On-Body Measurements and Characterization of Wireless Communication Channel for Arm and Torso of Human

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Abstract—This paper discusses the propagation channel between two half-wavelength dipoles placed near a human body. Different parts of the body are investigated separately. Statistical properties of the wireless on-body channel have been investigated. Path loss parameters and time domain channel characteristics are extracted from the measurement data. Path loss models for the arm and torso have been derived. A comparison with a path loss model near a flat, homogeneous medium has been made.

Keywords— Propagation channel, human body, wireless body area network (WBAN), path loss, delay spread

I. 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 human body and the nodes are connected through a wireless communication channel. According to the implementation, these nodes are placed in a star or multihop topology [1]. A WBAN offers many promising new applications in home/health care, medicine, multimedia, sports and many other areas, all of which make advantage of the unconstrained freedom of movement a WBAN offers.

An important step in the development of a WBAN is the characterization of the physical layer of the network, including an estimation of the delay spread and the path loss between two nodes on the body. This requires a detailed characterization of the electromagnetic wave propagation and antenna behavior near the human body. Propagation near flat, homogeneous and layered phantoms has been investigated in [2]-[3]. Papers [4]-[5]-[6] characterize the wireless on-body channel for some specific configurations of the transmitter and receiver.

In this paper, measurements are performed on a real human using two half-wavelength dipoles, considering different parts of the human body separately. A large number of transmitter and receiver positions are considered. The on-body channel is characterized for the arm and torso. Path loss models have been determined and the lognormal behavior has been validated. Also models for the delay spread and mean excess delay have been developed and the statistical behavior has been analyzed.

In Section II the measurement setup and the different configurations that were investigated, are described. Then the on-body channel characteristics are examined. Section III presents path loss models for both the arm and torso. In Section IV a time domain analysis is performed and the mean excess delay and delay spread are discussed. Finally, Section V summarizes the conclusions of this paper.

II. MEASUREMENT SETUP

A. Configuration

Two identical half-wavelength dipoles at 2.45 GHz, with a length of 5.7 cm and a diameter of 1 mm, are placed at various positions on a human body. The dipoles are balanced for radiation near the body using a λ/4-bazooka balun. In all measurements the dipoles are placed 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 we investigate the wireless channel for a separation of 5 mm between body and antennas.

Models are developed for the channel characteristics along the human arm and torso. Fig. 1 shows the measurement setup and the antenna positions on the arm and torso. Tx and Rx represent the transmitting and receiving antenna, respectively.

Fig. 1 Measurement setup: (a) antenna positions on the body (■ = Tx and × = Rx position), (b) picture of the setup for measurements on the arm.
First, measurements are performed on a stretched arm. The transmitting antenna Tx is placed at a fixed position on the wrist and the receiving antenna Rx is moved along various positions towards the shoulder (see Fig. 1a). The distance between the antennas varies from 5 cm up to 40 cm in steps of 1 cm. These measurements are performed on two persons (male and female, age 23). A total of 214 measurements are carried out to extract propagation statistics.

The measurements on the torso are performed on a male person lying on a table with the arms along the body. The transmitter is placed at approximately shoulder height at one of three different positions (left, middle, or right, see Fig. 1a). The receiver is placed directly below the transmitter and is moved along a straight line in steps of 2 cm. The antenna separation varies from 5 cm up to 30 cm. A total of 102 measurements are performed on the torso.

B. Measurements

The measurements are performed in a modern laboratory/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 (see Fig. 1) in the frequency range from 300 kHz to 4 GHz. This frequency range is necessary to be able to distinguish the direct and the reflected waves in the time domain. We obtain a resolution of 0.25 ns.

Time domain analysis is performed by calculating the channel impulse responses $s_2(t)$ using the Inverse Fast Fourier Transform (IFFT) of the measured $S_{21}$-parameters. Fig. 2 shows the normalized impulse response from 0 ns to 40 ns for a measurement on the arm and an antenna separation of 20 cm. It can be seen that most energy is received via the direct path with different multipath reflections after some time.

