JOURNAL OF ELECTROMAGNETIC ENGINEERING AND SCIENCE, VOL. 15, NO. 4, 213~218, OCT. 2015

http://dx.doi.org/10.5515/JKIEES.2015.15.4.213
ISSN 2234-8395 (Online) · ISSN 2234-8409 (Print)

Body-Worn Spiral Monopole Antenna for On-Body Communications

Nikolaj P. B. Kammersgaard[1,2] · Søren H. Kvist[2] · Jesper Thaysen[2] · Kaj B. Jakobsen[1,*]

Abstract

A novel body-worn spiral monopole antenna is presented. The antenna consists of a ground plane and a spiral monopole. The antenna was designed for Ear-to-Ear (E2E) communication between In-the-Ear (ITE) hearing instruments at 2.45 GHz and has been simulated, prototyped, and measured. The antenna yielded a measured and simulated E2E path gain at 2.45 GHz of –82.1 dB and –85.9 dB, respectively. The radiation pattern of the antenna when mounted in the ear is presented and discussed.

Key Words: Body-Centric Communication, Creeping Waves, In-the-Ear Hearing Instruments Antenna, On-Body Path Gain, WBAN.

I. INTRODUCTION

Body-worn antenna research for body-centric communication has increased over the last decade. Ever smaller electronics have enabled a wide range of new applications where wireless communication can be implemented. Many of these new applications have been developed for medical devices, such as hearing instruments (HIs). There is considerable interest within the HI industry in obtaining Ear-to-Ear (E2E) communication between HIs. An E2E link improves the acoustic performance of HIs as well as the usability. Besides E2E communication there is an interest in communication with both on- and off-body accessories, for example smartphones, smart watches, or TVs. By the use of the license-free and worldwide industrial, scientific, and medical (ISM) band between 2.40 GHz and 2.48 GHz both E2E and accessory communication can be obtained. At the same time it will enable communication with electronics with Bluetooth. Antennas suitable for Behind-the-Ear (BTE) HIs have been presented in the literature with an E2E path gain of –52 dB [1]. BTE HIs are located behind the ear and are mass produced whereas In-the-Ear (ITE) HIs are placed in or right outside the ear canal and are custom-made to fit the user's ear and ear canal. This makes it harder to achieve a high E2E path gain for ITE HIs. The ITE antennas that have been presented in the literature have not yielded E2E path gains significantly above –90 dB [2, 3]. In the following a novel ITE antenna, which is the first to make E2E communication feasible between ITE HIs is presented. The antenna was first presented briefly in [4]. This is an augmentation of the article presented in [5].

II. THEORY

At 2.45 GHz, the human body is very lossy [6]. Therefore, the electromagnetic energy cannot propagate through the body. It has been shown that the electromagnetic energy propagates around the human body as creeping waves instead [7]. Models for the E2E propagation channel have been presented in [8, 9].

Manuscript received June 3, 2015 ; Revised August 12, 2015 ; Accepted August 21, 2015. (ID No. 20150603-035J)

[1]Department of Electrical Engineering, Electromagnetic Systems, Technical University of Denmark, Kongens Lyngby, Denmark.
[2]GN ReSound A/S, Ballerup, Denmark.
[*]Corresponding Author: Kaj B. Jakobsen (kbj@elektro.dtu.dk)

These models estimate the E2E path gain by the use of a number of elliptic paths around the head. For each of these paths, an estimate of the magnitude of the creeping wave launched in each path is made. The attenuation along each path is calculated by a closed-form expression. Finally, the contributions of each of the paths are added to give the path gain. In [9], the on-body gain is used to estimate the magnitude of the launched creeping waves. The on-body gain will be used to evaluate the radiation pattern of the antenna presented here. The phase of the electric field has been included in the on-body gain to account for the initial phase differences in the launched creeping waves. This means that the on-body gain is an untraditional gain that has both a magnitude and a phase, which can be expressed as:

