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# Assessment of on-body skin-confined propagation for Body Area Network

Qiang Zhang, Julien Sarrazin, *Member, IEEE*, Massimiliano Casaletti, *Member, IEEE*, Philippe De Doncker, and Aziz Benlarbi-Delai

**Abstract**—This letter assesses the potential of using surface waves to implement secure on-body communications. The propagation medium being the human skin, a transverse resonance method is used to analyze existing modes within the multilayered structure that composes the human tissues. Confinement capabilities as well as propagation losses are investigated for frequency up to 60 GHz. It is shown in particular that the 3-10 GHz band could allow secure communications up to few tens of centimeters. This frequency band is furthermore considered as Ultra Wideband channels in the IEEE 802.15.6 standard dedicated to Body Area Networks.

**Index Terms**—Body Area Networks (BAN), propagation, multilayered human body model, dispersion analysis, on-body communication, transverse resonance method

## I. INTRODUCTION

In the past decade, wireless communication systems around the human body have attracted an increasing attention from researchers. Due to aging population issues, the intensive care units in hospital have an arising need of real-time remote monitoring and treating for patients. This task may be achieved by Body Area Networks (BANs), which interconnect wearable sensors and actuators around human body with an external interface. IEEE 802.15.6 standard has been established in order to provide a short-range, extremely low power, highly reliable wireless communications in BANs with data rates up to 10 Mbps [1].

Since the transmitted information is user's private vital signs, such as heart rate and blood pressure, high data security is required in the system. However, the wireless communications have an unbounded nature, which makes the BAN vulnerable to interception. A robust approach to enhance the security is to ensure it at the physical layer. Three physical layers are considered in the IEEE 802.15.6 standard: ultra-wideband

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(UWB) PHY [2], narrowband (NB) PHY [3], and human body communication (HBC) PHY [4]. HBC uses the human body as a transmission medium, which inherently confines the signal to the body area thereby exhibiting interesting features regarding privacy issues. At 16 MHz and 27 MHz (i.e. operating frequencies considered for HBC in the standard), capacitive coupling exhibit much higher power efficiencies than galvanic coupling [4]. However, with capacitive coupling, the signal is less confined within the body and performance is strongly environment-dependent. Indeed, the capacitance between the floating electrode of sensors and the environment directly influences the received power, thereby making a robust implementation tricky.

While NB and UWB on-body propagation at few hundreds of megahertz up to a few gigahertz have been widely investigated [5]–[9], the confinement of on-body surface waves (SW) inside the human skin as a solution for secure communications has not been paid much interest. Authors in [5] investigated the wave propagation using a multilayered human model. However, a single geometry has been studied and few physical insights have been given. Consequently, the goal of this letter is to study the propagation mechanisms that take place within the skin in order to assess their suitability to support a secure communication between on-body sensors. To that aim, section II introduces the topology of the multilayer geometry that is used to model the human tissues and results including confinement capabilities and propagation losses are presented in section III. Conclusion and perspective are given in section IV.

## II. MULTILAYERED HUMAN BODY MODEL

On-body propagation is often studied using full-wave simulations with complete human body models. However, in addition to be a large numerical problem when frequency gets higher, it does not enable a full understanding of propagation phenomena. Consequently, a simpler model modeling the human tissues as a flat multilayer geometry is considered such as in [5], which enables determining the discrete propagation modes that can be supported by such a structure. Flat geometries have been shown to be valid enough in the case of on-body communications using Norton theory for instance [10].

As presented in Fig. 1, each layer represents a different human tissue (i.e. skin, fat, and muscle) characterized by a complex permittivity  $\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon_r' - j\varepsilon_r'')$ , where  $\varepsilon_0$  is

the vacuum permittivity,  $\epsilon_r$  is the body tissue relative permittivity, and an  $e^{j\omega t}$  time convention is considered. The permittivity values for skin, fat, and muscle can be found in [11] for frequencies ranging from 10 Hz up to 100 GHz. According to different locations and different persons, skin thickness was found in medical documents ranging from 0.1 to 5 mm, and fat from 1 to 30 mm [12]–[15]. In most parts of human body, such as forearm and chest, skin thickness is about 1mm. In this paper, various skin and fat thicknesses are considered in order to analyse how these properties influence the on-body propagation.

