Skin-Equivalent Phantom for On-body Antenna Measurements At 60 GHz

Nacer Chahat, M. Zhadobov, and Ronan Sauleau
Institute of Electronics and Telecommunications of Rennes (IETR), UMR CNRS 6164
University of Rennes 1
Rennes, France
nacer.chahat@univ-rennes1.fr

***Abstract*— The extension of body area networks (BAN) from microwaves to millimeter waves requires to develop appropriate experimental phantoms emulating the dielectric properties of human skin for the characterization of wearable antennas, on-body propagation channel, and absorption of the electromagnetic power by the human body. Here we introduce a broadband skin-equivalent semi-solid phantom whose composition is optimized to coincide with measured values of the human skin permittivity in the 55-65 GHz range.**

Keywords- Body-area network (BAN); body-centric wireless communications; experimental phantom; millimeter waves.

I. INTRODUCTION

Body-centric wireless communications refer to wireless networking between wearable and/or implanted antennas and another antenna located on, off, or in the body. Near-future applications include personal healthcare, entertainment, detection and identification systems, sport, smart home, space, and military applications [1].

Although many innovations for on-body communication technologies have recently emerged, it is still not possible to reach very high data rates. Developing BAN in the 60-GHz band is considered as a promising solution to overcome this limitation. This solution also offers several advantages compared to BAN at lower frequencies [2]. First, it ensures the confidentiality and low interference with neighboring networks due to the strong oxygen-induced attenuation of 60-GHz radiations in the atmosphere. Second, the size of the on-body equipment is significantly reduced.

Recently, two 60-GHz antennas for on-body communications have been introduced [3]. The interactions of millimeter waves with the human body have been reviewed in [4].

In order to experimentally evaluate the performance of on-body antennas in V-band, it is necessary to develop appropriate tissue-equivalent phantoms. Such phantoms can also be used to investigate the on-body channel in a reproducible and well-controlled manner. Besides, they can be used as a representative model for measurements of the energy absorption induced in real human bodies by on-body antennas, which is very challenging and involves some ethical issues.

In this work, the skin permittivity has been measured and a semi-solid phantom has been developed and optimized to mimic the measured skin permittivity in the 55-65 GHz range.

II. MEASUREMENT OF THE SKIN PERMITTIVITY

A. Measurements of the human skin permittivity

The skin permittivity ($\varepsilon^{*}=\varepsilon' - j\varepsilon''$) has been measured on seven subjects at two specific locations, namely the wrist and forearm. We used an open-ended slim coaxial probe designed by Agilent Technologies (Santa Clara, CA) to determine the complex permittivity of lossy liquids and semi-solids up to 67 GHz [5].

All volunteers were informed about the purpose of the measurements and have a solid background in electromagnetics. Four measurements have been performed with the same calibration at each location and for each volunteer. Thus 28 measurements are available in total for each location. The measured skin temperature is equal to 32.5±0.5°C.

Measurements performed from 55 GHz to 65 GHz have demonstrated very small variations between the skin permittivities at wrist and forearm (difference less than 4%). Therefore, only one model defined by the average of all measurements performed at wrist is considered here. The results are represented in Fig. 1 and compared with Gabriel *et al.* [6] and Alekseev *et al.* [7] data. Gabriel *et al.* reported extrapolated complex permittivity of human skin up to 110 GHz based on measurements performed below 20 GHz. A very good agreement is demonstrated for the three data sets. Alekseev *et al.* carried out reflection measurement with an open-ended waveguide and proposed a homogeneous and multilayer human skin models fitting the experimental data.

Recently we presented a new method for determining the dielectric properties of skin at millimeter waves based on heating kinetics [8]. The results obtained at 60 GHz are summarized in Table I and compared to direct measurements and previously published results. The absolute deviations compared to Gabriel's data at 60 GHz are of 0.5% and 3.7% for the real and imaginary parts, respectively. Good agreement is also obtained with Gabriel *et al.* and Chahat *et al.* data.

This work was supported by "Agence Nationale de la Recherche" (ANR), France under Grant ANR-09-RPDOC-003-01 (Bio-CEM project) and by "Centre National de la Recherche Scientifiques (CNRS)", France.

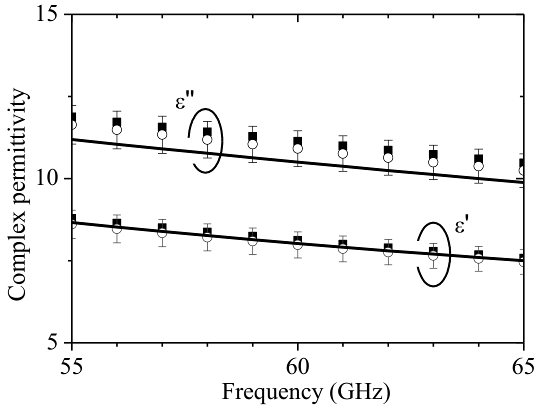

Fig. 1. Comparison of our experimental result for the wrist skin permittivity (——) with Gabriel *et al.* (■) and Alekseev *et al.* (○) models. Error bars represent ±5% deviations around Gabriel's reference values.

