

WBAN in-Body Channel: Dielectric Perspective

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Abstract

The next generation of wireless systems is sprouting towards personal area networks. Among them, a very promising application is the Wireless Body Area Network (WBAN) used for health monitoring and ubiquitous computing. Ultra-Wideband (UWB) communication is one of the potential transmission techniques for wireless networks. To optimize receiver structures and antennas for UWB-WBANs with respect to energy efficiency and complexity, the distinct features of the body area network channel have to be considered. Consequently, it is necessary to know the propagation mechanisms in the human body. In this paper, we limit ourselves to dielectric properties affecting transmission of electromagnetic wave through human body. We especially focus on the link through the human body and mull over the direct transmission of electromagnetic wave as possible propagation mechanisms. We demonstrate theoretically and by compilation of dielectric properties, which were performed in the frequency range between 0.013–3.0 GHz, that the human body is a big shadowing contributor in body area network (WBAN) radio systems due to strong attenuation. Dielectric properties also change with frequency as made known by compilation. These results hold up the significance of channel characterization.

Keywords

Dielectric, Maxwell's Equations, Muscle, Fat, Blood, Penetration Depth, Conductivity, Attenuation, Permittivity, Permeability.

1. Introduction

Wireless Body Area Networks (WBANs) have ensnared interest in recent years because of a number of promising applications such as health monitoring or ubiquitous computing. Like everyday attire, in a WBAN, several small nodes are placed directly on the human body or close to it. Since WBAN nodes acquire

their power from rechargeable batteries or by energy harvesting, it is essential that they are extremely energy-efficient [1]. Above and beyond the energy efficiency, the nodes shall be of low complexity to play down costs. Ultra-Wideband (UWB) communication is one transmission technology promising low-power consumption [2], interference robustness [3], high local capacity [4], and less complex hardware for WBANs [5]. Meticulously, Impulse-Radio (IR) [6] transmission appears to be well suited to trim down complexity, since major parts of narrowband communication systems such as mixers, RF (Radio Frequency) oscillators, or Phase-Locked Loops (PLLs) can be omitted in IR systems [7]. In order to accomplish the requirements mentioned above on energy efficiency and complexity reduction, the distinct behaviour of the propagation channel has to be taken into account. For WBANs, this means that the effects of propagation on or around the body have to be identified. To optimize receiver structures and antennas for UWB WBANs with respect to energy efficiency and complexity, the distinct features of the body area network channel have to be considered. Consequently, it is necessary to know the propagation mechanisms in the human body. In this paper, we limit ourselves to dielectric properties affecting transmission of electromagnetic wave through human body. We specially focus on the link through the human body and consider direct transmission of electromagnetic wave as possible propagation mechanisms. We show theoretically and by compilation of dielectric properties, which were performed in the frequency range between 0.013–3.0 GHz, that the human body is a big shadowing contributor in Body Area Network (WBAN) radio systems due to strong attenuation. Dielectric properties also change with frequency as shown by compilation.

The remainder of this paper is organized as follows. In section 2, mathematical model of dielectric properties has been shown. Results, depending upon the compilation data, have been discussed in section 3. In section 4, conclusion has been drawn.

2. Propagation Through Biological Media

Let us assume that a biological medium is infinite in extent, source-free, isotropic, and homogeneous. The medium is isotropic if ϵ is a scalar constant, so \mathbf{D} (electric displacement field vector) and \mathbf{E} (electric field vector) are the same in every direction. A homogeneous medium is one for which ϵ (relative permittivity), μ (relative permeability), and σ (conductivity) are constants. For this case, Maxwell's equations become

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2.1)$$

$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (2.2)$$

$$\vec{\nabla} \cdot \vec{B} = 0 \quad (2.3)$$

$$\vec{\nabla} \cdot \vec{D} = 0 \quad (2.4)$$

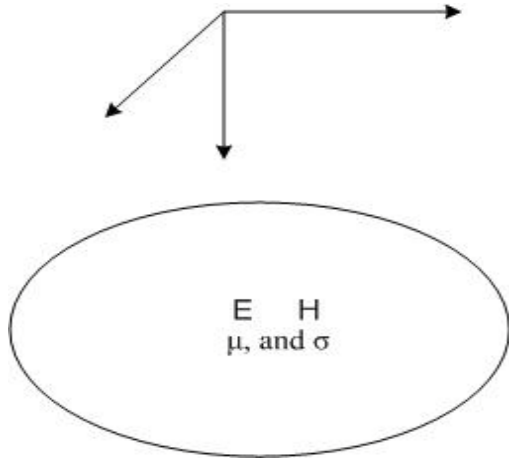


Figure 1: A biological body under electromagnetic (EM) radiation.