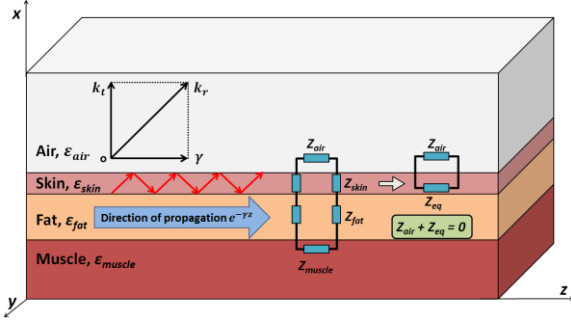


Fig. 1. Multilayered human body modeling and Transverse Resonance Method mechanism

The 4-layers air-skin-fat-muscle model is presented in Fig. 1. Dimensions along  $y$ -axis and  $z$ -axis (direction of propagation) are supposed infinite. In addition, the air and muscle layers are also supposed infinite in the positive and negative  $x$ -axis direction respectively. The complex intrinsic wavenumber of each layer  $k_i$ , at a given frequency, is determined as  $k_i = \omega \sqrt{\epsilon_i(\omega) \mu_0}$ , where  $\omega$  and  $\mu_0$  represent the angular frequency and the vacuum permeability respectively, and  $\epsilon_i(\omega)$  is the frequency-dependent complex permittivity of the tissue “ $i$ ”. This wave vector is decomposed into a transverse component  $k_t$  and a  $z$ -axis component  $\gamma = \alpha + j\beta$ , where  $\alpha$  represents the attenuation constant and  $\beta$  the propagation constant along  $z$ -axis. A wave propagation toward positive  $z$ -axis is here represented using the convention  $e^{-\gamma z}$ .

To satisfy the boundary condition for the propagation,  $\gamma$  should be identical in all layers. Knowing that the real part of  $\epsilon_{skin}$  is greater than the ones of  $\epsilon_{air}$  and  $\epsilon_{fat}$ , and since the muscle layer is considered infinite, propagating waves are mostly confined in the skin, as indicated by red arrows in Fig. 1, forming a stationary wave in the transverse direction. In the tissues surrounding the skin, the waves should exhibit an exponential transverse decay behavior. To determine the dispersion within the structure, the Transverse Resonance Method (TRM) is used [16]. For a propagation mode to exist,  $k_t$  should satisfy the TRM condition:  $Z_{air} + Z_{eq} = 0$ , where,  $Z_{eq}$  represents the impedance exhibited by the tissues at the skin/air interface. The transverse impedance of a homogenous layer “ $i$ ” is given by  $Z_{TM}^i = \frac{k_t}{\omega \epsilon_i}$  for TM mode (magnetic field normal to the  $x$ - $z$  plane) and  $Z_{TE}^i = \frac{\omega \mu_i}{k_t}$  for TE mode (electric field normal to the  $x$ - $z$  plane). Complex solutions  $\gamma$  of these complex equations were found numerically in order to plot the dispersions diagram. To validate the code, obtained results

have been compared with CST Microwave Studio in the case of lossless tissues with an eigenmode analysis and in the case of lossy tissues with the port mode solver. An agreement better than 0.1% has been observed on both the propagation constant value and the attenuation constant. Using these solutions and by expressing the boundary conditions at each interface between tissues, electric field  $\mathbf{E}$  and magnetic field  $\mathbf{H}$  can be determined. The Poynting vector is therefore calculated in order to illustrate the energy distribution of the modes in the next section.

### III. RESULTS

#### A. Dispersive Analysis

Dispersion and attenuation for modes propagating up to 60 GHz are calculated and results are shown in Fig. 2a for a 0.5 mm-thick skin and a 13 mm-thick fat layer. The first mode is a TE mode, starting propagating at about 8 GHz, which is confined within the skin layer. In addition, two other solutions are found which have a propagation constant very close, but smaller, to  $k_0$  and to  $k_{fat}$ , respectively. The first solution represents a fast wave with respect to the semi-infinite air medium while the second one represents a fast wave with respect to the semi-infinite fat medium. Both are proper solutions and represent the so-called Zenneck surface waves (ZW) at the air/skin and fat/skin interfaces respectively.

