Model of the Human Body as Signal Transmission Medium for Body-Coupled Communication

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***Abstract*—Research on signal propagation models is an essential aspect of Radio Frequency (RF) research, and over the years, numerous models have been developed for various applications. However, emerging communication methods such as Body-Coupled Communication (BCC) require the creation of new models. In this extended abstract, we introduce a mathematical model that approximates the human body as an electronic component schematic. We provide closed-form expressions of the model. The results demonstrate a close correlation between the amplitude-frequency response predicted by the model and the experimental data gathered from volunteers.**

***Keywords*—BCC, signal propagation, signal loss, human body**

I. INTRODUCTION

The development of microelectronics, material science and artificial intelligence has enabled the placement of various types of sensors on the human body to form body-area networks (BANs). These networks provide valuable data sources for medical and fitness applications. The signals measured by the on-body sensors must be collected in a single location to translate raw measurements into clinically relevant information. This collection device can take the form of a smartwatch, or a device that communicates with the smartwatch, such as a mobile phone, cloud or edge server. In both cases, the potentially private and sensitive data must be transmitted from the on-body sensors to a BAN gateway device. While existing options such as Bluetooth and WiFi are available for this purpose, they are susceptible to security issues and side-channel attacks through on-air signal sniffing. Body-Coupled Communication (BCC) is a new communication technology that utilizes the human body for data transfer, reducing the attack surface by avoiding data transmission over the air.

BCC uses low-voltage AC as the carrier wave, typically in frequencies ranging from 0.05 to 20+ MHz. In galvanic coupling (”voltage-mode”) BCC, four electrodes are connected to the human body. In capacitive coupling, only two are connected and two left floating. The main research challenge here is that the human body’s properties as a transmission medium are not yet fully understood. To address this issue, the BCC project has collected a dataset from over 20 volunteers. This abstract presents a mathematical model in this extended abstract that approximates the human body as an electronic circuit. Our goal is to determine the amplitude-frequency response (AFR), also known as the transfer function, of the proposed model and assign nominal values to the circuit components so that the AFR of the model aligns with the real data obtained from experimental measurements.

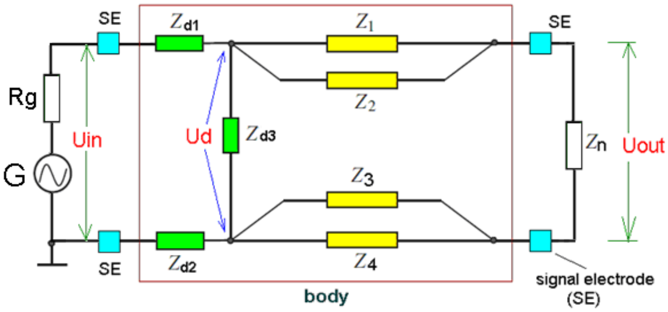

Fig. 1: Electrical circuit model of the human body.

The main differences between our model and existing ones are twofold. Firstly, our model includes inductive elements, in addition to the usual resistive and capacitive components, to account for multiple peaks in the AFR curve. Secondly, to facilitate analysis and localization, we removed certain cross-links between the components in the model.

II. ELECTRICAL CIRCUIT MODEL OF THE HUMAN BODY

The problem of finding the AFR can be formulated as finding the frequency-dependent transfer coefficient K_f:

$$K_f := \frac{U_{out}}{U_{in}} \tag{1}$$

The answer can also be expressed in dB, as the voltage gain of the system, equal to $20 \log K_f$.

The proposed model is shown in Fig. 1. It is a modified version of the model proposed in [1], [2]. The circuit of interest is within a box circled by a rectangular contour, labeled “body”. At the input point of interest of the body it is connected by means of two signal electrodes (SE) to the output of a tunable harmonic voltage generator G with internal resistance R_g. The output of the model by means of similar signal electrodes is connected to a measuring instrument with input impedance Z_n.

Our model consists of two parts. The first part is depicted on the left (transmitter) side of the figure. It includes the divider resistances Z_{d1}, Z_{d2}, Z_{d3} and acts as a frequency independent body impedance, including the impedance of electrode-skin coupling [1]. It is possible to simplify the algebraic expression of the transfer coefficient with very little loss of accuracy by replacing the oscillator voltage U_{in} and the divider resistances Z_{di} with an equivalent oscillator with voltage U_d and a small internal resistance, so that:

$$K_f = \frac{U_d}{U_{in}} \cdot \frac{U_{out}}{U_d} \tag{2}$$

Let's denote the first ratio with K_{left} and the second ratio with K_{right}. The left side of the model is simple to analyze:

$$K_{left} = \frac{R_{d3}}{R_{d1} + R_{d2} + R_{d3}} \tag{3}$$

Finding an analytic expression for the right side is the main task of the subsequent analysis.

