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Antenna Radiation Characterization for On-Body Communication Channel Using Creeping Wave Theory

Zhongkun Ma¹, Julien Sarrazin¹, Luca Petrillo², Theodoros Mavridis², Philippe De Doncker² and Aziz Benlarbi-Delai¹
¹(Université Pierre et Marie Curie, UPMC): L2E Department, F-75005 Paris, France, mazhongkun@gmail.com, julien.sarrazin@upmc.fr, aziz.benlarbi_delai@upmc.fr
²(Université Libre de Bruxelles, ULB): OPERA Department-Wireless Communications Group, B-1050 Brussels, Belgium, luca0702@gmail.com, tmavridi@ulb.ac.be, pdedonck@ulb.ac.be

Abstract—Creeping wave theory is re-visited for BAN (Body Area Network) channel modeling. The formulation takes the characteristics of both antenna and human tissues into account. The field density at a certain distance from the radiating antenna can be directly determined by input power and on-body antenna gain. It is observed that the complicated on-body antenna gain measurement can be replaced by measuring antenna gain above infinitely large PEC (perfect electric conductor) plane to determine field density. Using time gating technique, the antenna gain above infinitely large PEC can be obtained by measuring continuous field on finitely large PEC, which is much easier to use in practice. The whole concept is validated through CST Microwave Studio. A very good agreement between the analytical model and full-wave simulation results is achieved.

Index Terms—Body area network (BAN), channel modeling, antenna characterization, creeping wave theory.

I. INTRODUCTION

The demand of continuous health monitoring for elders and patients combined with on-going development of low-power devices and miniaturization of wireless application has triggered a new generation of wireless networks, which is known as body area network (WBAN) [1-3]. In order to optimize the battery life for electronics devices, it is crucial to know all the propagation mechanisms in BAN channel to determine the link budget. A channel model can be mainly categorized as statistical and deterministic approaches. The statistics approach models the characteristics of the path loss due to body movements [2], [3], which is out of the scope of this paper. This paper focuses on deterministic approach, which leads to insights regarding on-body propagation.

The first theoretical treatment for on-body deterministic channel model was presented in [4], where author introduces a four-layer Norton wave formulation covering the frequency range from 1 GHz to 11 GHz for BAN. Later on, this Norton wave approach was validated at 60 GHz too [5]. In addition to this approach that models the body surface as a planar multilayer structure (stratified Skin/Fat/Muscle structure), creeping wave theory treats the body as a dielectric cylinder. The advantage of the later approach is allowing predicting path loss of the communication link when two transceivers are located on opposite sides of the body, or when there is no line-of-sight.

Creeping wave formulations, originally intended to be applied to a Hertzian dipole radiation around the bending earth surface in [6], is firstly employed for BAN channel modeling at 2.45 GHz in [7]. As Norton wave approach, it can also be employed for BAN channel modeling at 60 GHz [8]. The dipole moment source in [7] was replaced to be a PIFA antenna in [9], which successfully establishes a link between the injected power, on-body antenna gain and field density. A drawback of creeping wave formulation approach is that it requires on-body antenna gain measurement, which is very difficult in practice as pointed out in [9], where only simulated gain in full-wave solver was employed to estimate the on-body antenna gain.

From the creeping wave formulation, it is clearly observed that the knowledge of the radiation pattern of antennas on an infinitely large PEC is sufficient to determine its radiated field on a lossy dielectric cylinder. Using time gating technique, the antenna is not necessary to be placed on infinitely large PEC. The goal of this paper is consequently to validate this approach using small monopole antennas as example using CST Microwave Studio.

II. CREEPING WAVE MODEL FORMULATION

The on-body communication channel investigated here considers two sensors closely located on the human body surface. For simplification reason, the human body is modeled as a homogeneous cylinder as illustrated in Fig.1. Some researchers treat the human body as elliptical cylinder as well [10], [11]. Our proposed antenna characterization approach can also be employed with these elliptical cylinder assumptions. Both PEC and dielectric cases are investigated at 2.45 GHz, where a relative permittivity of 50 and conductivity of 1.7 S/m is considered for the dielectric [12]. The cylinder radius $r$ is chosen as 10 cm in order to model human’s head.
It is well known that the horizontal component (i.e. tangential to the body surface) of the electric field suffers more attenuation compared to the vertical component (i.e. normal direction to the body surface) [4]. Therefore, only the vertical polarization is considered throughout this paper.

