Department of Human and Engineered Environmental Studies
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Master's Thesis

Analysis and evaluation of transmission characteristic of intra-person human body communication by the number of contact electrodes of transmitter and receiver

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Contents

Chapter 1 Introduction

1.1 Background

With the increasing population of the aging people, the needs of health applications such as health care system and health monitoring system are growing. The wearable devices and the wireless communication which connecting the devices are necessary in order to realize the real-time health monitoring. The wireless network around the human body is called Wireless Body Area Networks (WBANs).

There are several types of WBANs for short transmission distance. For example, Wireless-Lan, Bluetooth, Zigbee and so on. The transmission frequency of Wireless-Lan and Bluetooth is 2.4 GHz, and the one of Zigbee is 860 MHz to 2483 MHz. The frequency of these communication is very high. As the frequency increases, more energy will be leaked into the environment[1].In addition, the human body itself will be the obstruction of the communication when transmitting the signal at high frequency[2]. Therefore, the wireless communication at lower frequency is needed in order to transmit the signal efficiently.

IEEE 802.15.6 supports three different frequency bands such as Ultra Wide Band (UWB), Narrow Band (NB) and Human Body Communication (HBC)[3]. The frequency for NB is 402 MHz to 2400 MHz, and the one for UWB is 3 to 5 GHz or 6 to 10 GHz[4]. Among them, the frequency of HBC is below 100 MHz, which is relatively low. Moreover, the human body is a better dielectric and conductor than the air. Thus, the high power consumption problem can be solved in HBC. It is also verified that the HBC device needs less than 1/8 power compared with a HC-06 Bluetooth module when transmitting at the same rate[5].

Besides the advantage like low power consumption, HBC is catching people’s eye because of its high security and intuitive interaction. The most significant feature of HBC is that human body is required for transmission. So the user needs to wear, touch or being close to the devices when sending or receiving the information by HBC, which makes HBC not only secret and covert but also brief and clear.

Based on the advantages above, HBC can be considered as one of the most promising energy-efficient candidates for short-distance communication. Further study of HBC is expected.

1.2 Introduction and the application of HBC

HBC is first introduced by Zimmerman in 1995[6]. Different from other wireless communication methods, HBC utilizes the human body as part of the transmission medium by attaching the flat electrodes to the skin. Basically, HBC can be divided into two types according to the transmission mechanisms. One is galvanic coupling human body communication (GC-HBC) and the other is capacitive coupling human body communication (CC-HBC).

In GC-HBC, the frequency is below several hundred kHz. The current running at the surface of the skin help transmit the signal. Therefore, one limitation of GC-HBC is that both of the transmitter and the receiver must be connected to the user.

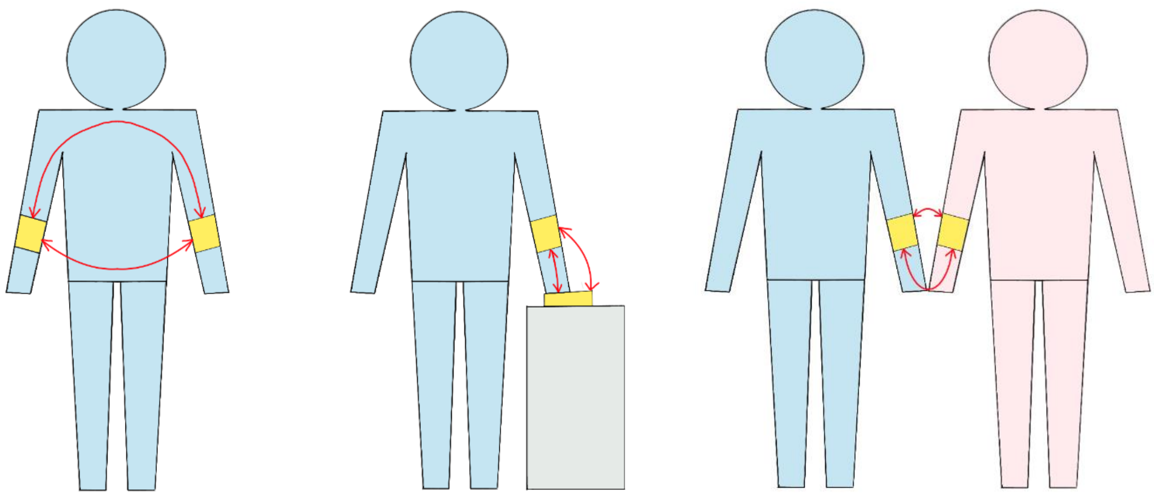
In CC-HBC, the frequency is around hundreds of kHz to dozens of MHz. The weak current running through the body and the capacitive coupling between the human body and the devices help transmit the signal. For this reason, when the user is not wearing the devices, the communication can still be successful if he is close to the devices. In addition, CC-HBC has higher transmission data rate and channel gain compared to GC-HBC[4]. Thus, this study places emphasis on the CC-HBC.

On the other hand, HBC can be divided into three types according to the application, as shown in Fig.1.1:

(a) HBC among several devices worn on one person

(b) HBC between the user and the stationary device

(c) HBC between two or several users



(a) **(b)** **(c)**

Fig. 1.1 Three forms of Human Body Communication divided by application

Intra-person HBC (a) is always applied to remote healthcare monitoring for pulse, blood pressure, blood glucose level and so on. HBC between man and stationary device (b) is widely used in keyless entry, cashless payment, position monitoring and so on. HBC between users (c) is utilized in exchanging the information. For example, changing the e-business card or sharing the music when shaking the hands.

This study investigated the intra-person HBC (a) rather than other two types of HBC due to the rising demands for healthcare monitoring.

1.3 Purpose of this research

The research related to HBC spans 2 decades, and the researchers have studied HBC from many aspects. For example, Jiasong Mu et al. provided HBC with higher energy efficiency and reliability of the data transmission for both static and mobile scenarios by adding minimum hop count between the transmitter and the receiver[7]. For the maximization of the received signal power, Arai et al. studied the impedance matching of human body communication receiver[8].

Except for improving the qualities such as low power consumption and reliable transmission, the application for Intra-person HBC is studied as well. Fukuro Koshiji et al. found that frequency shift key modulation of 10.7 MHz could stably transmit the heartbeat data[9]. Yueming Gao et al. investigated the human motion detection of the left arm by sensors work in HBC[10].

However, HBC is still not applied to our daily life. It is partly because that a lot of factors need to be considered when designing the wearing devices for application such as the size, the material, the electrode shape and so on. Maria Amparo Callejon et al. found that bigger copper ground receiver electrode worked better for intra-person HBC[11]. Jingna Mao et al. found that ground electrodes of the wearable devices with more sides helped reduce the channel loss when transmitting the signal through the arm[12].

Although some conclusions about the electrodes were given, the researchers carried out the experiments with different electrode contacting conditions. Furthermore, Hachisuka K. et al. found that the gain would change due to the assignment of the electrodes of the receiver and the transmitter[13]. Therefore, the study on the influence of the contacting condition of the electrodes of the transmitter and the receiver is necessary.

Additionally, when putting HBC into practice, the devices' wearing position, the users' posture and the anti-noise ability must be taken into account.

As for the wearing position, Nie Zedong et al. attached the one-electrode transmitter and placed one-electrode receiver at eight positions including the front and the back of the body and found that the HBC is almost insensitive to the motions at 45 MHz by experiment[14].

There are some previous works about the posture, for example, J. H. Hwang et al. found that the channel for HBC had a dynamic signal loss, which had a wide variation depending on body posture, composition of dielectric materials, and the coupling condition on the return path[15]. Taewook Kang et al. found that the channel attenuation would decrease as the ground electrode of the device moved closer to the earth ground when using the one-electrode transmitter and the one-electrode receiver at various frequency[16]. Yoshifumi Nishida et al. found that users' posture would cause the different distribution of the electric field and then led to the results that the coupling between the transmitter and the receiver became strong or weak when using the two-electrode transmitter and one-electrode receiver at 20 MHz by experiment[17].

Regarding of the anti-noise ability, Takayuki Ogasawara et al. found that when there is metal object close to the user, the transmission did not have significant degradation when using the one-electrode transmitter from 100 kHz to 20 MHz by experiment[18]. K.-I. Oh et al. found that the sensed digital noise at the electrode could be larger than the transmitted signal if the TX was attached far away from the RX on human body, where it interfered with the restoring the transmitted signal and thus degraded the performance of the human body communication system[19].

