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The effects of electrode impedance on receiver sensitivity in body channel communication

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A R T I C L E I N F O

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A B S T R A C T

The effects of the electrode interface on a receiver sensitivity in a body channel communication (BCC) are studied to clarify the characteristics of the electrode interface in the BCC, and revisit the noise and sensitivity analysis against the conventional method exploited in a radio frequency (RF) communication. First, the paper describes the noise characteristics in the electrode interface and examines the relationship between the noise and the contact impedance in the BCC frequency region. Then, we introduce a sensitivity analysis method dedicated to the BCC receiver by means of a receiver gain and an output noise spectral density. To verify the sensitivity analysis method, we implemented a direct conversion BCC receiver in 0.18 μm CMOS technology. By measuring the gain, output spectral density, and sensitivity of the receiver with respect to the various source impedance values, we found that the calculated value through the proposed analysis method agrees well with the theoretical value within 2.5 dB difference.

1. Introduction

Recent achievements in information and communication technology (ICT) enable the new paradigm of the Internet of Things (IoT), in which everything is interconnected through the World Wide Web [1]. Among the IoT applications, mobile healthcare is getting more and more attention due to the aging society, increment of medical expenses, and the necessity of managing chronic diseases which are the number one cause of death [2]. The key technology for the mobile healthcare is short-range connectivity among various physiological sensors and wearable devices carried by human bodies for continuous and ambulatory connection. Accordingly, the wireless body area network technology is an optimal network system around the human body, taking account of the human body effects on the overall system as well as low system cost and long battery lifetime requirements. As a representative short range communication technology (<2 m) beyond the wireless personal area network (WPAN), IEEE Standard 802.15.6: Wireless Body Area Networks or WBAN is composed of a common media access control layer (MAC), which supports three different physical layers (PHYs), which are narrowband (NB) PHY, ultra-wideband (UWB) PHY, and body channel communication (BCC) PHY. The three heterogeneous PHYs are due to the stringent requirements associated with WBAN transceivers such as energy efficiency, interference rejection, low cost, QoS scalability, network coexistence, safety, and so on. The NB PHY using frequency bands of ISM (industry-science-medical), MBAN (medical BAN; 2360–2400 MHz), and MICS (medical implant communication service; 402–405 MHz) is to provide highly reliable wireless communication while the UWB PHY in 3.75–4.25 GHz and 7.74–8.24 GHz frequency band is dedicated for a high data throughput. Another PHY is BCC, which utilizes the surface of the human body as a communication medium. It mainly focuses on energy-efficiency due to the low path loss thanks to the high conductivity of the human body. The low energy consumption of a BCC transceiver has been proven in a variety of previous implementations [3–6] and the standard document of IEEE 802.15.6 [7].

Nevertheless, compared to the radio frequency (RF) communications of NB and UWB PHY which propagate through an air channel with an antenna interface, the understanding of BCC has not been well established and considered, especially in the interface between the human body and electrodes, whereas the analysis of the body channel characteristics has been an active research area [8–12]. Since there has been a lack of comments on the electrical property of the electrode interface in previous research, and even in the standard document, 50-Ω antenna impedance is widely misapplied in the BCC transceiver without any consideration of the electrode interface. Such approaches are unsatisfactory to implement the BCC transceiver because they are not able to consider the electrical property of the electrode interface, such as its impedance and the noise characteristics.

While the previous researches on BCC were exploited a 50-Ω

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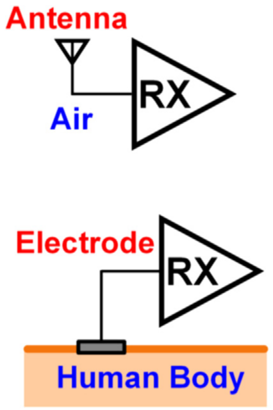

Fig. 1. Comparison between RF and BCC receivers.

resistive impedance as a conventional RF receiver assumes, we, for the first time, tackle the effects of the electrode interface on the BCC receiver, which is beneficial to the researchers seeking the way of designing and measuring the BCC transceiver using electrode interface. By describing the noise characteristics in the electrode interface, we propose a new sensitivity analysis equation, dedicated to the BCC receiver. The proposed method is verified through the CMOS chip fabrication, together with thorough measurements.

Fig. 1 shows a simple circuit diagram of the RF and BCC receiver to consider and understand the electrode interface of the BCC transceiver. The most notable difference from the fixed and 50-Ω matched antenna interface in RF is that the electrode interface in BCC receives the signal through variable or unfixed contact impedance (R_{cont}) between the electrode and the human body. Due to this uncertain source impedance, the noise characteristics in the electrode interface and their effects on the BCC receiver should be revisited against the conventional sensitivity analysis in the RF receiver. Therefore, in this paper, we provide an analysis of the noise characteristics in the electrode interface and their effects on the receiver sensitivity in BCC for the proper electrode utilization.