$$G_{\text{on-body}}(\theta,\varphi) = \int_0^{\pi} G_\theta(\theta,\varphi)\, \mathrm{e}^{\mathrm{j}\angle E_\theta(\theta,\varphi)} \sin\theta \;\mathrm{d}\theta, \qquad (1)$$

where $G_\theta(\theta,\varphi)$ is the θ-component of the gain for the antenna mounted on the head, and $E_\theta(\theta,\varphi)$ is the θ-component of the electric field for the antenna when it is mounted on the head. It is noted that it is only the θ-component that is included in the equation. This is due to the fact that the φ-component is attenuated much faster than the θ-component [10].

III. EXPERIMENTAL SETUP

The antenna consists of a ground plane connected to a monopole with radius *r*. The antenna is shown in Fig. 1. The advantages of this design are that the electronics for the HI can be placed on the ground plane, and the antenna is very simple to implement. To reduce the size, the monopole is spiraled with a spiral radius *R*, which is reduced by *d* for each turn. The parameters used can be seen in Table 1. The antenna is self-resonant since the length of the monopole corresponds to approximately a quarter wavelength at 2.45 GHz. The antenna was matched for 50 Ω. The antenna was placed in the ear, so the plane of the spiral monopole (xy-plane in Fig. 1) coincides with the surface of the head. This means that, seen from the front of the head, the antenna is completely hidden by the tragus (i.e., the cartilaginous fleshy projection that partially co-

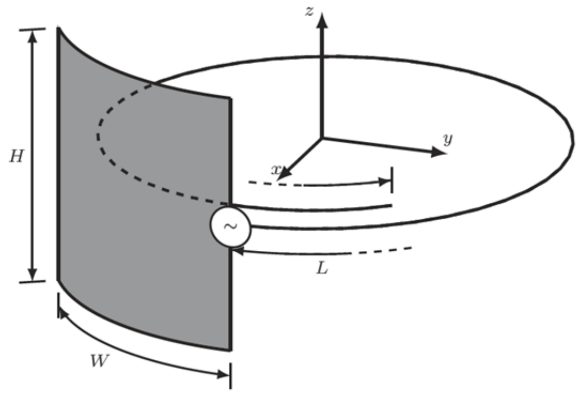
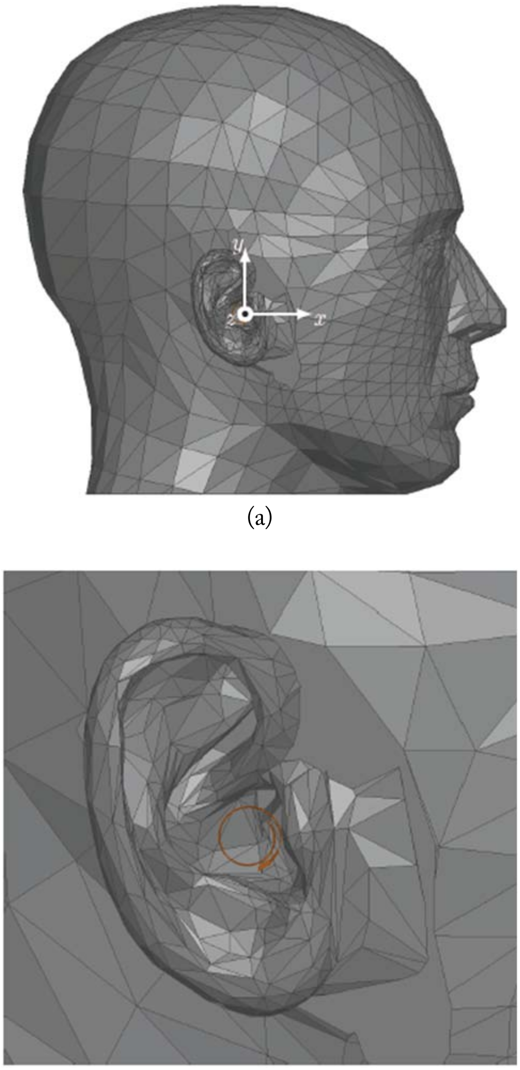


Fig. 1. The spiral monopole antenna. The radius and length of the spiral are *R* and *L*, respectively. The wire has a radius *r*.

