LETTER

Measuring the Transmission Characteristic of the Human Body in an Electrostatic-Coupling Intra Body Communication System Using a Square Test Stimulus

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SUMMARY This study employs a simple measurement methodology that is based on the de-convolution of a square test stimulus to measure the transmission characteristics of the human body channel in an electrostatic-coupling intra body communication system. A battery-powered square waveform generator was developed to mimic the electrostatic-coupling intra body communication system operating in the environment of the ground free. The measurement results are then confirmed using a reliable measuring method (single tone) and spectral analysis. The results demonstrate that the proposed measurement approach is valid for up to 32.5 MHz, providing a data rate of over 16 Mbps.

key words: *square waveform, deconvolution, intra-body communication*

1. Introduction

Intra-body commutation (IBC) is a wireless scheme in which the human body functions as a transmission medium [1], [2]. IBC systems are divided into two categories - *electrostatic coupling* (ESC) and *electromagnetic waveguide* (EMW) systems. The ESC system is a ground free system in which the environment provides the signal return path. An EMW system produces electromagnetic waves using two electrodes, and treats the human body as a waveguide through which to transmit signals.

Figure 1 schematically depicts a simplified circuit model of the ESC IBC system. The transmitter and receiver with different battery-powered sources employ the electrode of a positive terminal to connect on the human body, respectively, and the electrode of a negative terminal remains ground free. Where R_L denotes the load resistor of the receiver and the output resistor of the transmitter is sufficiently small to be neglected. Additionally, $\mathrm{Gnd_T}$ and $\mathrm{Gnd_R}$ are the ground of the transmitter and the receiver, respectively. Since $\mathrm{Gnd_T} \neq \mathrm{Gnd_R}$, a signal return path from the $\mathrm{Gnd_T}$ and $\mathrm{Gnd_R}$ through the environment to the earth ground is represented by using capacitors C_{GT} and C_{GR}. Accordingly, the capacitors C_{GT} and C_{GR} degrade the transmitted signal quality, especially for low frequency band signal. Here, assume

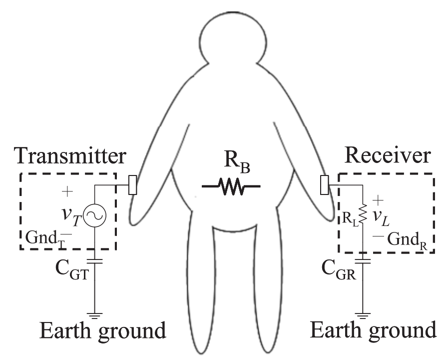

Fig. 1 Simplified circuit model of the ESC IBC system.

that $C_{GT} = C_{GR} = C_G$. Since the capacitor C_G [1] typically range between several hundreds fF and several pF, which are smaller by several hundred times than most of all the capacitors associated with the human body [3], [4], in which the human body can be replaced by a simplified equivalent impedance R_B [4]. Hence, the ESC IBC system becomes a high pass system with a transfer function shown in Eq. (1a) and a high pass 3 dB frequency $f_{h3\,dB}$ shown in Eq. (1b).

$$H(s) = \frac{V_L(s)}{V_T(s)} \cong \frac{R_L}{R_L + R_B} \times \frac{1}{1 + \dfrac{2}{sC_G(R_L + R_B)}} \quad (1a)$$

$$f_{h3\,dB} = \frac{1}{\pi C_G(R_L + R_B)}. \quad (1b)$$

Figure 2 depicts the simplified model of two measurement methods conventionally used to determine the channel characteristics of the ESC IBC system. Figure 2(a) shows a grounded measurement [5]–[7], in which both the instrument waveform generator and the measuring instruments share a common ground from the power line ground. Figure 2(b) illustrates an ungrounded measurement [8]–[11], in which the output of the instrument waveform generator is isolated from the power line ground by using a high series impedance (typically 1 MΩ in parallel 45 nF smaller than the reactance of the capacitor C_G in Fig. 1).

