Characterization of RF Propagation in Muscle Tissue for Passive UHF RFID Tags

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Abstract

In this paper, we present an analytical analysis and study of the propagation of radio frequency (RF) energy in muscle tissue. The workings of passive UHF RFID tag backscatter are studied. Backscatter field strength propagation models are used to describe the skin effect on muscle tissues. Energy dissipation and field intensities are studied for humans and larger vertebrates using a modified Friis propagation model for passive tag backscatter. An analytical evaluation is conducted for the electric field in muscle tissues for near-field distances. It is shown that the maximum electric field inside a sphere of muscle tissue for a typical passive UHF RFID tag with a loaded meander tag antenna is less than 70dBV/m, which is more than two orders of magnitude lesser than the limits for safe exposure to RF energy produced by mobile devices, as adopted by the Federal Communications Commission (FCC).

1. Introduction

The characterization of RF propagation is a theoretical modeling approach used in understanding wave theory for a specific environment. This wave theory is sufficiently well accomplished, that it has proven highly accurate in modeling various different scenarios involving RF radiation in specific environments. RF propagations near humans and large vertebrates have always been an actively studied research field. Nevertheless, very little work is currently being conducted to analyze new technologies such as RFID as applied to biological-electromagnetic field effects. Such technologies have a huge potential in many applications that would involve embedding tags (also known as transponders) into biological entities not limited to humans. A living organism subjected to a static field or to a non-radiating near field will typically extract energy from the source at low frequencies. However, the quantitative description of these mechanisms by which this extraction takes place is very different at higher frequencies [1]. Therefore a study on the electromagnetic backscatter on humans and large vertebrates would yield significant ideas on the technological impacts in temperature increase as compared to arterial temperatures. As passive wireless devices pervade the healthcare space, the power density of these electromagnetic spectrums will dominate and thereby dictate the radiation levels. These passive wireless communication systems must be characterized and analyzed to allow us to understand the impacts that they contribute towards the absorption by human or biological bodies.

In this paper, the workings of passive UHF RFID tag backscatter is studied in muscle tissues. Section 2 presents a background on passive UHF RFID tag antenna systems. A propagation model for the RFID tag backscatter is presented and used to study field variations in free space and muscle tissues in this section. Section 3 is dedicated to the study of RF fields in human and large vertebrate tissues. In this section, the skin effect, energy dissipation and field intensities are studied for high frequency exposures. This section is also dedicated to the study of the biological effects when related to the tag backscatter propagation models. Analytical evaluations are presented in this section to illuminate and visualize the electric field penetrations through muscle tissues. We draw the relevant conclusions in Section 4.

2. Tag Antennas and Propagation

The application specific integrated circuits in RFID tags are typically directly connected to the antennae. The thevenin equivalent of the tag antenna is represented in Equation 1.

$$Z_a = R_a + jX_a \text{ and } Z_c = R_c + jX_c \tag{1}$$

Antenna impedances are typically matched to the high impedance to maximize the collected power, where Equation 1 is the complex antenna impedance and the complex chip (load) impedance [2]. In order to maintain the maximum tag range, Equation 1 is often matched at the minimum power level required for the chip to work [2-4]. However, it is possible in some tags that when the reader is significantly close to the tag, a severe mismatch occurs which causes dead zones or no read zones.

The power density of an electromagnetic wave incident to the RFID tag antenna in free space may be calculated using Equation 2 [5], where P_t is the transmitted power, G_t is the gain of the transmitting antenna and r is the distance to the tag. The power collected by the tag antenna may also be calculated using this equation. This power is defined by the maximum power delivered to the complex conjugate matched load [2], where A_e is the effective area of the antenna, and G is the tag antenna gain.

$$S = \frac{P_t G_t}{4\pi r^2} \ , \ P_a = S A_e \quad \text{and} \quad A_e = \frac{\lambda^2}{4\pi} G \tag{2}$$

The power re-radiated by the tag is found using Equation 3. It is the power dissipated by the antenna resistance multiplied by the tag antenna gain [2], where K is a factor defining the load impedance mismatch on the amount of re-radiated power [2]. Equation 3 also depicts this factor, where R_a, Z_a and Z_c are the components from Equation 1.

$$P_{re-radiated} = K P_a G \quad \text{and} \quad K = \frac{4R_a^2}{|Z_a + Z_c|^2} \tag{3}$$

Using Equations 1, 2 and 3, Table 1 is derived to show the values for factor K for different antenna load impedances. Similarly, using Equations 1 through 3 and the assumption that the antenna is loaded with the complex conjugate impedance, Equation 4 is deduced.

Table 1: Factor K for different antenna load impedances [2]

Z_c	0	Z_a^*	∞
K	$4R_a^2/(R_a^2 + X_a^2)$	1	0

$$P_{re-radiated,\ K} = \frac{P_t G_t \lambda^2 R_a^2}{4\pi^2 |Z_a + Z_c|^2 r^2} G^2 \quad \text{and} \quad P_{re-radiated,\ 1} = \frac{P_t G_t \lambda^2}{16\pi^2 r^2} G^2 \tag{4}$$

In the following section, an overview of the biological effects of electromagnetic field on humans and large vertebrates are presented. The skin effect, energy dissipation and field intensities are discussed in this section to bring light to the propagation of waves through muscle tissues.

