Mathematical Simulation of the Implant Capacitive Coupling Intra-Body Communication Based on Transfer Function Method

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Abstract. Implant intra-body communication (IBC) provides a data transmission method between sensor units which implanted in human body. Compared with the wearable sensors, the implantable devices have significant applications in biomedical monitoring system which is used for monitoring patient’s condition. In this paper, IBC among implanted sensors based on capacitive coupling has been proposed, and the circuit model of implant capacitive coupling IBC was proposed. Furthermore, the transfer function was derived from the model and the parameters in the circuit model were calculated. Finally, the simulations were carried out along different signal transmission distances and different heights to the ground based on the transfer function method. The results indicate that the mathematical simulation based on the proposed transfer function offers an important approach to analyse the characteristic of implant intra-body communication based on capacitive coupling.

1. Introduction
The technology of intra-body communication (IBC) offers novel data communication method in many fields [1], and it is particularly important for wearable or implantable medical devices to communicate with other sensor devices in biomedical monitoring system [2], as show in Fig.1. The medical implants have important applications in monitoring, diagnosis and treatment of many diseases. Compared with other short-distance communication technology, the technology of IBC has the advantages of high reliability, anti-interference and low power consumption [3,4].

Fig. 1 The biomedical monitoring based on IBC technology.

There are two main coupling techniques of IBC, which include galvanic coupling and capacitive coupling. In wearable IBC, it has been proved that the method of capacitive coupling has the advantages of lower attenuation and power consumption. In this paper, IBC among implantable sensors based on capacitive coupling has been proposed and a circuit model of it was established.
according to its communication mechanisms. Furthermore, the transfer function based on the circuit model was derived to describe the mathematical relationship among the signal transmission paths within the human body, transmitter, receiver, electrodes, etc. Finally, the simulation of implant capacitive coupling IBC was achieved by using the developed transfer functions and the parameter that we obtained.

2. Transfer function

2.1 Circuit model of implant capacitive coupling IBC

In implant capacitive coupling intra-body communication, the signal is coupled into the human body at the transmitter, and is detected at the receiver, as shown in Fig.2(a). The electrode of implant capacitive coupling IBC used in our research consists of a signal electrode and a ground electrode. The signal electrode is penetrated in the insulation layer and contacted the muscle layer indirectly in order to enhance the quality of signal. The ground electrode is a spherical shell in order to strengthen the signal which is transmitted. The insulating material around the ground electrode makes it isolate from the muscle and reduces the coupling with the signal electrode though it, which can enhance the signal transmission quality and the sensitivity of detection.

According to Fig.2(a), the circuit model of implant intra-body communication can be described as shown in Fig.2(b). In Fig.2(b), $Z_{k1}$ and $Z_{k2}$ are the impedance between the ground electrodes and human body. The transverse impedances of two signal electrodes are represented as $Z_{b1}$ and $Z_{b2}$ the impedances of two insulating shells are represented as $Z_{b1}$ and $Z_{b2}$. $C_{g1}$ and $C_{g2}$ represent the coupling capacitance between the coupling path of the electrodes and the external ground. $Z_{a1}$ and $Z_{a2}$ are the impedance of additional coupling return path between ground electrodes and signal electrodes. In the circuit model, $V_{in}$ represents the output voltage of the transmitting device, and $V_{out}$ represents the output voltage of the receiving device. In addition, the current of circuit mesh is $i_c$.

And then, a matrix form can be obtained based on Eq.1, which is calculated as:

$$
\begin{bmatrix}
-R_0 + Z_{a1} & -Z_{a1} \\
-Z_{a1} & -Z_{a1} + C_{g1} + C_{g2} + Z_{b1} + Z_{b2} + Z_{a1} + Z_{a2} \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3 \\
i_4
\end{bmatrix}
=
\begin{bmatrix}
V_{in} \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 \\
-1 & 1 & 0 & 0 \\
-1 & -1 & 1 & 0 \\
-1 & -1 & -1 & 1
\end{bmatrix}
\begin{bmatrix}
i_1 \\
i_2 \\
i_3 \\
i_4
\end{bmatrix}
$$

(2)
Finally, the attenuation of the implant intra-body communication based on capacitive coupling can be obtained by

\[
\text{Attenuation} = 20 \log_{10} \left( \frac{V_{\text{out}}}{V_{\text{in}}} \right) = 20 \log_{10} \left( \frac{Z_{\text{in}}}{Z_{\text{out}}} \right)
\]  

(3)

3. Parameters

The human body consists of head, torso, leg and arm, so \( Z_{\text{bk}} \) is used to represent the transverse impedance according to the “\( k \)” part of the body. In order to calculate \( Z_{\text{bk}} \), it is assumed that the impedance of human body equivalents to different tissue layers in parallel.