Although a lot of researchers considered the practical situations, their results could not be compared because they did the experiment at different frequency by devices with different electrode contacting conditions, and in different environment as well. The channel loss of HBC is strongly dependent on the termination impedance of the receiver end[20]. In the meanwhile, the characteristics of HBC channel strongly depend on the environment and the situation[18]. Therefore, studying the influence of the electrode contacting conditions of the devices in practical use such as changing the posture, wearing position and the anti-noise ability is of great significance.

In this paper, the effect of the devices' electrode contacting condition due to the signal attenuation will be discussed. The devices' electrode contacting condition points to the wearable transmitter and receiver with one-electrode or two-electrode contacting straightly with the human body. Considering the practical application for intra-person HBC, three situations: doing various postures, wearing the receiver at different parts of the body and using HBC with the noise in the environment will be analyzed through both the simulation and the experiment at 21 MHz.

1.4 Organization of this thesis

This paper is organized by four chapters as follows:

Chapter 1 introduces the background of HBC and describes the purpose of this research.

Chapter 2 simulates different situations such as swinging the arm, standing, walking and so on to find out how the devices' electrode contacting condition will affect the transmission according to the signal attenuation. Then discovers the reasons of the results above.

Chapter 3 carries out the experiment with the wearable devices to verify how the electrode contacting condition will influence the transmission according to the signal attenuation.

Chapter 4 concludes the works in this research and discusses issues for future research.

This paper is composed of the above contents. The experiments in this paper were performed with the approval of the Ethics Review Committee of Tokyo University.

Chapter 2 Transmitter and receiver used in simulation and experiment

2.1 Purpose of studying the number of contacting electrodes of the devices

The electrode contacting condition of the transmitter and the receiver affects the transmission of the signal. In chapter 1, some studies focused on the devices' conditions such as shape, material, size and so on. However, the number of the contacting electrodes has not been studied.

The capacitive coupling among the transmitter, receiver, human body and the environment changes as the number of the contacting electrodes changes. Therefore, it is necessary to find out the transmission characteristic of the transmitter and receiver with one and two electrodes contacting to the human body.

In this chapter, transmitter and receiver used in simulation and experiment are introduced respectively.

2.2 One-electrode transmitter and two-electrode transmitter used for intra-person HBC

One-electrode transmitter and two-electrode transmitter used in simulation and experiment are described in this section.

2.2.1 Transmitter used in simulation

Model of one-electrode transmitter is shown in Fig. 2.1, which consists of a signal source, a signal electrode, a floating ground, and a resistor.

The floating ground corresponds to a circuit board in reality. The source voltage is set to 1V. The frequency is set to 21 MHz according the standard IEEE 802.15.6[21], which is applied to WBANs used in medical field and healthcare field. The resistor R_{tx} is set to 50 Ω, which is the standard output impedance of a signal source.

The size of the electrode will affect the signal transmission. In previous researches, it was found that the received signal increased as the area of the floating ground increased. Considering that the transmitter is worn at the body, it should be made compact and small. Thus, in this study, the signal electrode is made into 8×24 mm, and the size of the floating ground is 40×24 mm, as shown in Fig. 2.1.

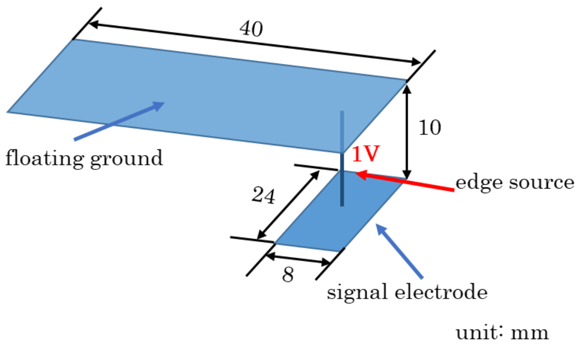


Fig. 2.1 Model of the one-electrode transmitter of the intra-person HBC

Model of two-electrode transmitter is shown in Fig. 2.2. The structure of the two-electrode transmitter is similar to that of the one-electrode transmitter. The difference is that the two-electrode transmitter has a ground electrode which is in contact with the human skin. This ground electrode is connected to the floating ground.

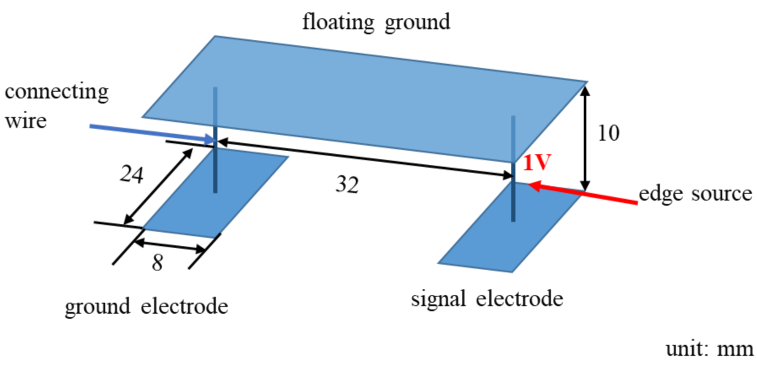


Fig. 2.2 Model of the two-electrode transmitter of intra-person HBC

2.2.2 Transmitter used in experiment

Circuit of the two-electrode transmitter is shown in Fig. 2.3. It consists of an oscillation circuit that outputs a sine wave of 20 MHz and a signal electrode for applying the signal voltage to the human body.

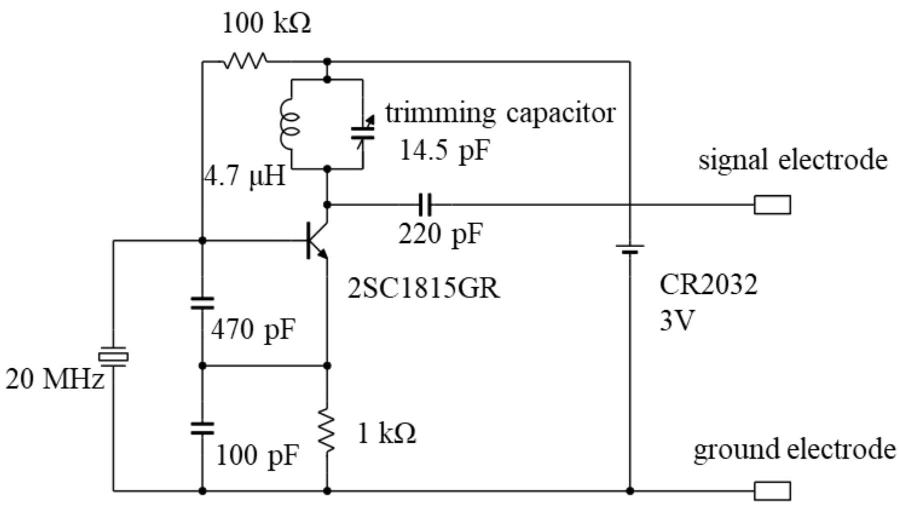


Fig. 2.3 Circuit of the two-electrode transmitter

Transmitter used in experiment is shown in Fig. 2.4. It is worn at the left wrist by magic tapes, as shown in Fig. 2.5. The transmitter consists of two parts, as shown in Fig. 2.6.

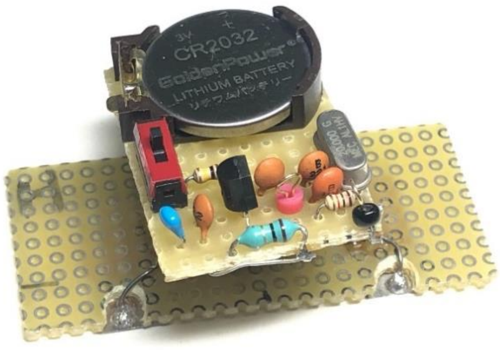


Fig. 2.4 Transmitter used in experiment

Fig. 2.5 Wearing the transmitter at the left wrist

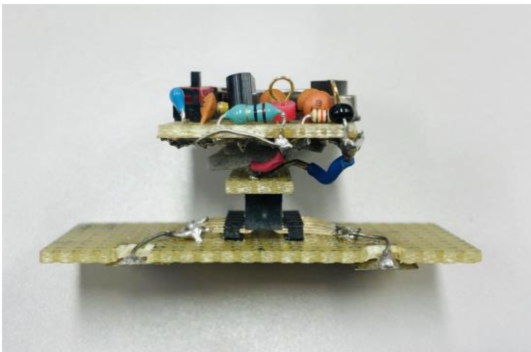


Fig. 2.6 Front view of the transmitter used in experiment

The top part of the transmitter is the circuit for transmitting the signal. As shown in Fig. 2.7, all elements are mounted on a 24×32 mm universal board. The Colpitts oscillation circuit is used. The frequency of the transmitter is set as 20 MHz, which is close to the frequency set in the simulation according to the standard IEEE802.15.6[21]. The power of the transmitter is provided by a coin battery (CR2032).

