Characterization of on-body communications at millimeter waves

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Abstract **– This paper presents a the study of on-body communications at millimeter waves. An analytical formulation is proposed by assuming a dipole source radiating on a flat skin, whose permittivity is suitably chosen to model human tissues at those frequencies, according to previous investigation. An experimental setup, consisting of two open-ended waveguides placed on the top of a skin-equivalent phantom, is then discussed in order to validate the theoretical analysis.**

1 INTRODUCTION

Recent developments of body area networks (BANs) enable the implementation of wireless communication systems on the human body for health monitoring, entertainment or sport applications.

In particular, the 57-64 GHz frequency band offers several advantages in terms of small sensor size, very high data rates (up to 7 Gb/s), high level of security and reduced interference among different BANs. On the other hand, many physical phenomena at these frequencies are not extensively investigated yet. For instance, high levels of absorption can be observed together with reflections due to the high dielectric contrast between the human skin and free space. A deeper knowledge of these effects is needed to define antenna specifications and to characterize the properties of the communication channel for BAN applications at millimeter waves.

With this analysis, our aim is to investigate the fundamental characteristics of the on-body propagation channel, in terms of different wave contributions (i.e. optical fields vs. surface waves), relevant attenuation rates, path gain, absorption in the human body, impact of the polarization on the performances of the on-body link [1].

This will be accomplished through both analytical and experimental results. In Section 2, an elementary arbitrarily-oriented dipole antenna is considered and placed above a lossy medium whose electromagnetic parameters are chosen to model the human skin according to the results of an extensive series of measurements. In Section 3, two linearly-polarized standard open-ended waveguides are placed on a skin-equivalent phantom. This experimental setup leads to a validation of the theoretical results. It also allows the investigation of aspects not described in the theory (effect of non-infinitesimal sources, power absorbed in the skin, etc.).

2 THEORETICAL ANALYSIS

In this section a simple analytical model is presented in order to study the fundamental physical mechanisms involved in the on-body communication of two antennas. The radiating source is modeled as a Hertzian dipole placed at a height h on a flat lossy medium, laterally unbounded, whose electrically permittivity is chosen according to the results of measurements in [2], [3]. In fact, as experimentally verified, at 60 GHz, due to the shallow penetration δ of the electromagnetic field into the human tissues ($\delta \approx 0.48$mm), the body surface can be modeled by a homogeneous semi-infinite skin layer.

With these assumptions, the electromagnetic field in the air region can be expressed through the approximations provided by Norton [4]. These approximations are valid in the limit of large absorption rate in the lossy medium and can be applied to arbitrarily oriented dipoles. The cases of vertical and horizontal dipoles are briefly described in the following.

The values of the parameters of interest are selected according to the BAN applications under investigation. For this reason, the height of the dipole is chosen not greater than 5 mm, while the distance between transmitter and receiver (an ideal electric field probe) is chosen between 5 mm and 500 mm.

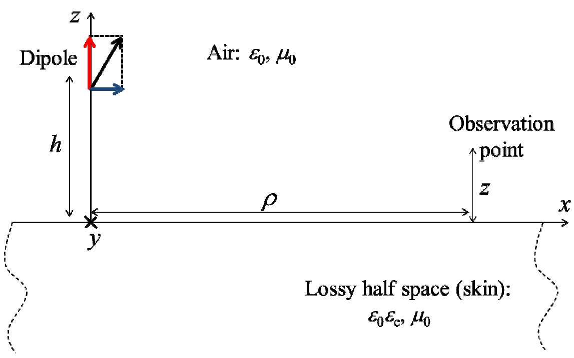

Figure 1: Lateral view of the theoretical model. The physical and geometrical parameters used in the paper are shown in the picture. An arbitrarily oriented dipole (*black*) can be decomposed into a vertical (*red*) and a horizontal (*blue*) component, separately studied in the paper. The infinitesimal dipoles are magnified for the sake of clarity.