Table 1. Optimized antenna design parameters

Parameter	Value (mm)
L	31
r	0.10
W	6.0
H	5.0
R	5.0
d	1.0



(a)

(b)

Fig. 2. The specific anthropomorphic mannequin (SAM) phantom head (a) with the coordinate system used and the realistic ear (b) where the antenna can be seen (orange).

Fig. 3. The fabricated prototype of the spiral monopole antenna. The connected coaxial cable and balun are seen at the top.

vers the entrance to the external ear).

Simulations were done in ANSYS HFSS 2014. The specific anthropomorphic mannequin (SAM) fitted with realistic ears was used. The head and ears were given homogeneous electrical parameters of $\varepsilon_r = 50$ and $\tan\delta = 0.5$. The antenna was modeled as copper. The simulation setup is shown in Fig. 2. It is noted that the coordinate systems indicated in Figs. 1 and 2(a) are the same.

The prototype used for the measurements can be seen in Fig. 3. ROHACELL HF ($\varepsilon_r = 1.05$ and $\tan\delta = 0.0001$) was used to support the antenna. The antenna was fed from a coaxial cable connected to a vector network analyzer. The cable was fitted with a balun to reduce the currents on the cable. The measurements were done in a radio anechoic chamber.

IV. RESULTS AND DISCUSSION

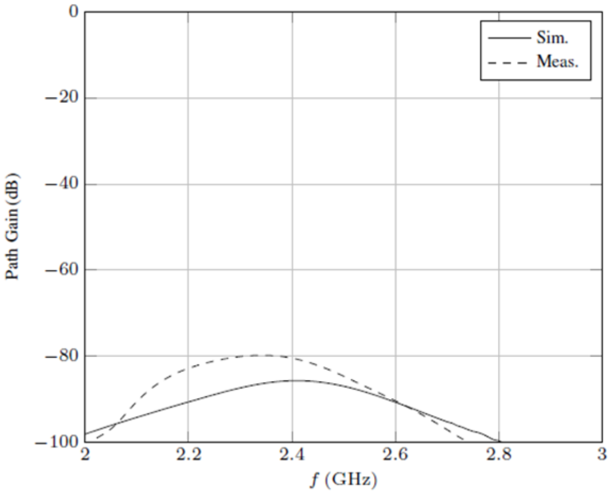


Fig. 4. Simulated (solid line) and measured (dashed line) Ear-to-Ear path gain.

Table 2. Measured and simulated Ear-to-Ear path gain

Path gain	Simulated (dB)	Measured (dB)	Difference (dB)
ISM band (better than)	−86.7	−83.5	3.2
2.45 GHz	−85.9	−82.1	3.8

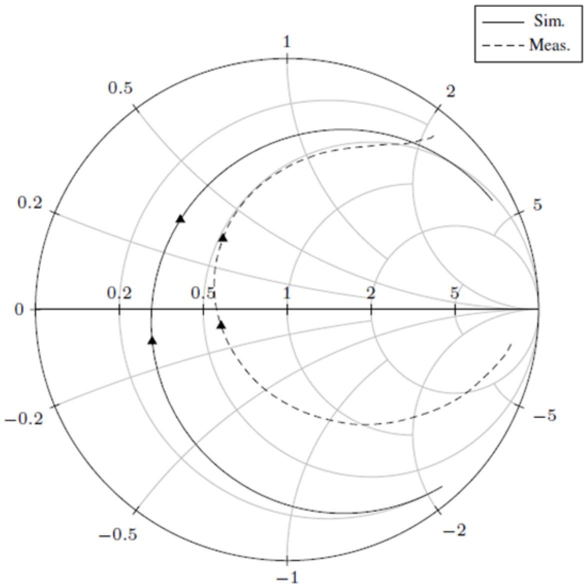


Fig. 5. Smith chart that shows the simulated (solid line) and measured (dashed line) reflection coefficient. The lower and upper frequencies in the ISM band are marked by triangles.

