Wireless Power Transfer to Mobile Wearable Device via Resonance Magnetic

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Abstract—**The wireless power transfer (WPT) efficiency of a mobile wearable medical device (MWMD) by Strongly Coupled Magnetic Resonance (SCMR) method is studied here for air-tissue interfaces. Specifically, SCMR's wireless power transfer from a source of air to a sensor close to tissue is analyzed. A comparison of wireless power transfer efficiency between resonant spirals at different distances are shown. The efficiencies achieved in different areas of the human body are also reported**

Keywords- **Wireless, magnetic resonance, wearable devices, tissue.**

I. INTRODUCTION

Wearable device application has an increasing variety of applications, this is used to monitor the health status of elderly patients or patients undergoing medical care at home,which can reduce cost and improve comfort[1]. It is also used for tracking human body kinematics to allow clinicians to classify and analyze a stroke patient's progress, which aid in the rehabilitation plan [2]. A mobile wearable medical device (MWMD) is also used in high-risk cardiac and respiratory patients to monitor and alert as necessary, the system might include periodical or continuous collection and evaluation of multiple vital signs [3]. MWMDs are saving and extending lives, dues to their ability to monitor, stimulate and regulate vital organs, and also communicate with host about the state of health of the these organs intelligently.

Wireless power transmission system for biomedical applications requires strict power lever, in order to avoid excessive heating of the tissue and resulting in significant tissue damage [4]. This restriction requires the design of low power source with high transmission efficiency for such system [5]. Three popular wireless powering techniques, which were proposed for the air-to-air transmission, have also used for the air-tissue scheme to meet the air-tissue requirement mentioned above: (a) inductive coupling, (b) strongly coupled magnetic resonance and (c) electromagnetic radiation. The strongly coupled magnetic resonance (SCMR) is the most promising of the three methods for MWMDs because of its high efficiency and range.

The SCMR method employs resonators to transmit power wirelessly and efficiently over mid-range distances [6], where the adverse effects of the low coupling coefficient between the two coils for inductive coupling are compensated for by the high-Quality factor of the four-element system to achieve high efficiency. The SCMR method is a non-radiative wireless mid-range power transfer method (10 – 300 cm) that has been recently developed [7-10]. It achieved approximately 40% efficiency in the air at a distance of 2 m with a single receiver [7]. In addition, the technique was also used to simultaneously power multiple receivers in the air, and approximately 60% efficiency was attained at a distance of 2 m in the air [10]. In [11] this technique was extended to the in-vitro and in- vivo experiments.

II. WPT IN SCMR WITH SPIRALS

The SCMR systems use resonant transmitters and receivers that are strongly coupled. Strongly coupled systems are able to transfer energy efficiently, because resonant objects exchange energy efficiently versus non-resonant objects that only interact weakly [7]. A standard SCMR system consists of four elements (typically four loops, or two loops and two coils). Here, an SCMR system based on spirals is shown in Fig. 1.

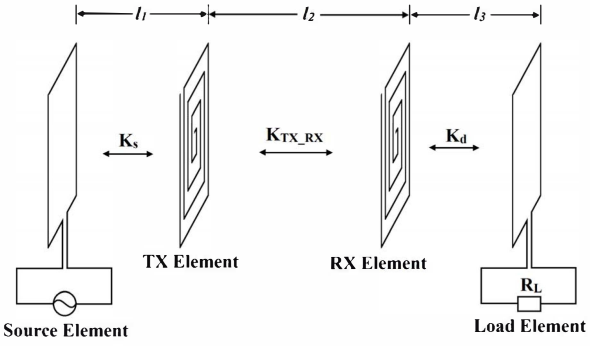

Fig. 1. Schematic of an SCMR system with spirals in the air, where K_S, K_{TX_RX} and K_d are the respective coupling coefficients.

The source element is connected to the power source, and it is inductively coupled to the TX element. The TX element must exhibit a natural resonance frequency that is identical to the RX. Both elements should be resonant at the frequency, where their Q-factor is naturally maximum. Furthermore, the load element is terminated with a load. For our analysis, we assume that the entire system operates in air. The resonance frequency of the spiral, f_r, can be calculated from [4]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The resonant frequency, f_r is also the operational frequency of the SCMR wireless powering system. The Q-factor of the resonance frequency can be written as:

$$Q = \frac{2\pi f_\mathrm{r} L}{R_\mathrm{ohm} + R_\mathrm{rad}} \quad (2)$$

where, L, R_ohm, and R_rad are the self-inductance, ohmic resistance and radiation resistance of the spiral. The inductance, L, of a spiral can be written as [13]:

