Statistical modeling of intrabody communication channels in various grounding conditions

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Abstract: In the development of intrabody communication systems, it is important to understand the effects of user’s posture on the communication channels. In this study, we conducted a statistical modeling of the dynamic intrabody communication channels in various grounding conditions of the transceivers. The proposed channel model was found to be useful to model the communication channels.

Keywords: intrabody communications, probability density function

Classification: Antennas and Propagation

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1 Introduction

In recent years, body-centric wireless communications have been studied because they have the potential to improve the quality of health care systems, support systems for specialized occupations, personal entertainment, and so on [1, 2]. They are generally classified into on-, in-, and off-body communications. On-body communications that use frequencies below several tens of megahertz are also known as intrabody communications [3].

In the development of intrabody communication systems, it is important to understand the effects of user’s posture on the communication channels. For example, a statistical channel model is necessary to estimate the required transmitting power, the required sensitivity and the dynamic range of the receiver. In addition, it will be useful to quantitatively discuss the dependence of the communication channels on various conditions. In this regard, Zedong et al. have measured the dynamic communication channels and made a statistical characterization in various environments [4]. However, the effects of the grounding conditions, which depend on applications, on the communication channels were not addressed in [4]. For this reason, we have measured the dynamic communication channels in several grounding conditions and have found that the variations in the channels are significant if both the transmitter (Tx) and the receiver (Rx) are not grounded [5]. In this study, we conducted further investigations based on statistical channel modeling [6].

2 Measurement instruments

To measure the dynamic signal transmission characteristics at arbitrary grounding conditions, we developed battery-powered Tx and Rx shown in Fig. 1(a) [5]. Both the Tx and the Rx consist of rectangular parallel-plate electrodes of 90 mm × 60 mm that are backed by FR-4 substrates of 1.6-mm thickness. The electrode that faces the human body is called the “hot” electrode, and that which faces space is called the “cold” electrode. The metallic faces of the hot and the cold electrodes are opposed each other and separated by a gap of 5 mm. The electrodes of the Tx are driven by a 10-MHz sinusoidal voltage source of 4 V with internal impedance of 50 Ω. On the other hand, the electrodes of the Rx are loaded by a receiving circuit of 5-kΩ input impedance. The received voltage was detected and sampled by a 10-bit analog-to-digital converter in a sampling interval of 50 ms. The sampled data are recorded on a microSD card. The measurable range is approximately from −90 to −3 dBV. The resolution of the sampled data is approximately 0.095 dBV. The details of the Tx and the Rx are described in [5].

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3 Measurement conditions

Fig. 1(b) shows the measurement setup in a shielded room of 10 m × 5.5 m × 3 m. Because the lowest-order resonant frequency of the shielded room is approximately 31 MHz, the resonant effect on the measured results at 10 MHz is negligible. The experimental subject was a 24-year-old male student, who is 1.85 m in height and 75 kg in weight. The Tx and the Rx were mounted on his abdomen and left wrist, respectively. On an expanded polystyrene board with a thickness of 100 mm placed on the floor of the shielded room, the subject moved his body according to the radio calisthenics #1, which is broadcasted by the Japan Broadcasting Corporation (NHK). The received voltage of the Rx was recorded during the sequence of which time length is 180 s under the following four grounding conditions:

- No GND Both the Tx and the Rx are not grounded.
- GND Tx The cold electrode of the Tx is grounded.
- GND Rx The cold electrode of the Rx is grounded.
- GND Tx & Rx The cold electrodes of the Tx and the Rx are grounded.

The Tx and the Rx were grounded to the floor of the shielded room through conducting cables. For each grounding condition, the time variation of the received voltage was measured twice. Then, a probability density function (PDF) \( f_{\text{meas}}(x) \) as a function of the received voltage \( x \) [dBV] was obtained by post-processing the measured data. Furthermore, the obtained PDF was smoothed by a simple moving average of ±0.5 dBV to remove jaggies.

4 Channel modeling method

As already reported in [5], the profile of the PDFs have several local peaks depending on the grounding conditions. To model the measured PDFs, a multiple normal distribution (MND) channel model is proposed, which is defined as follows:

\[
 f_{\text{meas}}(x) = \sum_{i=1}^{N} w_i \frac{1}{\sqrt{2\pi}\sigma_i} \exp \left[ -\frac{(x - \mu_i)^2}{2\sigma_i^2} \right],
\]

(1)

1This relation is opposite to that in [5]
2The results reported in [5] were not smoothed.
where $N$ is the number of normal distributions that constitute the MND model, and $\mu_i$, $\sigma_i$, and $w_i$ are the mean, the standard deviation, and the weighting factor of the $i$-th normal distribution, respectively. The parameters $\mu_i$, $\sigma_i$, and $w_i$ were determined so as to minimize the integrated value of the squared residuals, i.e. they were obtained by solving an optimization problem described as follows:

$$\minimize R \equiv \int_{-\infty}^{\infty} [f_{\text{MND}}(x) - f_{\text{meas}}(x)]^2 dx$$

subject to

$$\sigma_i > 0, \quad i = 1, \ldots, N;$$

$$w_i > 0, \quad i = 1, \ldots, N;$$

$$\sum_{i=1}^{N} w_i = 1.$$  \hspace{1cm} (2) \hspace{1cm} (3) \hspace{1cm} (4) \hspace{1cm} (5)

