V-Band Velocity Estimation of Creeping Waves around the Human Body

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Abstract—This letter investigates the phase velocity of an electromagnetic wave propagating between two sensors located on the human body surface by using the formulation of a creeping wave around a circular cylinder. The study is performed for both horizontal and vertical polarizations. The velocity is studied over the V-band. It is theoretically shown that the variation of the phase velocity is negligible over the bandwidth. Measurements are conducted on a metallic circular cylinder to assess the validity of these formulations. Then, an experimental validation of the circular cylinder assumption for the human body is performed. Deviation between the measurements and the theoretical circular model is between 2 and 3.5%.

Index Terms—Body Area Networks, Millimeter waves, 60 GHz, Velocity, Creeping wave, V-Band.

I. INTRODUCTION

The emergence of 60 GHz communicating systems presents multiple advantages for BANs such as antenna miniaturization [1], high data rates, low system interferences and bandwidth availability [2].

Static propagation models have been proposed for off- [3] and on-body [4]–[6] propagation. Also, dynamic measurements have been performed to evaluate the fading of the signal between two mounted devices [7], [8].

This letter proposes to analytically and experimentally study phase velocity of the creeping wave model developed in [4] which deals with the propagation of electromagnetic waves between two sensors on the human body at 60 GHz.

II. ANALYTICAL VELOCITY OF CREEPING WAVES

A. Creeping Wave Formulations

In [4], a creeping wave formulation has been obtained from an asymptotic derivation of the radiation of a Hertzian dipole at the surface of a large dielectric cylinder [9]. The cylinder modeling the body is immersed in free-space. The cylinder has a radius a, a principal axis ẑ, relative permeability µr and relative complex permittivity εr depending on the conductivity σ by εr = ε′r + jε″r/2ωε0 with ε′r defined as the real part of the relative permittivity and ε0, µ0 are respectively the free-space permittivity and permeability. A time dependence e^jωt is assumed and suppressed, where ω = 2πf is the angular frequency and f is the frequency. The Hertzian dipoles and the observation point are assumed to be respectively located at heights hs and hr from the cylinder surface. By assuming these heights small with respect to the radius, the distance between the source and the observation points is ρs = aθ where θ is the angle measured between the source and observation point. The geometry is presented in Fig. 1.

A uniform formulation has been provided for the Hertzian dipole oriented normally and tangentially to the surface of the cylinder. The case of the ĵ oriented dipole is noted by the index v and the electric field Ev is along the ĵ component. The index h stands for a dipole oriented along ẑ and the electric field Eh is along the ẑ component.

It has been shown [3], [4] that the first creeping wave mode is dominant and it can be written as:

\[ E_{v,h} = c_{v,h} e^{-j(k + mτ_{v,h} / a)ρ_s} \]  

(1)

In (1), the complex coefficient cv,h depends on a, hs, hr and ω [4]. It is important to note that it also depends on ρs but in magnitude (ρs have no impact on the phase). The wavenumber is defined as k = ω/c and m = (ka/2)^1/3. The τv,h is the first zero of

\[ W'(τ_{v,h}) - q_{v,h} W(τ_{v,h}) = 0 \] 

(2)

where W(τ) is a Fock-type Airy function defined with the standard Airy function A(·) as W(τ) = 2e^3π/6√πA(e^14π/3τ) and qv,h = −jmZh with Zh = √εh and Zv = 1/Zh.