The electric field radiated by a source at a distance \( \rho_s \) over a cylinder of radius \( r \) can be written as a sum of clockwise and anti-clockwise propagating waves (see Fig. 1):

\[
E_{\text{total}}(\rho_s) = E(\rho_s) + E(2\pi - \rho_s)
\]

(1)

each wave can be then expressed as:

\[
E(\rho_s) = E_0(\rho_s)W(\rho_s, r, \epsilon_r, h_{TX}, h_{RX})
\]

(2)

where \( E_0 \) is the inverse distance field, which corresponds to the electric field radiated by an antenna above a conducting plane in free space. \( E_0(\rho_s) \) can be written as:

\[
E_0(\rho_s) = \frac{\eta_0}{2\pi} \sqrt{\frac{P_m G}{\rho_s}} e^{-k_0 \rho_s}
\]

(3)

where \( P_m \) is the antenna’s input power, \( G \) is the antenna gain over infinitely large conducting plane, \( \rho_s \) is the distance between the source and the observation point, \( k_0 \) is the wave number, \( \eta_0 \) is the vacuum wave impedance. \( W \) is the attenuation function that takes into account the losses due to the human tissue’s complex permittivity \( \epsilon_r \) and the curvature of the surface. \( h_{TX}(h_{RX}) \) stands for the distance between the body surface and transmit (receive) antenna. Using \( W \), the creeping wave formulation transforms the radiated field on a flat surface to the radiated field around the circular section of a cylinder by a weighting function as demonstrated later. The detail of \( W \) expression is given in [8], [9].

Eq. (2) and (3) implies that complicated on-body antenna gain measurements could be substituted by measuring antenna gain above infinitely large PEC plane. This is this aspect that is proposed to be investigated in the following.

\[
E(2\pi - \rho_s) = E(\rho_s)
\]

\[
E(2\pi - \rho_s)
\]

III. CONCEPT VALIDATION

A monopole antenna (4.5 mm height with 10x10 mm² PEC ground plane and excited by 0.5 mm delta gap current source) is chosen as antenna under test (AUT). The simulated result from CST frequency domain solver is plotted in Fig. 2, together with the analytical result based on creeping wave theory.

For the simulation case, AUT is located on the cylinder surface in the normal direction to generate vertical polarization along the cylinder surface. Full-wave simulation is employed to obtain the radiated field around the cylinder, which is time consuming.

For the creeping wave analytical case, the gain of AUT above infinitely large PEC plane is firstly simulated in CST, which is much faster than the previous full-wave simulation case. Then this simulated gain is used in the analytical model described in Eq. (1) to (3) to obtain the radiated field. The CST simulated azimuthal gain \((\theta = 90^\circ)\) of AUT is 1.61 dBi and 4.76 dBi when locating in free space and above infinitely large conducting plane, respectively. The later one is employed in \( E_0 \) formulation in Eq. (3) to determine the radiated field of the monopole antenna above the infinitely large PEC plane. No normalization is then performed to compare the radiated E-field intensity between full-wave and analytical results.

AUT is located at \( \rho_s = 0 \) and measured field is from \( \rho_s = 0 \) to \( \rho_s = 2\pi \times 628 \text{ mm} \). For comparison purpose, AUT is assumed to be perfectly matched and consequently accept an identical power of 1 Watt for all the tested cases. The simulated field and analytical field are total E-field in Cartesian coordinate system and \( r \)-component E-field (other components being negligible) in cylinder coordinate system, respectively.

As shown in Fig. 2, a very good agreement between analytical and CST results is observed. It has to be emphasized again that there is no normalization for all the cases and yet absolute intensity values agree. It is also observed the E-field difference between PEC and dielectric cylinder case is only about 2.5 dB by comparing (a) and (b) in Fig. 2. Similar result is also observed by replacing the monopole antenna to patch antenna. In order to reduce the discrepancy of the numerical method [13], these above cases were re-simulated in CST with the time domain solver and a similar conclusion has been obtained.

IV. ANTENNA GAIN MEASUREMENT BY TIME GATING TECHNIQUE

As shown in the previous section, the complicated on-body antenna gain measurement can be substituted by measuring antenna gain above infinitely large PEC. Unfortunately, measuring the antenna gain above infinitely large PEC is still not practical. However, by using time gating technique, the antenna gain above infinitely large PEC can be obtained from measurements performed on finite size good conductor plane.