The simulated and measured E2E path gain is shown in Fig. 4. In the entire ISM band, the simulated and measured path gains are better than −86.7 dB and −83.5 dB, respectively. The measured and simulated E2E path gains in the ISM band and at 2.45 GHz are given in Table 2. It is noted that this is within the dynamic range of many standard Bluetooth ICs. Since the antenna is completely φ-polarized in free space it might be possible to obtain a better path gain with a θ-polarized antenna as shown for BTE antennas [11]. The simulated and measured reflection coefficient, plotted in a Smith chart, can be seen in Fig. 5 and in a magnitude plot in Fig. 6. As seen the antenna is matched for the entire ISM band. The measurement and simulation results correspond well. It is seen that the measurements are more broadband than the simulations. One of the possible causes is higher loss in the measurements resulting in the higher real part of the input impedance which appears in Fig. 5. Furthermore, the effect of the cables can have had an impact, particularly outside the ISM band that the balun is designed for. The lower and more broadband reflection coefficient also accounts for the higher path gain in the measurements. Finally, it is noted that the head and ears used for the measurements is not the same as for the simulations.

The magnitude and phase of the simulated on-body gain

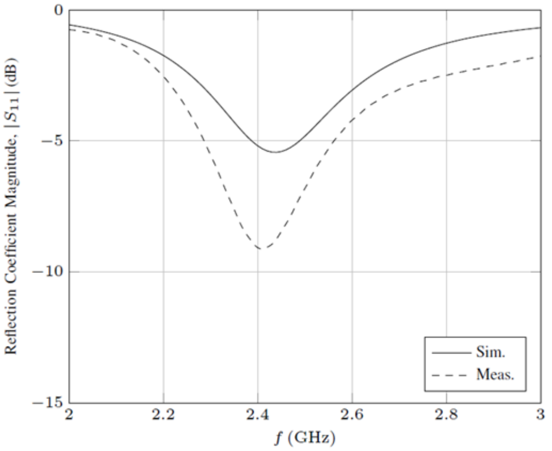


Fig. 6. Magnitude of the reflection coefficient, simulated (solid line) and measured (dashed line).

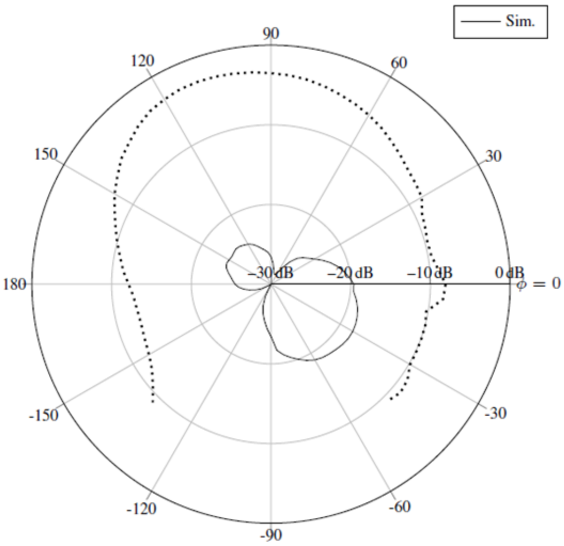


Fig. 7. Magnitude of the simulated on-body radiation pattern at 2.45 GHz (solid line) on top of the head contour (dashed line).