Using following identities:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{E} = \vec{\nabla}(\vec{\nabla} \cdot \vec{E}) - \nabla^2 \vec{E} \quad (2.5)$$

$$\vec{B} = \mu \vec{H} \quad (2.6)$$

$$\vec{D} = \epsilon \vec{E} \quad (2.7)$$

$$\vec{J} = \sigma \vec{E} \quad (2.8)$$

where, ϵ , μ , and σ are relative permittivity, relative permeability, and conductivity of the medium, \mathbf{H} is

magnetic field vector, \mathbf{B} is magnetic flux density, \mathbf{J} is the displacement current. We can find the expressions for *wave equation*:

$$\left(\nabla^2 - \mu\sigma \frac{\partial}{\partial t} - \mu\epsilon \frac{\partial^2}{\partial t^2} \right) \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (2.9)$$

In view of the fact that equations governing \mathbf{E} and \mathbf{H} in the biological material (Maxwell's equations) are linear and keeping in mind that any arbitrarily time-varying function can be expressed as a sum of number of sinusoidal functions, time dependence of the fields, \mathbf{E} and \mathbf{H} , can be given by the factor $e^{j\omega t}$ so that

$$\frac{\partial}{\partial t} \equiv j\omega$$

$$\frac{\partial^2}{\partial t^2} \equiv -\omega^2$$

Using the relationships in (2.9), the wave equation becomes

$$\nabla^2 \vec{E} + \gamma^2 \vec{E} = 0 \quad (2.10)$$

where

$$\begin{aligned} \gamma^2 &= \omega^2 \mu\epsilon - j\omega\mu\sigma \\ &= \omega^2 \mu\epsilon_0 \left(\epsilon' - j \frac{\sigma}{\omega\epsilon} \right) \\ &= \frac{\omega^2}{c^2} (\epsilon' - j\epsilon'') \end{aligned} \quad (2.11)$$

where c is the free space velocity (3×10^8 m/s) and γ is the propagation constant. This is in general, a complex quantity and may be written in the form

$$\gamma = \alpha + j\beta$$

where the attenuation constant is

$$\alpha = \frac{\sqrt{2}c}{\omega\sqrt{\epsilon'} \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} + 1 \right)^{1/2}} \quad (2.12)$$

for $\frac{\epsilon''}{\epsilon'} \leq 1$

$$\alpha = \frac{\omega\sqrt{\mu\epsilon'}\left(\frac{\epsilon''}{\epsilon'}\right)}{\sqrt{2}} \quad (2.13)$$

and the phase constant in radians per meter is

$$\beta = \frac{\sqrt{2}c}{\omega\sqrt{\epsilon'}\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)^{1/2}} \quad (2.14)$$

for $\frac{\epsilon''}{\epsilon'} \leq 1$

$$\beta = \omega\sqrt{\mu\epsilon'}\left[1+0.125\left(\frac{\epsilon''}{\epsilon'}\right)^2\right] \quad (2.15)$$

Using equation (2.15), the wavelength λ can be determined by

$$\lambda = \frac{2\pi}{\beta} \quad (2.16)$$

If the incident wave is a linearly polarized uniform plane wave travelling along the z-direction, then, for \mathbf{E} and \mathbf{H} , equation (2.9) is of the form

$$\vec{E} = E_i e^{-\alpha z} e^{j(\omega t - \beta z)} \mathbf{i}_x \quad (2.17)$$

$$\vec{H} = H_i e^{-\alpha z} e^{j(\omega t - \beta z)} \mathbf{i}_y \quad (2.18)$$

where $E_i = \eta H_i$

The intrinsic impedance of biological material η is given by

$$\eta = \sqrt{\frac{\mu}{\epsilon'}} \left[1 - 0.378 \left(\frac{\epsilon''}{\epsilon'} \right)^2 + j0.5 \left(\frac{\epsilon''}{\epsilon'} \right) \right] \quad (2.19)$$

The Pointing Vector, that is, the power flowing per unit area of cross section (W/m^2), gives the power density associated with an EM wave

$$\vec{P}_i = \vec{E}_i \times \vec{H}_i \quad (2.20)$$

For a uniform plane wave, time-average power flowing is given by

$$P_i = \frac{|E_i|^2}{2\eta} = \frac{1}{2} \eta |H_i|^2 \quad (2.21)$$

The permittivity and frequency may also determine how far the EM wave penetrates into the body. The term depth of penetration (D_p) usually quantifies this. For objects with homogeneous properties and with RFR incident at right angles to the surface, depth of penetration is defined as the distance at which the power density is decreased by absorption to about 0.13534 of the body's surface value. However, the magnitude of the electric and the magnetic field reduces by a factor of 0.36788. Depth of penetration is defined as

$$D_p = \frac{1}{\alpha} \quad (2.22)$$

where α is the attenuation constant of the material in nepers per meter.