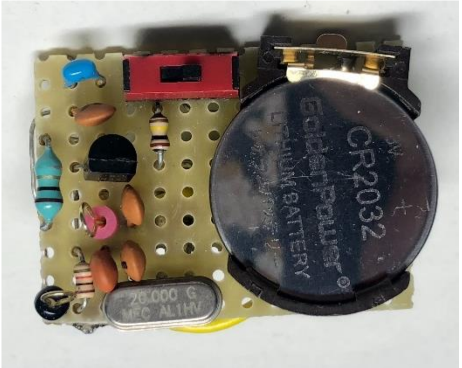
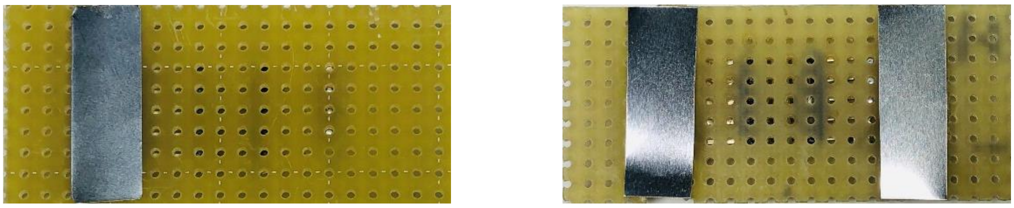


Fig. 2.7 Top part of the transmitter

The bottom part of the transmitter is for the electrodes. As shown in Fig. 2.8 (a), the bottom layer of the one-electrode transmitter is a signal electrode. The bottom layer of the two-electrode transmitter, as shown in Fig. 2.8 (b), consists of a signal electrode and a ground electrode.

The material of the electrodes is stainless steel. The size of the electrodes is 8×24 mm, and the distance between the electrodes is 32 mm, which are the same with the settings in simulation.



(a) Bottom of the one-electrode transmitter **(b) Bottom of the two-electrode transmitter**

Fig. 2.8 Bottom part of the transmitter

The top layer and the bottom layer are connected by a 10-pin connector as shown in Fig. 2.9.

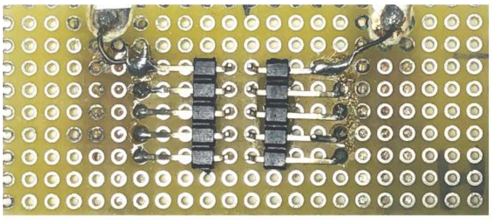


Fig. 2.9 10-pin connector

2.3 One-electrode receiver and two-electrode receiver used for intra-person HBC

One-electrode receiver and two-electrode receiver used in simulation and in experiment are introduced in this section.

2.3.1 Receiver used in simulation

Model of the one-electrode receiver used in simulation is shown in Fig. 2.10, which consists of a signal electrode, a floating ground, and a resistor R_{rx}. The resistor R_{rx} is set to 2000 Ω to receive the signal.

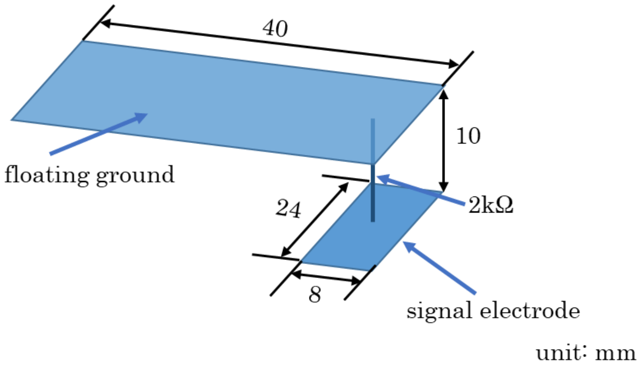


Fig. 2.10 Model of the one-electrode receiver

Model of the two-electrode receiver is shown in Fig. 2.11. Besides the signal electrode, the ground electrode is also attached. The size of the receiver is same with the size of the transmitter.

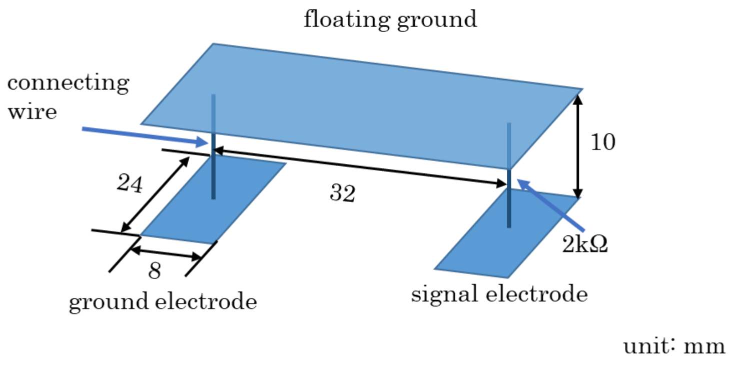


Fig. 2.11 Model of the two-electrode receiver

2.3.2 Receiver used in experiment

The circuit of the receiver used in experiment is shown in Fig. 2.12. It consists of an amplifier circuit and a comparator circuit. The circuits are powered by two coin batteries (CR2032). With the voltage regulator, the input voltage of the receiver can stably be 3.3 V.

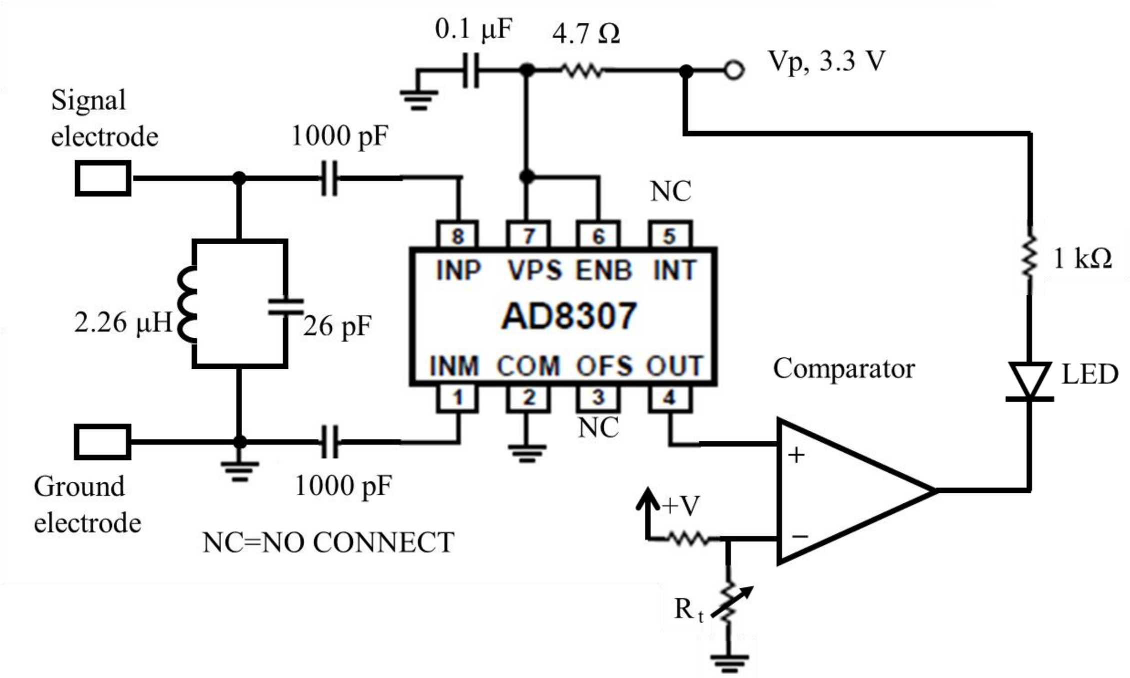


Fig. 2.12 Circuit of the receiver

Receiver used in the experiment is shown in Fig. 2.13, which can be divided into two parts. The top part of the receiver is shown in Fig. 2.14, which is a receiving circuit that receives a 20 MHz signal.

