Progress in Body-Worn Antennas for On-Body Propagation

Kaj B. Jakobsen

Department of Electrical Engineering, Electromagnetic Systems, Technical University of Denmark,
Ørsteds Plads, Building 348, DK-2800 Kgs. Lyngby, Denmark
kbj@elektro.dtu.dk

***Abstract*—On-body propagation and on-body antennas for body-centric wireless communications are presented. The on-body communications rely on creeping waves launched and received by the antennas, respectively. Path gain and bandwidth at 2.4 GHz for different types of body-worn antennas for head-centric communications are presented. Further, an on-body channel model, to be used to find the optimal radiation pattern, is presented.**

***Index Terms*—Wearable antennas; wireless body-area networks (WBAN); creeping waves; medical devices; IoT (Internet of Things) .**

1. Introduction

Wearable antennas for on-body propagation and Internet-of-Things (IoT) have received much attention in the literature in recent years. Head models [1] and pinna model [2] have been developed to speed up the development of on-body antennas for head-centric communication in addition to a theoretical study of the electromagnetic fields at the surface of a human-body cylinder [3]. The effect of anatomical variation of the head on the ear-to-ear path gain has been studied in [4]. The morphological investigation showed that the waves creeps along different paths and constructive and destructive interference was observed, which can result in an increased package error rate PER. Diversity was studied in [5] and radiation pattern optimization was investigated in [1] as a way to reduce the PER. In this paper the recent progress in body-worn antennas for on-body propagation is summarized.

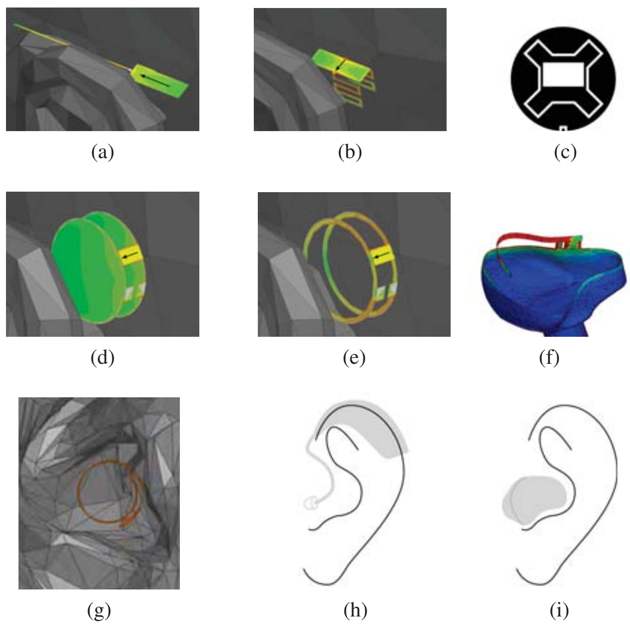


Fig. 1. On-body antenna types: a straight monopole antenna that rests on top of the ear (a) [6], a meandered monopole antenna that is fed at the center of the side of the ground plane (b) [6], and a meandered slot antenna (c) [7]; two antenna types with two parallel, circular plates (d) and one with two parallel rings (e), respectively [6]; a custom shell antenna (f) [8], and and a spiral antenna (g) [9], [10]. The antennas in (a), (b), (d), (e), and (f) are shown with simulated surface current distributions. Behind-the-Ear (BTE) (h) and In-the-Ear (ITE) (i) hearing instrument (HI) types in the use position [6].

2. Antenna Types

Different on-body antenna types are shown in Fig. 1. Unbalanced antennas are shown in Fig. 1a–b and balanced in Fig. 1c–f. Behind-the-Ear (BTE) and In-the-Ear (ITE) hearing instruments (HI) are shown in Fig. 1h and Fig. 1i, respectively. In Table I the measured ear-to-ear on-body path gain, the fractional bandwidth, and polarization are given in addition to the type of HI (BTE or ITE) for the different on-body antennas.

3. Creeping waves

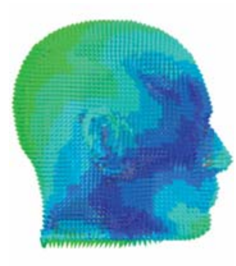
In Fig. 2 simulations on a specific anthropomorphic mannequin (SAM) head with ears of the electric field vectors (a) and the magnitude of Poynting vector (b) at the surface of the head are shown. It is seen that the electric field of the launched creeping wave is perpendicular to the surface of the head. From the Poynting vector plot it is seen that most of the field creeps behind the back of the head (green) and less (blue) in front of the eyes.

4. Path Gain and On-Body Antenne Gain

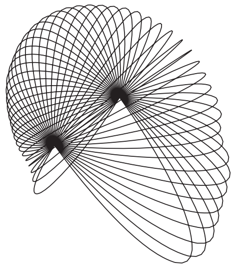
Ear-to-ear (E2E) path gain (PG) models are presented in [1] [17]. The on-body channel is modeled as a number of creeping waves along elliptical along the head as shown in Fig. 2c. The on-body radiation pattern is given by

$$G_{\text{on-body}}(\phi) = \int_0^{\pi} G_{\theta}(\theta, \phi) \sin(\theta) d\theta \ , \qquad (1)$$

(a)



(b)



(c)

Fig. 2. Electric field vectors (a) and Poynting vector magnitude (b) that shows the interference pattern on a SAM head with ears. Head model (c) that consists of 50 elliptically-shaped paths [1], [11]–[13].

