

Propagation Characteristics of Human Body Communication in Brain-Controlled Functional Electrical Stimulation

Jingzhen Li, Yuhang Liu, Zedong Nie
Shenzhen Institutes of Advanced Technology, Chinese Academy of Science
Shenzhen 518055, China
zd.nie@siat.ac.cn

ABSTRACT

Human body communication (HBC), which uses the human body as a propagation medium, is a promising communication technology in brain-controlled functional electrical stimulation (FES). In order to study the propagation characteristics of HBC channel between intra-brain and body implant, a 45kg pig was employed as an experimental subject in this paper. The channel characteristics of amplitude and group delay were investigated by vector network analyzer (VNA) over different frequencies (from 0.3MHz to 200MHz). A battery powered transmitter and receiver were adopted to study the influence of electrode size and type. Experimental results show that the optimal HBC frequency for brain-controlled FES applications is from 5MHz to 50MHz. Electrode size have little impact on signal transmission in body channel. In addition, signal transmission is insensitive with the electrode type.

Categories and Subject Descriptors

B.4.2 [INPUT/OUTPUT AND DATA COMMUNICATIONS]:
Input / Output Devices -Channels and controllers

C.2.1 [COMPUTER-COMMUNICATION NETWORKS]:
Network Architecture and Design-Wireless communication

General Terms

Measurement, Performance, Design, Experimentation, Human Factors, Verification

Keywords

Human body communication, Propagation characteristics, Channel, Electrode, Brain-controlled functional electrical stimulation

1. INTRODUCTION

It is reported that more than 130,000 people each year suffer from spinal cord injury all over the world [1]. Spinal cord injury leads to the paralysis of limbs, which has a great impact on daily

activities. For paralyzed patients, a traditional rehabilitation method is functional electrical stimulation (FES), which attempts to restore motor behaviors to paralyzed limbs by electrically stimulating nerves or muscles [2, 3]. However, FES is restricted to several grasp patterns by using pre-programmed stimulus. Moreover, the stimulus is not controlled by human brain. Recently, brain-controlled FES, which adopts the brain-neural signals to control electrical stimulus, is regarded as a potential treatment to restore the goal-directed movement of paralyzed limbs [4]. Several primary investigations of brain-controlled FES were conducted in [5, 6]. Neural signals for movement were firstly acquired from the electrodes that were implanted in intra-brain. Then the neural signals were converted to stimulator commands, and then the stimulator commands were transmitted to stimulator, which was implanted in the forearm of experimental subject. At last, stimulator generated electrical stimulus to restore the movement of paralyzed arm. In aforementioned works, a robust, low power and security communication between intra-brain and body implant plays an important role in brain-controlled FES. The traditional wire communication and wireless communication technologies would be considered in brain-controlled FES. However, wire communication is inconvenient to wear. Moreover, wire communication involves a high risk of infection. Wireless communications, such as Bluetooth, Zigbee and other commercial wireless communications, have the risk of inter-network interference and unauthorized interception of information due to the communication distance is up to dozens of meters [7]. In addition, the high power consumption and low data rate are also the limitations when the traditional wireless communications are applied in brain-controlled FES [8].

Human body communication (HBC), which uses the human body as a propagation medium, is a prospective solution for body area networks [9, 10]. Compared with other traditional wireless communications, HBC has the advantage of low power consumption, high efficiency and high data rate [11, 12]. Furthermore, HBC is motion insensitive and environmental independent [13]. Therefore, HBC is regarded as a promising communication in brain-controlled FES. However, thus far, few papers have tackled the propagation characteristics of HBC channel between intra-brain and body implant.

In this paper, HBC is proposed as a communication technology for brain-controlled FES. We investigated the propagation characteristics of the channel between intra-brain and body implant through VNA. The influence of electrode size and electrode type to signal transmission in 45MHz had also been demonstrated by a battery powered transmitter and receiver. This

paper is structured into four sections. Section 2 is the experimental setup about HBC in a Bama pig. Section 3 explains the measurement results. The final section is conclusion.

2. EXPERIMENTAL SETUP

In order to analyze the propagation characteristics of HBC channels, experimental measurement is conducted. A liquid phantom is difficult to represent the electrical properties of human's tissue because the liquid phantom is a homogeneous medium. Considering the electrical properties of mammal's tissue and geometric shape are similar to human, a Bama pig, weighting 45kg, was used as an experimental subject in our investigation. All surgical and experimental procedures have been approved by the Institutional Animal Care and Use Committee (IACUC, No.S-20150125-01). The experimental equipments included VNA, transmitter, receiver and electrodes.