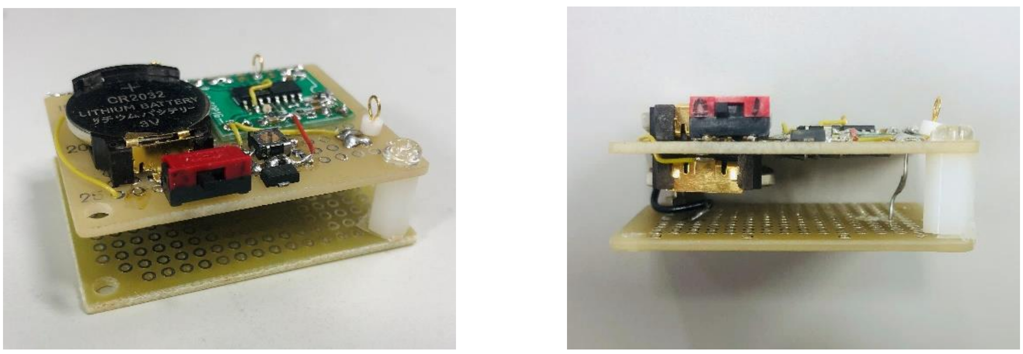


Fig. 2.13 Receiver used in experiment

Fig. 2.14 Top part of the receiver

Log amplifier AD8307 is used to amplify the signal since the received signal is too small to be accurately measured. The log response of the amplifier from the data sheet is shown in Fig. 2.15. 10 dBm corresponds to 1 V, -10 dBm corresponds to 0.1 V[22]. The log response of the amplifier at 20 MHz is measured since the signal is transmitted at 20 MHz for intra-person HBC. Voltage of known amplitude is input to the amplifier by the function generator. The output voltage is measured by the voltmeter.

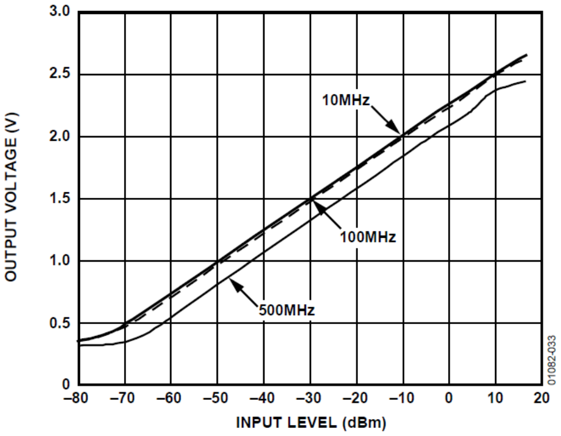


Fig. 2.15 Log response at 10 MHz, 100 MHz, and 500 MHz

The log response of the amplifier at 20 MHz is shown in Fig. 2.16. The unamplified voltage can be calculated by the equation 1-1.

$$V_{output} = 0.2144 \times \ln(V_{input}) + 2.1843 \ \ [V] \tag{1-1}$$

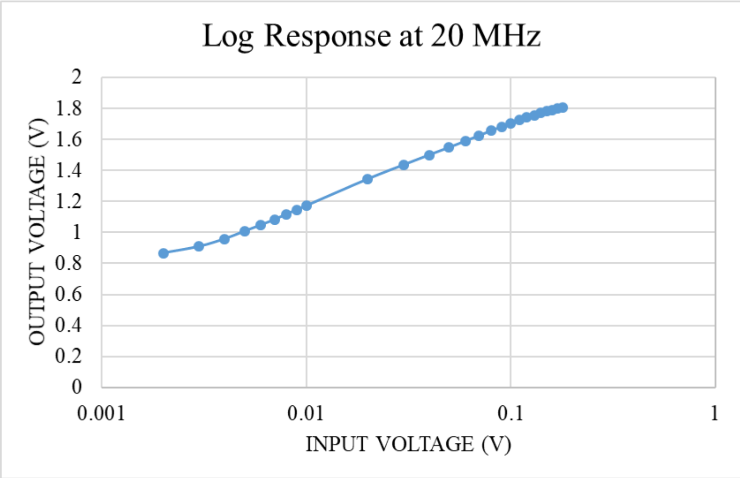


Fig. 2.16 Log response at 20 MHz

Besides, if the amplified signal is directly measured, the cables of the oscilloscope will affect the measurement when they are connected to the wearable receiver. Thus, a comparator is used to compare the voltage of the signal with the voltage of the LED. When the resistor R_t is adjusted until its voltage is same to the voltage of the amplified signal, the LED lights. The resistor R_t is adjusted by plastic screwdriver as shown in Fig. 2.17. The amplified voltage can be measured without the influence of the measuring equipment by indirectly measuring the voltage of the LED.

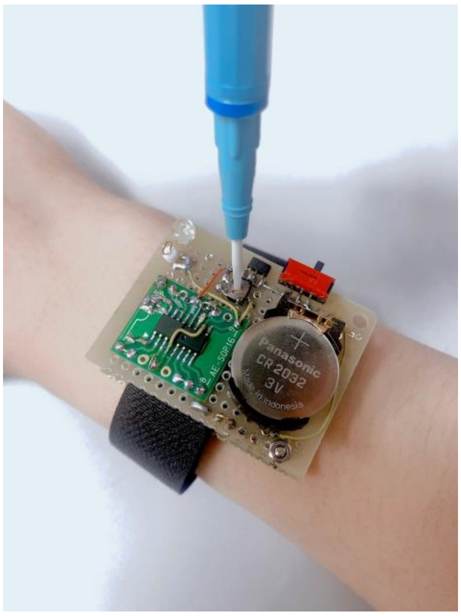
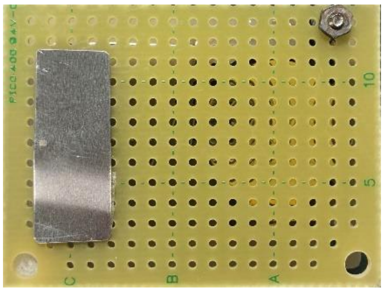
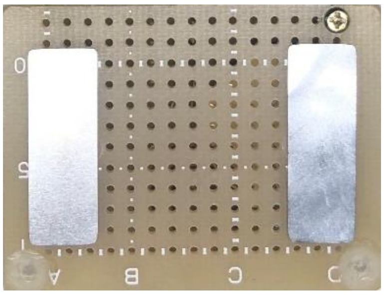


Fig. 2.17 Adjusting the resistor R_t

The bottom part of the receiver is for the electrodes, as shown in Fig. 2.18. The signal electrode functions as an antenna for receiving signals. When using the two-electrode receiver, a ground electrode is added to the electrode layer. The size of the electrodes is 8×24 mm, and the distance between the electrodes is 32 mm, which are the same with the settings in simulation.



(a) Bottom of the one-electrode receiver



(b) Bottom of the two-electrode receiver

Fig. 2.18 Bottom part of the receiver

2.4 Conclusion

Since the coupling between the wearable devices and the human body changes when using the transmitter and receiver with different numbers of contacting electrodes, it is necessary to study the characteristic of the one-electrode and two-electrode devices.

In this chapter, transmitter and receiver used in simulation and experiment are introduced in detail. For the transmitter and receiver used in the simulation, the model, size and settings are introduced. For the devices used in the experiment, the circuit is explained and the structure and the size are introduced.

Chapter 3 Evaluation of the number of devices' contacting electrodes according to the receiver's wearing position

3.1 Purpose of evaluating the devices' contacting electrode numbers according to the receiver's wearing position

The couplings among the transmitter, the receiver and the human body change when wearing the receiver at different parts of the body. Moreover, wearing devices with different numbers of the electrodes also leads to different coupling mechanisms. It is necessary to combine the number of the devices' contacting electrodes and the receiver's wearing position in order to find out the electrode contacting condition that is suited for the practical use.

In this chapter, both simulation and experiment were carried out to evaluate the number of devices' contacting electrodes according to the receiver's wearing position.

3.2 Evaluation according to the simulation

3.2.1 Model of the human body

Fig. 3.1 shows the model of the human body that consists of 7 parts: head, shoulder, torso, two arms and two legs.

The whole human body is modeled as uniform muscle. The electrical conductivity and the relative permittivity are set to the values of muscle at 21 MHz, which are 0.6445 S/m and 107.899 respectively.