Fig. 1. Geometry of the analytical problem.
Hence, the phase velocity $v_{\psi}$ of a creeping wave propagating on a distance $d$ can be easily derived from (1):

$$\Delta \psi = (k + m \text{Re}(\tau_{v,h}))/a \cdot d$$

where $\text{Re}(\cdot)$ stands for the real part. The phase $\Delta \psi$ of this correlation linearly varies with frequency [10], it can be written as:

$$\Delta \psi = \frac{2\pi f}{v_{\psi}^v} \cdot d$$

Hence, the phase velocity $v_{\psi}^v$ is given by:

$$v_{\psi}^v = \frac{2\pi f}{(k + m \text{Re}(\tau)/a)} = \frac{c}{1 + \frac{m \text{Re}(\tau_{v,h})}{ka}}$$

Equation (5) represents the phase velocity of a creeping wave around a circular cylinder. The phase depends basically on two parameters: the radius $a$ and the frequency $f$. The term $m/ka$ is trivial to evaluate since it is algebraic. However, the phase velocity also depend on the term $\text{Re}(\tau_{v,h})$ which is not straightforward to calculate since $\tau_{v,h}$ is the solution of (2). In the following, it is proposed to numerically evaluate $\text{Re}(\tau_{v,h})$ over the bandwidth. These simulations are conducted for a cylinder having the same permittivity as the human skin and a PEC cylinder. The result is presented in Fig. 2. It is important to note again that the variation of $\tau_{v,h}$ is negligible with the radius of the cylinder $a$.

### B. Velocity Assessment and Numerical Study

The phase shift $\Delta \psi$ of a creeping wave propagating on a distance $d$ can be easily derived from (1):

$$\Delta \psi = (k + m \text{Re}(\tau_{v,h}))/a \cdot d$$

where $\text{Re}(\cdot)$ stands for the real part. The phase $\Delta \psi$ of this correlation linearly varies with frequency [10], it can be written as:

$$\Delta \psi = \frac{2\pi f}{v_{\psi}^v} \cdot d$$

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### III. Experimental Validation

To assess the validity of the proposed model, two measurement campaigns have been conducted. The first one has been realized using a perfectly conducting (PEC) cylinder in order to precisely verify the theoretical path gain. The second campaign has been conducted on a human. Its purpose was to evaluate the validity of the model to emulate a real body although it has been developed for a cylinder.

#### A. Experimental Velocity estimation method

In [12], a frequency correlation analysis for wideband signals is proposed to evaluate the phase velocity of on-body waves. The correlation is estimated between two observation locations noted 1 and 2 spaced by a distance $d$. The complex correlation $\rho$ is given by:

$$\rho = \frac{E[S_1 S_2^*]}{\sqrt{E[|S_1|^2] E[|S_2|^2]}}$$

where $S_1$ and $S_2$ are the frequency channel transfer functions between the source and the observation points 1 and 2, $*$ denotes the complex conjugate operation and $E[]$ stands for the expect value that averages channel realisations.

The method proposes to estimate the coefficient $(2\pi d/v_{\psi})$ of equation (4) between the phase and the frequency for different distances $d$. Then, using the obtained coefficient with $d$, the phase velocity can be easily obtained. This method will be used in the following in order to assess analytically and experimentally the phase velocity of a creeping wave.

#### B. PEC Measurement Campaign

1. **Experimental Set-up:** The measurements were conducted with an Agilent E8361C VNA and U-band horn antennas (20 dB gain) in an anechoic chamber. To increase the
dynamic range, two amplifiers have been used (the first at the transmitter side and the second at the receiver side). To make the measurements, the brass cylinder has been vertically mounted on a rotor and could therefore rotate around its axis. The measurements have been performed from 0° to 90° with a 10° step. A pyramidal horn antenna has been used as electromagnetic waves radiator. The antenna 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. The receiving (Rx) and transmitting (Tx) horn antennas were placed tangentially to the cylinder to maximize the amount of power received from the creeping wave. The cylinder had a 0.2 m radius, a height of 1.2 m and the Rx horn antenna was placed at middle height. The measurements have been conducted from 50 to 60 GHz with a 66.67 MHz step. The IF bandwidth of the VNA was 1 Hz in order to have the highest dynamic range possible.

The coaxial cables have about 6 dB/m losses. To avoid the need of long distance cables and maximize the received power, the VNA was put inside the anechoic chamber and covered by absorbing material. Time gating has been performed to increase the dynamic range.

