Analytical Creeping Wave Model and Measurements for 60 GHz Body Area Networks

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Abstract—The propagation of 60 GHz electromagnetic waves around a human body is studied analytically and experimentally. The body is treated here as a circular lossy cylinder, which is an approximation of the human torso. Analytical formulations based on creeping wave theory are given and discussed for both vertical and horizontal polarizations. An exact path gain expression is derived from analytical formulations and a simpler first order approximation is given. Path gain coefficients are shown for frequencies spanning the world available 60 GHz unlicensed band and for several sizes of the torso. Finally, the results of an experimental campaign conducted in an anechoic chamber to isolate the contribution of on-body propagation are reported. The measurement of the distance dependence of the received power on a brass cylinder and on a human body for both vertical and horizontal polarizations confirmed theoretical predictions.

Index Terms—60 GHz propagation; BAN; creeping waves; channel model

I. INTRODUCTION

Miniaturization of integrated components and the more and more pervasiveness of electronic devices let industries and research laboratories imagine Body Area Network (BAN) of wearable computers [1]. One of the most important aspect of future BANs will be the absence of cables connecting worn devices, thus making Wireless BAN (WBAN). Although researches in the past years concentrated mainly on communication systems working around 2.45 GHz [2]–[4] and in the 3.1–10.6 GHz spectrum [5], [6] because of the high availability and low cost of devices, the appearance of the first 60 GHz standards [7] and communicating systems [8] encourages studies in the field of WBAN at this frequency. Indeed, one of the major advantages of 60 GHz communication resides in its limited coverage due to high propagation losses. This involves the possibility of setting up very small wireless networks. Compared to 2.45 GHz, a 60 GHz WBAN would truly permit the coexistence of several personal area networks with many wearable devices communicating around a human body and non-interfering with others WBAN [9].

Link performances between communicating nodes in on-body networks are dependent of their respective positions and body movement and posture. However, an analytical model may be useful to understand experimental data and propagation mechanisms. Furthermore, because of the small wavelength at 60 GHz, full-wave simulations are hardly possible. Hence these computational issues emphasize even more the need for 60 GHz analytical models.

In this work we propose a model based on creeping wave theory to predict the attenuation of vertically and horizontally polarized electromagnetic waves around the human torso at 60 GHz, which extends previous works, conducted on plane surfaces [10], [11]. After recalling creeping waves formulation for the Hertzian dipole radiating above a conducting cylinder, we derive a linear path gain expression permitting to predict the attenuation of vertical or horizontal polarized electromagnetic fields propagating on a circular path around a cylinder having the electromagnetic properties of a human body for frequencies around 60 GHz. Finally, we show measurement results to confirm analytical outcomes.

II. ANALYTICAL MODEL

In our study, we consider the interface between air, indicated as medium 0, and a lossy conductor, indicated as medium 1 and representative of the human body, with a complex permittivity $\varepsilon_1 = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon - j \sigma / \omega)$ and permeability $\mu_0$. Around 60 GHz, the human body can be approximated by only considering the skin, whose electric parameters at these frequencies are $\varepsilon_r = 7.98$ and $\sigma = 36.4$ S/m [12]. In fact, skin depth [13] at 60 GHz is approximately equal to 0.5 mm which is fairly thin if compared to its thickness (2-3 mm). Thus, the 60 GHz model of the human body does not have to take into account the presence of muscles and fat, since the field penetrating the skin is sufficiently attenuated.

We assume a suppressed time dependency $e^{j \omega t}$, where $\omega$ is an angular frequency. Since we are considering on-body communication links, source and observation points will be assumed close to the interface in the air region through the entire communication. The geometry we are taking into account (Fig. 1) is an homogeneous lossy cylinder of radius $a$, surrounded by air, which is a simplified model for a human torso. In this communication, all the variables are defined in SI units. However, for sake of readability, numerical values are often presented in derivative units.

Both source and observation points will be assumed to lie on a $z$ constant plane, namely $z = 0$, since we are considering a circular path on the cylinder. The distance between source and observation points will be indicated as $\rho_s = \rho_a$, where $\theta$ is the angle measured between the source and the observation point.

Creeping waves formulations will be adopted to calculate vertically and horizontally polarized waves excited by Hertzian dipoles located near the surface of the cylinder.