\[
Z_{\text{bk}} = \frac{1}{\sum_{k=1}^{5} \frac{1}{Z_{k}}} = \frac{1}{\sum_{k=1}^{5} \frac{1}{R_{k}}} = \frac{1}{\sum_{k=1}^{5} \sigma \epsilon_{k} S_{k} + j \omega \epsilon_{0} \sum_{k=1}^{5} \sigma_{k} S_{k}}
\]  

(4)

where \( L_{k} \) is the actual distance of signaling pathway, \( S_{k} \) is the area of human body cross-section, \( \epsilon_{0} \) is relative permittivity and \( \sigma_{0} \) is conductivity. According to the Eq.4, the transverse impedance corresponding to the different signaling pathway and signal frequencies can be calculated.

The impedance from the transmitter (receiver) to human tissue through the insulating material can be abstracted as the impedance between coaxial capacitor. The capacitance \( C_{k} \) can be obtained by Eq.5.

\[
C_{k} = (\ln \frac{R_{1}}{R_{2}})^{-1} \cdot \frac{2 \pi \epsilon_{0} \epsilon_{r} L}{(\sigma A)^{2}}
\]  

(5)

where \( \epsilon_{r} \) is relative permittivity of insulating material, \( R_{1} \) and \( R_{2} \) are the radius of ground electrode and insulating material respectively. Furthermore, \( R_{1} \) can be simply obtained by \( R_{1} = L \cdot (\sigma A)^{4} \), where \( L \) expresses the thickness of insulating material, \( A \) expresses the superficial area. In addition, the impedance of additional coupling return path between ground electrodes and signal electrodes can also be calculated by similar method.

There are no accurate calculation or measurement methods of the capacitance to the ground, which is important to the transmission of signal in implant IBC[5]. The calculation method of the capacitance to ground will be analyzed to achieve the simulation though transfer function method.

Since the value of the capacitance will increase when any conductive object is closed to the human body which can provide a coupling path, the capacitance is calculated with the assumption that a person stands in an open space. In addition, the coupling capacitances between the transceiver grounds and the human body are highly affected by the body posture, therefore, the body is set to a static state here. The capacitance between the human body and the external ground can be defined as

\[
C_{\text{ground}} = C_{\text{proximity}} + C_{\text{infinity}}
\]  

(6)

In Eq.6, \( C_{\text{proximity}} \) is the capacitance that caused by the proximity influence of the earth and \( C_{\text{infinity}} \) is the capacitance of the object which is infinite distance from the external earth.

4. Simulations

Due to the inconvenience and inflexibility of the in vivo measurement intra human body, we simulate the attenuation of the signal transmission based on the electrical properties and dimensions of human body. The electrode is implanted in human arm and the radius of the arm is 5cm. According Eq.3, Eq.4, Eq.5 and Eq.6, the simulation can be achieved. The curves of signal attenuation at different distance (15 cm, 25 cm and 35 cm) are shown in Fig.3(a), and the height of arm to the ground is 50 cm. It can be seen from Fig.3(a) that the attenuation decreased when the frequency increases from 200kHz to 4MHz, and at 4MHz~10MHz the attenuation has little change. What’s more, the distance has comparatively less effect on the attenuation curve of the implant communication based on capacitive coupling. However, when the frequency beyond 10MHz, the attenuation becomes higher, which is caused by that electrical properties of human tissues are variable with different frequencies.

Furthermore, we analyze the influence of different height to the ground and the simulation at height 0~1m is carried out when the frequency is 5MHz, which is shown in Fig.3(b). The attenuation
becomes lower as the height increases, while the variation decrease as the height increases. According to the Fig.3(b), the attenuation of the signal transmission has a sharp change when the height is less than 0.1 m. On the other hand, the increase of the height has less influence on the attenuation of the signal transmission when the height is higher than 0.4 m. It can be explained that the capacitance between the human body and the ground has little changed when the height higher than 0.4 m.

5. Conclusions
In our paper, an implant capacitive coupling intra-body communication is proposed. We derived the transfer function based on the circuit model and deduced the parameters in proposed circuit model. Furthermore, the simulations of different conditions were achieved using transfer function method. From our research, we get that the signal attenuations of implant capacitive coupling intra-body communication basically unchanged when the distance of the transmission path increases or decreases. On the other hand, the attenuation of implant communication based on capacitive coupling becomes lower as the height increases, and it has little change when the height is over 0.4 m. Our research shows that the technology of implant capacitive coupling IBC is more suitable in those applications where higher frequencies and longer body distances are required, and it will have good performances and application prospects in biomedical field.

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