Propagation Modeling for UWB Body Area Networks: Power Decay and Multi-Sensor Correlations

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Abstract—Body Area Networks are now accepted as an important part of 4th generation mobile technology. These networks operating at very low consumption, efficient power radio communications have to be developed. A promising solution is using multi-sensor MIMO (MS-MIMO) ultra-wideband (UWB) systems: each sensor carries one antenna, while the central device uses an antenna array. Thereby, this paper proposes a new analytical channel model for the diffracted waves mechanism. This is derived from the existing IEEE 802.15.4a standard channel model and innovates with space-time considerations.

I. INTRODUCTION

Recent researches and advances in ultra low power technologies enable the realization of a new kind of wireless personal and body-centric network, known as Body Area Networks (BAN). BANs connect independent sensors placed on the human body and measuring physiological and contextual information. These information are then carried out toward a central body-worn device, such as a personal digital assistant (PDA). Data transmissions may be direct or via multi-hops using other sensors as relays. Examples of applications deal with sensors to monitor heart activity, blood pressure, breathing rate or skin temperature for diagnostic or automatic emergency calls. Eventually, the healthcare and medical treatment of a patient can be partly practiced remotely.

Considering the BAN as a relevant scenario, the IEEE 802.15.4a group has developed a low complexity, low cost, low range and low power physical layer based on the promising ultra-wideband (UWB) technology [1]. UWB systems are characterized by an emitted signal bandwidth exceeding the lesser of 500 MHz or 20% of the center frequency. A large bandwidth and a low power spectral density lead to several advantages such as low interference to and from other systems, low sensibility to fading and accurate positioning due to fine time resolution [2].

The purpose of this paper is to provide a new channel model, based upon the IEEE standard and to extend it from single-input single-output (SISO) UWB systems to multi-sensor multiple-input multiple-output (MS-MIMO) UWB systems. In MS-MIMO systems, the central device centralizes most of the computational complexity and uses an antenna array, while other sensors carry one antenna. This architecture allows to exploit the array gain to enhance the signal-to-noise ratio (SNR), or the diversity to robustify the link or to improve the capacity of the transmission [3].

The paper is organized as follows: in section II, the measurement set-up is described. In section III, the generic channel model is presented. The power attenuation description is detailed in section IV while the space-time correlations are summarized in section V.

II. MEASUREMENT SET-UP

Radio propagation measurements are carried out on a single person whose body is in a standing position, arms hanging along the side (Fig.1). A Rohde&Schwarz ZVA-24 multi-port vector network analyser (VNA) measures the complex frequency-domain transfer function in the 3 GHz to 7 GHz range, setting up a 4 GHz bandwidth. The complex time-domain response is obtained by means of an inverse fast Fourier transform on the complex baseband frequency signal on which a Hamming windowing is applied to reduce side lobes. Omni-directional Skycross SMT-3T010M UWB antennas are selected since their small-size and low-profile characteristics precisely match body sensors requirements. Unfortunately, the closeness of the body distorts their radiation pattern and their impedance ($S_{11} > -5$ dB). A dielectric
material of 5 mm is thus used to move apart the antenna from the body skin, $S_{11}$ decreasing below $-9$ dB. The antenna de-embedding is not realised and that our model includes both the channel and the antenna effects. Using low-loss coaxial cables to inter-connect all the components, and selecting a fine IF-bandwidth resolution of 100 Hz to enlarge the channel dynamic range (about 120 dB) improve the analysis capability.

Analogous to the IEEE standard procedure, the measurement scenario focuses on the characterization around the body. The transmit antenna is placed by a distance $r$ from the middle axis of the torso (toward the left side). Regarding the receiver, a two-antenna array is considered in order to extend existing models to a MS-MIMO case. This array is made of an antenna placed on the front axis ($R_{x0}$ in Fig. 1) and a second one placed at a distance $d$ (toward the right side). Channel parameters are extracted from 7 levels separated by 4 cm along the body height. As seen in Fig. 1, for each array level, the transmitter is shifted one level below and one level above the receive array in order to improve the number of points for statistical accuracy. Actually, a total of 21 impulse responses is obtained for each combination of $r$ and $d$.

