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***Abstract*—The propagation of 60 GHz electromagnetic waves around a human body is studied. The body is treated as a circular cylinder. Analytic formulations based on creeping wave theory for both vertical and horizontal polarizations are given. Measurements conducted on a brass cylinder confirmed theoretical results.**

***Index Terms*—Millimeter wave propagation; Surface waves; Wireless body sensor networks; Millimeter wave measurements**

I. INTRODUCTION

Miniaturization of integrated components and systems and the increasing pervasiveness of electronic devices have led industries and research laboratories imagine Body Area Network (BAN) of wearable computers [1]. One of the most important aspects of future BANs will be the absence of cables connecting devices worn on the body, thus making Wireless BAN (WBAN). Although research in the past years concentrated mainly on communicating systems functioning around 2.4 GHz because of the high availability and low cost of devices, the appearance of the first 60 GHz standards [2] and communicating systems [3] encourages studies in the field of WBAN at this frequency. Compared to 2.45 GHz, a 60 GHz WBAN, due to high propagation losses, would truly permit the coexistence of several personal area networks with many wearable devices communicating around a human body and not interfering with other WBANs.

Extending previous studies on path loss prediction on planar body surfaces at 60 GHz [4], in this work we propose a model based on the creeping wave theory to predict the attenuation of vertically and horizontally polarized electromagnetic waves around cylindrical human bodies at 60 GHz.

II. ANALYTIC MODEL

We consider the interface between air, indicated as medium 0, and a loss conductor, indicated as medium 1 and representative of the human body, with a complex electric permittivity $\underline{\varepsilon}_1 = \varepsilon_0 \underline{\varepsilon}_r = \varepsilon_0 \varepsilon_r - \mathrm{j}\,\sigma/\omega$ and magnetic permeability equals to air μ_0. Around 60 GHz, human body can be approximated by only considering the skin, whose electric parameters at these frequencies are $\varepsilon_{rr} = 7.98$ and $\sigma = 36.4$ S/m [5]. In fact, its skin depth [6] at 60 GHz is approximately equal as 0.5 mm which is sufficiently small compared to its thickness (2-3 mm). Thus, the 60 GHz model of the human body does not have to take in account for the presence of underlying tissues, since the field penetrating in the skin is sufficiently attenuated.

We assume a suppressed time dependency $e^{+\mathrm{j}\,\omega t}$, where ω is an angular frequency. The geometry under consideration is an homogeneous loss cylinder of radius a surrounded by air, which is a simplified model for a human torso. For most of the curves we will choose a value of a equal as 0.2 m, as it has been motivated in [7]. Source and observation points, assumed close to the interface in the air region, are spaced by the radial distance $\rho_s = \theta a$, where θ is the angle measured between them. A cylindrical coordinate system is adopted.

In order to study the attenuation of the field propagating at the surface of the human torso on a circular path, we adopt creeping waves formulation to calculate the field excited by Hertzian dipoles located near the surface of the cylinder: we will show that such formulations can model the propagation of both vertical and horizontal polarized waves.

The hypothesis permitting to adopt this model are that the radius of the cylinder is larger than the wavelength in free space and that the complex permittivity's magnitude of the material filling the cylinder is much larger than unity. Both conditions are fulfilled for our analysis. Moreover, if the Hertzian dipole and the observation point are not placed on the surface of the cylinder but are in its closeness, "height-gain" functions can be introduced under the hypothesis that both are smaller than the range ρ_s [8].

The curves shown in this section have been normalized with respect to the ρ component of the electric field radiated by a vertical Hertzian dipole placed on the surface of a PEC cylinder of radius $a = 0.2$ m and calculated at $\rho_s = 5$ mm at 60 GHz.

