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Path-Loss Models for Wireless Communication Channel along Arm and Torso: Measurements and Simulations

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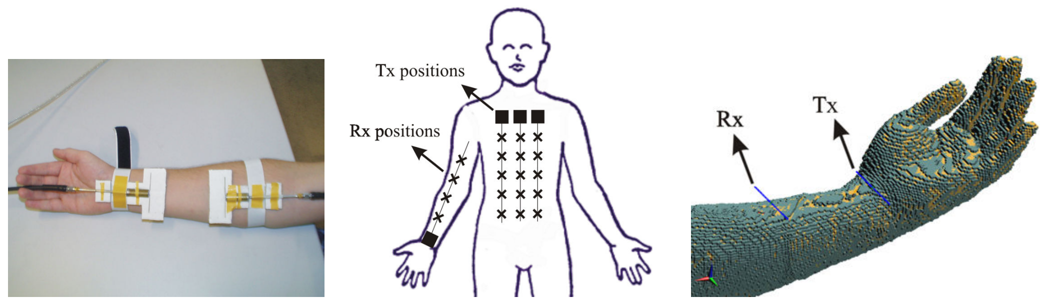
Introduction

A Wireless Body Area Network (WBAN) connects independent nodes (e.g., sensors and actuators) that are situated in the clothes, on the body or under the skin of a person. The network typically expands over the whole body and the nodes are connected through a wireless communication channel. A WBAN offers many promising new applications in home/health care, medicine, sports, and many other areas. An important step in the development of a WBAN is the characterization of the physical layer and the description of the electromagnetic wave propagation and antenna behavior near the human body. Propagation near flat, homogeneous and layered phantoms has been investigated in [2]. In this paper, measurements are performed on a real human using two half-wavelength dipoles, considering different parts of the human body separately. Path-loss models are developed for the on-body channels along the arm and torso. The measurement results are verified with FDTD (Finite-Difference Time-Domain) simulations, using an anatomically correct configuration of the arms.

Measurement and Simulation Setup

Two identical $\lambda/2$-dipoles at 2.45 GHz are placed at various positions on a human body, parallel to each other and lined up for maximal power transfer. The propagation channel characteristics depend strongly on the height of the antenna above the body [2]. In this paper the separation between body and antennas measures 5 mm. Fig. 1 shows the measurement setup (a) and the transmitter (Tx) and receiver (Rx) positions on the arm and torso (b). The measurements are performed in a modern office. A vector network analyzer (Rohde & Schwarz ZVR) is used to determine the S_{21}(f)-parameter between Tx and Rx for the different positions.

A total of 214 measurements are performed on a stretched arm of two persons (male and female, age 23). Tx is placed on the wrist and Rx is moved towards the shoulder, see Fig. 1 (b). The distance between the antennas varies from 5 cm up to 40 cm in steps of 1 cm. A total of 102 measurements are performed on the torso of a 23-year-old male person. Tx is placed at approximately shoulder height at one of three different positions (left, middle, or right), see Fig. 1 (b). Rx is placed directly below Tx and is moved along a straight line in steps of 2 cm. The antenna separation varies from 5 cm up to 30 cm.



(a) (b) (c)

Figure 1: (a) Picture of the setup for measurements on the arm, (b) Measurement setup: antenna positions on the body (■ = Tx and x = Rx), (c) Simulation setup: arm of Visual Human in SEMCADX.

The results of the measurements along the arm are compared with FDTD simulations in SEMCADX, using an anatomically correct model of the arms, provided by the Visible Human project of the National Library of Medicine [3]. The characteristics of the human body tissues have been obtained from [4] and the FDTD cell size in the arm model varies from 1 mm^3 to 8 mm^3. The antenna models have equal dimensions as the $\lambda/2$-dipoles used for the measurements, and are placed 5 mm above the arm, see Fig. 1 (c). The transmitter is placed on the wrist and the distance to the receiver varies from 5 cm up to 20 cm in steps of 1 cm.