2.1 Vector Network Analyzer

Vector network analyzer (VNA, Agilent E5061A) is used to analyze the amplitude and group delay of different channels. The frequency sweep range is set from 0.3MHz to 200MHz. The transmitting electrode and receiving electrode are connected to the Port 1 and Port 2 of VNA, respectively.

2.2 Transmitter and Receiver

A battery powered transmitter and receiver, which are designed by our team, are adopted to investigate the influence of electrode size and type to signal transmission in particular channel and frequency. The transmitter incorporates a direct digital synthesizer and a microprocessor. The transmitter is able to output a sine wave at 45MHz. The output power of sine wave is 0 dBm. The receiver consists of a 45MHz band pass crystal filter, a logarithmic power detector and a microprocessor. There is a 10-bit analog-to-digital converter integrates in the microprocessor. The measurement data are analog-to-digital converted and stored to secure digital card for off-line analysis. Fig.1 illustrates the calibrated relationship between the input power (dBm) and digital output (10-bit A/D converter).

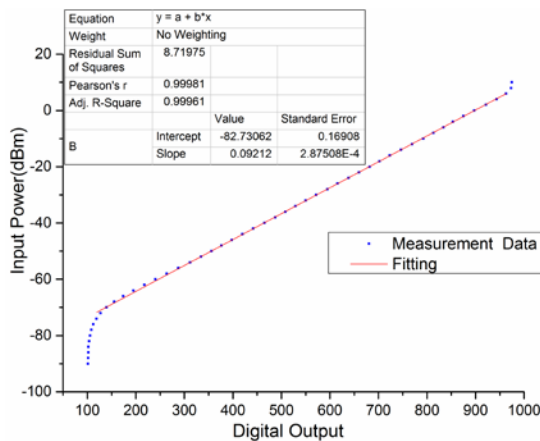


Figure 1. Calibrated relationship between the input power and digital output from 10-bit A/D converter.

2.3 Electrode

Electrodes are adopted to achieve signal transmitting and receiving. Two types of electrodes are utilized in this paper. The conducting electrode is made of copper and coaxial cable. The insulated electrode, whose the surface is insulated, is made of

copper, coaxial cable and polyvinyl chloride (PVC) tape. Two sizes of conducting electrodes are also used in the experiment. Fig.2 demonstrates the pictures of electrode.

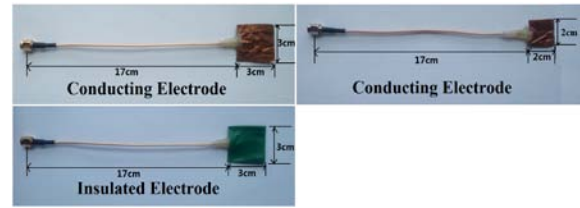


Figure 2. The pictures of electrode.

2.4 Experiment Setup

At the beginning of experiment, a pig was practiced euthanasia via anesthetic injection. Then an electrode was implanted in the pig's intra-brain by surgical persons after the skull was opened. Some positions of pig's body were gashed through T cut method. The incisions were sutured after the electrodes were implanted in the incisions. Three experiments were set up in the paper. All experiments were performed in an animal anatomy laboratory. The pig was placed on the test-bed and the electrodes were implanted in pig's intra-brain and body.

As Fig.3 showed, in order to investigate the propagation characteristics of different channels, four channels were measured by VNA in experiment I. Specifically, the transmitting electrode was implanted in pig's intra-brain. The receiving electrodes were implant in pig's back, belly, left foreleg and left hind leg, respectively. The amplitude and group delay of different channels were considered in our investigation. Snapshots of data (1,601) were acquired from VNA in every experiment when the frequency sweep range was set from 0.3MHz to 200MHz.

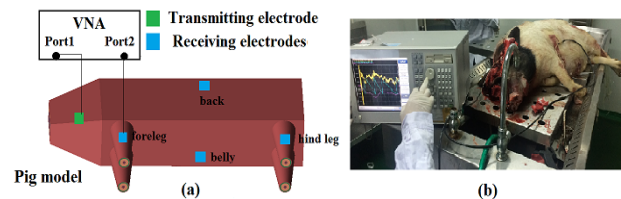


Figure 3. (a)Diagram of experiment I ; (b)Measurement of amplitude and group delay via VNA.