A. Vertical dipole

Let a Hertzian dipole be radially placed on the surface of the cylinder in the air at $z = 0$. We define this case as the vertical configuration, in analogy with most of the literature

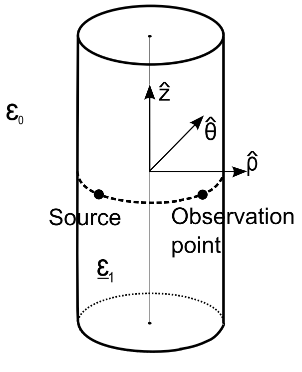

Fig. 1. Geometry

[7], [9]. The electric field close to the surface of the cylinder has a ρ component and a negligible θ component, while the magnetic field is directed towards $\hat{z}$. The electric field is then vertically polarized with respect to the surface of the cylinder and the ρ component (which we call E_v) of the electric field is [10]:

$$E_v = \frac{\mathrm{j}\,\omega\mu_0 I dl}{2\pi}\frac{e^{-\mathrm{j}\,\omega\rho_s/c}}{\rho_s}e^{-\mathrm{j}\,\pi/4}\sqrt{\pi\xi}\frac{F(h_s)F(h_r)}{\tau_1 - q_v^2}e^{-\mathrm{j}\,\xi\tau_1} \quad (1)$$

with

$$F(h) \simeq \frac{W\left(\tau_1 - \sqrt[3]{\frac{2}{k_0 a}}k_0 h\right)}{W(\tau_1)} \quad (2)$$

$$\xi = \sqrt[3]{\frac{\omega a}{2c}}\frac{\rho_s}{a} \quad (3)$$

$$q_v = -\mathrm{j}\,\sqrt[3]{\frac{\omega a}{2c}}\sqrt{\frac{1}{\underline{\varepsilon}_r}} \quad (4)$$

and τ_1 is the first zero of

$$W'(\tau_i) - q_v W(\tau_i) = 0 \qquad i = 1, 2, ... \quad (5)$$

$W(\tau)$ with its derivative are Fock-type Airy functions defined in [10] and [11] by $W(\tau) = \sqrt{\pi}\,[B_i(\tau) - \mathrm{j}\,A_i(\tau)]$. $F(h)$ is the "height-gain" function. Equation (1) is commonly known as creeping wave and it is an evanescent wave. For a source radiating close to the surface of the cylinder, two creeping waves traveling in opposite directions have to be taken in account and then the total field is:

$$E_T = E_v(\theta) + E_v(2\pi - \theta) \quad (6)$$

The vertical component of the electric field radiated by a vertical Hertzian dipole around the surface of different cylinders is drawn in Fig. 2. Source and observation points are 1 mm above the surface of the cylinder.

The attenuation rate of the electric field at 60 GHz traveling around the cylinder is approximately equals as 3 dB/cm for a radius of 20 cm. Reducing the radius of the cylinder, even if it slightly increases the attenuation rate, permits to enhance the strength of the electric field in the backside of the cylinder, since traveled distances are smaller for a given θ. Comparing PEC and human body, a cylinder made of PEC augment the propagation of the vertical polarized creeping wave. This result is easily explained by considering that the human body at 60 GHz is poorly conducting and propagation losses are thus larger than for a PEC. The interference between the waves traveling in opposite sense around the cylinders appears around 180 ° in Fig. 2.

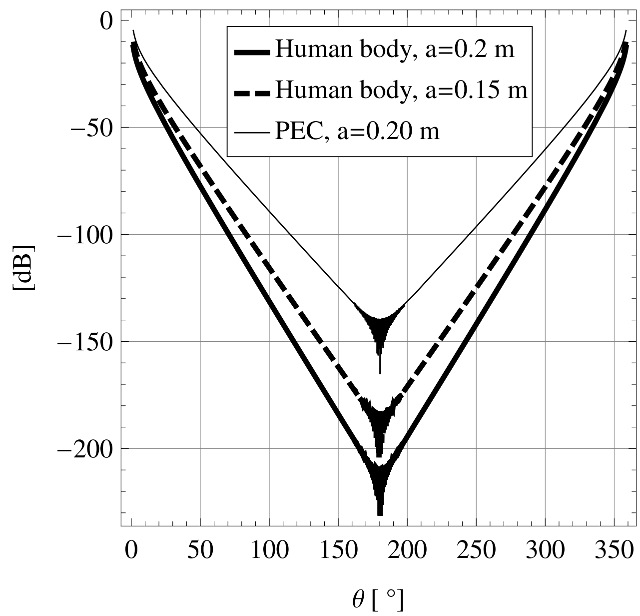

Fig. 2. Vertical Hertzian dipole: magnitude of the ρ component of the electric field as function of θ at the surface of cylinders with different radii and electromagnetic properties. $h_s = 1$ mm, $h_r = 1$ mm.