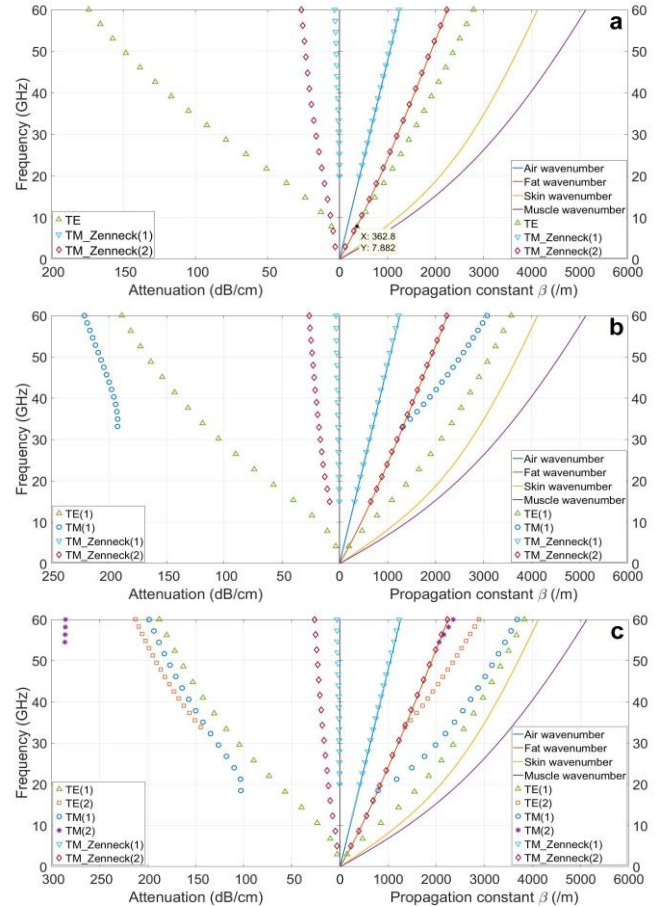


Fig. 2. Propagation and attenuation constants in the direction of propagation for three different skin thicknesses (0.5 mm, 1 mm, 1.5 mm) (fat thickness is 13 mm)

However, ZW cannot be excited separately from other surface-wave contribution when using a finite-size source [17]. Moreover, as shown later in section III-C, although these solutions contribute to describe the total field distribution, they are too loosely bounded to the interface to be useful for on-body communication.

Fig. 2b and 2c show the same results when the skin thickness is increased to 1 mm and 1.5 mm respectively. The same ZW solutions are naturally found. As expected, the fundamental TE mode has a cut-off frequency that decreases when skin thickness increases. Moreover, as the frequency increases, higher order propagation modes appear successively. The cut-off frequencies are shown in Table. I. In the three studied models, the second TE mode is only found with the 1.5 mm-thick skin model, and the first TM mode only with the 1 mm-thick and 1.5 mm-thick skin models.

TABLE I

CUT-OFF FREQUENCIES OF DIFFERENT MODES FOR THREE DIFFERENT MODELS

Skin thickness	TE(1)	TM(1)	TE(2)	TM(2)
0.5 mm	8 GHz	-	-	-
1.0 mm	4 GHz	33 GHz	-	-
1.5 mm	3 GHz	18 GHz	34 GHz	54 GHz

The attenuation of each mode along the direction of propagation is given in terms of dB/cm on the left-hand side of the figures. Only the fundamental TE mode exhibits reasonable attenuation for frequencies below 8 GHz, which could be suitable for on-body ranging transmission (not considering ZW). As the frequency increases, its attenuation becomes significantly larger. Higher order propagating modes have always larger attenuations. Fig. 3 shows the attenuation with respect to frequency of the TE fundamental mode for six different skin thicknesses, ranging from 0.5 to 3 mm. It is noted that, at a given frequency, thinnest skins exhibit the lowest attenuation.

Sensitivity of today's receiver could then allow communication in the range of few tens of centimeters.