The right side of the model includes a circuit consisting of complex resistances Z_1, Z_2, Z_3, Z_4, each of which is connected in series R, L, C (resistance, inductance, capacitance) with the same indexes:

$$Z_i = R_i + 2j\pi f L_i + \frac{1}{j2\pi f C_i}, \tag{4}$$

where f is the frequency of the signal. Further in this paper, we are going to replace $j2\pi f$ with the complex variable p.

In most of the models described in existing literature, the human body is represented as an RC circuit; L elements are typically not included. However, as shown in Fig. 2, the AFR of the human body in the 0.05 to 20 MHz frequency band has a number of resonances, two of which are well pronounced. It is not easy to obtain such resonances in the model using only RC elements, therefore we model it as an RLC circuit instead.

If we represent the parallel connections Z_1 and Z_2 as Z_{12}, but Z_3 and Z_4 as Z_{34}, then using circuit analysis, we get the following expression for K_{right}:

$$K_{right} = \frac{Z_n}{Z_{12} + Z_n + Z_{34}} \tag{5}$$

Expanding the Z values according to the Eq. 4 and multiplying it with K_{left}, we obtain an expression for the transfer operator's coefficients:

$$K_p = \frac{Z_n R_{d3}\left(ap^5 + bp^4 + cp^3 + dp^2 + ep\right)}{hp^6 + ip^5 + kp^4 + gp^3 + mp^2 + np + q}, \tag{6}$$

The full expressions of the coefficients a to q are too cumbersome to provide here in full, but will be available in the project's deliverables. Finally, to complete the solution and find K_f as a function of frequency, one can replace p in Eq. 6 back with $j2\pi f$; here we skip this due to space limits.

III. INSTANTIATION OF THE MODEL

In this section, we show how to instantiate the model in a specific example. By changing the nominal values of the elements, we can adjust the shape of the AFR model to the real experimental AFR of the human body.

First of all, in our dataset collection experiments R_g and Z_n are set to 50 ohm, since this resistance is commonly used in RF engineering. Subsequently, let's take an example measurement from the dataset that describes the AFR of the human body between transmitter electrodes placed on on the right leg's loin muscle, and receiver electrodes placed on the left leg's knee. The frequency response expression according to the model is:

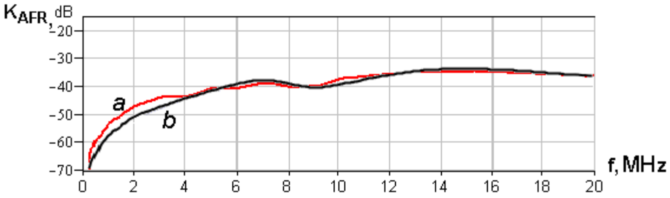

Fig. 2: Amplitude-frequency response (signal loss) of the body for a particular measurement: a) experimental, b) model.

$$K_p = \frac{N_p}{D_p}, \tag{7}$$

where:

$$N_p = 6.6 \cdot 10^{-52} p^5 + 4.4 \cdot 10^{-44} p^4 + 9.3 \cdot 10^{-36} p^3 + \\ + 2.4 \cdot 10^{-28} p^2 + 2 \cdot 10^{-20} p$$

$$D_p = 6 \cdot 10^{-58} p^6 + 6.8 \cdot 10^{-50} p^5 + 1.5 \cdot 10^{-41} p^4 + \\ + 8.9 \cdot 10^{-34} p^3 + 8.9 \cdot 10^{-26} p^2 + 2.2 \cdot 10^{-18} p + 1.1 \cdot 10^{-10}$$

It corresponds to the following nominal values: $Z_{d1} = Z_{d2} = 60\,\mathrm{ohm}$; $Z_{d3} = 18\,\mathrm{ohm}$; $L1 = 15\,\mu\mathrm{H}$; $R1 = 240\,\mathrm{ohm}$; $C1 = 45\,\mathrm{pF}$; $L2 = L3 = 5\,\mu\mathrm{H}$; $R2 = R3 = 200\,\mathrm{ohm}$; $C2 = C3 = 25\,\mathrm{pF}$; $L4 = 4.5\,\mu\mathrm{H}$; $R4 = 220\,\mathrm{ohm}$; $C4 = 18.5\,\mathrm{pF}$. The nominal values are found empirically using an electronic circuit simulator Multisim. Using automated search with software like Z-view is in our future work. The modulus of K_p is the desired AFR.

Fig. 2 shows comparison of the model with experimental data; close match between the two is visible in a wide range of frequencies.

IV. CONCLUSION

This extended abstract presents a novel electrical circuit model of the human body. The model is intended for use in modeling and estimating signal loss in galvanic-mode body-coupled communication. Our future plans include deriving the nominal values of the model circuit's elements from properties of the human body such as body dimensions, BMI, body fat % and others.

ACKNOWLEDGMENTS

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