In experiment II, in order to analyze the influence of electrode size to signal transmission, the 2cm×2cm and 3cm×3cm electrodes were utilized. Fig.4 is the diagram of experimental setup and experimental process. The power variation of the channel between the pig's intra-brain and left foreleg was investigated when the transmitter (TX) and receiver (RX) were connected different sizes of electrodes. Four comparative experiments were conducted and 2,000 valid data were collected in each experiment.

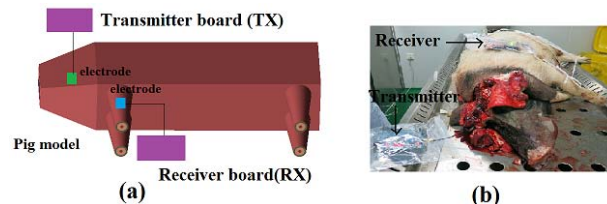


Figure 4. (a) Diagram of experiment II ; (b) Measurement of different electrode size via transmitter and receiver.

In experiment III, the influence of electrode type to signal transmission was considered via the battery powered transmitter and receiver. The conducting electrode and insulated electrode were adopted in this experiment. Transmitter (TX) and receiver (RX) were connected different types of electrodes. The channel is from pig's intra-brain to belly. The process of experiment III is similar to experiment II. Four comparative experiments were executed and 2,000 valid data were collected in each experiment.

The specifications of all the experiments that we have been conducted are as the table I listed.

Table 1. Experiments description

	Electrode Size	Electrode Type	Experimental Description
EXP . I	TX:3cm×3cm RX:3cm×3cm	TX: conducting electrode RX: conducting electrode	Research propagation characteristics of four channels via the VNA from 0.3 MHz to 200MHz
EXP . II	TX: various RX: various	TX: conducting electrode RX: conducting electrode	Research the influence of electrode size via transmitter and receiver at 45 MHz
EXP . III	TX:3cm×3cm RX:3cm×3cm	TX: various RX: various	Research the influence of electrode type via transmitter and receiver at 45 MHz

3. RESULTS AND DISCUSSION

3.1 Propagation Characteristic of Different Channels

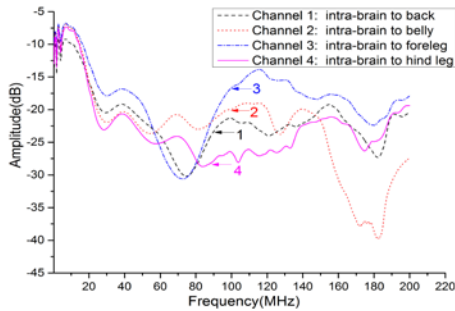


Figure 5. The characteristics of amplitude in four channels.

The amplitude of channel plays an important role in wireless communication. It determines the transmitter power, receiver sensitivity and other parameters. It is favorable to reduce the complexity of transceiver if the attenuation of amplitude is small and not related to channels. Fig.5 illustrates the propagation characteristics of amplitude (in dB) in different channels, while the frequency sweep range of VNA is from 0.3MHz to 200MHz. The amplitude of all channels is over -8dB when frequency is 10MHz. The channels have a low pass characteristic. With the increase of frequency, the amplitude of channel 1 is fading. Other channels also have a similar fading. Meanwhile, all four channels have a peak value of amplitude at 40MHz. In addition, the trend

of amplitude is independent of body channels when frequency is below 50MHz. However, the fluctuations of amplitude in four channels are different when the frequency is over 50MHz. The amplitude of channel 1 and channel 3 is the smallest when the frequency is about 70MHz. For channel 2 and channel 4, the minimum value of amplitude is -40dB at 180MHz and -28dB at 85MHz, respectively. Therefore, the channel has a great impact on signal amplitude if the frequency is over 50MHz.

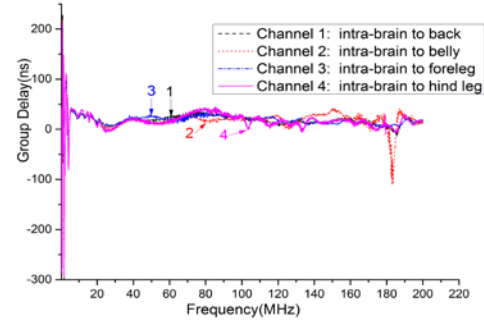


Figure 6. The characteristics of group delay in four channels.

