Optimal Position of the Transmitter Coil for Wireless Power Transfer to the Implantable Device

Jinghui Jian and Milutin Stanaćević

Abstract— **The maximum deliverable power through inductive link to the implantable device is limited by the tissue exposure to the electromagnetic field radiation. By moving away the transmitter coil from the body, the maximum deliverable power is increased as the magnitude of the electrical field at the interface with the body is kept constant. We demonstrate that the optimal distance between the transmitter coil and the body is on the order of 1 cm when the current of the transmitter coil is limited to 1 A. We also confirm that the conditions on the optimal frequency of the power transmission and the topology of the transmission coil remain the same as if the coil was directly adjacent to the body.**

I. INTRODUCTION

Implantable devices have long been utilized in a variety of important biomedical applications and the impact of these devices on the health care has been significant. After the great success of pacemakers and cochlear implants, the emerging technological innovations could lead to further breakthroughs in health monitoring and combating a wide range of disorders. In the design of implantable devices, providing the wireless power to the device and data communication link are the critical parts of the system design and RF power harvesting and telemetry through inductive coupling [1], [2], [3] present a commonly used solution.

The early research work on the power transfer focused on the power transmission operating at frequencies in the range from 1 MHz to 10 MHz [4], [5] because of the attenuation of the EM field by the body at high frequencies. Correspondingly, these designs were based on quasi-static analysis of the EM field. Recently, it was shown that the optimal transmission frequency through a biological tissue in case of mm-size coils is in GHz range [6]. However, if the transmitter coil is on the order of few centimeters, the optimal frequency is around 100 MHz [7].

In these studies, the transmitter coil was directly adjacent to the skin. The limit on the maximum power that can be delivered to the implantable device depends on the electrical field at the interface with the body and moving away the transmitter coil from the body can result in higher maximum possible power delivered. With the increased distance of the transmitter coil from the body, the power efficiency drops and the maximum deliverable power to the implant is limited by the maximum current that can be supplied to the transmitter coil. We investigate the affect of the different positions of the transmitter coil with respect to the body on the optimal transfer frequency, topology of the transmitter coil and the maximum deliverable power to the implant.

The paper is organized as follows. Section II discusses the inductive link design, the power efficiency, the power deliverable to the implant and regulations on the EM field based on the human safety. In Section III, the simulation results for the inductive link with variable distance of the transmitter coil to the skin are presented. In Section IV the conclusions of the presented work are summarized.

II. DESIGN OF INDUCTIVE LINKS

The inductive link for wireless power transfer to the implantable device comprises the transmitter coil with the power amplifier outside the body and the receiving coil with the integrated circuitry inside the body. The design parameters for the inductive link include the sizing of the coils, the distance between the coils and the electrical properties of the material between the coils. These parameters are defined by the application and the location of the implantable device in the body.

The parameters that describe the inductive link are the maximum power that can be delivered to the implantable device, the power efficiency and the voltage amplitude at the terminals of the implantable coil. To obtain these parameters, different models of the inductive link have been applied. In the quasi-static analysis, lump-element models and corresponding closed-form expressions based on the geometrical parameters of the coils are extracted for the evaluation of the link [4]. Straight, fast and suitable for iterative calculations as this method is, the lump-element models are less accurate at high frequencies especially in the cases involving layers of dispersive dielectric material. This results in the use of the numerical full-wave solvers to simulate the whole structure and generate network parameters. We use a commercial FEM (finite element method)-based full-wave electromagnetic field solver HFSS (high frequency structural simulator) to simulate and extract the network parameters of the designed inductive links.

A. Delivered Power and Power Efficiency

Two important parameters in the design of the inductive link are the power efficiency and the maximum power that can be delivered to the receiving coil. The overall power transfer efficiency of the inductive link, including the external transmitter and internal receiver circuitry, is the product of the efficiency of the transmitter (efficiency of the power amplifier), power transfer efficiency from the transmitter coil

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*This work was supported by NSF CAREER Award 0846265.

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

to the receiving coil η_C and the receiver efficiency (on-chip rectifier conversion efficiency). Assuming that the efficiency of the power amplifier and the receiving circuitry are fixed, we focus on the efficiency of the power transfer between the coil pair, η_C.