III. 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:

$$P_{\text{dB}}(d) = P_{0,\text{dB}} + 10n \log_10(d / d_0) = -|S_{21}|_{\text{dB}}$$

(1)

where $P_{0,\text{dB}}$ 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 $|S_{21}|_{\text{dB}}$, which allows us to regard the setup as a two-port network for which we determine $S_{21}$. In the following we present path loss models for the human arm and torso.

A. Arm and torso

Fig. 3 shows the measured path loss versus Tx-Rx separation for the arm and torso. The circles indicate the individual measurements taken along the stretched arm and the full line represents the path loss model obtained through fitting of the arm measurement data. The crosses indicate the individual measurements taken along the torso and the dotted line represents the path loss model obtained through fitting of the torso measurement data. Table 1 shows the parameter values of the fitted path loss models for the arm and torso according to equation (1), and the variation $\sigma$ 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, but the path loss along the torso is higher than the path loss 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. The path loss exponent of both models is almost the same ($n \approx 3.3$). For the measured path loss along the torso, we observe a slightly higher variation around the path loss model (standard deviation $\sigma = 6.1$ dB) 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 $P_{0,\text{dB}}$ and the path loss exponent $n$ obtained in this paper, are consistent with previous results: in [7], a path loss exponent of $n = 3.1$ and a path loss value of $P_{0,\text{dB}} = 44.6$ 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.
Fig. 3 Measured path loss and fitted models versus antenna separation.

Table 1 Parameter values of the path loss models for the arm and torso.

<table>
<thead>
<tr>
<th>parameter</th>
<th>arm</th>
<th>torso</th>
<th>arm + torso</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$ [cm]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$P_{ref}$ [dB]</td>
<td>32.2</td>
<td>41.2</td>
<td>35.7</td>
</tr>
<tr>
<td>$n$ [-]</td>
<td>3.35</td>
<td>3.23</td>
<td>3.38</td>
</tr>
<tr>
<td>$\sigma$ [dB]</td>
<td>4.1</td>
<td>6.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Instead of investigating different parts of the body separately, we can also define an averaged path loss model for the whole human body. For this purpose we consider a path loss model obtained through fitting of all measurement data. The path loss model for the arm and torso measurements altogether is also shown in Fig. 3 (dashed line). This curve lies between the previously derived path loss models. The parameter values of this model are shown in Table 1.

B. Cumulative distribution function

Figs. 4 and 5 show the cumulative distribution function (CDF) of the deviation of measured path loss and model for the arm and torso. It was shown in [8] that the variation around the mean path loss is well described by a lognormal distribution (see lognormal fits in Figs. 4 and 5).

The mean values $\mu$ and the standard deviations $\sigma$ of the lognormal distributions for the arm and torso, fitted using a least-square error method, are provided in Table 2. For waves traveling along the torso, we again observe a slightly higher variation ($\sigma = 5.5$ dB) compared with transmission along the arm ($\sigma = 3.4$ dB). The values of the CDF parameters in Table 2 indicate that the path loss models show very good correspondence with the measurement results. The mean values of the fitted CDFs of the deviation is close to 0 dB and the standard deviations differ less than 1 dB from the standard deviation of the measured values (see Table 1: 0.7 dB and 0.6 dB difference for arm and torso, respectively).

Fig. 4 Cumulative distribution function of the deviation of measured path loss and model along the arm and lognormal distribution fit.

Fig. 5 Cumulative distribution function of the deviation of measured path loss and model along the torso and lognormal distribution fit.

Table 2 CDF of the deviation of measured path loss and model for the arm and torso: lognormal distribution fit.

<table>
<thead>
<tr>
<th>lognormal fit</th>
<th>arm</th>
<th>torso</th>
<th>arm + torso</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ [dB]</td>
<td>3.4</td>
<td>5.5</td>
<td>4.1</td>
</tr>
<tr>
<td>$\mu$ [dB]</td>
<td>-0.2</td>
<td>-0.7</td>
<td>-0.3</td>
</tr>
</tbody>
</table>
C. Comparison with flat, homogeneous medium

In Fig. 6 we compare the path loss models obtained using a least-square error fit of the measurement data (for the arm and torso) with a model derived from simulation results near a flat, homogeneous medium representing muscle tissue (specific relative permittivity \( \varepsilon_r = 53.57 \) and conductivity \( \sigma = 1.81 \) S/m at 2.45 GHz) [3]. In this path loss model, \( P_0, d \) and \( n \) are defined by a formula depending on the height \( h \) above the medium (see equation (3) in [3]).