B. Horizontal dipole

Let a Hertzian dipole being placed in the air close to the surface of the cylinder with its axis parallel to the $\hat{z}$ direction. We define this case as the horizontal configuration. The case of a Hertzian dipole placed parallel to the $\hat{z}$ axis on the surface of the cylinder is much more complicated than the previous case, since, in the general loss case, all of the six component of the electromagnetic field are involved [12]. However, for the scope of this communication we are only interested in the fields propagating around the cylinder at $z = 0$, which is the direction perpendicular to the axis of the dipole. In this case, only the transverse component of the electric field is involved and the field is then horizontally polarized. Formulations similar to the previous case have been given in [8] and, with the same notations introduced above, the θ component of the electric field at the surface of the cylinder (which we name E_h) is:

$$E_h = \frac{\mathrm{j}\,\omega\mu_0 I dl}{2\pi}\frac{e^{-\mathrm{j}\,\omega\rho_s/c}}{\rho_s}e^{-\mathrm{j}\,\pi/4}\sqrt{\pi\xi}\frac{G(h_s)G(h_r)}{\tau_1' - q_h^2}e^{-\mathrm{j}\,\xi\tau_1'} \tag{7}$$

with

$$G(h) \simeq \frac{W\left(\tau_1' - \sqrt[3]{\frac{2}{k_0 a}}k_0 h\right)}{W(\tau_1')} \tag{8}$$

$$q_h = -\mathrm{j}\,\sqrt[3]{\frac{\omega a}{2c}}\sqrt{\varepsilon_r} \tag{9}$$

and τ_1' is the first zero of

$$W'(\tau_j') - q_h W(\tau_j') = 0 \qquad j = 1, 2, ... \tag{10}$$

$G(h)$ is the "height gain" function for horizontal polarization. In Fig. 3 we have drawn the horizontal component of the electric field excited by a Hertzian dipole located on the surface of the cylinder. The result on PEC cylinder is not reported because of its small magnitude; however, the attenuation rate of a horizontal polarized wave traveling around a PEC cylinder is slightly the same as for the human body case with the same radius value.

With respect to the vertical case, the curves drawn in Fig. 3 reveal that the field traveling around the surface of the cylinder having the same electromagnetic properties of the human body at 60 GHz is much more attenuated. On a cylinder of radius equals as 20 cm, the attenuation rate of E_h is approximately equal as 4 dB/cm. Thus, vertical polarized waves should be preferred for a wireless link on a circular path around the torso surface.

III. Measurements

In this section we report results of Network Analyzer (*Agilent E8361C*) measurements carried out in an anechoic chamber on a brass cylinder. The cylinder radius has been chosen equal as 0.2 m and its height equal as 1.2 m. The cylinder was vertically mounted on a rotor and could thereafter rotate around its axis.

Antennas are 3 cm x 2.3 cm pyramidal horns with a gain of approximately 20 dBi. A pyramidal horn antenna has been attached to a vertical support and placed as close as possible to the cylinder. A second, identical horn antenna was joined to the surface of the cylinder. Then, different distances between the two horn antennas were achieved with a precision of 1 ° by simply turning the cylinder around its axis. In order to perform both vertical and horizontal polarization measurements, the pyramidal horns have been mounted with their E-plane perpendicular to the cylinder surface (vertical polarization) or parallel (horizontal polarization). In both case an amplifier as been put at the transmit side. Measures have been performed in the band 50 to 60 GHz.

In Fig. 4 we have drawn vertical and horizontal polarization measurements and the corresponding theoretical predictions.