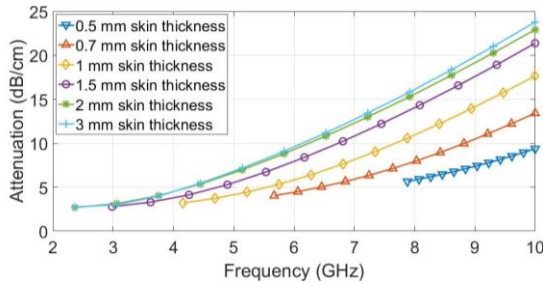


Fig. 3. Attenuation of the TE fundamental mode for different skin thickness models (0.5 - 3 mm) up to 10 GHz (fat thickness is 13 mm)

### B. SW confinement

All solutions but Zenneck ones have a propagation constant  $\beta$  ranging between fat wavenumber  $k_{fat}$  and skin wavenumber  $k_{skin}$ , and represent consequently slow waves (SWs) confined within the skin. However, it is to be noted that since  $Re(\epsilon_{muscle}) > Re(\epsilon_{skin})$ , a SW that propagates within the skin would also propagate within the muscle. However, the surface wave launcher is likely to be located at the skin-air interface. So if the transverse attenuation within the fat is large enough, the amount of the SW energy guided within the muscle layer shall

be small. To quantify this assumption, the transverse attenuation within the fat layer is given in Fig. 4 for the fundamental TE mode. It can be observed that the attenuation is always greater than 5 dB/cm in the 4-10 GHz range of interest. Thus, depending on the fat thickness, the SW will not leak much in the muscle tissue.

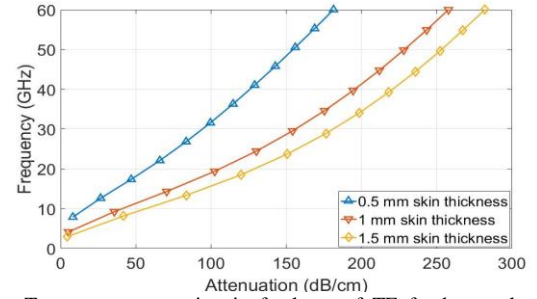


Fig. 4. Transverse attenuation in fat layer of TE fundamental mode for different skin thickness models (0.5 mm, 1 mm, 1.5 mm) up to 10 GHz (fat thickness is 13 mm)

To investigate the confinement of the SW within the skin with respect to the field decay in the air, Fig. 5 shows the transverse attenuation constant in the air for the fundamental TE mode. In the frequency ranging below 10 GHz, the field decays away by about 15 dB/cm and up to 70 dB/cm as the frequency increases. Such an attenuation ensures that on-body SW propagation is confined enough in order to avoid any eavesdropper to intercept the communication. It is also observed that this attenuation is more than twice as high as the attenuation along the direction of propagation.

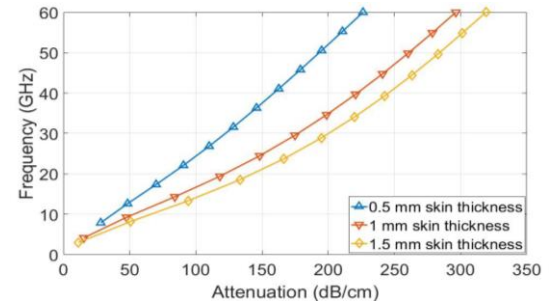


Fig. 5. Transverse attenuation in air layer of TE fundamental mode for different skin thickness models (0.5 mm, 1 mm, 1.5 mm) up to 10 GHz (fat thickness is 13 mm)

### C. Field Distribution

Fig. 6 exhibits the power distributions of the fundamental TE mode at 4 GHz and 6 GHz in the case of a 1 mm-thick skin. It is clearly visible that operating at 6 GHz exhibits better skin-confinement property, but the attenuation in the direction of propagation is also greater. TE mode at 4 GHz has a 3.2 dB/cm attenuation in the direction of propagation, 15.9 dB/cm and 5.7 dB/cm in the transverse direction in the air layer and fat layer respectively. As for 6 GHz, the attenuations