III. CHANNEL IMPLEMENTATION

Previous works have highlighted three distinct multi-path and scattering mechanisms taking place when two sensors placed on the body communicate [4], [5], [6], [7]:

- Propagation through the body. The weak penetration in the body at high frequencies enables to neglect this mechanism.
- Diffraction around the body. The wave propagates analogous to a surface wave, whose properties are related to the body characteristics.
- Reflection off the body parts (mainly the arms) and off objects in the surrounding environment (e.g. the ground, ceiling and walls).

Our channel model focuses on the characterization around the body. Knowing that $h_{ix}$ ($x = 1, ..., n_t$) for each element array $i$ (Fig. 2), the concatenating channel vector $H [n_a n_t × 1]$ for the whole array is defined as follows:

$$
H = \begin{bmatrix} H_1 & H_2 & \cdots & H_{n_a} \end{bmatrix}^T
$$

where $H_i = \begin{bmatrix} h_{i1} & h_{i2} & \cdots & h_{in_t} \end{bmatrix}$.

(1)

In these channels, variations are basically due to the diffracted waves and to the body reflections. Similarly to the IEEE model [8], we found that small-scale fading amplitude distribution reasonably matches a lognormal distribution according to the Akaike criterion\(^1\), whatever the position $d$ of the receive antenna. Analyzing a lognormal distributed system in the linear domain is equivalent to considering the system in the dB domain with a Gaussian distribution. This approach being easier to implement is favoured.

Generating $n_a$ discrete impulse responses of $n_t$ taps in dB starts with a vector of $n_a n_t$ uncorrelated, zero mean, unit variance normal variables $N(0, 1) [n_a n_t × 1]$. This vector is then multiplied by the square root of the covariance matrix $C [n_a n_t × n_a n_t]$. The power level of each tap is then adjusted by adding the appropriate mean amplitude $M = [M_{ix}] [n_a n_t × 1]$ and by subtracting the corresponding path loss $PL_i$. The covariance matrix is composed of square covariance sub-matrices $C_{ij} [n_t × n_t]$ that introduce the standard deviations $\sigma_{ix}$ $\sigma_{iy}$ and the correlation coefficient $\rho_{(ix, iy)}$ between each tap (numbered $x$) of the $i$th element and each tap (numbered $y$) of the $j$th element. Two kinds of covariance sub-matrices are involved depending on $i$ and $j$ : delay covariance ($i = j$) and delay-domain spatial covariance sub-matrices ($i \neq j$).

$$
|H|_{dB} = C^{1/2} N(0, 1) + M - PL
$$

(2)

$$
C = \begin{pmatrix}
\text{diag}(C_{11}, C_{22}, \ldots, C_{n_a n_a}) + \\
\sum_{i=1}^{n_a-1} \sum_{j=i+1}^{n_a} (e_i^T e_j \otimes C_{ij} + e_j^T e_i \otimes C_{ij}^T)
\end{pmatrix}
$$

(3)

\(^1\)A set of potential distributions was compared including for example Rayleigh, Gamma, Rice or Nagakami.

\(^2\)If the matrix is positive definite, the upper triangular Choleski factorization can be applied.
\[ C_{ij} = \begin{pmatrix} \sigma_{i1} \sigma_{j1} \rho_{(i1,j1)} & \cdots & \sigma_{i1} \sigma_{jn_t} \rho_{(i1,jn_t)} \\ \vdots & \ddots & \vdots \\ \sigma_{in_t} \sigma_{j1} \rho_{(in_t,j1)} & \cdots & \sigma_{in_t} \sigma_{jn_t} \rho_{(in_t,jn_t)} \end{pmatrix} \]  

In (3), \( \otimes \) denotes the Kronecker operation, \( \text{diag}(X) \) is a matrix with the vector \( X \) on the diagonal, and \( e_k[1 \times n_a] \) is the canonical vector.