![Fig. 1. Geometry of the analytical problem.](image_url)
III. HERTZIAN DIPOLE FORMULATION

Dating back to studies concerning electromagnetic wave propagation on the surface of the Earth [14], creeping waves formulations were originally intended to be applied to a Hertzian dipole radiating at the surface of a large (if compared to wavelength) lossy sphere. However, Paknis showed that the same formulations could model the propagation of electromagnetic waves on a circular path around a lossy cylinder [15]. In recent years, such formulations have been adopted to predict the field propagation around human torso and head at 2.45 GHz for on-body communications [16], [17].

A twofold hypothesis permits to use this model: (i), the radius of the cylinder must be larger than free space wavelength and (ii), the complex permittivity of the material filling the cylinder must be much larger than unity. Both conditions are fulfilled in our analysis. Moreover, if the Hertzian dipole and the observation point are not placed on the surface of the cylinder but are in its vicinity at heights $h_s$ and $h_r$, respectively, “height-gain” functions $F(v)$ can be introduced under the hypothesis that both $h_s$ and $h_r$ are smaller than the range $\rho_s$ [18].

We aim to provide a uniform notation for the field radiated by a Hertzian dipole oriented normally or tangentially to the surface of the cylinder and not ed in its vicinity at heights $h_s$ and $h_r$, respectively, “height-gain” functions $F(v)$ can be introduced under the hypothesis that both $h_s$ and $h_r$ are smaller than the range $\rho_s$ [18].

Formulations for these two cases have been given separately in [15], [18], and can be rewritten as:

$$E_{v,h} = \frac{j \omega q d}{2\pi} e^{-j \omega \rho_s/c} \frac{e^{-j \pi/4 \sqrt{\xi}}} {\rho_s} \sum_{i=1}^{\infty} \frac{F_{v,h}(h_s)F_{v,h}(h_r)} {\tau_i^{v,h}} \exp(-j \xi \tau_i^{v,h})$$

with

$$F_{v,h} \simeq \frac{W(\tau_i^{v,h} - \sqrt{\frac{\omega \rho_s}{2c a}} k_0 h)} {W(\tau_i^{v,h})}$$

$$\xi = \sqrt{\frac{\omega \rho_s}{2c a}}$$

and $\tau_i^{v,h}$ are the zeros of

$$W(\tau_i^{v,h}) - q_{v,h}W(\tau_i^{v,h}) = 0 \quad i = 1, 2, ...$$

$I$ is the current flowing in the dipole, $dl$ is its length and $c$ is the speed of light in vacuum. $W(\tau)$ is a Fock-type Airy function defined in [14], [15] by $W(\tau) = \sqrt{\pi |B_i(\tau) - j A_i(\tau)|}$. $F$ is the “height-gain” function.

IV. PATH GAIN

In order to give a practical, ready to use approximation of the decay of the electric field on a circular cylinder having the electromagnetic properties of the human body around 60 GHz, two zones with respect to $\rho_s$ are defined. The first one, $0 < \rho_s < \rho_s^T$, is the zone where the fields radiated by a Hertzian dipole located close to the surface of the cylinder cannot be approximated by only the first term of (1). Therefore, more than one zero of (5) need to be taken into account. In this zone, precise evaluation of the fields decay is strongly dependent on the height of the Hertzian dipole above the surface of the cylinder, mainly because the field reflected off the cylinder surface can add constructively or destructively to the direct field. Consequently, considering also that this zone is restricted to small tangential distances from the source, we will not give an expression of the path gain in this zone.

In the second zone, $\rho_s > \rho_s^T$, only one zero of (5) is needed to compute (1). Here, the field exponentially decays and it is commonly known as creeping wave.

In [19], $\rho_s^T$ is some value much greater than $a \sqrt{2c/\omega}$ for source and observation points close to the interface between the air and the conductor. This condition can be relaxed and a heuristic expression for the choice of $\rho_s^T$ can be given by introducing the relative error in linear scale between equation (1) calculated with the first 10 terms of the sum, and equation (1) calculated with only the first term of the sum. We found that $\rho_s^T = 0.2a + 0.04$ permits to keep this error smaller than 5% for values of $h_s$ and $h_r$ smaller than 5 mm, for frequencies comprised between 57 and 66 GHz, and BAN scenarios (0.1 m ≤ $a \leq 0.2$ m).