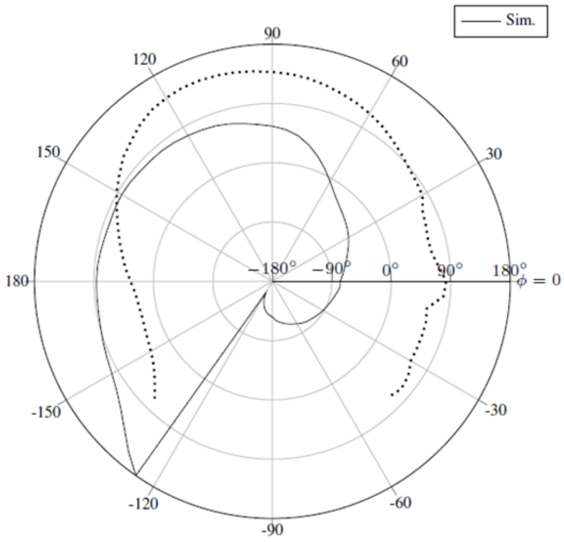


Fig. 8. Phase of the simulated on-body radiation pattern at 2.45 GHz (solid line) on top of the head contour (dashed line).

calculated from Eq. (1) can be seen in Figs. 7 and 8, respectively. From Fig. 7 it is seen that the radiation pattern has two lobes, which are in opposite directions. The radiation patterns for other ITE antennas found in [8, 12] exhibit the same characteristic, which might indicate that this is a general trend for ITE antennas and is caused by the ear. Furthermore, it is seen that the lobe in the forward direction has the highest gain. The BTE antennas presented in the literature have had their main lobe in the backward direction; see for example [9]. Therefore, contrary to BTE antennas, it is important to understand how the creeping wave propagates across the face. The previously mentioned E2E on-body path gain models in [8, 9], which model the head with elliptic curves, have been tested with antennas where the main path is behind the head. Since the face is not as well modeled with elliptic curves as the back of the head, it is suggested that these models be tested with the main path around the front of the head. The phase of the on-body gain seen in Fig. 8 has a spiral characteristic corresponding to the shape of the antenna. This is different from the phase pattern in [12] and indicates that the phase is not only determined by the presence of the ear. Furthermore, it is noted that the two lobes are out of phase.

V. CONCLUSION

A novel ITE antenna has been designed, simulated, prototyped, and measured. It is the first ITE antenna that is feasible to implement and yields a high enough path gain to be used with standard Bluetooth ICs. The measured and simulated E2E path gain at 2.45 GHz was –82.1 dB and –85.9 dB, respectively. The antenna was well matched in the entire ISM band. The on-body radiation pattern was presented and discussed. The radiation pattern showed two lobes. The main lobe was toward the front of the head and thus opposite to what has been observed for BTE antennas. Therefore, it is suggested that it is investigated whether the existing models of the E2E path gain can be improved. Furthermore, it was found that it is possible to modify the phase of the on-body gain for ITE antennas through the antenna design.

REFERENCES

[1] S. H. Kvist, S. Ozden, J. Thaysen, and K. B. Jakobsen, "Improvement of the ear-to-ear path gain at 2.45 GHz using parasitic antenna element," in *Proceedings of 6th European Conference on Antennas and Propagation (EuCAP)*, Prague, Czech Republic, 2012, pp. 944–947.

[2] R. Chandra and A. J. Johansson, "Miniaturized antennas for link between binaural hearing aids," in *Proceedings of 2010 Annual International Conference of the IEEE Engineering in*

Medicine and Biology Society (EMBC'10), Buenos Aires, Argentina, 2010, pp. 688–691.

[3] L. Huitema, S. Sufyar, C. Delaveaud, and R. D'Errico, "Miniature antenna effect on the ear-to-ear radio channel characteristics," in *Proceedings of the 6th European Conference on Antennas and Propagation, (EuCAP)*, Prague, Czech Republic, 2012, pp. 3402–3406.

[4] N. P. I. Kammersgaard, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "In-the-ear spiral monopole antenna for hearing instruments," *Electronics Letters*, vol. 50, no. 21, pp. 1509–1511, 2014.