To illustrate the concept, the AUT, which is the same one as in previous section, is placed above a PEC plane with size of 1200 x 1200 mm² as shown in Fig. 3. To measure the propagating electric field radiated by the source, perfect probes are used in simulation in order to firstly assess the approach. Five E-field probes are placed on the PEC surface.
along a common axis to determine the influence of their
position while calculating the antenna gain obtained with
time gating. All of them are separated by a distance $d = 50$ mm.
The nearest and farthest ones to the radiating source are
50 mm and 250 mm, respectively.

Recorded E-fields are plotted together in Fig. 4(a) for each
probe in the time domain. The position of recorded pulses in
time is consistent with the location of each probe with respect
to the radiated. The reflected wave from finite-size PEC
plane’s edges shows up between 4 ns and 6 ns. These
reflected waves do not exist if the size of the ground PEC is
infinitely large. Consequently, a time gating is performed such
that only the response up to 3 ns remains. All reflections
occurring after 3 ns are consequently filtered. The truncated
time domain signal is transformed to frequency domain by
Fourier transformation, so $E_d(p_0)$ is obtained. Based on Eq.(3),
the antenna gain can be then calculated by:

$$G = \frac{2\pi}{\eta_0} \frac{\left( |E_d(p_0)| \times p_{in} \right)^2}{60}$$

In order to see if the chosen gating window will influence
the results, the gating window varies from 2.5 ns to 6 ns by a
step of 0.034 ns. All the results are summarized in Fig.4 (b).
The solid line and dot line present the antenna gain by time
gating technique when placing AUT on infinitely large and
finitely large PEC (size is 1200 x 1200 mm$^2$), respectively.
Ideally they should be identical if the reflected wave of the
finite PEC case can be completely removed by choosing a
proper gating window. As shown in Fig.4 (b), the result of
infinitely large PEC case is identical no matter what gating
window is chosen, because there is no reflected wave, which
can be treated as the reference for finite PEC case to achieve.

To obtain correct antenna gain using Eq.(4), the probe
needs to be placed in the far field region. For the nearest
probe, it obtains a 4.15 dBi gain (infinite PEC case), which is 0.61
dB less than that of far field approach (4.76 dBi). One
possible reason is this probe is too near to the source and still
in the near field of the antenna. As a result, it implies that for
very low frequency, the size of the finite PEC needs to be
very large. As the distance between the probe and the source
increases, the obtained gain increases as well. When the
distance increases to 250 mm, the probe is probably in the far
field of the antenna because the gain obtained by time gating
technique is almost identical as that of far field approach for
infinitely large PEC case. To see it clearly, the antenna gain
obtained by different probes’ positions is plotted in Fig. 5,
where gating window is fixed as 2.5 ns for each probe. It is
clear that as the distance between the probe and the source
increases, the obtained gain increases and starts to converge to
the far field gain around 250 mm when the probe is in the far
field.

If gating window is chosen between 2.5 ns and 3.5 ns,
antenna gains obtained from the finite PEC cases match those
from infinitely large PEC cases very well for all the probe
positions except the one at 250 mm from source. This is
because at 250 mm distance, the probe is closed to the edge of
the finite PEC, the incident and reflected wave cannot be
distinguished at that location. As gating window increases
from 3.5 ns to 6 ns, the obtained gain from the finite PEC
cases oscillates because the contribution of reflected waves is
not entirely canceled.

Calculated radiated field over cylinder using creeping wave
formulation with antenna gain obtained by time gating
technique above finite PEC is also plotted Fig. 2. The antenna
gain is determined by the probe placed 200 mm away from
the source and the gating window is chosen as 2.5 ns. A very
good agreement is observed. This agreement proves the
concept that when employing creeping wave theory for BAN
channel modeling, the complicated on-body antenna gain
measurement can be replaced by measuring antenna gain
above finite PEC, which is much easier to use in practice.


Fig. 3. Simulation setup for gain measurement by time gating technique.

Fig. 4. a) The measured propagated field density versus time by the five probes and b) The antenna gain above infinitely large PEC measured by time gating technique.

Fig. 5. The antenna gain above infinitely large PEC measured by time gating technique (gating window is 2.5 ns) at different probes’ positions.

V. Conclusion

Creeping wave formulation is re-visited for body area network channel modeling. This paper showed that the required complicated on-body antenna gain measurement can be replaced by measuring antenna gain above a finite PEC plane. A very good agreement between the analytical model and full-wave simulation results is achieved. It was also noticed that the probe to the source distance should be carefully chosen such that measurements are performed in far-field and that reflection from PEC’s edges can be distinguished from incident. Perspectives of this work are now to validate the whole concept by experiment.

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VII. References