In order to give a path gain expression of $E_v$ in the second zone, we have to note that for the first term in (1), the $\rho_s$ dependency of the module of $E_v$ is:

$$|E_v(\rho_s)| = E_0 e^{\text{Im}[\tau_i^{v,h}]/\sqrt{\rho_s}} = E_0 e^{-m_v \rho_s / \sqrt{\rho_s}}$$

$$m_v = -\text{Im}[\tau_i^{h}] \frac{\omega a}{2c a}$$

where $\text{Im}[\tau_i^{v,h}]$ is the imaginary part of $\tau_i^{v,h}$. Therefore, with respect to a reference distance $\rho_s^0 \geq \rho_s^T$, the path gain is:

$$G(\rho_s) = G(\rho_s^0) - 10 \log_{10} \frac{\rho_s}{\rho_s^0} - n_v(\rho_s - \rho_s^0)$$
\[ n_v = 20n_v \log_{10} e \]  

In the above expressions, \( G \) is the path gain expressed in dB and \( n_v \) is the power decay exponent for vertical polarization. It is worth noting that (8), with \( n_v \) computed using (9), is exactly equivalent to \( E_v \) evaluated with only the first zero of (5). However, an approximate expression of (8) starting from a first order series expansion of the logarithm can be derived. Then, expanding around \( \rho_a \):

\[ G(\rho_s) \approx G(\rho_a) - n'_v(\rho_s - \rho_a) \]  

with

\[ n'_v = n_v + \frac{10}{\rho_a \ln 10} \]  

The error incurred in approximating (8) by (10) is equal to the residual of the Taylor series of the logarithm, which is equal to \(10(\rho_s - \rho_a)^2/(2\rho_a^2 \ln 10)\).

The same reasoning can be carried out for the path gain of horizontally polarized waves. Thus, we can define two new power decay exponents \( n_h \) and \( n'_h \), which are:

\[ n_h = -20 \ln(\frac{r}{h}) \sqrt{\frac{\omega a}{2c}} \frac{1}{a} \log_{10} e \]  

\[ n'_h = n_h + \frac{10}{\rho_a \ln 10} \]  

Table I represents useful insights for the power management and routing strategies of a 60 GHz BAN.

V. MEASUREMENTS

An experimental campaign was carried out in an anechoic chamber to measure the propagation at the surface of a cylindrical body. All measures are performed with an Agilent E8361C Vector Network Analyzer in an anechoic chamber. Since large losses due to the coaxial cables were found at 60 GHz (6 dB/m), the VNA was placed inside the anechoic chamber to limit the length of the cables feeding the field probes. The measured parameter was \(|S_{21}|^2\) between the probes.

A. PEC measurements

In a first step we compared the creeping wave model at 60 GHz with the field measured on a brass cylinder of radius equal to 20 cm and of height equal to 1 m. Brass offers a good trade-off between mechanical properties, price and high electric conductivity, which allows to assimilate it to PEC for the frequency under exam (brass conductivity is equal to \(2.56 \times 10^7 \) S/m [20]). The brass cylinder was vertically mounted on a rotor and could rotate around its axis. A pyramidal horn antenna has been used as transmitter. It has a gain of 20 dB and a beamwidth of 10°. The aperture size is 2.3 cm x 3 cm. It has been mounted directly on the surface of the cylinder, at middle height. A field probe has been realized by fixing a second identical antenna on a vertical stand. The probe was then moved at the surface of the cylinder, at the same height as the source. Different distances between source and probe were achieved by rotating the cylinder (only the transmitter is fixed to the cylinder). Both antennas are located tangentially to the surface of the cylinder and the distance between the horns and the cylinder was equal to zero. Consequently, the distance between the phase center of the horns and the cylinder was equal to half the horns’ aperture: 1.5 cm for vertical polarization and 1.15 cm for horizontal polarization. A schematic representation of the measurement setup is drawn in Fig. 2. The VNA noise level is equal to approximately -100 dB.