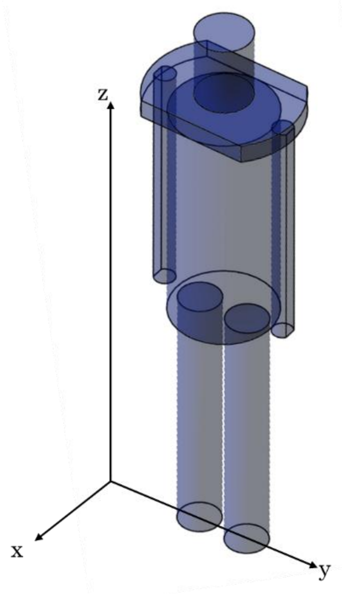


Fig. 3.1 Model of the human body

The detail of the model is shown in Fig. 3.2. The height of the body is 1710mm. From top to bottom, the data of the parts of the body are:

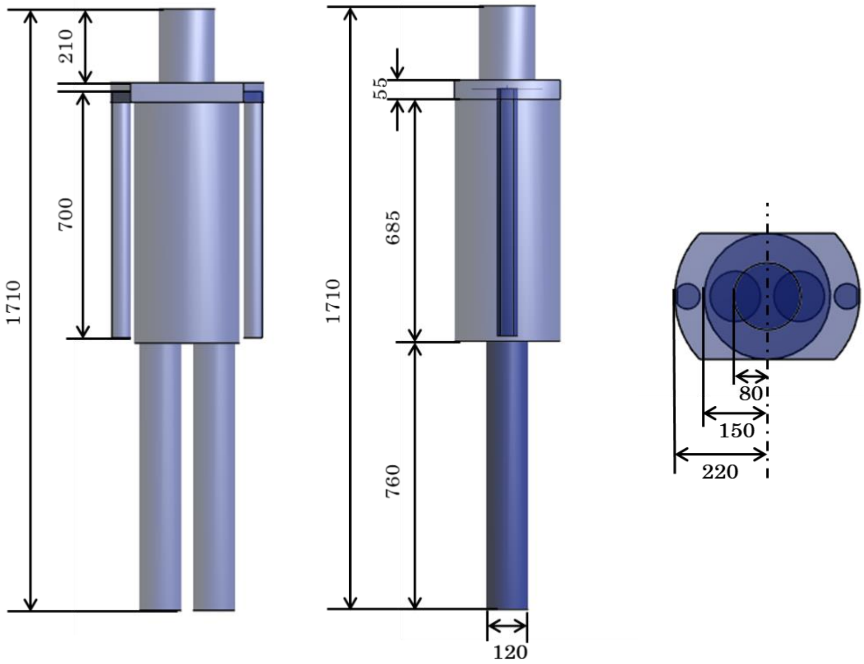
(a) Head: A cylinder. The diameter is 160 mm, and the length is 210 mm.

(b) Shoulder: Top view is shown in Fig. 3.2(b). The diameter is 440mm and the length is 55 mm.

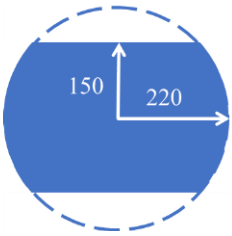
(c) Torso: A cylinder. The diameter is 300 mm, and the length is 685 mm.

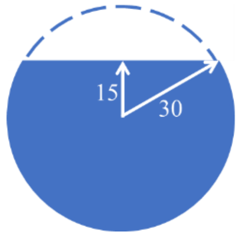
(d) Arm: Normal section is a circular segment as shown in Fig. 3.2(c). The diameter is 60 mm, and the length is 700 mm.

(e) Leg: A cylinder. The diameter is 120 mm, and the length is 760 mm.



(a) Detail of the human body model





unit: mm

(b) Top view of the sholder **(c) Normal section of the arm**

Fig. 3.2 Data in detail of the model of the human body for intra-person HBC

3.2.2 Receiver's wearing position

The most commonly used wearable devices are smart bands or smart watches that are worn at the wrist. Wireless headphones also have a place in the wearable device market. In addition, in medical field, equipment used near the heart are usual. When the user needs to move the upper limbs at a large range, such as doing sports, the devices worn on the ankle are also necessary. The situations mentioned above are investigated in this chapter.

In this study, the transmitter is worn at the left wrist, which is the most common wearing position. The receivers are worn at 8 positions, as shown in Fig. 3.3: (A) left upper arm, (B) right upper arm, (C) right wrist, (D) chest, (E) left ear, (F) right ear, (G) left ankle, and (H) right ankle.

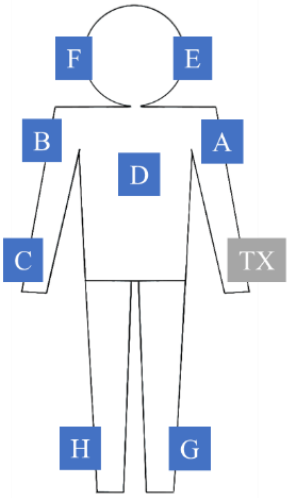


Fig. 3.3 Wearing positions of the devices

3.2.3 Results when wearing the receiver at 8 positions

When using the devices with different numbers of contacting electrodes, 4 combinations are considered:

(a) one-electrode transmitter and one-electrode receiver

(b) one-electrode transmitter and two-electrode receiver

(c) two -electrode transmitter and one-electrode receiver

(d) two -electrode transmitter and two -electrode receiver

With the simulation SEMCAD, we can get the output voltages of the transmission in four situations. The signal attenuation can be calculated by equation (3-1). The input voltage is set as 1 V in simulation. The results when wearing the receivers at different positions are shown in Table 3.1 and Fig. 3.4.

$$\text{Signal attenuation} = 20 \times \log\left(\frac{Voltage_{out}}{Voltage_{in}}\right) \ [dB] \tag{3-1}$$

Table 3.1 Signal attenuation when wearing the receiver at 8 positions

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	-64.79 dB	-68.13 dB	-56.26 dB	-54.72 dB
B	right upper arm	-87.71 dB	-97.50 dB	-88.93 dB	-87.69 dB
C	right wrist	-86.68 dB	-107.12 dB	-84.16 dB	-94.48 dB
D	chest	-86.89 dB	-98.98 dB	-89.81 dB	-83.52 dB
E	left ear	-90.82 dB	-105.55 dB	-93.36 dB	-99.58 dB
F	right ear	-90.56 dB	-111.87 dB	-96.09 dB	-101.42 dB
G	left ankle	-82.70 dB	-115.56 dB	-79.63 dB	-106.33 dB
H	right ankle	-84.83 dB	-111.97 dB	-83.51 dB	-110.57 dB

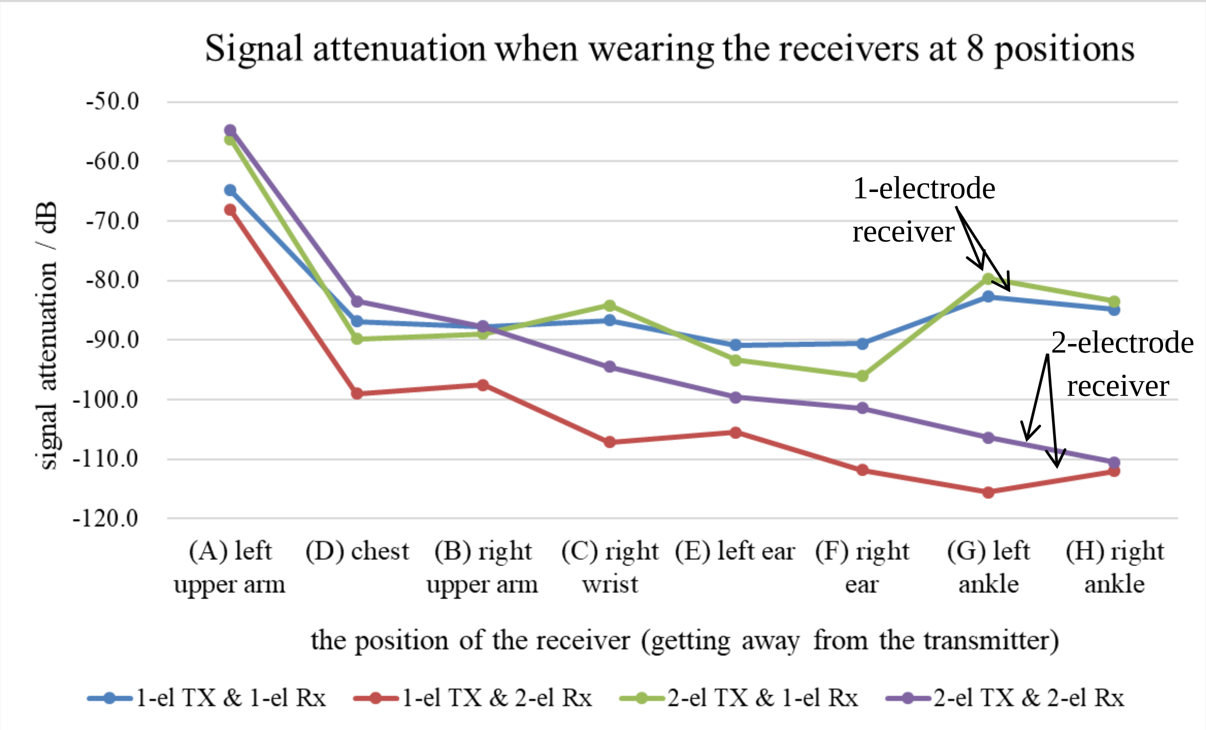


Fig. 3.4 Signal attenuation when wearing the receivers at 8 positions

The results showed three characteristics.