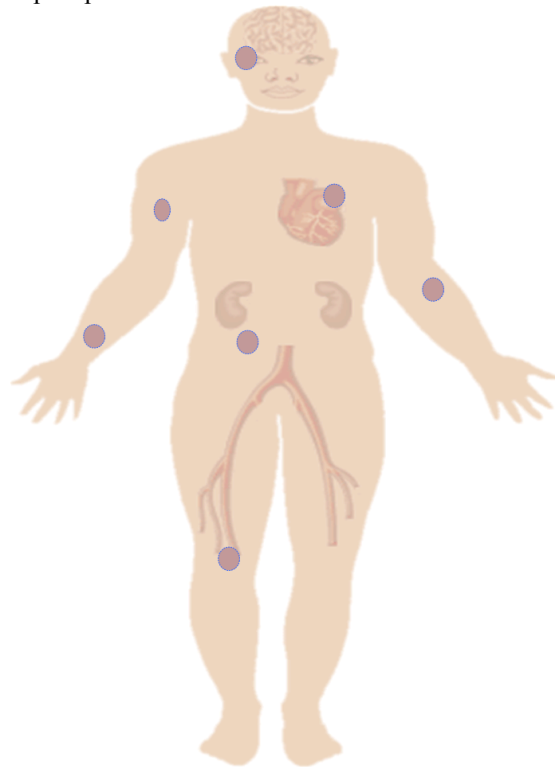


Figure 2: A human body with sensors.

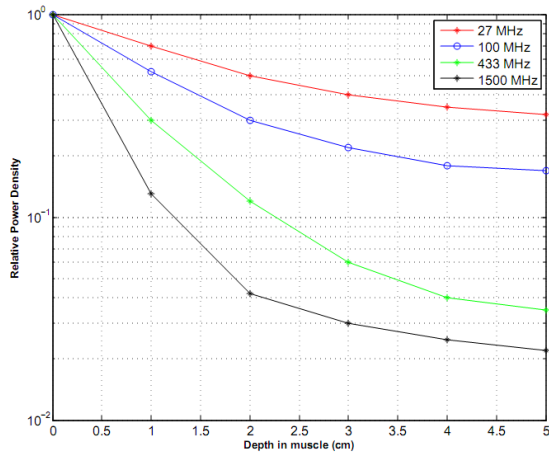


Figure 3: Power absorption in muscle as a function of depth at different frequencies.

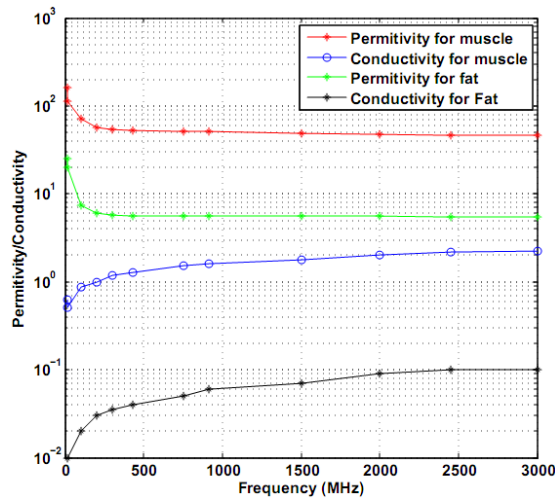


Figure 4: The variation of electrical properties of muscle and fat with frequency.

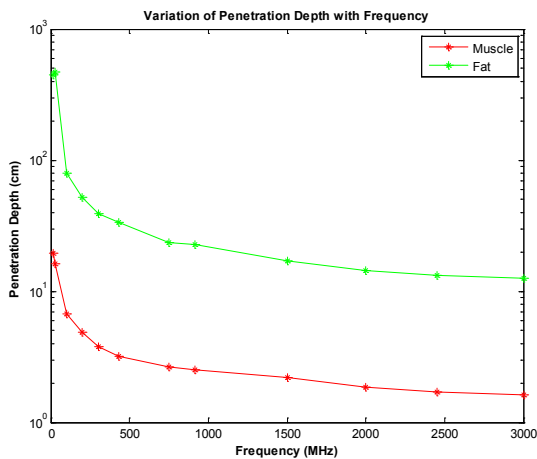


Figure 5: Variation of Penetration depth with frequency.