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2.1 Vertical dipole

If a vertical dipole is considered, the radiated field has an azimuthal symmetry, thus depending only on the radial ρ and vertical z variables. Furthermore, a dominant vertical field E_z over the radial E_ρ is always obtained in the range of parameters of interest for BANs.

The vertical electric field in the air can be expressed as the sum of two contributions

$$E_z(\rho,z) = E_z^{\mathrm{GO}}(\rho,z) + E_z^{\mathrm{N}}(\rho,z) \qquad (1)$$

E_z^{GO} is the geometrical-optics field (GOF), due to the direct radiation of the source and the first reflection from the flat surface; E_z^{N} is the so-called Norton wave, whose contribution can be dominant over the GOF near the surface. Hence, it can be considered as the correction term to the geometrical-optics field needed to restore the total field, when the observation point approaches the skin.

These two contributions can be evaluated through asymptotic approximations valid for different ranges of distances. Simple results are obtained, not shown here for the sake of brevity, providing an accurate estimation of the spatial decay of the total field. In turn, this leads to values for the coefficient n defining the path gain G of the communication link, expressed as

$$G(\rho) = G(\rho_0) - 10n\log\left(\frac{\rho}{\rho_0}\right), \qquad (2)$$

ρ_0 being a reference distance.

In Fig. 2 we show the magnitude in dB of the electric fields excited by a vertical dipole placed at the skin interface. The fields, computed with Norton's formulations, are also compared with CST results up to ρ = 100 mm. The perfect agreement fully validates Norton's approximations for 60 GHz on-body communications.

In this specific case, when the source is placed at the interface, the GOF is not present, and only the Norton wave is excited.

In an *intermediate region* [Fig. 2(a)], the value n = 3.5 provides a good agreement with the results. On the other hand, in the *far region* [Fig. 2(b)], the field is well described by a choice of n = 4. These values are in perfect agreement with the asymptotic evaluations which could be done for the Norton field and confirm the usefulness of the analytical approach. The full details about the field computation lead to correct estimations also when the dipole is not placed on the surface.

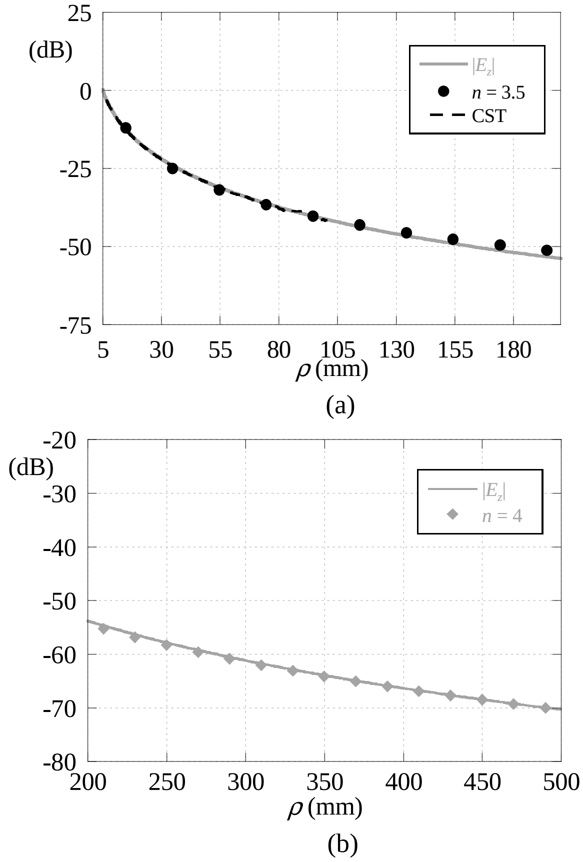

Figure 2: Vertical dipole radiating on the skin surface. Magnitude of the electric field along the radial direction (a) Radial distances 5 mm < ρ < 200 mm. (b) Radial distances 200 mm < ρ < 500 mm.