TABLE I
OVERVIEW OF THE SKIN ELECTRICAL PROPERTIES AT 60 GHZ

Reference	ε*	Method
Gabriel *et al.* [6]	7.98-*j*10.90	E
Alekseev *et al.* [7]	8.12-*j*11.14	M
Chahat *et al.* [8]	7.28-*j*9.82	M
Our measurements	8.02-*j*10.5	M

E: extrapolation; M: direct measurement.

B. Power absorption in the skin

Using the above-described permittivity data, we first calculated the power attenuation in homogeneous skin models. This allows estimating the minimal thickness of the phantoms. Power decreases exponentially in the skin as a function of depth. The attenuation of the power density (PD) and specific absorption rate (SAR) at 60 GHz are plotted in Figs. 2 and 3, respectively for each dielectric model reported in Table I. The PD and SAR are maximal at the skin surface. Very slight differences are obtained suggesting that the variations on the reported dielectric properties (Table I) have a small influence on the PD and SAR results. The results show that only 0.1% of the incident power reaches the 1 mm depth implying that the phantom thickness can be practically limited to several millimeters.

III. SKIN-EQUIVALENT PHANTOM IN THE 55-65 GHZ RANGE

The phantom composition has been optimized to approximate the reference permittivity values [8]. The phantom permittivity measured in the 55-65 GHz range using a coaxial slim probe is represented in Fig. 4. The phantom permittivity measured at 60 GHz equals to $\varepsilon^*=7.4-j11.4$. Compared to the measured skin values, errors of 7.7% and 8.6% are found respectively for the real and imaginary part of the permittivity, whereas they respectively equal to 7.3% and 4.6% compared to Gabriel *et al.* data.

These small deviations are acceptable for antenna measurement and dosimetric studies since they lead to negligible variations of the power reflection coefficient at the phantom/air interface (1.4% for the normal incidence at 60 GHz) and of the penetration depth (8%) compared to skin. Furthermore, they result in SAR deviations of only 6.8% and 4.5% compared to the measured skin permittivity and Gabriel *et al.* data, respectively. It is worthwhile to note that the accuracy of this phantom is also sufficient for dosimetric studies and similar to the one of phantoms developed at microwaves. For instance, the phantom proposed in [9] shows discrepancies of ±10% within the 3.1-10.6 GHz range, and the broadband tissue-equivalent liquid [10] shows variations of ±11% within the 0.3-6 GHz range.

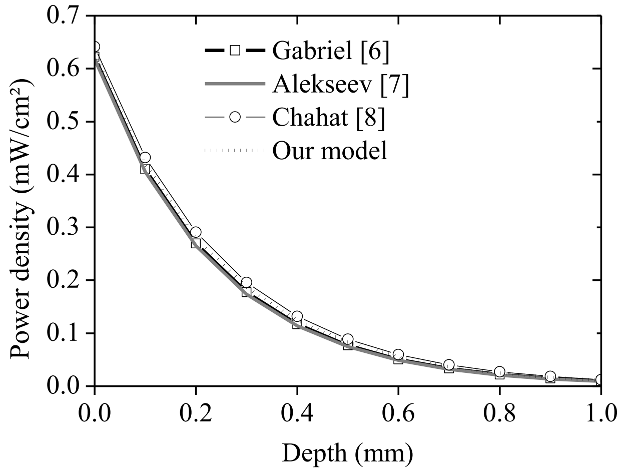

Fig. 2. Attenuation of the PD in the skin for an incident power of 1 mW/cm² at 60 GHz.

As similar variations are expected for different locations on the body and due to the inter-individual changes (because of the difference of water concentration in tissues), this phantom can be used successfully as a representative body surface model for antenna measurement, on-body channel characterization, and determination of the power absorption in the body. A fabricated prototype of a human hand is presented in Fig. 5.

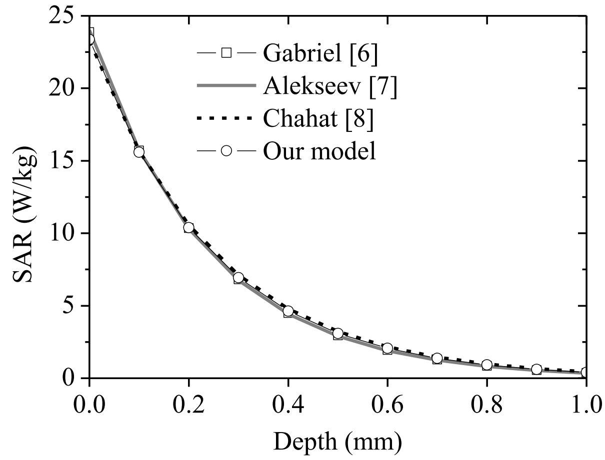

Fig. 3. Attenuation of the SAR in the skin for an incident power of 1 mW/cm² at 60 GHz.