All of the above measuring approaches have a signal return path provided from the power line of the instrument. Such a signal return path is not present in the ESC IBC systems shown in Fig. 1. Therefore, certain model mapping must be done to transform the channel model with physical metal wire as the ground return loop to the one that uses the

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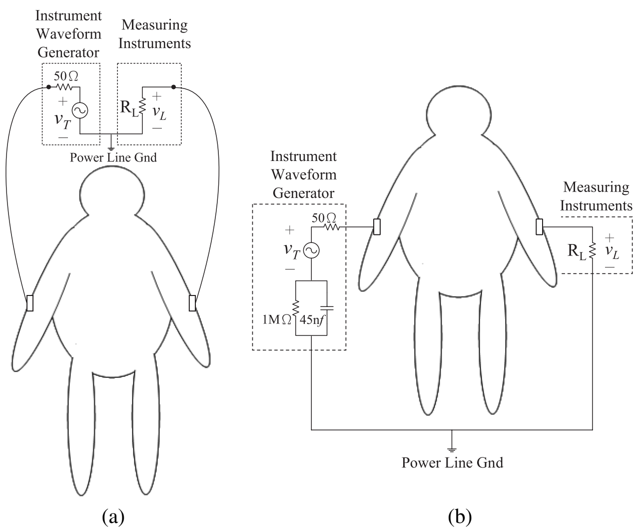

Fig. 2 (a) Grounded measurement. (b) Ungrounded measurement.

environment as the ground return loop.

This work develops the use of a square wave as the test stimulus to simplify the measuring procedure. A battery-powered square waveform generator is applied to generate the test stimulus that imitates the environment of the ESC IBC system. De-convolution skill measures channel transmission characteristic, obtaining both amplitude and phase responses. Twenty-two single-tone signals with fundamental harmonics with high SNR are employed to confirm the proposed measurement method. The current study utilizes the obtained and confirmed channel characteristic in a wideband IBC transmission system that directly transmits the baseband signal to simplify the circuit design and reduce the power consumption.

2. De-Convolution of Square Test Stimulus

Sinusoidal waveforms of various frequencies are conventionally adopted to measure the frequency response of a channel. However, generating numerous sinusoidal waveforms of various frequencies is difficult, especially in a ground-free environment. This study proposes the use of a square wave as the test signal because it contains multiple frequency components and is easy to implement. It employs de-convolution to extract the frequency response.

2.1 De-Convolution

In the frequency domain, the output is the product of the input and the transfer function. Given the system transfer function $H(s)$, the output is

$$V_O(s) = V_I(s) \times H(s). \tag{2}$$

In the time domain, the corresponding operation is the convolution operation.

$$v_o(t) = v_i(t) \otimes h(t). \tag{3}$$

To obtain $H(s)$, divided the output $V_O(s)$ by the input $V_I(s)$. Such an operation in the time domain is called de-convolution.

$$H(s) = \frac{V_O(s)}{V_I(s)}. \tag{4}$$

2.2 Square Test Stimulus

A square waveform comprises multiple frequency components or harmonics. It allows information to be obtained over a wider frequency range from a single measurement. A square waveform of amplitude A_0, period T_p, and a duty cycle x_d can be expressed as in Fourier series:

$$|V(n)| = x_d \times A_o \times \text{sinc}\,(n\pi x_d), \quad n = 1, 3, 5, 7, \ldots . \tag{5}$$

where $|V(n)|$ is the amplitude of the nth harmonic. For an ideal square wave with a 50% duty cycle, Eq. (5) is simplified as

$$|V(n)| = \frac{A_o}{n\pi}, \quad n = 1, 3, 5, 7 \ldots . \tag{6}$$

The human body is a noisy channel. To ensure that measurements are sufficiently accurate, the effect of noise must be taken into account. A human body can be modeled as an impulse response $h(t)$ with an additive noise source $\upsilon_{Bn}(t)$. The output signal is expressed as

$$\upsilon_o(t) = \upsilon_i(t) \otimes h(t) + \upsilon_{Bn}(t). \tag{7}$$

where $\upsilon_i(t)$ is the applied square wave. In frequency domain it is

$$V_O(n) = V_I(n)\,H(n) + V_{Bn}(n). \tag{8}$$

Here, where $V_{Bn}(n)$ is the noise amplitude at the frequency of the nth harmonic. The corresponding *signal-to-noise ratio* (SNR) is

$$SNR(n) = \frac{V_I(n)\,H(n)}{V_{Bn}(n)} = \frac{A_o/n\pi}{V_{Bn}(n)}. \tag{9}$$