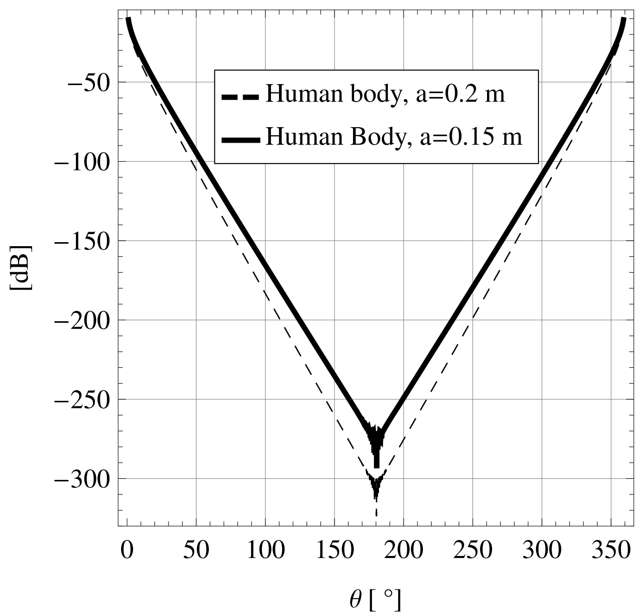

Fig. 3. Horizontal Hertzian dipole: magnitude of the θ component of the electric field as function of θ at the surface of cylinders with different radii. $h_s = 2$ mm, $h_r = 2$ mm.

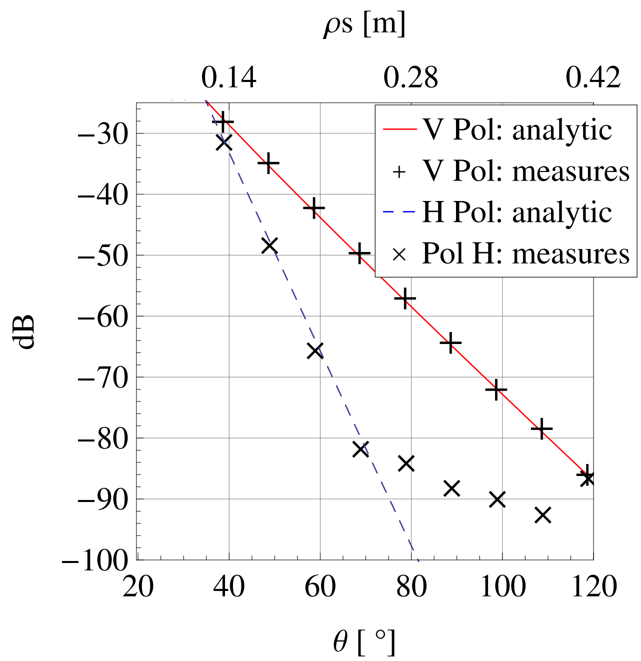

Fig. 4. Vertical and horizontal polarization measurement results compared with theoretical attenuation prediction for a PEC cylinder of radius a=0.2 m.

Experimental results fit very well by the creeping wave formulations introduced in the previous section. However, it can be noticed that horizontal polarization measurements diverge from the theoretic prediction from 80 ° . This should be explained because of the strong attenuation of horizontal polarized waves, which fall under the signal reflected by the anechoic chamber walls. A similar issue has already been observed in [13]. This consideration clearly reveals that, in an indoor environment, the signal propagating on the body surface can be overcome by the reflections on the environment. However, the knowledge of the attenuation on the surface of the body is necessary before conducting investigations on wireless BAN at 60 GHz in real environments.

IV. Conclusion

In this paper creeping wave formulation for both vertical and horizontal polarized electromagnetic waves traveling on a circular path around a cylinder are given. Such formulations can be used to predict the attenuation rate of an on-body 60 GHz communication link. Vertical polarized waves attenuation is approximately equal as 3 dB/cm, while for horizontal polarization is approximately equal as 4 dB/cm. Measurements carried at 60 GHz on a brass cylinder are in perfect agreement with creeping waves theoretical model. Measurements reveals that, even in an anechoic chamber, the signal propagating at the surface of the cylinder can be overcome by the reflections on the environment. Thus, models and experiments in a real indoor scenario are needed to complete the propagation mechanism for wireless BAN at 60 GHz. In future experiments, measurements on a human torso are also expected to confirm theoretical results.

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