The solution of this problem was obtained through the following procedure:

1. The solution was searched globally by the genetic algorithm (GA) [7].
   - This step is necessary to avoid converging on local optima.
   - The program was implemented by using the “genalg” library [8] for the programing language R.
   - The population size (popSize) is 200, 200, 500, and 1000 in the cases $N = 1, 2, 3, \text{and } 4$, respectively.
   - The number of iterations (iters), also known as generation, is 100.
   - The mutation rate (mutationChance) is 0.01.
   - About 20% chromosomes shall be kept on the next generation (elitism).
   - Additional constraints $\sigma_i < 100 \text{ dBV}$ and $-100 \text{ dBV} < \mu_i < 0 \text{ dBV}$ are imposed.

2. The better solution was searched locally by the Nelder–Mead method [9].
   - The program was implemented by using the default optimization function “optim” of the programing language R.
   - The final parameters obtained by the GA were used as default parameters in this step.
   - The optimization process was terminated if the difference between the values of $R$ at the current and the previous steps is less than $10^{-8} \text{ dBV}^{-1}$.

It should be noted that the procedure described above is one example. The better searching methods, if available, may be used to obtain the solution of the problem defined by Eqs. (2)–(5).

5 Results

Fig. 2 compares the measured PDF and the MND model, where $N = 4, 3, 2, \text{and } 1$ in the conditions “No GND,” “GND Rx,” “GND Tx,” and “GND Tx & Rx,” respectively. In addition, the numerical values of the obtained parameters and the integrated value of the squared residuals are summarized in Table I.

The PDF in the condition “No GND” has the most complex profile. However, it is reasonably approximated by the MND model of $N = 4$. The first and the second peaks corresponds to the first and the second normal distributions of $\mu_1 = -85.72 \text{ dBV}$ and $\mu_2 = -73.96 \text{ dBV}$, respectively. In addition, the PDF between these peaks is very low. This fact means that the received voltage tends to lapse into extremely low levels with a probability of approximately 7% ($w_1 = 0.07227$) and is
likely due to the shadowing by the body parts [5]. In the range approximately from −75 to −65 dBV, many distributed peaks constitute a broad profile and they are approximated by the third and the fourth normal distributions of $\mu_3 = -70.81$ dBV and $\mu_4 = -64.12$ dBV. This trend is observed only in this condition, and is likely due to the effect of the direct signal path formed between the Tx and the Rx [5, 10].

The PDF in the condition “GND Rx” is totally well approximated by the MND model of $N = 3$. However, the first peak approximately at $-69$ dBV is not well fitted, and this tendency was not resolved even if the number of normal distributions is $N \geq 4$. This result suggests that there is room to improve the MND model for this case.

The PDFs in the conditions “GND Tx” and “GND Tx & Rx” are relatively simple. Therefore, they are sufficiently approximated by the MND models of $N = 2$ and $N = 1$, respectively.

The results described above suggest that the proposed MND model is useful to model the dynamic intrabody communication channels even if the PDF has a complex profile.

| Condition          | $i$ | $\mu_i$ [dBV] | $\sigma_i$ [dBV] | $w_i$   | $R$ [dBV$^{-1}$] |
|--------------------|-----|--------------|-----------------|--------|-----------------|
| No GND             | 1   | -85.72       | 1.999           | 0.07227| $6.184 \times 10^{-4}$ |
|                    | 2   | -73.96       | 0.8186          | 0.2974 |                 |
|                    | 3   | -70.81       | 4.482           | 0.5475 |                 |
|                    | 4   | -64.12       | 1.455           | 0.08290|                 |
| GND Rx             | 1   | -63.42       | 6.188           | 0.2174 | $9.735 \times 10^{-4}$ |
|                    | 2   | -56.02       | 1.531           | 0.3164 |                 |
|                    | 3   | -54.33       | 0.9748          | 0.4662 |                 |
| GND Tx             | 1   | -48.46       | 1.297           | 0.03130| $8.123 \times 10^{-4}$ |
|                    | 2   | -44.96       | 1.251           | 0.9687 |                 |
| GND Tx & Rx        | 1   | -21.16       | 1.182           | 1.000  | $1.167 \times 10^{-3}$ |
6 Conclusion

In this study, the dynamic intrabody communication channels were measured in several grounding conditions, and a MND model is proposed to model the measured PDF of the received voltage. The results suggest that the proposed MND model is useful to model the dynamic intrabody communication channels even if the PDF has a complex profile.

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