$$L = \left[\frac{\mu_\mathrm{o} N^2 \left(\frac{d_\mathrm{in} + d_\mathrm{out}}{2}\right) c_1}{2}\right]\left[\ln\left(\frac{c_2}{\alpha}\right) + c_3\alpha + c_4\alpha^2\right] \quad (3)$$

where, $c_1 = 1.27$, $c_2 = 2.07$, $c_3 = 0.18$ *and* $c_4 = 0.13$, are the constants derived based on the geometrical layout of the square spiral; and α is the fill ratio defined by $\alpha = (d_\mathrm{in} - d_\mathrm{out})/(d_\mathrm{in} + d_\mathrm{out})$. The ohmic and radiation resistances can be written as [11], [12]:

$$R_\mathrm{ohm} = \frac{\ell_\mathrm{tot}}{4\sqrt{WT}}\sqrt{\pi\mu_\mathrm{o}\rho f}\left(1 + \frac{R_\mathrm{p}}{R_\mathrm{o}}\right) \quad (4)$$

$$R_\mathrm{rad} = 31200\left(\frac{f}{c}\right)^4\left(\sum_{i=1}^{N} d_i^2\right)^2 \quad (5)$$

where, d_i is the side length of the ith turn of the spiral, ρ is the spiral's conductor resistivity, c is the speed of light, and $\sqrt{\pi\mu_\mathrm{o}\rho f}$ represents the conductor's sheet resistance [12]. The factor $R_\mathrm{p}/R_\mathrm{o}$ in (4) represents the proximity effect factor that accounts for the additional resistance due to the closeness of the conductors. In order to derive analytical expressions for Q_max and f_max, the analytical and simulation setups are chosen such that the proximity effect is negligible reducing (4) to:

$$R_\mathrm{ohm} = \frac{\ell_\mathrm{tot}}{4\sqrt{WT}}\sqrt{\pi\mu_\mathrm{o}\rho f} \quad (6)$$

It should also be noted that (3) – (6) are effective in SCMR analysis only when $\ell_\mathrm{tot} < \lambda/3$ [12]. The Q-factor of a resonant spiral can be expressed in terms of its geometrical parameters using (2), (4), (5) and (6) [13]as:

$$Q = \frac{\pi f_\mathrm{r}\mu_\mathrm{o} N^2\left(\frac{d_\mathrm{in} + d_\mathrm{out}}{2}\right) c_1\left[\ln\left(\frac{c_2}{\alpha}\right) + c_3\alpha + c_4\alpha^2\right]}{\frac{\ell_\mathrm{tot}}{4\sqrt{WT}}\sqrt{\pi\mu_\mathrm{o}\rho f_\mathrm{r}} + 31200\left(\frac{f_\mathrm{r}}{c}\right)^4\left(\sum_{i=1}^{N} d_i^2\right)^2} \quad (7)$$

The maximum possible Q-factor, Q_max, of a spiral and the frequency, f_max, where Q_max occurs, can be derived from (7) using standard calculus as:

$$f_\mathrm{max} = 120.44\times10^6\left[\frac{\ell_\mathrm{tot}\sqrt{\mu_\mathrm{o}\rho}}{\sqrt{WT}\left(\sum_{i=1}^{N} d_i^2\right)^2}\right]^{2/7} \quad (8)$$

$$Q_\mathrm{max} = \frac{\pi f_\mathrm{max}\mu_\mathrm{o} N^2\left(\frac{d_\mathrm{in} + d_\mathrm{out}}{2}\right) c_1\left[\ln\left(\frac{c_2}{\alpha}\right) + c_3\alpha + c_4\alpha^2\right]}{\frac{\ell_\mathrm{tot}}{4\sqrt{WT}}\sqrt{\pi\mu_\mathrm{o}\rho f_\mathrm{max}} + 31200\left(\frac{f_\mathrm{max}}{c}\right)^4\left(\sum_{i=1}^{N} d_i^2\right)^2} \quad (9)$$

III. WIRELESS POWERING OF MWMD DEVICE

Equations (8) and (10) are used to calculate the geometrical parameters of the TX and RX spirals in order to achieve maximum power transfer and minimize tissue exposure to electromagnetic field. This is based on the FCC specification the exposure limits for tissue to radio frequency (RF) energy from wireless devices for biomedical applications [14]. The specification of the models are: The TX spiral model dimensions are $N = 45$, $d_{in} = 4$mm $d_{out} = 272$ mm, $w = 2$ mm and the material is copper. The RX spiral model dimensions are $d_{in} = 3.8$ mm $d_{out} = 243$ mm, w = 1.7 mm. The distance between TX and RX Spiral are 10, 20 and 30 cm. The RX spiral is 3 mm from the skin and embedded in a dielectric with a permittivity value of 4.2 to simulate clothing effect. The models were simulated in HFSS with Human phantom model in which the various tissues are already characterized. Fig. 2 shows the part of the human phantom included in our simulations with the planar SCMR system. The efficiency plots for the different parts of the body examined are shown in Fig. 3 and Fig. 4.