The resulting \( |H|_{dB} \) is then a vector of \( n_a n_t \) correlated normal variables. At last, the final channel expression is obtained by converting the amplitude taps from the dB domain to the linear domain and by adding a phase with uniform distribution between \([0, 2\pi]\), as found experimentally.

\[ \text{IV. POWER ATTENUATION AROUND THE BODY} \]

\[ \text{A. Path loss} \]

As foreseen in [9] and assumed in [1], an isolated diffracted wave propagating around the body follows an exponential decay. Yet, the on-body channel involves waves diffracted by body parts, each carrying a part of power. In Fig. 1, when the transmitter Tx is moved toward the back, these delayed multi-path components are not negligible as compared to the main diffracted wave, and their contribution must be taken into account in the path loss.

Extending the IEEE standard to a multi-antenna system requires to check the validity of the path loss model when the antenna is off-centered, involving a disymmetric of the body configuration, as the arms distance. In Fig. 3, the path loss around the body was estimated for a set of distances \( d \) by integrating the power of the 20 first taps of measured impulse responses. The fading was removed by averaging the data at the same transmit distance. In all cases, an exponential law reasonably matches the data. Whatever the position of the receiver Rx, the same parameters of the path loss are extracted and the model is only dependent on the relative distance between Tx and Rx:

\[ \text{PL}(R)_{dB} = \text{PL}(R_0)_{dB} + \gamma (R - R_0) \]  

where \( R \) is the distance between the transmit and receive antennas (here, \( R = r + d \)), \( \text{PL}(R_0)_{dB} \) is the path loss for a reference distance \( R_0 \), and \( \gamma \) is the slope coefficient in dB/cm. All the parameters can be found in Tab. I.

\[ \text{Table I} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 )</td>
<td>reference distance</td>
<td>8 cm</td>
</tr>
<tr>
<td>( \text{PL}(R_0)_{dB} )</td>
<td>path loss for a reference distance ( R_0 )</td>
<td>55.18 dB</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>slope coefficient</td>
<td>1.26 dB/cm</td>
</tr>
<tr>
<td>( n_t )</td>
<td>length of an impulse response</td>
<td>20 taps</td>
</tr>
</tbody>
</table>

In Fig. 3, the exponential fit of the power of the first tap is also illustrated. By comparing to the path loss model, the steeper slope of the main diffracted wave clearly demonstrates the growing contribution of the delayed multi-path component when the distance increases, as expected.

\[ \text{B. Mean in the dB domain} \]

To determine the contribution of each tap, the path loss law is multiplied to the impulse responses in the linear domain, so that the average relative energy around the body is unity. Fig. 4 shows in dB the mean amplitudes \( M_{ix} \) of each tap (numbered \( x \)) relative to the mean amplitude of the first tap \( M_1 \). A dual-slope model best describes the decay with delay:

\[ M_{ix} = \begin{cases} M_1 + \mu_1(x - 1) & 1 \leq x \leq n_{hp} \\ M_1 + \mu_1(n_{hp} - 1) + \mu_2(x - n_{hp}) & n_{hp} < x \leq n_t \end{cases} \]

This exponential decay results from interfering echoes from the body itself. Likewise, the first-slope coefficient \( \mu_1 \) of
this model increases with \( d \) and \( r \) owing to longer distances increasing the delayed multi-path component contributions, as already observed in section IV-A.