For an acceptable SNR level and a known noise floor $V_{Bn}(n)$, the maximum number of applicable harmonics is

$$n = \frac{A_o/\pi}{SNR(n) \cdot V_{Bn}(n)}. \tag{10}$$

3. Experimental

Figure 3 depicts the experimental setup. A battery-powered square wave generator is placed on the left wrist (*Point 1*) and an Agilent 54382D oscilloscope is connected to either the left arm 40cm away (*Point 2*) or the right wrist 1.5 m away (*Point 3*). The measured human body sample is 1.75 m height and weights 70 kg. The stainless steel electrodes connect the human body to both the square wave generator and the oscilloscope. A load resistor switch is employed to change the resistance of the load resistor R_L from 50 Ω to 50 kΩ.

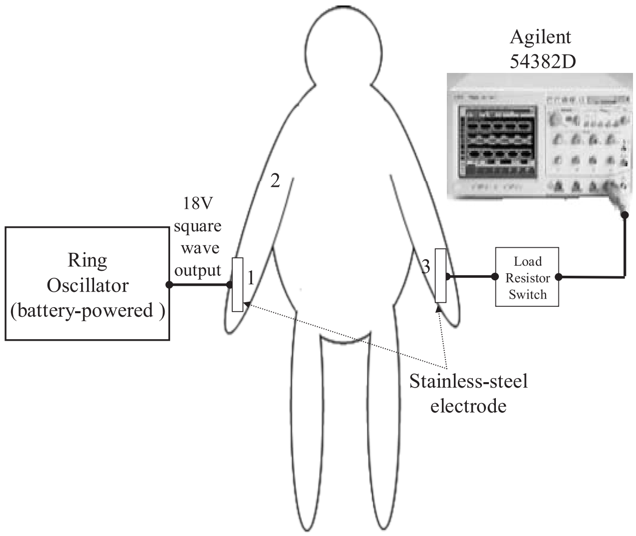

Fig. 3 Block diagram of the experimental setup.

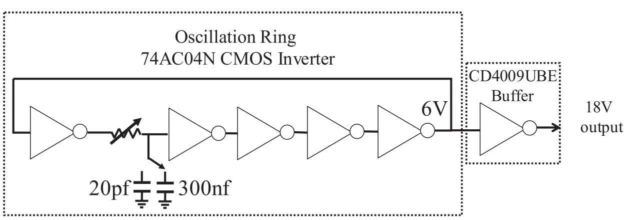

Fig. 4 Architecture of the battery-powered square wave generator.

Figure 4 presents the architecture of the proposed battery-powered square wave generator that is made from a ring oscillator that consists of 74AC04N inverters to imitate an ESC IBC system operating in a ground-free environment. It is buffered by CD4009UBE to produce 18 V square wave with a 46% duty cycle. A capacitor and a variable resistor are utilized to tune the oscillation frequency up to 22.5 MHz.

The experimental is performed in following four steps:

1. The square wave generator output is measured to obtain the stimulus signal $v_i(t)$.
2. The body output signal $v_o(t)$ is then measured.
3. The Matlab tool is employed to translate the measured signals from the time domain to the frequency domain.
4. The de-convolution of $V_O(s)$ by $V_I(s)$ is performed to yield $H(s)$ using Eq. (4).

In this study, for an expected SNR of 30 dB under the noise floor, −67 dB, of the human body, the maximum number of harmonics n calculated using Eq. (10) was 360. In the de-convolution of square waves, 20 kHz and 100 kHz square waves are utilized to reconstruct the channel response $H(s)$ from 20 kHz to 6.1 MHz with a frequency spacing of 40 kHz (applied harmonics $n = 305$) and from 6.1 MHz to 32.5 MHz with a frequency spacing of 200 kHz (the applied harmonics $n = 325$), respectively.