[5] N. P. I. Kammersgaard, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Body-worn spiral monopole antenna for body-centric communications," in *Proceedings of 2015 International Workshop on Antenna Technology (iWAT2015)*, Seoul, Korea, 2015.

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

[7] J. Ryckaert, P. De Doncker, R. Meys, A. de Le Hoye, and S. Donnay, "Channel model for wireless communication around human body," *Electronics Letters*, vol. 40, no. 9, pp. 543–544, 2004.

[8] R. Chandra and A. J. Johansson, "A link loss model for the on-body propagation channel for binaural hearing aids," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 12, pp. 6180–6190, 2013.

[9] S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Ear-to-ear on-body channel model for hearing aid applications," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 1, pp. 344–352, 2015.

[10] P. S. Hall, Y. Hao, Y. I. Nechayev, A. Alomalny, C. C. Constantinou, C. Parini, et al., "Antennas and propagation for on-body communication systems," *IEEE Antennas and Propagation Magazine*, vol. 49, no. 3, pp. 41–58, 2007.

[11] S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Polarization of unbalanced antennas for ear-to-ear on-body communications at 2.45 GHz," in *Proceedings of 2011 Loughborough Antennas and Propagation Conference (LAPC)*, Loughborough, UK, 2011, pp. 1–4.

[12] N. P. I. Kammersgaard, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Pinna model for hearing instrument applications," in *Proceedings of 2014 Loughborough Antennas and Propagation Conference (LAPC)*, Loughborough, UK, 2014, pp. 141–143.

Nikolaj P. B. Kammersgaard

received the B.Sc. and M.Sc. degrees in electrical engineering from the Technical University of Denmark, Lyngby, in 2013 and 2014, respectively. Since 2014, he has been affiliated with GN ReSound A/S, a Danish hearing aid manufacturer, where he is currently pursuing an Industrial Ph.D. degree in cooperation with the Technical University of Denmark. His research interests include on-body antennas and propagation, as well as electrically small antennas and physical limitations of antennas. He was awarded the Student Paper Award for best student paper at the International Workshop on Antenna Technology 2015.

Søren H. Kvist

received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Technical University of Denmark, Lyngby, in 2007, 2009, and 2014, respectively. Since 2009, he has been affiliated with GN ReSound A/S, a Danish hearing aid manufacturer, where he is currently employed as an antenna engineer. His research interests include on-body antennas and propagation, as well as electrically small antennas and physical limitations of antennas. Dr. Kvist was awarded first prize for the IET best student paper at the Loughborough Antennas and Propagation Conference 2011.

Jesper Thaysen

received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Technical University of Denmark, Lyngby, in 1998, 2000, and 2005, respectively. Since 2008, he has been employed at GN ReSound A/S, a Danish hearing aid manufacturer, where he currently acts as the Director of the Radio Systems Group in R&D. His research interests include small antennas and on-body antennas and propagation. He has overseen more than 40 B.Sc. and M.Sc. students, as well as three Ph.D. students, as the company representative in university-industry cooperative projects.

Kaj B. Jakobsen

received the B.Sc. and the M.Sc. degrees in electrical engineering from the Technical University of Denmark, Kgs. Lyngby, in 1985 and 1986, respectively, the Ph.D. degree in electrical engineering from the University of Dayton, Dayton, Ohio, USA, in 1989, and the HD in Organization and Management, Copenhagen Business School, Copenhagen, Denmark, in 2000. From 1986–1989, he was a Fulbright Scholar at the Department of Electrical Engineering, University of Dayton. Since 1990, he has been with the Department of Electrical Engineering, Technical University of Denmark, where he is an Associate Professor. His research interests are in body-centric wireless networks, wireless body area networks, and body sensor networks. In 1989, he received the NCR Stakeholder Award and was appointed Teacher-of-the-Year at the Technical University of Denmark in 1994.