2.2 Horizontal dipole

The field excited by a horizontal dipole oriented along the x axis has a dependence on the azimuthal angle; the analysis is therefore more complex in this case. For this reason, the field should be observed on two different principal planes: the E plane (φ = 0°) and the H plane (φ = 90°). On these planes, two polarizations are observed.

In the E plane, the Norton wave has a similar behavior as the Norton wave described for the vertical dipole. This leads to similar choice for the n parameter in the path gain (2).

In the H plane, the field is mainly polarized along the azimuthal, rather than vertical, direction. The asymptotic decays of the Norton and of the GOF are met in this case much closer to the dipole, so that no intermediate zone is found on this plane. The parameter n = 4 is valid for all the radial distances of interest, apart a small region where reactive fields dominate.

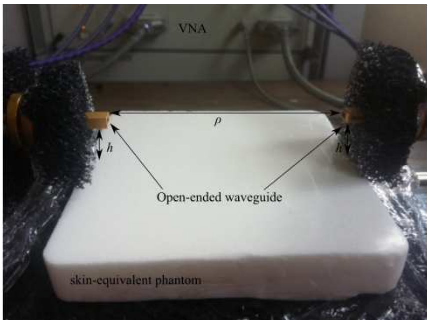

Figure 3: Measurement set-up: two open-ended waveguides close to a skin-equivalent phantom.

3 EXPERIMENTAL ANALYSIS

In this section, an experimental setup is described and used to verify the theoretical results discussed in Section 2. The setup consists of two linearly-polarized standard open-ended WR-15 waveguides close to a skin-equivalent phantom realized as in [3] (see Fig. 3). The phantom permittivity and conductivity at 60 GHz agree with the values used in the previous Section, and have been measured using a technique based on heating kinetics for an independent validation of the setup [3].

Experimental data of the path gain, computed by measuring the transmission coefficient between the two waveguides, are compared to the theoretical model (Fig. 4), confirming the analysis performed. For instance, the choice $n = 4$ perfectly agrees with the measurements in the far zone, as predicted in the previous section.

4 CONCLUSION

On-body propagation aspects at millimeter waves have been studied with both a theoretical and a experimental approach, in order to characterize the path gain according to different distance ranges, polarizations, and physical and geometrical parameters of interest describing the link.

Future works will describe the influence of layered configurations of textiles placed over the skin with suitable modifications to the theoretical model implemented here.

Acknowledgments

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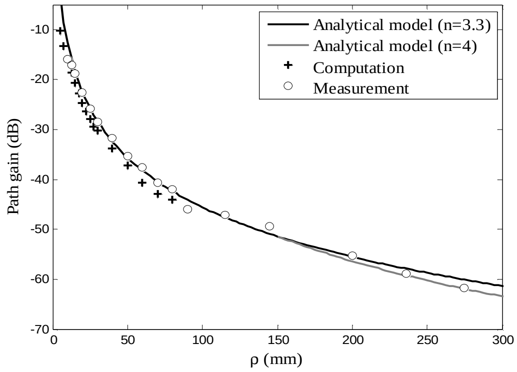
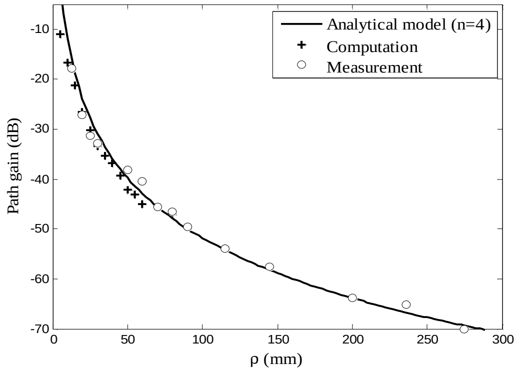


(a)



(b)

Figure 4: Comparison between the path gain model (solid line), computed (+), and measured results (○) for $\lambda_0 < \rho < 60\lambda_0$. The waveguides are placed on the phantom interface. (a) Vertically polarized source, (b) horizontally polarized source.

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