The investigation compares the results of the proposed method with those obtained using single tone test procedures. For single tone measurement, square waves of 22 frequencies between 400 kHz and 22.5 MHz were applied. The channel response is the output fundamental harmonic divided by the input fundamental harmonic. When only the fundamental harmonics are taken into account, the SNR is much higher and the measurements are more precise.

No current flowed through the tested human body when the test stimulus frequency was less than 1 kHz. The maximum power dissipated in the tested human body with a high-frequency test stimulus was 0.144 uW/kg. This experiment satisfies the limit on DC current of 50 μA (rms) at frequencies of up to 1 kHz, which was recommended by the International Electrotechnical Commission (IEC) [13] and the Association for the Advancement of Medical Instrumentation (AAMI) [14], and the basic limit on exposure of 0.08 W/kg, recommended by the World Health Organization (WHO) [15].

4. Results and Discussion

Figures 5 and 6 plot the verification results from the left wrist to the left arm and from the left wrist to the right wrist. The load resistor varies from 50 Ω to 50 kΩ. Table 1 summarizes $f_{h3\,dB}$ of various measurements. Measurement results reveal that a capacitor C_G exists in the measurement system in order to construct a signal return path from the battery-powered waveform generator and the measuring instrument to the earth ground respectively which mimics the ESC IBC system described in Sect. 1 and Fig. 1.

Comparing Fig. 5 and Fig. 6 reveals that the system gain measured from the left wrist to the left arm exceeds that from the left wrist to the right wrist. This finding implies that the body impedance R_B from the left wrist to the left arm is smaller than that from the left wrist to the right wrist. Hence, the body impedance R_B is proportional to the distance between the measurement points.

All cases both in Figs. 5, 6 and Table 1 indicate that the human body channel exhibits a high pass function whose $f_{h3\,dB}$ is inversely proportional to the load resistor R_L and the body impedance R_B. Experimental results are consistent with the description in Sect. 1 and Eq. (1). Hence, the R_L value can be manipulated to transform the transmission characteristic of the ESC IBC system.

The maximum variation among the verification results is less than 2 dB. The traditional measurement procedures are simplified by de-convolution of a square test stimulus. With the measured channel transmission characteristic, the implementation of baseband intra-body communication without modulation and demodulation scheme is feasible, and reduces hardware overhead and power consumption.

5. Conclusions

This study develops a simplified method for measuring the transmission characteristic of the ESC IBC system. The square test stimulus simplifies the measurement procedures