To maximize the power efficiency, we assume that there are matching networks for transformation of the input and load impedance to achieve the optimum efficiency, with a slight power efficiency loss in the matching network. The maximum achievable efficiency for the power transfer can be expressed as [7]

$$\eta_C = \frac{\chi}{\left(1+\sqrt{1+\chi}\right)^2}, \tag{1}$$

where

$$\chi = \frac{|Z_{12}|^2}{\mathrm{Re}(Z_{11})\mathrm{Re}(Z_{22}) - \mathrm{Re}^2(Z_{12})}, \tag{2}$$

where Z_{ij} are the extracted Z parameters of the inductive link. Using the optimal load, we can also calculate the maximum power delivered to the implantable device, as well as the maximum voltage at the terminals of the receiving coil.

B. Safety Issues Regarding RF Exposure

Established effects to the human body due to exposure to EM field originate from the exposure to the electric field inside the body, while no adverse health effects have been directly linked to the magnetic field [3]. At the low frequencies, the EM exposure leads to the electrostimulation of the muscles and nerves caused by electric current or field. At the higher frequencies, heating of the tissue caused by internal electric field becomes predominant while the appearance of the electrostimulation diminishes [8]. Thermal effect on the tissue is evaluated by specific absorption rate (SAR), which describe the EM power absorption rate by biological tissue. Generally SAR, unit of which is watts per kilogram, can be expressed by physical properties of the tissue and the internal electric field strength:

$$SAR = \frac{\sigma\,|\mathbf{E}|^2}{\rho} \tag{3}$$

where σ and ρ represent conductivity and mass density of the exposed tissue. E is the electric field strength in the tissue.

IEEE guidelines [9], as well as the ICNIRP guidelines [10] used in European Union set the averaged SAR limits for general public under localized exposure to 4 W/kg over 10 g tissue of extremities and pinnae and 2 W/kg over 10 g any other tissue. In the United States, Federal Communications Commission (FCC) restricts the localized exposure SAR for the general public at 4 W/kg over 1 g tissue for extremities and 1.6 W/kg over 1 g tissue for other parts of the body [11]. The electrical field and SAR limits for safety evaluation can be obtained by numerical EM simulator [8]. To maximize the available energy for implantable device inside the body, as much energy as possible should be delivered without violating the guiding regulations, which means that our efforts should be focused on reducing the electrical field of the transmitter coil.

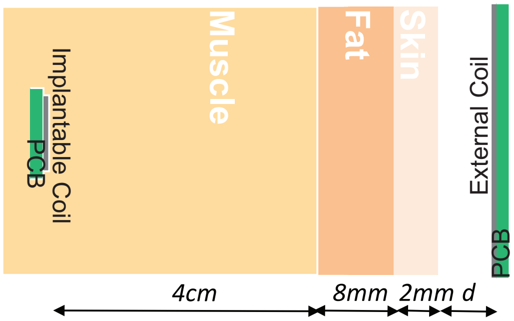

Fig. 1. Model of the wireless channel for the Smart Pill application.

III. SIMULATION RESULTS FOR THE OPTIMAL POSITIONING OF THE TRANSMITTER COIL

We are investigating the optimal positioning of the transmitter coil with respect to the body in order to achieve optimal power transfer to the implantable receiving coil. The electrical field and SAR drop off dramatically in the vicinity of the coil. As the transmitter coil is moved away from the body, the driving current of the coil can be increased as long as the SAR in the body is lower than 1.6 W/kg. Although the power efficiency will drop, the maximum power that can be delivered to the implantable device increases with the distance.

We have investigated two possible applications of the implantable devices to illustrate a general optimization problem in the design of wireless power transfer links. According to the proposed applications, we have selected the depth of the implantable coil and sizing of both transmitting and receiving coils as the maximum allowable for these scenarios. For the analysis of the the effect of the material between the coils, the sizing of the coils and the depth of the implant in the body is the same in these two applications.

The sizing of the implantable coil will be constrained to 3 mm × 3 mm with the implant depth in the body of 5 cm. The number of turns of the implantable coil is chosen to be 3. The maximum size of the transmitting coil will be limited to 5 cm in diameter. Since the wire width of the coil affects the resistive and radiation consumption of the transmitter coil, we choose a value of 3 mm for the width of the wire in this coil. The optimal values of the number of turns and the spacing between the wires will be investigated. The coils are designed as planar spiral coils on a printed circuit board (PCB).

We will observe the power efficiency of the link and the maximum possible power delivered to the implant along with the maximum required current provided by the power driver for the maximum delivered power as a function of the distance between the transmitter coil and the body. We have described in Section II the simulation methods and calculations we used to obtain these values.