Group delay reflects the delay time between output envelopes and input envelopes. It is an index to evaluate the phase nonlinearity and wave distortion. The transmittal signal has least distortion if group delay is constant. Fig.6 demonstrates the propagation characteristics of group delay (in ns) in different channels. The curves of group delay in all four channels are similar when the frequency sweep range is from 0.3MHz to 180MHz. Thus, the group delay is almost independent of body channels. The fluctuation range of each channel is approximately from -300ns to 200ns when frequency is below 0.5MHz. With the increase of frequency, the fluctuations of group delay in all four channels have weakened. The fluctuation range of channel 1 is between -5ns and 38ns when the frequency is from 5MHz to 180MHz. Other channels also have the similar fluctuation range. Therefore, the curves of group delay at all four channels are relatively smooth. In other word, the group delay of channels is more stable when the frequency is from 5MHz to 180MHz.

According to the measurements of amplitude and group delay, the frequency from 5MHz to 50MHz is supposed to be the optimal frequency in HBC channels. The trend of amplitude is independent of channels. Meanwhile, the group delay of channels is stable.

3.2 Influence of Electrode Size

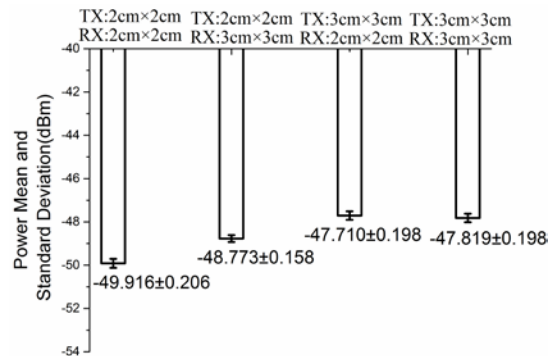


Figure 7. The influence of electrode size.

Fig.7 describes the influence of electrode size to signal transmission. Typically, the received signal power are -45.063 dBm, -46.425dBm, -47.710dBm and -46.336dBm, respectively, when the transmitter (TX) and receiver (RX) are connected different sizes of electrodes. Furthermore, the power standard deviations are 0.206dB, 0.158dB, 0.198dB and 0.198dB in all four comparative experiments. Experimental results show that electrode size has little impact on signal transmission. The electrode size plays an important role in the miniaturization of HBC system. Therefore, a promising method to achieve miniaturization is adopting small size electrode due to the independence of electrode size to signal transmission.

3.3 Influence of Electrode Type

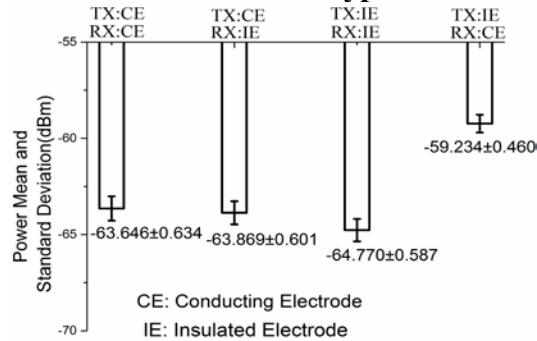


Figure 8. The influence of electrode type.

Fig.8 illustrates the influence of electrode type to signal transmission. The received signal power is -59.234dBm when transmitter (TX) is connected insulated electrode and receiver (RX) is connected conducting electrode in the fourth experiment. In addition, the received signal power of other experiments is approximately -64dBm. Furthermore, the power standard deviation is similar in all four comparative experiments. Therefore, overall, signal transmission is insensitive with electrode type. From the point of biological compatibility, the material of electrode is flexible because the electrode type has little impact on signal transmission.

4. CONCLUSION

In this paper, the propagation characteristics of channel between pig's intra-brain and body implant were investigated. The frequency from 5MHz to 50MHz is supposed to be the optimal frequency in HBC channels. The trend of amplitude is independent of channels when frequency is from 5MHz to 50MHz. Meanwhile, the group delay of channels is stable. Experimental results show that electrode size and electrode type have little impact on signal transmission. The independent of electrode size is helpful to achieve the miniaturization of HBC system. The insensitivity of electrode type indicates that the choice of electrode material in HBC is flexible. Overall, from the preliminary results, HBC is appropriate for the communication in brain-controlled FES. In the next phase, we will demonstrate statistical significance of HBC channels through a large of experiments.

5. ACKNOWLEDGMENTS

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