording chip, a possible

TABLE II. DIMENSIONS OF THE SIMULATED ANTENNA DESIGNS

Geometrical Parameters	***TX-Under Skull (mm)***	***TX-Above Skull (mm)***	***RX (mm)***
l_1	2.3	2.0	15.0
l_2	10.3	8.5	17.0
l_3	2.7	3.2	0.0
l_4	1.1	1.5	0.0
l_5	0.8	1.2	0.0
l_6	0.8	0.6	0.0
l_7	1.5	2.0	13.0
L_a	12.0	12.0	30.0
l_{s1}	1.5	2.0	13.0
l_{s2}	1.0	1.5	7.0
l_{s3}	0.8	1.3	6.0
w_1	10.0	9.5	15.0
w_2	1.2	1.4	0.0
w_3	2.4	3.0	0.0
w_4	0.8	1.0	1.8
W_a	12.0	12.0	27.0
w_{s1}	3.0	2.0	27.0
w_{s2}	7.0	4.5	18.0
w_{s3}	11.0	12.0	27.0

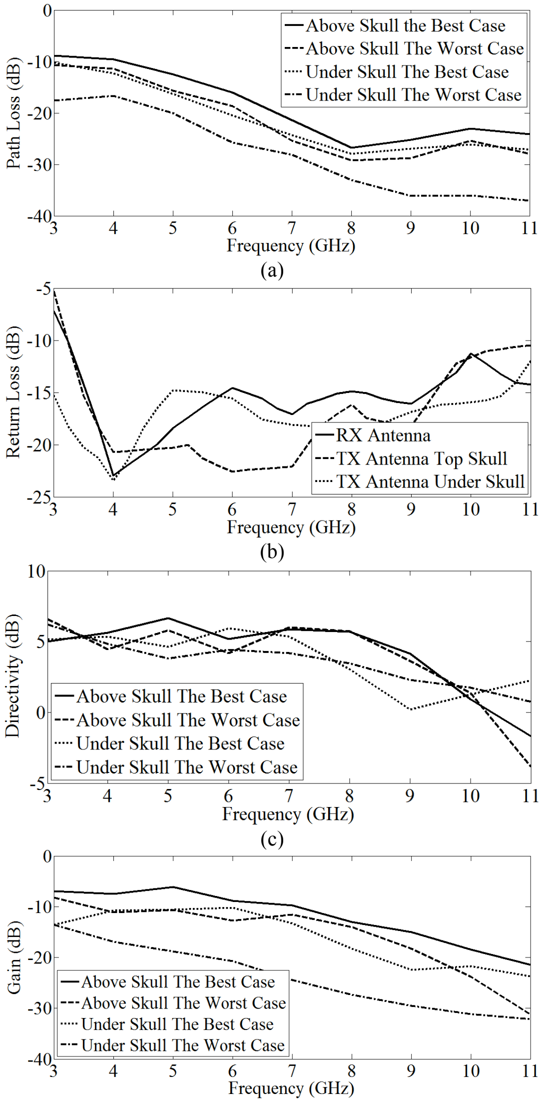
arrangement of which is outlined in Fig. 3b, can be connected using wires. The dimensions of the designed antennas are summarized in Table II.

III. SIMULATION RESULTS

The comparison of the path loss for the best case and the worst case is depicted in Fig. 4a. In general, it shows that when the thicknesses of the tissues and the frequency are increased, the path loss also increases. At higher frequencies, the loss tangent of tissues increases, which causes more loss when electromagnetic waves propagate in tissues with higher thickness. The simulation results obtained within the whole UWB band are discussed in the next section in order to establish a suitable comparison between the two proposed scenarios illustrated in Figure 2a and 2b.