Fig. 6 shows that the models derived from the on-body measurements deliver a higher path loss than the model for the flat, homogeneous medium. Path loss models for flat, homogeneous tissues may thus underestimate the actual path loss near a human body. The path loss exponent of the flat, homogeneous muscle simulating tissue \( (n = 3.87) \) is somewhat higher than those of the arm and torso.

IV. DELAY SPREAD MODEL

Time domain analysis is performed by analyzing channel impulse responses \( h(t) = s_2(t) \), that are calculated from the measured frequency transfer functions from 300 kHz to 4 GHz (see Section II. B) and performing the IFFT.

Power delay profiles (PDP) were calculated for all the measurement positions. For the following analysis only peaks (see Fig. 2) of less than 35 dB below the maximum value of the PDP are taken under consideration. The PDP is characterized by the first central moment (mean excess delay \( \tau_0 \)), and the square root of the second moment (RMS delay spread \( \tau_{rms} \)). The RMS delay spread provides a figure of merit for estimating data rates for multipath channels [9]. The mean excess delay \( \tau_0 \) is defined as

\[
\tau_0 = \frac{\sum_{i=1}^{N} \tau_i h(\tau_i)^2}{\sum_{i=1}^{N} h(\tau_i)^2} \tag{2}
\]

and the delay spread \( \tau_{rms} \) as

\[
\tau_{rms} = \sqrt{\frac{\sum_{i=1}^{N} \tau_i^2 h(\tau_i)^2}{\sum_{i=1}^{N} h(\tau_i)^2}} - \tau_0^2 \tag{3}
\]

where \( h(\tau_i) \) is the time domain impulse response at time \( \tau_i \) obtained from the measurement data.

A. Arm and torso

Figs. 7 and 8 show the mean excess delay \( \tau_0 \) and the RMS delay spread \( \tau_{rms} \) versus antenna separation for both measurement cases (arm and torso). The values of \( \tau_0 \) and \( \tau_{rms} \) increase with antenna separation. A linear fit for \( \tau_0 \) and an exponential and logarithmic fit (with breakpoint \( d_{bp} \)) for \( \tau_{rms} \) are performed, using a least-square error method. The fits have the following equations (with distance \( d \) in cm):

\[
\tau_0 (d) = A \cdot d + B \ [\text{ns}] \tag{4}
\]

\[
\tau_{rms} (d) = C(e^{D \cdot d} - 1) \ [\text{ns}] \quad \text{for } d \leq d_{bp} \tag{5}
\]

\[
\tau_{rms} (d) = E + F \ln\left(\frac{d}{d_{bp}}\right) \ [\text{ns}] \quad \text{for } d > d_{bp} \tag{6}
\]

The parameter values of the fits are shown in Table 3. For the measurements along the torso, the variation around the fitted models is slightly higher (\( \sigma = 1.9 \) ns for \( \tau_0 \) and \( \sigma = 1.4 \) ns for \( \tau_{rms} \)) compared with the measurements along the arm (\( \sigma = 1.1 \) ns for \( \tau_0 \) and \( \sigma = 1.1 \) ns for \( \tau_{rms} \)).

<table>
<thead>
<tr>
<th>parameter</th>
<th>arm</th>
<th>torso</th>
</tr>
</thead>
<tbody>
<tr>
<td>A [1/cm]</td>
<td>0.35</td>
<td>0.76</td>
</tr>
<tr>
<td>B [ns]</td>
<td>-1.11</td>
<td>-2.71</td>
</tr>
<tr>
<td>C [ns]</td>
<td>1.53</td>
<td>0.58</td>
</tr>
<tr>
<td>D [1/cm]</td>
<td>0.09</td>
<td>0.23</td>
</tr>
<tr>
<td>E [ns]</td>
<td>10.07</td>
<td>12.38</td>
</tr>
<tr>
<td>F [ns]</td>
<td>6.17</td>
<td>6.13</td>
</tr>
<tr>
<td>( d_{bp} ) [cm]</td>
<td>23.0</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Fig. 6 Comparison of the path loss models derived from the measurements along the arm and torso, with a model near a flat, homogeneous medium.
that both models show very good correspondence with the measurement results. The mean values are close to 0 dB and the standard deviations differ less than 0.1 dB from the variation of the measured values discussed in Section IV. A.