**b) Results:** The method presented in section III-A was used on the measurements. The phase of the correlation is drawn in Fig. 3 for two particular values as example. As expected, the phase varies linearly with respect to the frequency. For each couple of measurements positions, the slope of the curve is calculated and presented in Fig. 4. The latter is analytically equal to \(2\pi f d / v_\phi\).

This allows one to obtain easily the phase velocity of the creeping wave since the slope is given with the distance \(d\).

The dynamic range for vertical polarization being higher than for horizontal polarization, measurements have been restricted for fewer distances in the horizontal case.

The slope of these curves is theoretically equal to \(2\pi f / v_\phi\). Hence, the phase velocity \(v_\phi\) can be directly obtained from these figures.

Finally, in Table II, the theoretical and measured phase velocities are summarized. It can be shown that the comparison between the measurements and theoretical model shows a relative error of less than 1%. These results allowed to assess the validity of the equations presented in section II. However, since the model is developed for body area networks, it is necessary to evaluate the accuracy of these equation on a real human body.

**C. Real Human Measurement Campaign**

**c) Experimental Set-up:** The measurements were conducted using a *Rhode & Schwarz ZVA-Z7* in a semi-anechoic room. Two V-band (1.85 mm) cables of 1 meter have been used with 10 dB of losses. To optimize the dynamic range, a 30 dB Low Noise amplifier have been placed at the receiver side. The transmitting and receiving antennas were standard V-band horns with 10 dB of gain. The measurements parameters and the human characteristics are summarized in Table. III.

The measurements have been carried out around the stomach of the subject and for each distance a collection of 10 measurements have been obtained and averaged. The channel has been obtained at each centimeter from 3 to 11 cm and the antenna have been placed on a belt explicitly designed for this measurement campaign. Time

![Fig. 3. PEC measurements. Example of measurement results for vertical polarization. Phase of the correlation with the frequency. The vertical and horizontal polarizations are recalled in the upper schema.](image1)

![Fig. 4. Slope of the phase with the frequency for each distance in vertical (left) and horizontal (right) polarizations.](image2)

<table>
<thead>
<tr>
<th>Table II</th>
<th>PEC Measurements. Comparison between Measured and Theoretical Phase Velocities.</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Vertical Polarization</td>
</tr>
<tr>
<td>Theoretical</td>
<td>(2.967 \times 10^8) m/s</td>
</tr>
<tr>
<td>Measured</td>
<td>(2.969 \times 10^8) m/s</td>
</tr>
<tr>
<td>Relative Error</td>
<td>0.08%</td>
</tr>
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</table>
Slope Coefficient

Theoretical Slope
Measurements fit
Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$f_{\text{start}}$</td>
<td>55 GHz</td>
</tr>
<tr>
<td>$f_{\text{stop}}$</td>
<td>65 GHz</td>
</tr>
<tr>
<td>$f_{\text{stop}}$</td>
<td>50 MHz</td>
</tr>
<tr>
<td>VNA IF Bandwidth</td>
<td>1 kHz</td>
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<tr>
<td>VNA Averaging</td>
<td>1</td>
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<tr>
<td>Stomach Perimeter</td>
<td>0.8 m</td>
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<tr>
<td>Equivalent Radius</td>
<td>12 cm</td>
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<tr>
<td>Height of the subject</td>
<td>1.68 m</td>
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<td>Gender</td>
<td>Male</td>
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</table>

TABLE IV
REAL HUMAN MEASUREMENTS. COMPARISON BETWEEN MEASURED AND THEORETICAL PHASE VELOCITIES.

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Theoretical</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>2.899 x10^8 m/s</td>
<td>2.906 x10^8 m/s</td>
</tr>
<tr>
<td>Horizontal</td>
<td>2.799 x10^8 m/s</td>
<td>2.846 x10^8 m/s</td>
</tr>
<tr>
<td>Relative Error</td>
<td>3.57%</td>
<td>2.10%</td>
</tr>
</tbody>
</table>

...3.5%. This can be easily explained by the human body being non-dispersive in the V band.

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