First of all, it was the receiver's number of contacting electrodes that determines the signal attenuation when considering the wearing position of the receiver. The received signal level of the one-electrode receiver was independent of the position where it is worn.

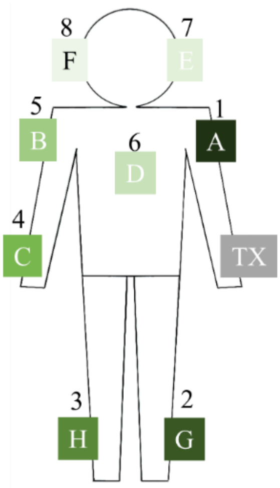
When wearing the one-electrode receiver at 8 positions, the differences of signal attenuation were 26.02 dB and 39.82 dB in maximum when wearing the one-electrode transmitter and two-electrode receiver respectively.

When wearing the two-electrode receiver at 8 positions, the differences of signal attenuation were 47.41 dB and 55.86 dB respectively when wearing the one-electrode transmitter and two-electrode receiver in maximum.

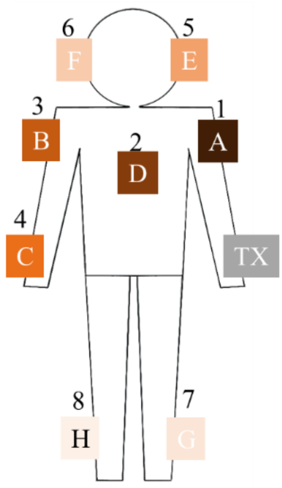
Secondly, the one-electrode receiver worked better at the extremity of the human body, such as (C) right wrist, (E) left ear, (F) right ear, (G) left ankle, and (H) right ankle. While the two-electrode receiver worked better at the middle part of the human body, such as (A) left upper arm, (B) right upper arm, and (D) chest.

Thirdly, when wearing the two-electrode receiver, the received signal decreased as the distance between the transmitter and the receiver increased. However, when wearing the one-electrode receiver, the signal attenuation did not change much with the distance between the devices.

The order of signal attenuation from small to large was shown in Fig. 3.5.



(a) When wearing the one-electrode receiver



(b) When wearing the two-electrode receiver

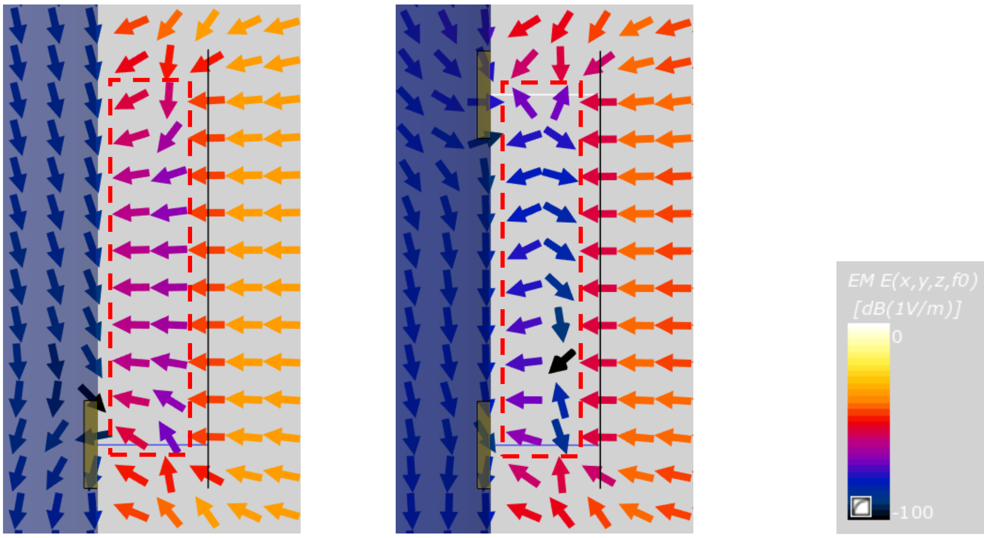
Fig. 3.5 Order of the performance of the receiver

3.2.4 Analysis on electric field distribution

Corresponding to the three characteristics found in the previous section, the electric field distribution diagrams are used to understand the characteristics of transmitters and receivers with different numbers of contacting electrodes.

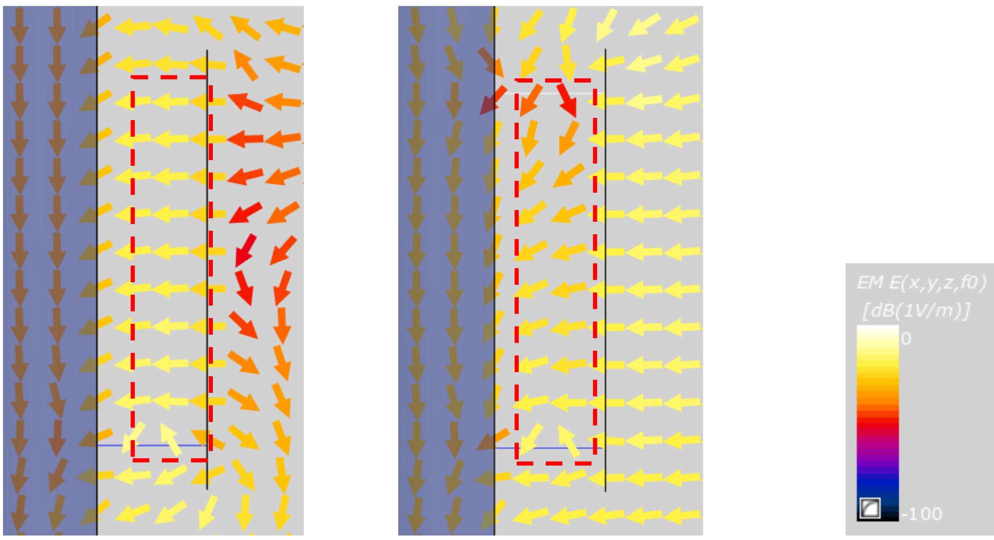
Firstly, when wearing the two-electrode receiver, the ground electrode and the floating ground were connected by the wire, which made it easier for current to flow from the wire and ground electrode to the body, and made the capacitive coupling between the ground electrode and floating ground weak. As shown in Fig. 3.6, the electric field around the one-electrode receiver was stronger than that around the two-electrode receiver when wearing the receiver at the left ankle.

Even when the two-electrode receiver worked better than the one-electrode receiver, its electric field between the ground electrode and floating ground was weaker. For example, the electric field distribution when wearing the two-electrode transmitter and wearing the receiver at the left upper arm were shown in Fig. 3.7.