3. Biological Effects and Backscatter in Muscle Tissues

The biological effects of electromagnetic fields are somewhat different for UHF waves as compared to lower frequency waves. At higher frequencies, both the electrical and magnetic fields of the incoming electromagnetic wave, after reflection at the boundary conditions, are further decreased due to energy dissipation [1]. Both $\boldsymbol{E}$ and $\boldsymbol{H}$ fields decrease exponentially with distance from the boundary as depicted in Equation 5.

$$g(z) = A e^{-\frac{z}{\delta}} \tag{5}$$

As described in Equation 5, the skin depth (δ) is defined as the distance at which the field decreases to $1/e = 0.368$ of its value just inside the boundaries [1]. The skin depth is described well by Equation 6, where p is the ratio of conduction current to displacement current in the given media. Notice that for high values of p, Equation 6 reduces to the familiar skin depth that is well suited for a good conductor. It is widely known that the skin effect becomes much more apparent and significant for humans and larger vertebrates at higher frequencies [1, 6]. In this study the brief descriptors would be Equation 6 as well as the Equations 1 through 5. These equations would yield a complete picture of the RFID tag impact on humans and large vertebrates.

$$\delta = \frac{1}{\omega\left[\frac{\mu\epsilon}{2}\left(\sqrt{1+p^2}-1\right)\right]^{1/2}} \ , \ p = \frac{\sigma}{\omega\epsilon} \gg 1 \quad \text{and} \quad \delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{6}$$

The electromagnetic backscatter from the RFID tag is well modeled using Equations 1 through Equations 6. However, to include the biological effects to human and large vertebrates, an inclusion of the skin effect is pertinent. In doing so Equation 5 is revisited to include the power re-radiated by the tag, where P_r is the power reflected at the boundary conditions of the human muscle tissue. The three important parameters are the power of the transmitted waves (P_t), power of the re-radiated waves (or incident waves) and the power of the reflected waves. From conservation of energy, it is known that Equation 7 is true.

$$A = P_{re-radiated} - P_r \quad \text{and} \quad P_t = P_{re-radiated} - P_r \tag{7}$$

Since the physics of transmitted, reflected and incident waves are well known, it is feasible to jump to the conclusions depicted in Equation 9 below, from Equations 7 and 8,

$$\frac{P_t}{P_{re-radiated}} = |T|^2 \frac{\eta_1 \eta_2^* + \eta_1^* \eta_2}{2|\eta_2|^2} \quad , \quad \Gamma = \frac{E_r}{E_{re-radiated}} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \quad \text{and} \quad T = \frac{E_t}{E_{re-radiated}} = \frac{2\eta_2}{\eta_2 + \eta_1} = 1 + \Gamma \tag{8}$$

$$\eta = \left(\frac{j\omega\mu}{\sigma + j\omega\epsilon}\right)^{1/2} \quad , \quad P_{re-radiated} = \frac{|E_{re-radiated}|^2}{|\eta_1|^2} R_1 \quad , \quad P_r = \frac{|E_r|^2}{|\eta_1|^2} R_1 \quad \text{and} \quad P_t = \frac{|E_t|^2}{|\eta_2|^2} R_2 \tag{9}$$

where η_1 and η_2 are the wave impedances, Γ and T are the reflection and transmission coefficients, R_1 and R_2 are the real parts of η_1 and η_2, and R_1 for air as the medium 1 is 377Ω. From the equations above and for known values, it is known that Equation 10 as depicted below is true and that the value p for air-muscle is approximately 0.59 [1, 6].

$$A = P_{re-radiated} \; when \; p \cong 0.59 \quad , \quad g(z) = P_{re-radiated} e^{-\frac{z}{\delta}} \quad \text{and} \quad \delta = \frac{1}{\omega\left[\frac{\mu\epsilon}{2}\left(\sqrt{1+\{0.59\}^2} - 1\right)\right]^{1/2}} \tag{10}$$

Since the Equation 4 is shown to describe the electromagnetic waves at the UHF RFID frequency bands well, Equation 10 can be derived for a typical scenario. Finally, combining Equations 8 and 9 with Equation 10, a complete model for the effects of tag backscatter on humans and large vertebrates is discovered,

$$g(r,z) = \frac{P_t G_t \lambda^2 R_a^2}{4\pi^2 |Z_a + Z_c|^2 r^2} G^2 e^{-z\omega\left[\frac{\mu\epsilon}{2}\left(\sqrt{1+\{0.59\}^2} - 1\right)\right]^{1/2}} \quad \text{and} \quad g(r,z) = \frac{P_t G_t \lambda^2}{16\pi^2 r^2} G^2 e^{-z\omega\left[\frac{\mu\epsilon}{2}\left(\sqrt{1+\{0.59\}^2} - 1\right)\right]^{1/2}} \tag{11}$$

where r is the distance of the reader from the tag and z is the depth into the muscle tissue. Recognize that the separation of the tag from the muscle tissue is ignored in this general theory but that the important reflected power is considered. Similarly, an extended generalization can be done using Equation 11 for a typical RFID matched tag. This effort is more easily visualized than the complete theory.

