Radio Propagation Models for In-Body Sensors

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Abstract

Radio technology has the potential to enable real-time collection and monitoring of physiological signals for better healthcare. Implantable biomedical sensors transmitting continuously physiological information to an external unit can facilitate the personalized treatment of chronic diseases. Other in-body medical devices like the wireless capsule endoscope have been proven extremely useful as a diagnostic tool for diseases in the gastrointestinal tract. Nevertheless, the design of efficient wireless communication systems to transmit reliably the information collected inside the body to an external receiver for display and analysis requires accurate radio propagation models. Because of the impossibility to conduct in-body measurements with human subjects, research in this field has made use of measurements in phantoms and intricate computer simulations. This paper surveys the different propagation models for implant communication that have been presented in the literature for narrowband and ultra wideband signals. Research challenges and perspectives for the improvement of the path loss models are discussed too.

1. Introduction

The population with chronic diseases is increasing worldwide. Real-time monitoring of various physiological signals is of utmost importance for the treatment of conditions like diabetes and for the management of cardiovascular diseases. Radio technology has the potential to enable real-time sensing and collection of physiological data to facilitate timely medication and early pre-hospital management of patients. This can be realized with the aid of wearable and implantable biomedical sensors with the capability to transmit wirelessly the collected information to an external unit for display and analysis. The IEEE Std 802.15.6-2012 specifies the technical requirements for short-range wireless communications for body area network (BAN) devices, which comprise on-body and in-body medical sensors. IEEE Std 802.15.6-2012 defines the characteristics of the physical (PHY) layer for the implementation of in-body devices in the frequency band of 402-405 MHz, which is allocated to the medical implant communication services (MICS) in many countries. This band offers good propagation behavior through human tissues and allows the fabrication of reasonable-size antennas, but its limited bandwidth constrains the communication devices to low data rates. Contrastingly, IEEE Std 802.15.6-2012 recommends the operation of on-body biomedical sensors in the various industrial, scientific, medical (ISM) bands as well as other bands approved by regulatory authorities; these bands comprise 13.5 MHz, 50 MHz, 400 MHz, 600 MHz, 900 MHz, 2.4 GHz, and the ultra wideband (UWB) spectrum of 3.1-10.6 GHz. The use of these additional frequencies for in-body BAN devices can enable novel applications like smart electronic pills for targeted drug delivery and therapeutic procedures due to the larger bandwidths potentially available above the MICS band, especially in the UWB spectrum. However, the transmitted signals from implanted nodes undergo significant attenuation as they propagate through several layers of living biological tissues and organs, an adverse effect that increases over frequency. Modeling the radio channel for implant communication is challenging. A number of ethical and technical issues prevent the realization of measurements with human subjects. Therefore, in order to characterize the propagation of radio signals through the human body, researchers have to carry out measurements in phantoms, i.e., chemical solutions specially formulated to mimic the dielectric properties of biological tissues. The drawback of these measurements is that the propagation medium is homogeneous with a single dielectric constant, unlike the human body, which is rather inhomogeneous. A more accurate approach consists in performing numerical simulations of wave propagation using a digital heterogeneous anatomical model, which accounts for the shape of the different organs and the several dielectric properties of the various types of tissues. Whichever approach is
applied, the obtained data has to be processed statistically to produce a path loss model. This paper surveys the different path loss models for implant communication that have been proposed in the literature. The remainder of the paper is organized as follows: In the next section we summarize the path loss models adopted in IEEE Std 802.15.6-2012. Section 3 presents the path loss models for implant communication using narrowband signals whereas Section 4 deals with UWB. Section 5 presents path loss models for electronic pills like the wireless capsule endoscope (WCE). Finally, the research challenges and perspectives for the improvement of the path loss models are briefly discussed in Section 6.

2. The IEEE Std 802.15.6-2012 Models

The Channel Modeling Subgroup within the IEEE 802.15.6 standardization defined the implant communication scenarios as those in which the BAN nodes are located inside the body. Three implant communication scenarios were identified, namely (S1) Implant to Implant, (S2) Implant to Body Surface, and (S3) Implant to External. Two channel models, namely CM1 and CM2, were developed to characterize the path loss in these scenarios [1]. S1 is characterized by CM1, whereas CM2 characterizes S2 and S3. In fact, S3 can be regarded as the combination of two links, one link from the implant to an on-body rely node (S2 link), and a second link from the rely node to an external device.

The CM1 and CM2 models provide the total loss along a propagation path of length $d$ by the Friis equation plus a scattering term $S$, i.e.:

$$PL(d)_{[\text{dB}]} = PL_0 + 10n\log_{10}(d/d_0) + S$$

where $PL_0$ is the path loss in dB at a reference distance $d_0$, and $n$ is the path loss exponent. The scattering is modeled as a normally distributed random variable (RV) with zero mean and standard deviation $\sigma_S$ in dB. The parameters of these models for deeply and superficially implanted BAN devices with $d_0 = 50$ mm are given in Table 1.

<table>
<thead>
<tr>
<th>Implant to Implant (CM1)</th>
<th>Implant to Body Surface (CM2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PL_0$</td>
<td>$n$</td>
</tr>
<tr>
<td>Deep tissue</td>
<td>35.04</td>
</tr>
<tr>
<td>Near surface</td>
<td>40.94</td>
</tr>
</tbody>
</table>

These models stemmed from the use of an innovative 3D immersive visualization and simulation platform, which included the frequency-dependent dielectric properties of more than 300 parts of a male human body [2].