A. Radiation, Return Loss and Path Loss

When the return loss of the UWB antenna is below -10 dB, and its directivity is above 0 dB, we conclude that the antenna is suitable for short range UWB communications [10]. The simulation results for the return loss are shown in Figure 4b. The return loss is below -10 dB within the entire frequency range of interest (from 3.1 GHz to 10.6 GHz). Figure 4c shows that the directivity for the best case (smallest skull thickness) and the worst case (largest skull thickness) are both above 0 dB for both transmit antenna locations. Because the loss due to biological tissues increases with frequency, the gain of the antenna decreases with frequency (Figure 4d). However, in addition to being dependent on the losses due to environment, the gain of the antenna is also dependent on the directivity of the antenna [10]. This demonstrates that the biological tissues are blocking and absorbing the radiation from the antennas, so that the radiation patterns become directional, favoring the broadside direction (from inside to the outside of the head).



(a)

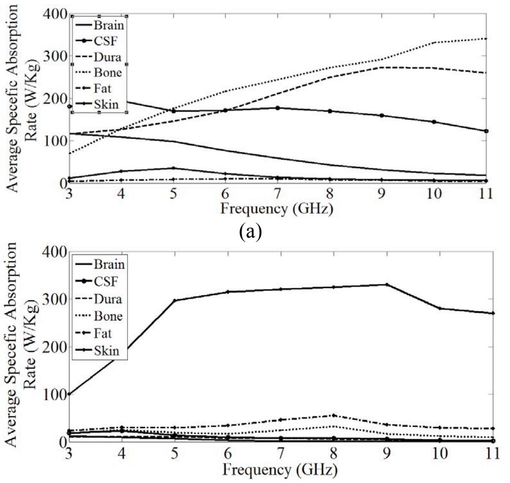
(b)

(c)

(d)

Figure 4. Simulated parameters of the three antennas: (a) path loss (b) return loss, (c) directivity, and (d) gain.

We investigated the effects of variability and uncertainty in the thickness and the dielectric properties of the various tissue layers on the overall channel of the wireless link for the two proposed scenarios exploiting the models in Fig. 2. The results obtained are significantly different from the results reported in previous work [6]. The antenna employed in that work does not cover the entire UWB band, where the path loss is evaluated, which explains such difference. For all scenarios, the air gap between the receiver antenna and the skin was set to 3 mm. The simulation results for both scenarios are plotted in Figure 4a. Note that P_t+G_t (maximum power of the transmitter plus maximum antenna gain) is limited to -41.3 dBm/MHz by the FCC mask for the maximum radiated power allowed. Since the bandwidth is around 7 GHz, the total value P_t+G_t allowed is :



(a)

(b)

Figure 5. ASAR for different tissues (a) position under skull (b) above skull.

$$\begin{aligned} P_t + G_t &= -41.3\left[\text{dBm}/\text{MHz}\right] + 10\log_{10}\left(7000\right)\left[\text{dB}\cdot\text{MHz}\right] \\ &= -2.84\left[\text{dBm}\right] = 0.5\text{mW}. \end{aligned} \quad (1)$$

The best case for the first scenario has a maximum gain of around -10 dB. The best case for the second scenario has a maximum gain of around -8 dB. Therefore the maximum P_t for the first scenario is 5.2 mW (7.16 dBm), and 3.3 mW (5.16 dBm) for the second scenario.

B. Average Specific absorption Rate (ASAR)

ASAR is a critical parameter for assessing the tissue safety of our transmissions. The peak 1-g ASAR distribution versus frequency [11] is simulated with HFSS for both scenarios (Figure 5). The antennas were simulated with HFSS in the UWB band for a delivered power of 1 W. The maximum peak 1-g ASAR of the microstrip antenna in both scenarios are similar, and are located around 320 W/kg when the transmitted power is 1W. These ASARs are much higher than the regulated ANSI limitation of 1.6 W/kg [11], hence we scale the power delivered by the implanted antennas to meet the ANSI limitations. This leads to a transmission power of 5 mW, and sending more power could harm the tissues [11]. Figure 5 shows that, in the second scenario, most power is absorbed by the skull and above tissues, which protect sensitive brain tissues from harmful effects. Note that for the first scenario, the ANSI restrictions are greater than those imposed by the FCC, so maximum power is set by the ANSI criteria, whereas for the second scenario, it is the FCC criteria that have precedence over the ANSI restrictions for maximum power. The sensitivity of the receiver is obtained as follow:

$$\begin{aligned} &\text{Receiver sensitivity}\left(\text{dBm}\right) + \text{Link margin}\left(\text{dB}\right) = \\ &\text{Maximum transmitter power}\left(\text{dBm}\right) + \text{Path Loss (dB)} \end{aligned} \quad (2)$$

For a link margin of 6 dB, the worst cases sensitivity of the receiver for both the first and the second scenarios are -36 dBm and -26 dBm respectively.