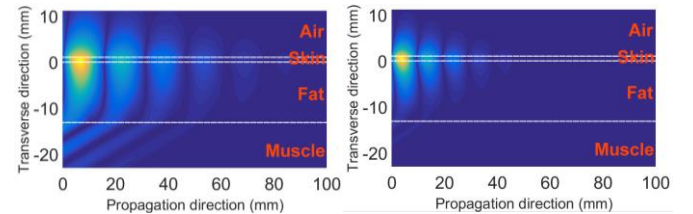


Fig. 6. Power distributions of TE fundamental mode for the 1 mm-thick skin and 13 mm-thick fat model at 4 GHz (left) and 6 GHz (right)



in the direction of propagation, in the transverse direction in the air and fat layers are 5.8 dB/cm, 26.1 dB/cm, and 15.0 dB/cm respectively. The transmission frequency should then be chosen considering a tradeoff between the confinement and attenuation requirements, knowing that the confinement property is associated with the transferred data security and the attenuation in the direction of propagation involves the range and data rate of the wireless system.

To better illustrate the behavior of the two Zenneck surface wave poles, their power distribution is shown in Fig. 7 for the 1 mm-thick skin model at 6 GHz. The first ZW propagating at the air/skin interface is loosely bounded and exhibits approximately no transverse attenuation in the air. The second ZW propagates at the skin/fat interface and has a low transverse attenuation in the fat layer (0.04 dB/cm in fat and 21.7 dB/cm in air). Consequently, despite their low attenuation in the direction of propagation, these two modes do not exhibit any confinement properties. More importantly, it is commonly accepted that these types of modes cannot be excited independently [17].

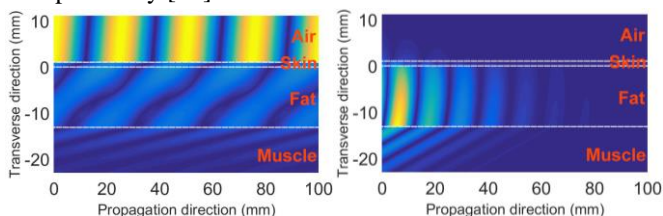


Fig. 7. Power distribution at 6 GHz for TM\_Zenneck(1) (left) and TM\_Zenneck(2) (right) of 1 mm-thick skin and 13 mm-thick fat model

#### D. Fat Thickness Influence

To study the influence of the muscle proximity to the skin on the fundamental TE mode, different thicknesses of fat ranging from 1 mm to 13 mm are studied, with the skin thickness fixed at 1 mm. The propagation and attenuation constants are given as a function of fat thickness in Fig. 8, with a frequency ranging from 4.5 GHz to 8 GHz. As shown previously, the propagation is less confined in skin at lower frequency, which makes it more vulnerable to the reflection from the fat/muscle interface. When the fat thickness decreases, larger attenuation and smaller  $\beta$  are observed at a given frequency. The confined propagation is less sensitive to the change of fat thickness at higher frequency. Also, the cut-off frequency increases when the fat thickness decreases. No confined mode was found in the model with a fat thickness less than 10 mm at 4.5 GHz, 5 mm for 5 GHz, and 3 mm for 6 GHz. The thickness of fat noticed in medical articles varies from 1 mm to 50 mm [15], so the operating frequency should be used with respect to the expected location

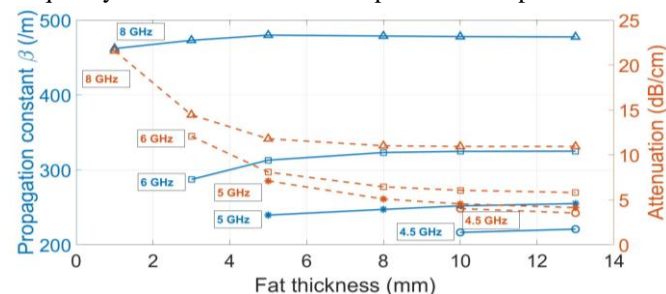


Fig. 8. Propagation and attenuation constants in the direction of propagation in function of fat thickness (skin thickness is 1 mm)

of sensors on the body, depending on the targeted application.

#### IV. CONCLUSION

In this work, a dispersion analysis of the propagating modes within human tissues has been presented using transverse resonance method. The influence of the different tissue layers has been highlighted. It has been observed that operating in the 3-10 GHz frequency range could allow short range propagation within the human skin. This type of communication would naturally enable secure on-body communications to ensure data confidentiality in BANs.

The perspective of this work is to design on-body surface wave launchers in order to verify whether the identified fundamental TE mode can be efficiently excited.

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