Path-Loss Model

To model the path loss between the transmitting and the receiving antenna as a function of the distance d, we use the following semi-empirical formula, expressed in dB and based on the Friis formula in free space:

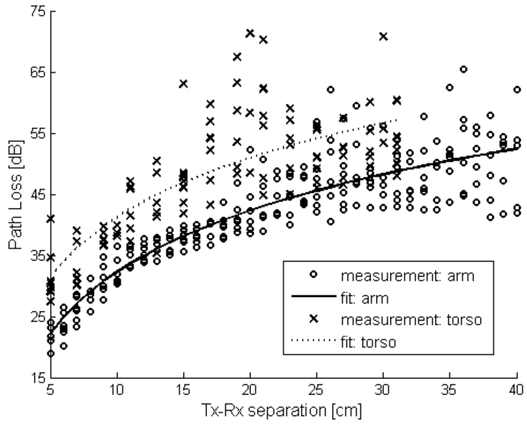
$$P_{dB}(d) = P_{0,dB} + 10n\ log(d/d_0) = -\left|S_{21}\right|_{dB} \tag{1}$$

where $P_{0,dB}$ is the path loss at a reference distance d_0 (10 cm in this paper), and n is the path-loss exponent, which equals 2 in free space. The path loss in this paper is defined as -$|S_{21}|_{dB}$, which allows us to regard the setup as a two-port network for which we determine S_{21}.

Measurement Results

Fig. 2 (a) shows the measured path loss versus Tx-Rx separation for the arm and torso. The circles and crosses indicate the individual measurements taken along the arm and torso respectively. The full line and the dotted line represent the path-loss models obtained using a least-square error fit of the measurement data along the arm and torso respectively. Fig. 2 (b) shows the parameter values of the fitted path-loss models for the arm and torso according to equation (1), and the variation σ of the measurement results around the model.

The path loss increases with antenna separation, as expected. The path loss along the torso and along the arm follow the same course: the path-loss exponent is



(a)

parameter	arm	torso
d_0 [cm]	10	10
$P_{0,dB}$ [dB]	32.2	41.2
n [-]	3.35	3.23
σ [dB]	4.1	6.1

(b)

Figure 2: Measured path loss and fitted models versus antenna separation (a) and parameter values of the path-loss models (b) for the arm and torso.

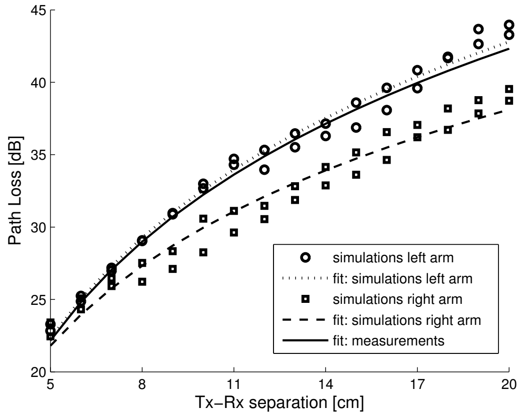
almost the same ($n \approx 3.3$). We observe a higher path loss along the torso than along the arm. This is probably due to the higher absorption in the larger volume of the trunk, and because the surface of the trunk is less flat than the surface of the stretched arm. Along the torso, the variation of the measured values around the model ($\sigma = 6.1$ dB) is slightly higher compared with the measurements along the arm ($\sigma = 4.1$ dB). This is because the measurements along the torso were performed on three different lines: left, middle, and right. The reference path loss $P_{0,dB}$ and the path-loss exponent n obtained in this paper, are consistent with previous results. In [5], a path-loss exponent of $n = 3.1$ and a path-loss value of $P_{0,dB} = 44.6$ dB at a reference distance $d_0 = 10$ cm were measured in a large empty room for waves traveling along the front of the torso.

Simulation Results

For the simulations, different configurations are used along the left and right arm. The inside of the left-arm model corresponds very well to the measurement setup. For the simulations along the right arm, the antennas are positioned on the side of the arm, where the surface is more bent. Fig. 3 (a) shows the simulated path-loss values and the fitted models versus Tx-Rx separation along the left- and right-arm configuration. The table in Fig. 3 (b) shows the parameter values of the fitted models according to equation (1), and the variation σ of the individual values around the model. The path-loss model obtained through fitting of the simulation results along the left arm shows excellent agreement with the model derived from the measurements. The path loss along the right-arm configuration is lower because the surface is less flat.

Conclusions

Path-loss models for the human arm and torso have been derived from on-body measurements. It is found that the path loss along the torso and along the arm



(a)

parameter	left arm	right arm
d_0 [cm]	10	10
$P_{0,dB}$ [dB]	32.6	30.0
n [-]	3.39	2.71
σ [dB]	0.7	1.0

(b)

Figure 3: Simulations along the arm: Path-loss values and fitted models (comparison with measured model) (a) and parameter values of the simulated models (b).

follow the same course. However, the path loss along the torso is higher than the path loss along the arm, due to the higher absorption in the larger volume of the trunk, and because the surface of the trunk is less flat than the surface of the stretched arm.

The results of the measurements along the arm are verified with FDTD simulations. The fitted path-loss model derived from the simulation results shows excellent correspondence with the model obtained from the measurements.

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