![Fig. 2. Measurement setup. Black dots indicate different measurement points.](image-url)

Path gain results are shown in Table I: different values of the radius of the cylinder have been chosen and frequencies covering the world-wide available spectrum around 60 GHz are shown as well. \( n'_v \) and \( n'_h \) can be calculated from the reported values of \( n_v \) and \( n_h \) by using equations (11) and (13) and by choosing a value of \( \rho_a \) greater than \( \rho'^v_a \).

<table>
<thead>
<tr>
<th>Frequency</th>
<th>( \varepsilon_r )</th>
<th>( n_v )</th>
<th>( n_h )</th>
<th>( n'_h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>57 GHz</td>
<td>8.34</td>
<td>4.10</td>
<td>3.29</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td>35.9</td>
<td>6.67</td>
<td>5.11</td>
<td>4.23</td>
</tr>
<tr>
<td>60 GHz</td>
<td>7.98</td>
<td>4.23</td>
<td>3.40</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>36.4</td>
<td>6.78</td>
<td>5.20</td>
<td>4.30</td>
</tr>
<tr>
<td>63 GHz</td>
<td>7.65</td>
<td>4.35</td>
<td>3.50</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>36.8</td>
<td>6.89</td>
<td>5.28</td>
<td>4.37</td>
</tr>
<tr>
<td>66 GHz</td>
<td>7.37</td>
<td>4.48</td>
<td>3.6</td>
<td>3.09</td>
</tr>
<tr>
<td></td>
<td>37.2</td>
<td>7.00</td>
<td>5.36</td>
<td>4.44</td>
</tr>
</tbody>
</table>

In Fig. 3 we have reported the results of the measurement on the brass cylinder for both polarizations. By comparison with the predicted results obtained with (8) normalized with respect to the first measurement, it can be concluded that the field in the zone we have measured decays as a creeping wave on the...
were aware that the fast decay of the creeping wave would have limited the maximum distance from source and probe, for which measurements can be possibly conducted taking into account the VNA noise floor. Consequently, we chose to measure the decay of the field radiated by a horn antenna placed on the front side of the torso, approximately on the nipple, in the curved region of the torso itself, under the arm. For this measurement, the VNA noise level was approximately equal to -75 dB, which is higher than PEC measurement since averaging was limited due to the need of faster acquisitions. In Table II we have summarized the relevant parameters of these measurements.

### Table II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torso perimeter</td>
<td></td>
<td>0.9 m</td>
</tr>
<tr>
<td>Approximated radius</td>
<td>(a)</td>
<td>15 cm</td>
</tr>
<tr>
<td>Height of the subject</td>
<td></td>
<td>1.68 m</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td>Male</td>
</tr>
<tr>
<td>Tangential distance step</td>
<td>(\Delta \rho_s)</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Number of steps</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Source position</td>
<td></td>
<td>Left nipple</td>
</tr>
<tr>
<td>Radial start value</td>
<td></td>
<td>19 cm</td>
</tr>
</tbody>
</table>

Measurements are plotted in Fig. 5 and 6. In the same figure we plotted the analytical prediction using creeping wave formulas for a cylinder of radius equal to 15 cm having the same electromagnetic properties of human skin at 60 GHz. Linear regression curves are plotted as well. For vertical polarization, the decay coefficient is equal to 3.18 dB/cm, while for horizontal polarization it is equal to 4.48 dB/cm. Deviation from linearity in both measurements for large \(\rho_s\) is due to reaching of noise floor. Although dispersion around the theoretical result is higher than in the PEC case, Figs. 5 and 6 show that the path loss profile of the field radiated by an electromagnetic source at the surface of the torso can be modeled in the curved zone by assuming that the torso has a circular section of radius equal to its perimeter divided by \(2\pi\).
Fig. 6. Horizontal polarization measurement results compared with the theoretical attenuation prediction on a human torso of radius $a=0.15$ m.

VI. 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. A linear path gain has been derived and values of the approximated power decay exponent have been summarized for different frequencies and values of the radius of the cylinder. Measurements on the torso of a real human body at 60 GHz show that the path loss of the field radiated by an electromagnetic source at the surface of the torso can be modeled in the curved zone by assuming that the torso has a circular section of radius equal to its perimeter divided by $2\pi$.

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