IV. CONCLUSION

Designing a reliable wireless data link in the presence of lossy tissues featuring frequency dependent dielectric properties is a challenging task. In this paper we have introduced a model of the channel in a brain monitoring application, and reported the simulation results for two scenarios employing a UWB wireless link. It was shown that due to the specificity of the problem, the antennas and the channel cannot be treated separately and needed to be simulated holistically. Three UWB microstrip monopole antennas were designed and simulated. The simulation was carried with HFSS and exploit a model including several layers having different dielectric constants in order to account for the effects of surrounding biological tissues. The maximum power allowed to be transmitted from the implanted antenna, taking into account the limits imposed by both the ANSI and the FCC, was determined. In future work, we will evaluate the needed receiver sensitivity. Then, the transmitter and receiver antennas will be fabricated and their performance will be measured using a realistic model of the biological medium. Evaluating the path loss between the receiver and the transmitter antenna will enable to calculate the impulse response of the link and to calculate the achievable bit error rate.

REFERENCES

[1] B. Gosselin, "Recent Advances in Neural Recording Microsystems," *Sensors*, vol. 11, pp. 4572-4597, 2011.

[2] U. M. Jow, and M. Ghovanloo, "Optimization of Data Coils in a Multiband Wireless Link for Neuroprosthetic Implantable Devices," *IEEE Trans. on Biomed. Circuits and Syst.*, Vol. 4, No. 5, Oct. 2010.

[3] Moo Sung Chae, Zhi Yang, Yuce, M.R., Linh Hoang, Liu, W, "A 128-Channel 6 mW Wireless Neural Recording IC With Spike Feature Extraction and UWB Transmitter," *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, Vol. 17, No. 4, Aug. 2009.

[4] M. Ojaroudi, C. Ghobadi, J. Nourinia, "Small Square Monopole Antenna With Inverted T-Shaped Notch in the Ground Plane for UWB Application," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 2009.

[5] T. F. Chien, H. C. Yang, C. M. Cheng, and C. H. Luo, "Develop CPW-Fed Monopole Broadband Implantable Antennas on the High Dielectric Constant Ceramic Substrates", *Microwave and Optical Technology Letters*, Vol. 52, No. 9, September 2010.

[6] M. Mark, T. Bjorninen,Y. D. Chen, S. Venkatraman, L. Ukkonen,L. Sydanheimo, J. M. Carmena and J. M. Rabaey, "Wireless Channel Characterization for mm-Size Neural Implants," *in The 32nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* pp. 1565 – 1568, Sept. 2010.

[7] Y. Duroc, A. Ghiotto, T.-P. Vuong, and S. Tedjini, "UWB Antennas: Systems With Transfer Function and Impulse Response," *IEEE Trans. Antennas Propag.*, vol. 55, no. 5, pp. 1449–1451, May 2007.

[8] S. Gabriel, R. W. Lau, and C. Gabriel, "The Dielectric Properties of Biological Tissues: III. Parametric Models for the Dielectric Spectrum of Tissues," *Physics in Medicine and Biology*, Vol. 41, No. 11, pp. 2271–2293, Nov. 1996.

[9] A. Drossos, V. Santomaa, and N. Kuster, "The Dependence of Electromagnetic Energy Absorption Upon Human Head Tissue Composition in the Frequency Range of 300–3000 MHz," *IEEE Trans. Microw. Theory Tech.*, Vol. 48, No. 11, Nov. 2000.

[10] D. Valderas, J. I. Sancho, D. Puente and C. Ling, *Ultrawideband Antennas: Design and Applications, London :* Imperial College Press, 2011.

[11] "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," *IEEE Standard* C95.1-2005, 2006.