**B. Cumulative distribution function**

In this section we verify whether $\tau_0$ and $\tau_{rms}$ follow a lognormal distribution. Other different empirical distributions were applied in previous research [6], however, lognormal proved to be the best fit. We investigate the deviation of the measured values and the models, see equations (4)-(6). Figs. 9 and 10 show the CDFs of these deviations and a lognormal distribution fit for $\tau_0$ and $\tau_{rms}$, respectively, for the measurements along the torso. For the measurements along the arm, we obtain similar CDF distributions.

The mean values and the standard deviations of the CDFs for the arm and torso, fitted using a least-square error method, are provided in Table 4. These parameters indicate

<table>
<thead>
<tr>
<th>lognormal fit</th>
<th>$\tau_0$</th>
<th>$\tau_{rms}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ [ns]</td>
<td>arm</td>
<td>torso</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>$\mu$ [ns]</td>
<td>-0.05</td>
<td>0.00</td>
</tr>
</tbody>
</table>
V. CONCLUSIONS

Path loss models for the human arm and torso have been derived. It is found that the path loss along the torso and along the arm follow the same course, but the path loss along the torso is higher than the path loss 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. The cumulative distribution functions of the deviation of measured path loss and models are well described by a lognormal distribution, for both the arm and torso. The mean values and the standard deviations of the lognormal fits indicate that the path loss models show excellent correspondence with the measurement results.

The models derived from the on-body measurements deliver a higher path loss than the model for a flat, homogeneous muscle simulating medium. Path loss models for flat, homogeneous tissues may thus underestimate the actual path loss near a human body.

Finally, the mean excess delay $\tau_0$ and the RMS delay spread $\tau_{rms}$ were studied. These parameters increase with antenna separation. Models have been determined for $\tau_0$ and $\tau_{rms}$ and show excellent correspondence with the measurement results. The cumulative distribution functions of the deviation of $\tau_0$ and $\tau_{rms}$ and the derived models are well described by a lognormal distribution, for both the arm and torso.

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REFERENCES


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The International Workshop on Wearable and Implantable Body Sensor Networks (BSN 2007) was held from 26th to 28th March, 2007 at the University Hospital Aachen, Germany. BSN 2007 is the fourth in the series of successful workshops launched three years ago at Imperial College in London. After the event was hosted by MIT in Boston last time, BSN 2007 returned to Europe and for the first time organized jointly with academia (RWTH Aachen University) and industry (Philips Research Europe, Aachen).

The last decade has witnessed a rapid surge of interest in new sensing and monitoring devices for healthcare and the use of wearable, implantable and ambient devices for medical applications. The papers presented at BSN 2007 by leading scientists from computing, biotechnology, engineering and medicine address general issues related to on-body and in-body sensors. They discuss the latest technical developments and highlight novel applications of body-sensor networks in clinical settings, at home and on-the-move. Topics covered include new medical measurements, smart bio-sensing textiles, low-power wireless networking, system integration, medical signal processing, multi-sensor data fusion, and on-going standardization activities.

International Federation for Medical and Biological Engineering

The IFMBE is an association of constituent societies and organizations which was established in 1959 to encourage and promote international collaboration in research and practice of the profession as well as in the management of technology and the use of science and engineering in medicine and biology for improving health and quality of life. Its activities include participation in the formulation of public policy and the dissemination of information through publications and forums. The IFMBE as the only international organization and WHO/UN accredited NGO covering the full range of biomedical/clinical engineering, healthcare, and healthcare technology management, represents through its 50 national and international member societies more than 120,000 professionals involved in the issues of improved health care delivery.

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