The rest of this paper is organized as follows. Section II describes the noise characteristics in electrode interface and examines how they are related to contact impedance in the BCC frequency band. In Section III, the noise circuit model is provided with the sensitivity and noise analysis for the BCC receiver. Based on the circuit model, the input referred noise in common source (CS) and common gate (CG) amplifiers are discussed further. To verify the receiver sensitivity analysis method with the measurement results, Section IV shows measurement setups and results through the silicon implemented BCC receiver with respect to the various source resistances. Finally, we conclude the paper in Section V.

2. Noise in electrode interface

The understanding of noise is important since it represents a lower limit to the magnitude of electrical signal that can be amplified by BCC receiver circuits without significant deterioration in signal quality. Since the existence of noise is basically due to the movement of the discrete electron charge, the electrode which interfaces the body with electrical currents is also associated with the fundamental electrical noise sources. In general, there are various sources of electronic noise, which are (1) shot noise associated with a direct-current flow, (2) thermal noise due to the random thermal motion of the electrons, and (3) flicker (1/f) noise associated with a flow of direct current with energy concentrated at low frequencies [13].

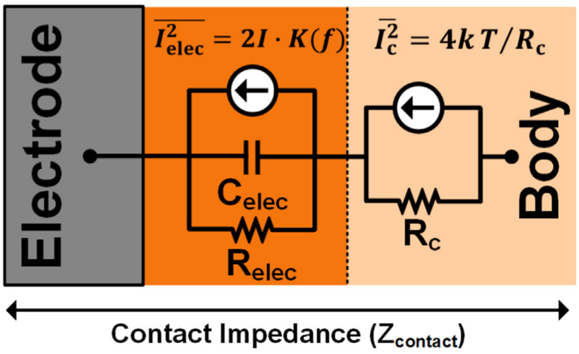

Fig. 2. Noise circuit model of the contact electrode.

According to the comprehensive study of noise processes in electrode interface [14], the noise circuit model of faradaic electrode interface (contact electrode) is shown in Fig. 2. The noise in electrode interface between the body and the electrode is originated from either thermal equilibrium noise created by body contact, or non-equilibrium excess noise produced by electrode contact. While the equilibrium noise ($\overline{I_{c}^{2}}=4kT/R_{c}$) shows the thermal noise from the contact resistance, the non-equilibrium noise ($\overline{I_{elec}^{2}}=2I\bullet K(f)$) represents the frequency dependent effect which is inversely proportional to the frequency at the electrode interface. The non-equilibrium noise is dominant over thermal noise in the low frequency region ($<$10 kHz) where most of physiological signals exist. On the other hand, as the frequency region of interest increases, not only the impedance constituted by R_{elec} and C_{elec} decreases but also the noise contribution from ($\overline{I_{elec}^{2}}$) starts to be negligible by means of its flicker noise circuit model of $K(f)$ in Fig. 2.

To find out the noise contributions from $\overline{I_{elec}^{2}}$ and $\overline{I_{c}^{2}}$ with respect to the frequencies, first, we measure the contact impedance ($Z_{contact}$) of the dry electrodes which is usually exploited in the BCC applications as shown in Fig. 3(a). At the same time, in Fig. 3(b), the noise power spectral density (PSD) of the electrodes is obtained to relate it with the contact impedance at the frequency band of the BCC. The dimension of the metal electrode is 3 cm by 2 cm, coated with the copper on the PCB board. The contact impedance is measured by constituting a closed current loop with current source (I_{o}), and get the voltage difference (V) between two identical electrodes [15]. We obtain two times the contact impedance as V divided by I_{o}, ignoring the tissue impedance (Z_{tissue}) of the human body. Fig. 3(a) shows the one time the contact impedance ($Z_{contact}$) versus a frequency up to 10 MHz. The contact impedance is almost resistive in the frequency range higher than 10 kHz.

The noise PSD of the electrodes measured by dynamic signal analyzer (SR 785) is shown in Fig. 3(b). The data is obtained from the differential signal between two closely spaced electrodes on the forearm at rest [16]. The noise floor of the dynamic signal analyzer is also added in the PSD graph by directly connecting two differential inputs. It is noteworthy that the PSD is nearly constant throughout the frequency range upper than 10 kHz, and we can roughly calculate the noise contribution from the thermal noise components generated by contact resistances. The loading effect can be ignored because the input impedance of the dynamic signal analyzer is larger than 1 MΩ. At the frequency higher than 10 kHz, the noise floor is −163 dBv/rootHz while the PSD in case that the inputs are connected with the electrodes is −161 dBV/rootHz. Therefore, the excessive thermal noise is −165 dBV/rootHz, which corresponds to the thermal noise generated by two 885 Ω resistors at the room temperature (T=300 K) as written in the