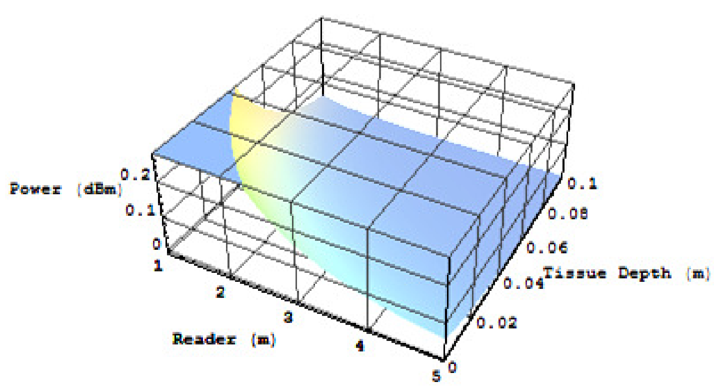
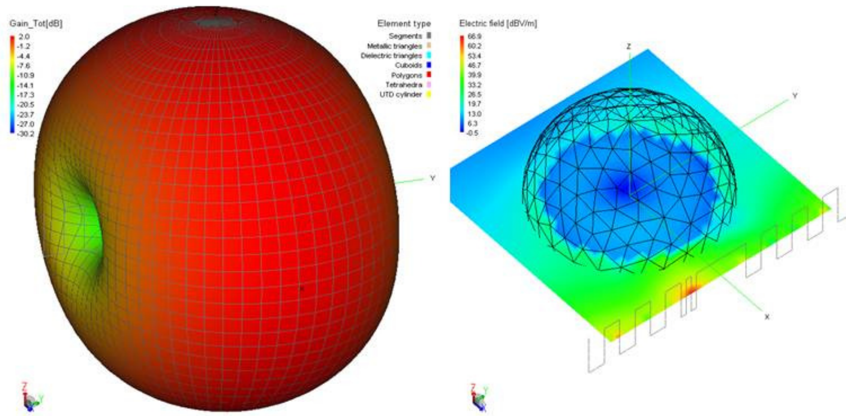


Figure 1: Power of the RF waves penetrating the muscle tissue

From Equation 11, for the values of a typical UHF RFID system with $P_t = 30dBm$ and $G_t = 18dBi$, a 3-dimensional plot is derived to depict the skin penetration in Figure 1. In this figure, the r-axis is the distance from the reader, while the z-axis is the depth penetration into the muscle tissue. With the depiction of Figure 1, the only remaining issue is the penetration of the electric field itself in the muscle tissue. To study this issue, an evaluation is conducted using the results from Equation 11 and Figure 1. An RFID tag with a geometry of a loaded meander as used in [7] is utilized. The loaded meander tag antenna in [7] is simulated in free space to depict the maximum tag antenna gain. The parameters as derived from [1, 5, 6] are used such that, $s = 0mm$, $w = 0mm$, $l = 96mm$, $b = 14mm$, $d = 9mm$, $a = 39/7mm$ and $x = 13/7mm$. Figure 2a depicts the 3-dimensional plot for the gain of the tag antenna in [7].



(a) (b)

Figure 2: Results: (a) Gain plot of the meander tag antenna; (b) E-field intensity for a sphere of muscle tissue

Using the maximum tag gain of the meander tag (2dBi) as depicted in Figure 2a along with Equation 11 and Figure 1, a study of the RFID tag 1cm away from the muscle tissue is conducted. This analytical evaluation is conducted for the reader-tag separation of approximately 1m. From Equation 1 and Figure 1 it is obvious that this constitutes a maximum power of 1.3mW. Using the information and knowledge derived previously, the meander tag is designed with a separation of 1cm from a muscle tissue in the form of a sphere. Figure 2b depicts the results obtained. Note that the field is plotted in decibels as the unit. The sphere of muscle tissue in Figure 2b is removed to allow observations of the fields inside. The wire-frame view depicts the surface of the sphere. The center of the meander tag antenna is located 1cm from the surface of the muscle tissue. Notice that the magnitude of the electric fields reduce tremendously as it approaches the center of the muscle tissue due to high absorption rates.

4. Conclusion

In this paper, a derivation of the RFID tag backscatter theory is presented. This theory is then fitted with fundamental biological effects using the skin effect theory derived specifically for muscle tissues from humans and large vertebrates. This comprehensive theory is then generalized for a typical RFID tag. The generalized theory is then used to visualize the RF penetration for a specific loaded meander tag design. Visualization of RF penetration is presented along with the tag gain in 3D. These results are finally used to depict the variation of the electric field both outside and inside a sphere of muscle tissue. It is found that the maximum electric field in a sphere of muscle tissue for the passive tag backscatter is 66.9dBV/m when placed in the near-field environment, which contributes to a specific absorption rate (SAR) of -21.2dBW/kg. This contribution is more than two orders of magnitudes lesser when compared to the FCC limit (1.6W/kg) for safe exposure to RF energy by mobile devices.

5. References

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