(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

Fig. 3.6 Electric field distribution when wearing the receiver at left ankle

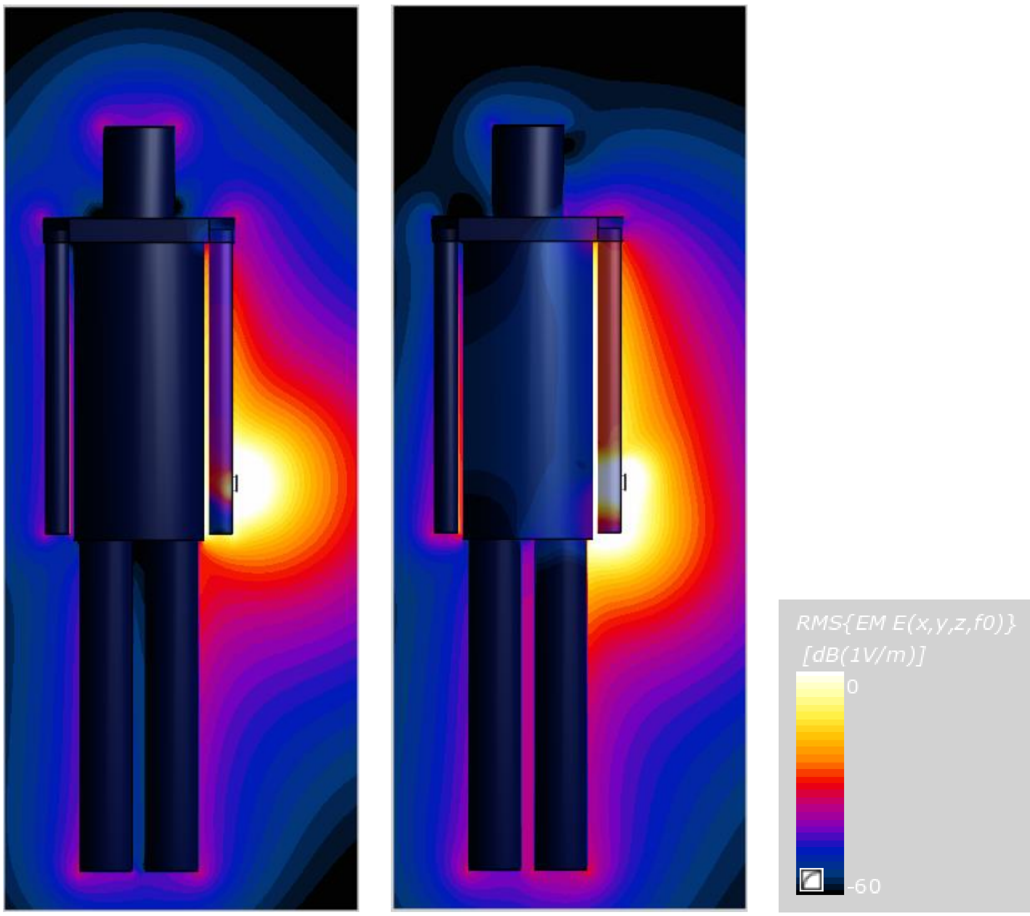


(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

Fig. 3.7 Electric field distribution when wearing the receiver at left upper arm

Secondly, not only the number of contacting electrodes of the receiver affected the signal attenuation, but also that of the transmitter did. As shown in Fig. 3.8, when wearing the one-electrode transmitter, the electric field was stronger at the extremity of the body. When wearing the two-electrode transmitter, the ground electrode attached to the human body made part of the body function as the ground. Thus, the signal tended to return to the body and the coupling between the body went stronger.

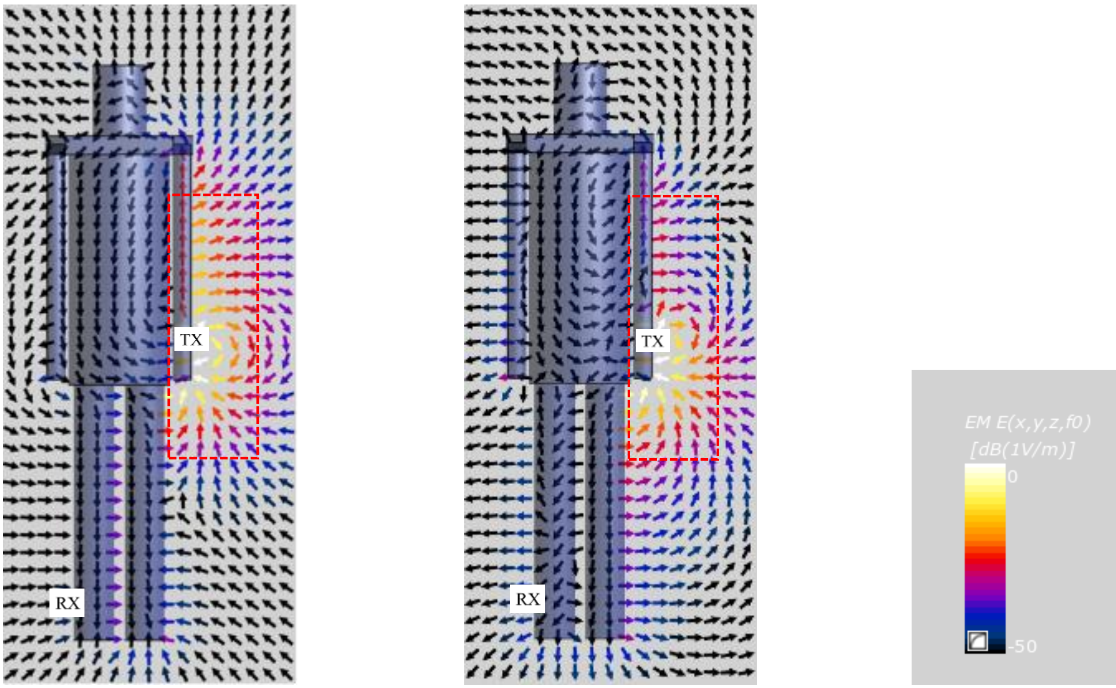
Similarly, the two-electrode receiver was more dependent on the coupling through the body because the ground electrode attached to the body made part of the human body into a huge ground, and promoted the return paths inside the body. When wearing the 1-el Rx, both of the coupling through the body and the forward path through the air contributed to the signal transmission so that it was more independent of the wearing position



(a) One-electrode transmitter **(b) Two-electrode transmitter** **(c) Scale of the color bar**

Fig. 3.8 Electric field distribution when wearing the transmitter at left wrist and not wearing the receiver

Thirdly, the received signal level of the two-electrode receiver was highly dependent on the distance between the devices. For example, when wearing the two-electrode transmitter, and wearing the receiver at (H) right ankle, the electric field around the transmitter was stronger when wearing the one-electrode receiver as shown in Fig. 3.9. The same phenomenon occurred when wearing the receiver at right wrist.

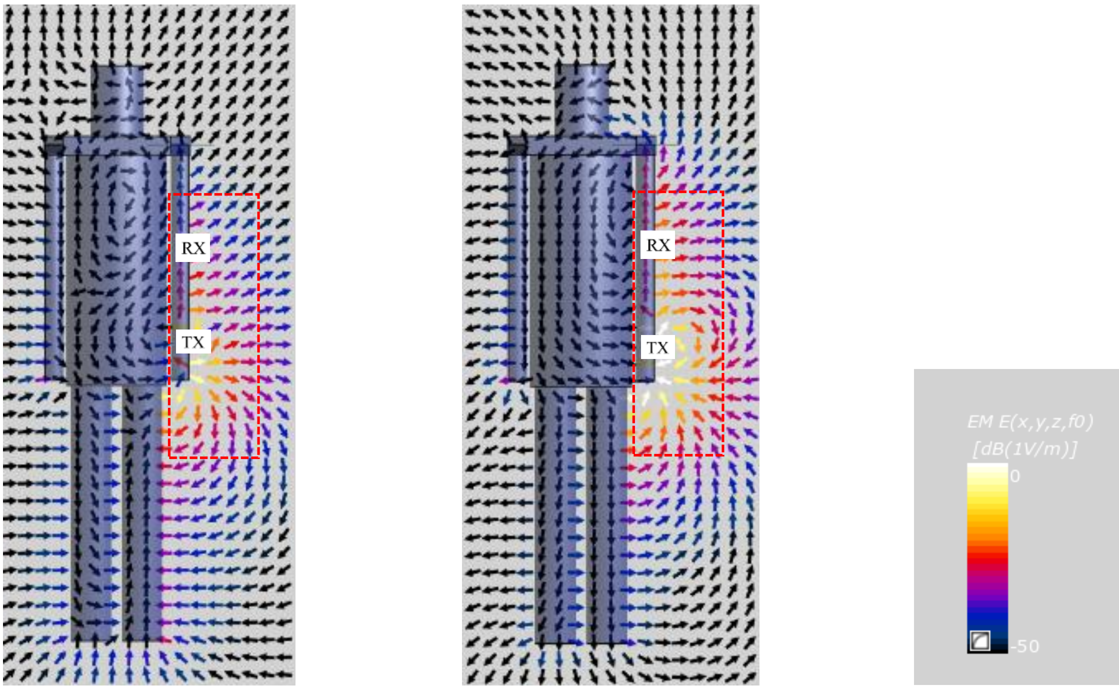


(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

Fig. 3.9 Electric field distribution when wearing the receiver at right ankle

When receiver was at (A) left upper arm, the electric field was stronger when wearing the two-electrode receiver as shown in Fig. 3.10.