The first-slope coefficient \( \mu_1 \) depends on the transmit location since a difference appears from the arm position. Actually, for a transmitter placed in the front of the body \((r \leq 23.5 \text{ cm})\), \( \mu_1 \) reasonably matches the equation (7), while for a transmitter placed in the back of the body \((r > 23.5 \text{ cm})\), this coefficient is best described by the equation (8).

\[
\begin{align*}
\mu_1 & = (-6.2 + 0.14 \, d) + (0.14 - 0.005 \, d) \, r \\
\mu_1 & = (-3 + 0.025 \, d) + (0.09 - 0.005 \, d) \, (r - 23.5) 
\end{align*}
\] (7) (8)

The breakpoint tap number \( n_{bp} \) fits with the arrival of diffracted waves from the counter-clockwise direction. These waves intensify the multi-path component mechanism and soften the receive power decay - explaining for the dual-slope model. Depending on the transmitter location, in the front or in the back of the body, earlier or later breakpoint times are found, respectively. However, a single breakpoint was fixed by a best-fit algorithm over all the measurement data. The second-slope coefficient \( \mu_2 \) slightly varies and is set constant.

\[
\mu_2 = -1.09
\] (9)

V. Correlated Standard Deviations

This section only gives an overview of the key features of the covariance matrix characteristics. More details and explanations can be found in [10]. The covariance matrix between position \( i \) and \( j \) is composed of the standard deviations (STDs) \( \sigma_{ix} \) \( \sigma_{jy} \) and the correlation coefficient \( \rho_{(ix,jy)} \) for taps \(|h_{ix}|_{\text{dB}}\) and \(|h_{jy}|_{\text{dB}}\).

The STDs are quite constant independently from the receiver position. Variations become slightly higher when the transmitter is placed in the back region of the body, especially in the vicinity of the arms, as illustrated in Tab. II.

<table>
<thead>
<tr>
<th>Transmitter location</th>
<th>Tap</th>
<th>( \sigma_{ix} ) (or ( \sigma_{jy} )) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>in the front of the body</td>
<td>first (x=1)</td>
<td>3.87</td>
</tr>
<tr>
<td>in the front of the body</td>
<td>other (( n \neq 1 ))</td>
<td>6.04</td>
</tr>
<tr>
<td>in the back of the body</td>
<td>first (x=1)</td>
<td>5.64</td>
</tr>
<tr>
<td>in the back of the body</td>
<td>other (( x \neq 1 ))</td>
<td>6.7</td>
</tr>
</tbody>
</table>

TABLE II Standard Deviation Values

Regarding the correlations, its is clearly highlighted in [10] that significant values are obtained for both the delay correlation between adjacent taps, and the delay-domain spatial correlation, confirming overlapped trajectories in a human body environment. Furthermore, these correlations are not affected by the receive antenna spacing if the transmitter is worn on the back of the body. For this region, Fig. 5 shows the spatial correlation coefficients \( \rho_{(ix,jy)} \) averaged over \( d \) for tap number \( x, y \in [1,35] \). A brighter main diagonal is observed, indicating a high correlation. Three correlated clusters are also identifiable: the dominant direct diffracted wave at the beginning of the impulse response \( \rho_{(i1,j1)} > 0.8 \), the dominant diffracted wave from the counter-clockwise direction \( \rho_{(i8,j8)} > 0.7 \), and the ground reflection \( \rho_{(i25,j25)} > 0.8 \).

However, it is also shown in [10] that reflections off the body parts decrease the correlation for a transmitter located in the front of the body, due to the spatial interferences similarly to a traditional indoor environment.

VI. Conclusion

This paper proposes a new analytical space-time channel model for UWB multi-sensor MIMO Body Area Networks. Here, each sensor carries one antenna and transmits pulses of 4-GHz bandwidth to a multi-antenna central device. The decay of tap mean amplitude with delay is best described by a dual-slope power law whose parameters depend on the transmit and receive antenna locations. Overlapped trajectories are also identified, leading to high-correlated diffraction waves for both the delay correlation and the delay-domain spatial correlation. However, spatial interference takes place owing to the reflections off the body parts and alters the correlation, that falls down with inter-spacing.

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REFERENCES