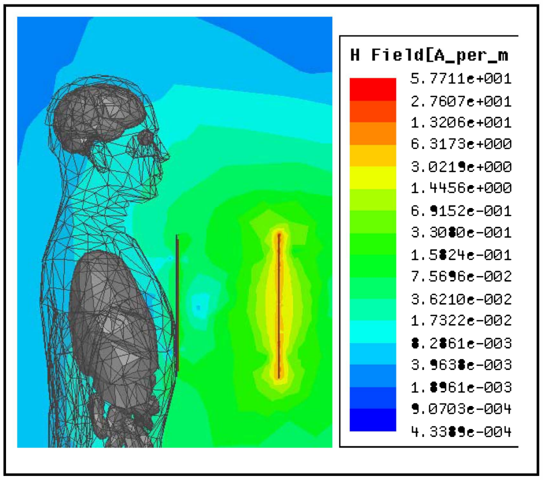

Figure. 2. The human body and magnetic field distribution at l_2 =20 cm.

The result of the SAR, magnetic and electric field distribution in two different parts of the body examined are shown in tables I and II.

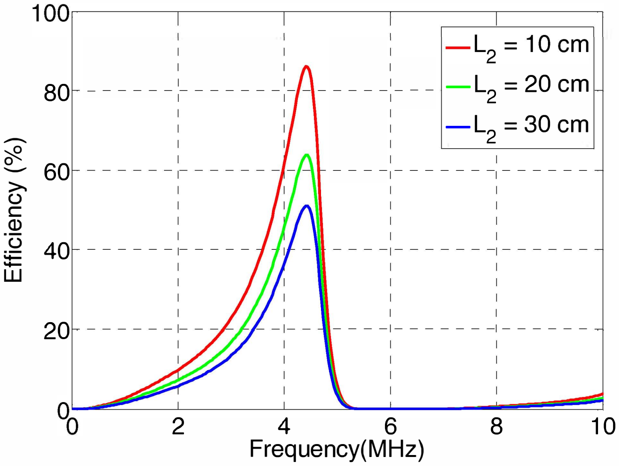

Figure. 3. Efficiency plot human chest at *3* mm distance.

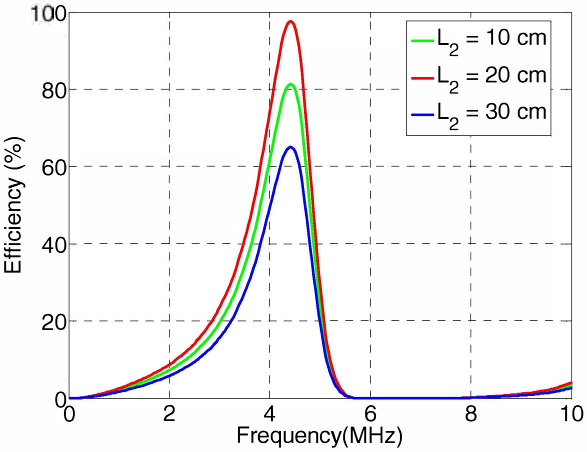

Figure. 4. Efficiency plot human head at *3* mm distance.

TABLE I
COMPARISON OF DIFFERENT DEPTH
WITH INPUT POWER OF 1 WATT IN FRONT OF THE CHEST

Distance (cm)	**Field Parameters and Efficiency**			
	Max E-field (V/m)	***Max H-field (A/m)***	***Max SAR (W/kg)***	***Efficiency (%)***
10	18	0.21	0.07	83
20	12	0.08	0.0004	64
30	0.9	0.004	0.00008	56

TABLE II
COMPARISON OF DIFFERENT DIFFERENT DEPTH
WITH INPUT POWER OF 1 WATT BESIDE THE HEAD

Distance (cm)	**Field Parameters and Efficiency**			
	Max E-field (V/m)	***Max H-field (A/m)***	***Max SAR (W/kg)***	***Efficiency (%)***
10	15	0.15	0.0005	92
20	5	0.05	0.00001	81
30	1.2	0.001	0.000002	63.5

The result shows that the SCMR has great potentials in MWMD, and has very low SAR , electric and magnetic field distribution close to the tissue, which is important for biomedical applications. It is planner, hence can be embedded in clothing easily.

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