3. Path Loss Models for Implants Using Narrowband Signals

Other narrowband propagation models for implants on 418 MHz and 916.5 MHz were presented in [3]; greater losses were encountered for the higher frequency band as expected. Propagation losses of body implanted antennas were computed in [4] via numerical simulations, namely 433 MHz, 915 MHz, 2450 MHz, and 5800 MHz. However, these simulations were done with simplistic single- and three-layer tissue structures and no mathematical formulas for the path loss were provided. On the other hand, numerical and experimental path loss investigations with ingested wireless implants in 402 MHz, 868 MHz, and 2.4 GHz were presented in [5]. Likewise, measurements in phantoms and numerical simulations of path loss for insulated dipole antennas in the ISM band at 2.457 GHz led to the following loss formulas for a propagation path length, $d$, of up to 8 cm [6]:

$$PL(d)_{[\text{dB}]} = (10\log_{10} e^2)\alpha_1 d + C_1 \quad \text{for} \quad d \leq d_{bp}$$

$$PL(d)_{[\text{dB}]} = (10\log_{10} e^2)\alpha_2 d + C_2 \quad \text{for} \quad d > d_{bp}$$

where $d_{bp} = 2.78$ cm is the optimal breakpoint for the best fitting to the measured data, $\alpha_1 = 0.18$ and $\alpha_2 = 0.12$ are attenuation factors, and $C_1 = 10.94$ dB and $C_2 = 18.34$ dB are fitting constants. Nevertheless, as in the previous case, a very simplistic homogeneous propagation scenario was used for both measurements and simulations.
4. Path Loss Models for Implants Using Ultra Wideband Signals

To the best of our knowledge, only two models for BAN devices implanted in the human chest have been reported in the literature for UWB signals. The first channel model [7] was developed through numerical simulations using a voxel anatomical model that included nearly 50 types of tissue with a spatial resolution of 2 mm. This channel model predicts a root mean square (RMS) delay spread of around 0.2 ns, but it does not provide a formula for path loss. The second channel model [8] stemmed from numerical simulations using an inhomogeneous anatomical model that included the dielectric properties of 24 different types of tissues with voxel resolution of 2 mm. It predicts a RMS delay spread below 1 ns, which is in agreement with [7], whereas the path loss is given as:

$$PL(d)_{[\text{dB}]} = PL_0 + k(d/d_0)^\eta + S$$  \hspace{1cm} (4)$$

where $PL_0 = 10$ dB for $d_0 = 1$ mm, $k = 0.987$ is a fitting constant, $\eta = 0.85$ is an empirical exponent, and $S$ is a normally distributed RV with zero mean and standard deviation $\sigma_S = 7.84$ dB. This formula is valid for $1 < d \leq 120$ mm and, although it differs from the Friis equation, it is the best fit to the simulation data. This model provides the path loss independently of antenna effects. This feature resulted from the torso being exposed to an incoming plane wave from the front while ideal electric field receiving probes were placed inside the chest, instead of using an implanted transmitting antenna. The same simulation approach was applied to obtain a UWB path loss model for the abdomen [9].

Unlike narrowband channels, additional frequency-dependant loss has to be included in the path loss calculation for the accurate characterization of UWB links. A simple model for computing the additional frequency-dependant loss in the frequency domain in 1-6 GHz can be found in [10].

5. Path Loss Models for Electronic Pills

For the design of radio links for electronic pills sensing pH, pressure, temperature, and other physiological variables, the use of path loss models for the abdomen can provide an adequate characterization of the channel [2, 9]. Nevertheless, the design of more sophisticated electronic pills like the WCE demanding higher data rates requires ad hoc accurate path loss models that account for the specific movement of the device along the gastrointestinal (GI) tract. A path loss formula for the 403.5 MHz narrowband link between a WCE and an on-body receiver located at the navel was developed in [11] by combining simulation and experimental data, and it is given as:

$$PL(d, \theta)_{[\text{dB}]} = a \cdot d + b + P(\theta) + S$$  \hspace{1cm} (5)$$

where $a = 1.92$ dB/cm is a gradient coefficient, $b = 39.85$ dB is the intercept coefficient, and $S$ is a normally distributed RV with zero mean and standard deviation $\sigma_S = 7.84$ dB. $P(\theta)$ represents the fluctuations in dB caused by the WCE direction, and it is computed as $P(\theta) = -20 \log_{10} \left( \left( \cos(\theta) \right)^2 + \left( 1 - x_c \right) \right)$, where $\theta$ is the angle between transmitting and receiving antennas, and $x_c$ is the difference between the main ($z$) and cross ($x$, $y$) electric field direction.

In [12] a 1-6 GHz UWB channel model for WCE was presented. This statistical model was developed with the aid of the same anatomical model as in [8, 9]. The path loss was given for several receivers located on a belt around the waist, and it was modeled by a Fourier double series (see [12] for mathematical details). Recent measurements in 2340-2620 MHz in a phantom are aimed at characterizing the WCE radio channel in one of the ISM bands [13].

6. Conclusion

Although a number of path loss models for implant communication have already been proposed, more accurate channel models for the different ISM frequency bands and the recently allocated BAN spectrum of 2360-2400 MHz have to be developed. Likewise, the specific radio channel for WCE has to be modeled for these frequencies. Frequency-dependant loss should not be neglected in UWB path loss calculations. The use of realistic anatomical voxel models is imperative to enhance the accuracy of the channel characterization. As outlined in [14], in-vivo measurements in animals for the validation of phantom- and simulation-based path loss models have to be pursued with the collaboration of specialists with clinical backgrounds.
7. Acknowledgments

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8. References