A. Smart Pill

The full benefits of the administered medication can be achieved only if the patient follows closely the prescribed

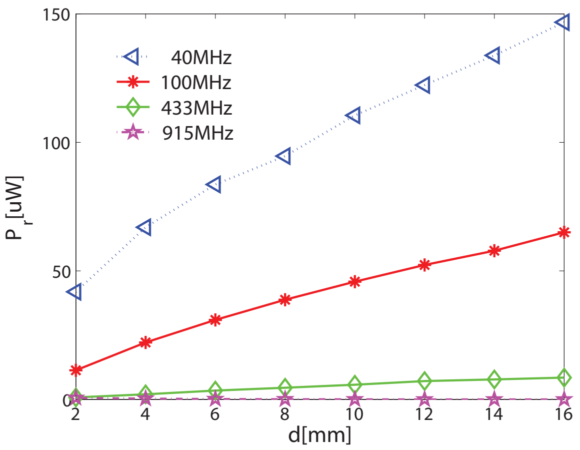

Fig. 2. The maximum deliverable power to the implantable device as the function of the distance between the transmitter coil and the skin.

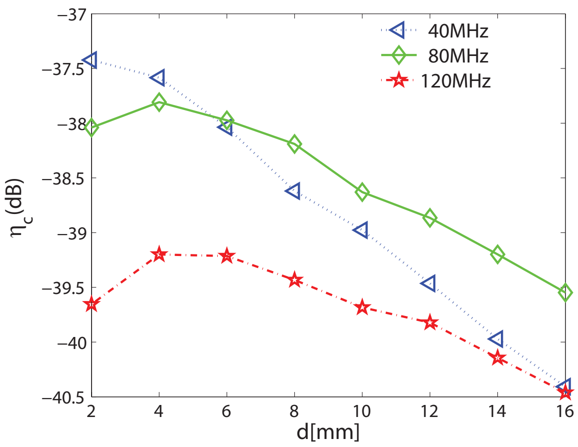

Fig. 3. The power efficiency as the function of the distance between the transmitter coil and the skin.

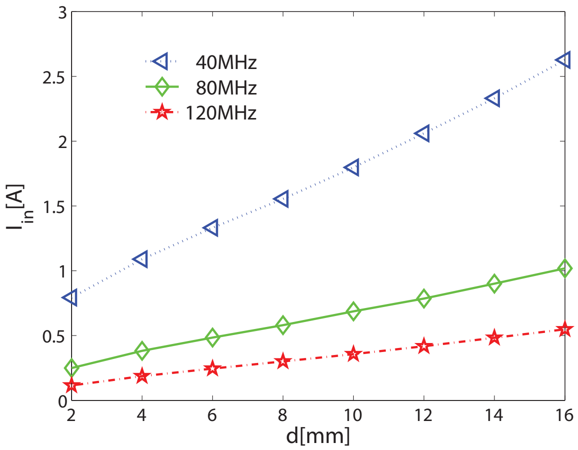

Fig. 4. The current of the transmitting coil required for the maximum deliverable power.

treatment regiment. Besides affecting the outcome of the treatment, non-adherence also induces a high burden on the health care system. We have proposed a design of wireless system based on a inductive link with a receiving coil embedded in a pill [13] for monitoring the ingestion of medicine and absorption into the body to insure the proper dosage control and usage. For this application, the wireless channel is modeled as the 2 mm skin, 8 mm of the fat and 4 cm of the muscle, as illustrated in Figure 1. The electric properties of each layer are obtained from [12]. We also add a 300 μm medical-grade silicone layer on the surface of the coils. Silicone layer can be used as coating for implant devices, and it also reduces parasitic parameters of the coil, increasing the quality factor as well as the transfer efficiency [5].

In the first simulation, we fix the topology of the transmitter coil by choosing the number of turns to be one. The distance between the transmisser coil and the body is varied. The maximum power that can be received by the implanted coil is shown in Figure 2 for frequencies from 40 MHz to 915 MHz in an effort to determine the optimum frequency of transmission. From Figure 2, we can see that with the increase of the frequency the maximum power that can be delivered drops in a similar fashion as in the case when the transmitter coil is next to the body. In the following simulations we will focus on the range of the frequencies around 100 MHz. The drop in the power efficiency for these frequencies is shown in Figure 3. As the maximum deliverable power is increased with the increased distance to the body, the limiting factor in the wireless link becomes the maximum current that the driver can provide to the transmitting coil. In the Figure 4 the current that is supplied to the driver for the maximum achievable power is shown. Assuming that the current is limited to 1 A, we can notice that for the lower frequencies this limit is reached at very small distances from the body, while for the higher frequencies, the current limit is reached at much greater distance. With this limitation on the current, we can conclude that the maximum deliverable power across the presented frequency range is almost the same, but at different distances from the skin and with decreasing power efficiency as the frequency is increased.