TABLE I
MEASURED EAR-TO-EAR ON-BODY PATH GAIN (PG), FRACTIONAL BANDWIDTH (BW), AND POLARIZATION AT 2.4 GHZ FOR THE DIFFERENT ANTENNA TYPES SHOWN IN FIG. 1.

Type	PG (dB)	BW (%)	Polarization	Ref.
BTE	−50	9.8	normal	[14]
BTE	−59	1.1	normal	[13]
BTE	−73	8.5	tangential	[13]
BTE	−80	3.3	tangential	[9]
ITE	−63	6.1	normal	[8]
ITE	−73	2.9	normal	[10], [15]
ITE	−73	3.1	tangential	[7]
ITE	−75	2.9	normal	[16]

where $G_\theta(\theta, \phi)\sin(\theta)$ is the components of the far-field radiation pattern that are oriented perpendicular to the head surface. Since the electric field of the launched creeping wave is perpendicular only the θ-component has to be included.

5. Optimal Radiation Pattern

To synthesize the optimal radiation pattern a genetic algorithm is used with the on-body channel model. To obtain a robust antenna design, a Monte Carlo analysis can be added to investigate the influence of, e.g., different head shapes on the path gain [1]. Full-wave simulations as HFSS would be very time consuming, i.e., in this case hours versus seconds.

6. Conclusion

The progress in body-worn antennas for on-body head-centric propagation has been reviewed. Typical values for the path gain (PG) is from -80 dB to -50 dB and the fractional bandwidth is from one to ten percent, respectively at 2.4 GHz.

References

[1] 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. 63, no. 1, pp. 344–352, Jan. 2015.

[2] N. Kammersgaard, S. Kvist, J. Thaysen, and K. Jakobsen, "Pinna model for hearing instrument applications," *2014 Loughborough Antennas and Propagation Conference, LAPC 2014*, pp. 1–3, Nov. 2014.

[3] N. P. I. Kammersgaard, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Electromagnetic fields at the surface of human-body cylinders," *Proceedings of the 2016 International Workshop on Antenna Technology (iWAT)*, pp. 170–173, 2016.

[4] S. Pehrson, S. H. Kvist, K. B. Jakobsen, and J. Thaysen, "Morphological investigation of the differences on the ear-to-ear path gain and the packet loss at 2.45 GHz," *34th Annual Antenna Measurement Techniques Association Symposium 2012*, pp. 43–48, 2012.

[5] P. F. Medina, S. H. Kvist, K. B. Jakobsen, and J. Thaysen, "Transmit and receive diversity in body-centric wireless communications," *34th Annual Antenna Measurement Techniques Association Symposium 2012*, pp. 38–42, 2012.

[6] S. H. Kvist, *Antennas and Propagation for Body-Centric Wireless Communications*. Ph.D. dissertation, DTU Elektro, Technical University of Denmark (DTU), Kgs. Lyngby, Denmark, ISBN 978-87-92465-47-4, 2013.

[7] W. H. Yatman, L. K. Larsen, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "In-the-ear hearing-instrument antenna for ISM-band body-centric ear-to-ear communications," *LAPC 2012 - 2012 Loughborough Antennas and Propagation Conference*, pp. 1–4, 2012.

[8] A. Ruaro, J. Thaysen, and K. B. Jakobsen, "Wearable shell antenna for 2.4 ghz hearing instruments," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 6, pp. 1–9, Jun. 2016.

[9] 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.

[10] N. Kammersgaard, S. Kvist, J. Thaysen, and K. Jakobsen, "Body-worn spiral monopole antenna for body-centric communications," *Proceedings of the 2015 International Workshop on Antenna Technology (iWAT)*, pp. 107–110, 2015.

[11] S. H. Kvist, S. Özden, J. Thaysen, and K. B. Jakobsen, "Improvement of the ear-to-ear path gain at 2.45 GHz using parasitic antenna element," *2012 6th European Conference on Antennas and Propagation*, pp. 944–947, 2012.

[12] S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "Investigation of the ear-to-ear radio propagation channel," *European Conference on Antennas and Propagation*, pp. 3796–3800, 2011.

[13] S. Kvist, J. Thaysen, and K. B. Jakobsen, "The effect of the head size on the ear-to-ear radio-propagation channel for body-centric wireless networks," *Loughborough Antennas & Propagation Conference*, pp. 345–348, 2010.

[14] S. Kvist, S. Özden, J. Thaysen, and K. B. Jakobsen, "Improvement of the ear-to-ear path gain at 2.45 GHz using parasitic antenna element," *European Conference on Antennas and Propagation*, pp. 4–7, 2012.

[15] N. Kammersgaard, S. Kvist, J. Thaysen, and K. Jakobsen, "Body-worn spiral monopole antenna for on-body communications)," *Journal of electromagnetic engineering and science (ISSN: 2234-8409)*, vol. 15, no. 4, pp. 213–218, 2015.

[16] N. P. I. Kammersgaard, S. H. Kvist, J. Thaysen, and K. B. Jakobsen, "In-the-ear circular-shaped balanced inverted-a antenna for hearing instruments," *IEEE Antennas and Wireless Propagation Letters*, 2016.

[17] 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.