Table 1: Electrical Properties of Muscle

f (MHz)	λ_0 (cm)	ϵ'	ϵ''	σ (mho/m)	λ (cm)	D_p (cm)
13	2307.69	160.0	864.0	0.62	101.26	19.65
27	1111.11	113.0	339.0	0.51	72.45	16.22
100	300.00	72.0	159.0	0.88	27.02	6.76
200	150.00	57.0	90.0	1.00	16.59	4.86
300	100.00	54.0	72.2	1.20	11.78	3.80
433	69.28	53.0	42.5	1.22	8.91	4.09
750	40.00	52.0	36.9	1.54	5.26	2.66
915	32.79	51.0	31.5	1.60	4.40	2.50
1500	20.00	49.0	21.2	1.77	2.80	2.18
2000	15.00	48.1	18.3	2.03	2.13	1.87
2450	12.24	47.0	16.2	2.20	1.76	1.70
3000	10.00	46.0	13.6	2.27	1.46	1.63

Table 2: Electrical Properties of Fat

f (MHz)	λ_0 (cm)	ϵ'	ϵ''	σ (mho/m)	λ (cm)	D_p (cm)
13	2307.69	25.00	8.4	0.01	455.33	449.40
27	1111.11	20.00	3.4	0.01	247.57	473.40
100	300.00	7.50	3.4	0.02	106.96	79.88
200	150.00	6.00	2.3	0.03	60.18	52.47
300	100.00	5.70	1.9	0.03	41.28	39.29
433	69.28	5.60	1.6	0.04	28.99	33.40
750	40.00	5.60	1.3	0.05	16.79	23.66
915	32.79	5.60	1.1	0.06	13.79	22.87
1500	20.00	5.55	0.9	0.07	8.46	16.95
2000	15.00	5.55	0.8	0.09	6.35	14.29
2450	12.24	5.50	0.7	0.10	5.21	13.27
3000	10.00	5.40	0.6	0.10	4.30	12.52

3. Results and Analysis

Figure 1 shows a biological body under electromagnetic radiation and Figure 2 shows a human body with sensors. The permittivity of biological tissues depends on the type of tissues (e.g. skin, fat, or muscle), water content, temperature, and frequency. However, the permittivity and frequency may also determine how far the EM wave penetrates into the body. The term depth of penetration (D_p) usually quantifies this. It is observed from Equation (2.17) and (2.18) that the wave gets attenuated as it propagates in the biological material along the z-axis. As shown from Figure 3, variation of radiation power density has been compiled for four different frequencies (27 MHz,

100 MHz, 433 MHz, and 1500 MHz) with respect to the depth in muscle. At a given depth, usage of lower frequency results in a higher power density as illustrated in Figure 3.

The electrical properties of biological materials and the operating frequency determine the EM interaction mechanisms. Biological materials are regarded as a lossy dielectric, which is macroscopically or microscopically heterogeneous. ϵ' is the real part of the complex relative permittivity, also called the dielectric constant, and ϵ'' is the imaginary part of the complex relative permittivity. Physically, ϵ' is a measure of the relative amount of polarization that occurs for a given applied electric fields, and ϵ'' is a measure of both the friction associated with changing polarization and drift of conduction charges. Variation of dielectric constant and conductivity for muscle and fat with respect to frequency has been shown in Figure 4. The values of both dielectric constant and conductivity vary substantially with frequency as illustrated in Figure 4. We discovered a distinct feature (demonstrated by Figure 5) which states that attenuation is more in fat than that in muscle with respect to frequency. All the data of dielectric properties from compilation have been presented in Table 1 and 2.

4. Conclusions

We limit ourselves to dielectric properties heart-rending transmission of electromagnetic wave through human body. The links through the human body and consideration of direct transmission of electromagnetic wave have been especially emphasized. It was shown theoretically and by compilation of dielectric properties, which were performed in the frequency range between 0.013–3.0 GHz, that the human body is a big shadowing contributor in body area network (WBAN) radio systems due to strong attenuation. It was also found that attenuation is more in fat than that in muscle with frequency. Dielectric properties change with frequency as shown by compilation. These results support the significance of channel characterization. From the above results we can infer that UWB-WBAN communication is pragmatically quite difficult. For UWB-WBAN, we should use the appropriate modulation technique to make it pragmatically feasible.

5. References

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