In [7], it is demonstrated that the optimal number of turns when the transmitting coil is adjacent to the skin in the similar scenario is one. To see if this parameter upholds in the situations where the transmitter coil is further from the body, we repeated the previous simulation for the different number of turns of the transmitting coil at the frequency of 100 MHz. We kept the distance between the traces at 1 mm. As shown in Figure 5, for the maximum delivered power, the optimal choice is still one turn.

B. Deep Brain Implantation

The second investigated scenario is the deep brain implantation. Deep brain stimulation is one of the most efficient techniques in combating tremor disorders, thereby significantly advancing the treatment of, for example, Parkinson's and Alzheimer's diseases, and epilepsy [14]. The materials between the coils are selected to mimic the scenario of the

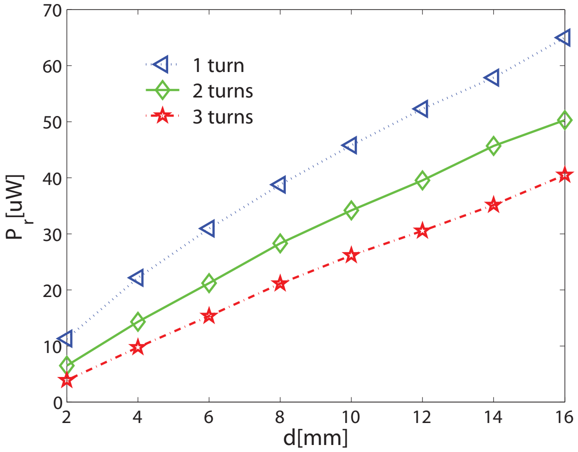

Fig. 5. The maximum deliverable power as the function of the number of turns in the transmitting coil at 100 MHz.

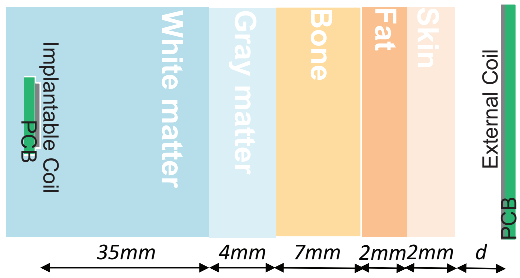

Fig. 6. Model of the wireless channel for the deep-brain implant.

deep brain implantation, with 2 mm of skin, 2 mm of fat, 7 mm of bone, 4 mm of gray matter, and 35 mm of white matter, as illustrated in Figure 6.

The maximum deliverable power to the implantable device as the function of the distance between the transmitting coil and the skin for different transmission frequencies is shown in Figure 7. We can notice that in this application, the similar conclusions about the optimal transfer frequency can be drawn as for the Smart Pill application, but with the lower maximum deliverable power in this case.

IV. CONCLUSION

We have demonstrated that the optimal distance between the transmitter coil and the body is on the order of 1 cm in two different applications of the wireless power transfer to the implantable device. The optimal transmission frequency in both applications is on the order of 100 MHz with the small number of turns of the transmitter coil. Future work will focus on the topology of transmitter coil in an effort to further reduce electrical field in the body and boost the maximum deliverable power to the implantable device.

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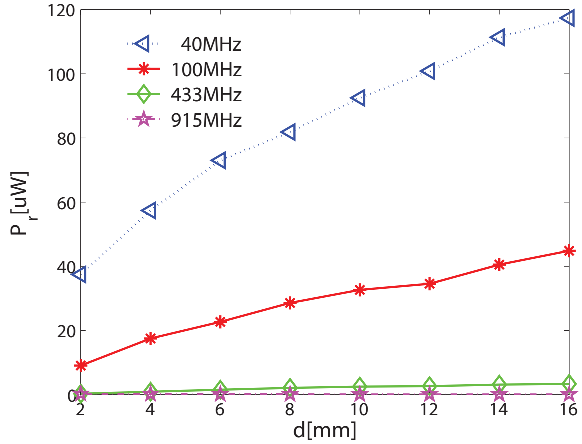

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