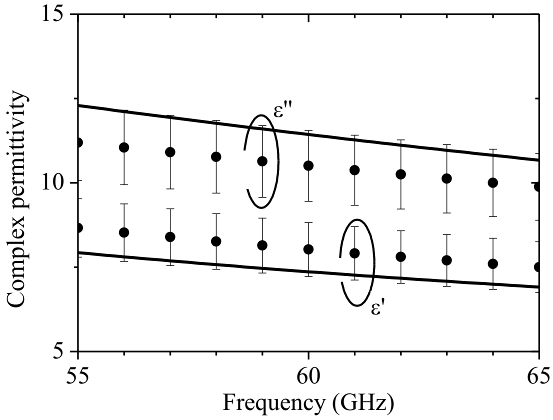

Fig. 4. Measured skin permittivity (●) and dielectric properties of the proposed phantom (──) in the 55-65 GHz range. Error bars represent ±10% of the measured skin permittivity.

Fig. 5. Photography of a skin-equivalent phantom representing a human hand.

IV. CONCLUSION

A semi-solid broadband skin-equivalent phantom has been designed and fabricated in order to emulate the permittivity values of human skin in V-band. It can be used for on-body antenna measurements and propagation channel characterization for BAN, as well as for electromagnetic dosimetry studies in the 55-65 GHz range.

First, the dielectric properties of the human skin have been measured *in vivo* using a coaxial slim probe. An excellent agreement was demonstrated with other reported skin permittivity in the 55-65 GHz range.

Second, a water-based semi-solid skin-equivalent phantom has been designed using in-house measured skin permittivity values as a reference. The maximum deviations of the phantom permittivity with respect to the human skin are of 7.7% (real part) and 8.6% (imaginary part) at 60 GHz. They are below 10% in the 55-65 GHz range. Such deviations are acceptable for antenna measurement and dosimetric studies since they lead to small variations of the power reflection coefficient, penetration depth, and SAR compared to skin.

The phantom is now used for wearable antenna measurements and complete numerical and experimental results for various off- and on-body 60-GHz antennas will be presented and compared during the conference.

REFERENCES

[1] P. S. Hall and Y. Hao, "Antennas and propagation for body centric communications systems," Artech House, Norwood, MA, USA, 2006, ISBN-10: 1-58053-493-7.

[2] S. L. Cotton, W. G. Scanlon, and B. K. Madahar, "Millimeter-wave soldier-to-soldier communications for covert battlefield operations," *IEEE Communications Mag.*, vol. 47, no. 10, pp. 72–81, Oct. 2009.

[3] X. Wu, L. Akhoondzadeh-Asl, Z. Wang, and P. S. Hall, "Novel Yagi-Uda antennas for on-body communication at 60 GHz," *Loughborough Ant. Propag. Conf.*, Loughborough, UK, pp. 153–156, Nov. 2010.

[4] M. Zhadobov, N. Chahat, R. Sauleau, C. Le Quément, and Y. Le Dréan, "Millimeter-wave interactions with the human body: state of knowledge and recent advances," *International Journal Microw. Wirel. Tech.*, vol. 3, no. 2, pp. 237–247, 2011.

[5] M. Zhadobov, R. Augustine, R. Sauleau, A. Di Paola, C. Le Quément, Y. Soubere Mahamoud, and Y. Le Dréan, "Complex dielectric permittivity of biological solutions in the 2-67GHz range," *Bioelectromagnetics* (available online http://onlinelibrary.wiley.com/doi/10.1002/bem.20713/pdf).

[6] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues," *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2271–2293, Nov. 1996.

[7] S. I. Alekseev and M. C. Ziskin, "Human skin permittivity determined by millimeter wave reflection measurements," *Bioelectromagnetics*, vol. 28, no. 5, pp. 331–339, Jul. 2007.

[8] N. Chahat, M. Zhadobov, R. Sauleau, and S. I. Alekseev, "New Method for Determining Dielectric Properties of Skin and Phantoms at Millimeter Waves Based on Heating Kinetics," *IEEE Trans. Microwave Theory Tech.*, in press.

[9] N. Chahat, M. Zhadobov, S. Alekseev, and R. Sauleau. "Human skin-equivalent phantom for on-body antenna measurements in the 60 GHz band," *Electronics Letters*, 2011. In press.

[10] T. Takimoto, T. Onishi, K. Saito, M. Takahashi, S. Uebayashi, and K. Ito, "Characteristics of biological tissue equivalent phantoms applied to UWB communications," *Electron. Commun. Japan*, vol. 90, no. 5, pp. 48–55, May 2007.

[11] "MCL-T broadband tissue equivalent liquid: 30 MHz to 6 GHz," available online at http://www.mcluk.org/pdfs/bbl.pdf.