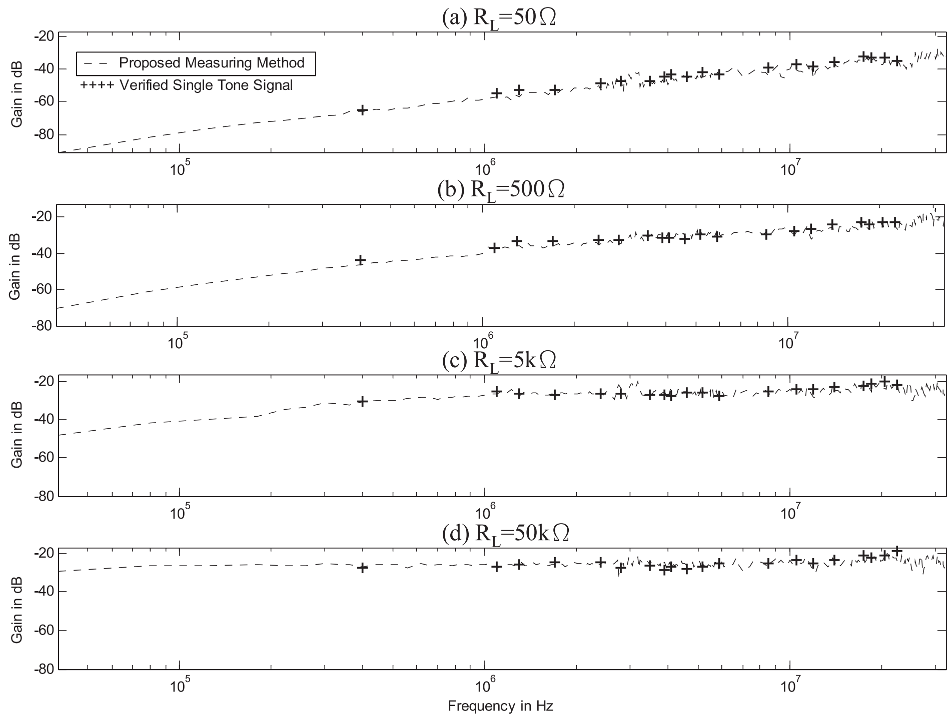

Fig. 5 Verification results from the left wrist to the left arm.

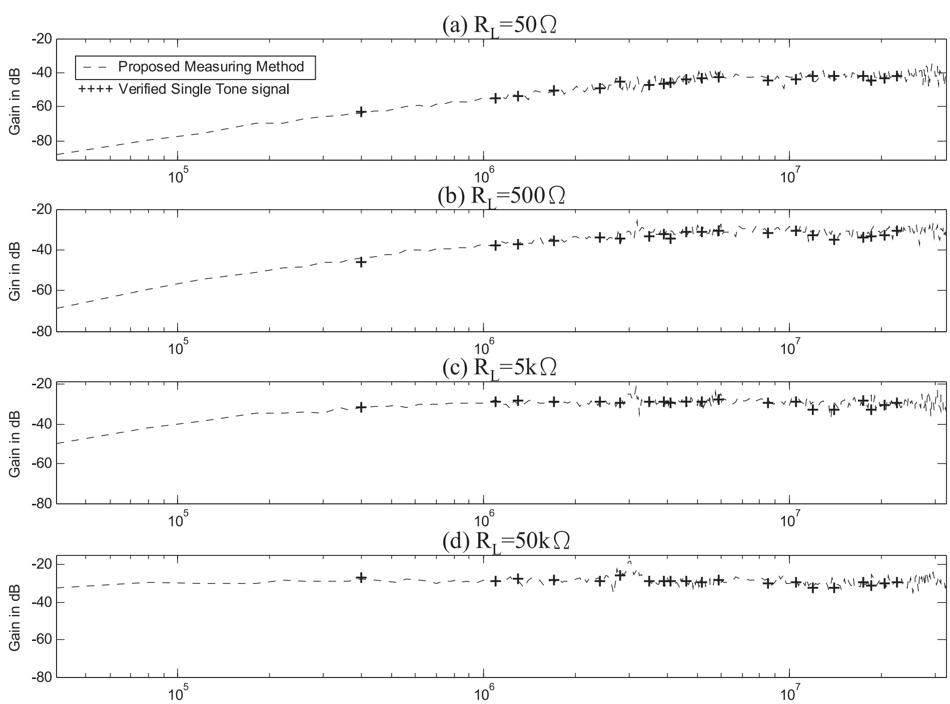

Fig. 6 Verification results from the left wrist to right wrist.

by as it constitutes numerous sinusoidal test stimuli. A battery-powered square waveform generator is employed to mimic the operating environment of the ESC IBC system. The proposed measuring method is verified using only the fundamentals of square waves from 400 kHz to 22.5 MHz with a load resistance from 50 Ω to 50 kΩ. The results show that the proposed model and measurement methodology are valid for 32.5 MHz and beyond, representing a data rate of over 16 Mbps.

Table 1 $f_{h3\,dB}$ of various measurements.

$R_L(\Omega)$	$f_{h3dB} \cong \frac{1}{\pi C_G (R_L + R_B)}$	
	From right wrist To	
	Right arm	Left wrist
50	30.3 MHz	28.2 MHz
500	5 MHz	3.7 MHz
5k	600 kHz	390 kHz
50k	70 kHz	40 kHz

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