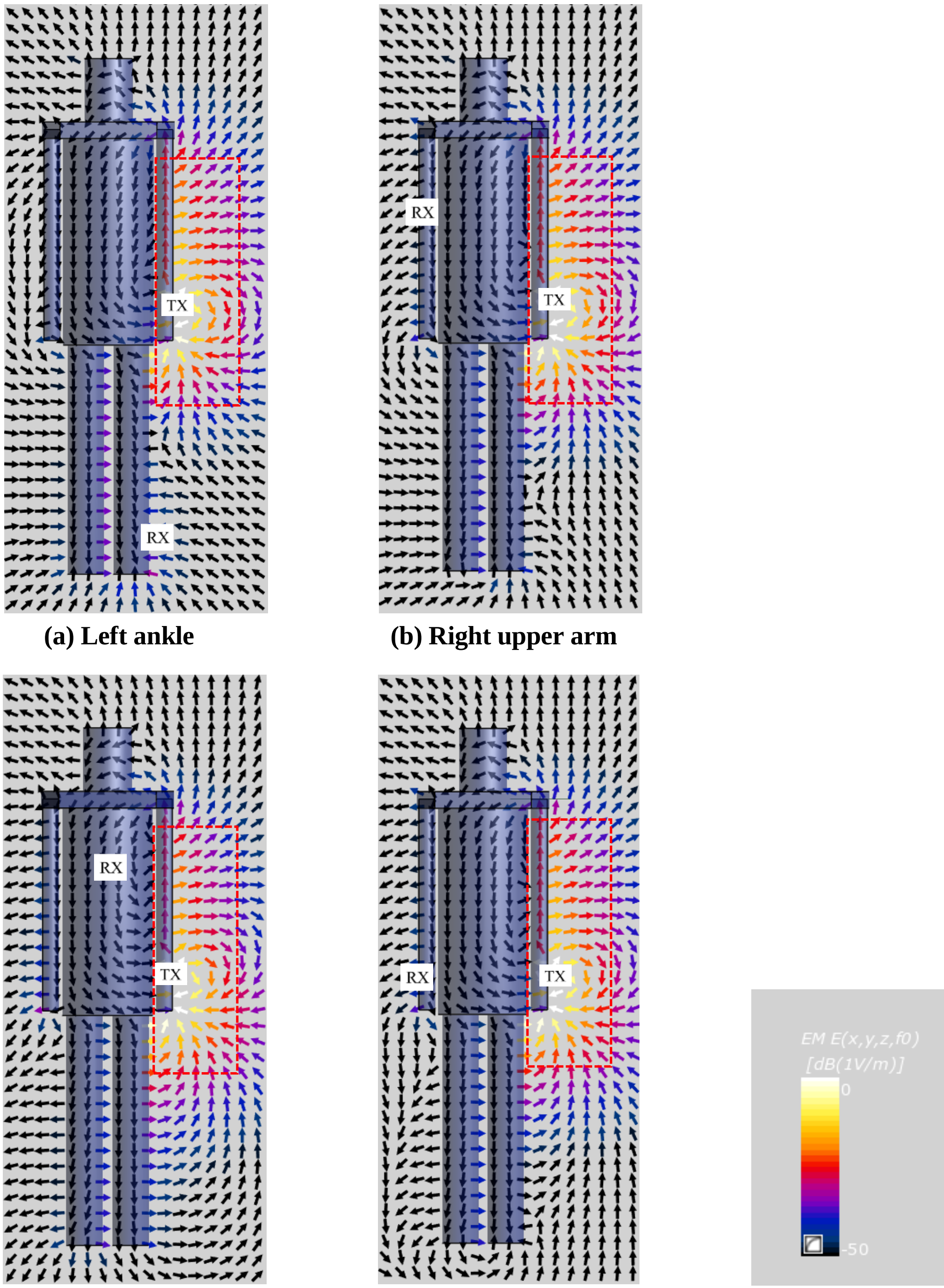
It was because when using the two-electrode receiver, parts of the human body acted as the ground and promoted the return path. When the two-electrode receiver was close to the transmitter, the signal attenuation was small. However, when the two-electrode receiver was far away from the transmitter, the signal also tended to return to part of the human body where was close to the transmitter. And thus, the signal reached the two-electrode receiver got weak.



(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

Fig. 3.10 Electric field distribution when wearing the receiver at left upper arm

When wearing the one-electrode receiver, the electric field distribution showed high similarity, as shown in Fig. 3.11. It was probably because the signal was transmitted mainly by the capacitive coupling through the air. Therefore, the one-electrode receiver could receive the signal more stably regardless of the wearing position.



(a) Left ankle **(b) Right upper arm**

(c) Chest **(d) Right wrist** **(e) Scale of the color bar**

Fig. 3.11 Electric field distribution when wearing the one-electrode receiver

3.3 Evaluation according to the experiment

3.3.1 Method of the measurement

The transmitter and the receiver were fixed on the human body by velcro tapes in the experiment. For example, the situation when wearing the receiver at the right wrist is shown in Fig. 3.12.

Fig. 3.12 When wearing the receiver at the right wrist

As mentioned in chapter 2, the voltage of the LED equals to the output voltage of the logarithmic amplifier when the LED just lights. The influence of the measuring equipment can be avoided by indirect measurement.

3.3.2 Results of the experiment

The output voltage of the logarithmic amplifier when wearing the receiver at different parts of the body is shown in Table 3.2.

According to the transmission characteristic of the amplifier AD8307, the actual received signal can be calculated by equation (3-2). Then, the signal attenuation can be calculated by equation (3-1). The input voltage is 3 V in experiment. The signal attenuation when wearing the receivers at 8 positions in the experiment are shown in Table 3.3.

$$\text{Actual voltage} = 4 \times 10^{-5} e^{4.6127 \times \text{output voltage of the amplifier}} \quad [V] \tag{3-2}$$

$$\text{Signal attenuation} = 20 \times \log\left(\frac{Voltage_{out}}{Voltage_{in}}\right) \quad [dB] \tag{3-1}$$

Table 3.2 Amplified voltage when wearing the receiver at 8 positions

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	0.376 V	0.499 V	0.646 V	0.781 V
B	right upper arm	0.413 V	0.537 V	0.443 V	0.460 V
C	right wrist	0.406 V	0.609 V	0.454 V	0.512 V
D	chest	0.351 V	0.341 V	0.352 V	0.341 V
E	left ear	0.451 V	0.453 V	0.439 V	0.376 V
F	right ear	0.419 V	0.496 V	0.397 V	0.435 V
G	left ankle	0.342 V	0.464 V	0.356 V	0.514 V
H	right ankle	0.357 V	0.499 V	0.335 V	0.503 V

Table 3.3 Signal attenuation when wearing the receiver at 8 positions

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	-82.44 dB	-77.49 dB	-71.63 dB	-66.19 dB
B	right upper arm	-80.94 dB	-76.00 dB	-79.77 dB	-79.06 dB
C	right wrist	-81.22 dB	-73.11 dB	-79.33 dB	-76.97 dB
D	chest	-83.45 dB	-83.86 dB	-83.38 dB	-83.83 dB
E	left ear	-79.45 dB	-79.36 dB	-79.92 dB	-82.44 dB
F	right ear	-80.70 dB	-77.62 dB	-81.58 dB	-80.09 dB
G	left ankle	-83.80 dB	-78.90 dB	-83.23 dB	-76.91 dB
H	right ankle	-83.21 dB	-77.52 dB	-84.07 dB	-77.36 dB

Different from results in the simulation, the signal attenuations were similar when wearing the one-electrode and two-electrode devices at different positions. Furthermore, when the transmitter was switched off, 0.287 V signal was detected, which equaled to -86.00 dB in signal attenuation. Thus, the received signal was too weak to be accurately measured when wearing the receiver at different parts of the body. Referring to the results of the simulation, only when wearing the receiver at the left upper arm, the signal attenuations were over -86.0 dB.

When wearing the receiver at the left upper arm, the situation that wearing the two-electrode transmitter and the one-electrode receiver performed best. The signal attenuation was 16 dB better than the situation that wearing the one-electrode transmitter and one-electrode receiver.

Even though the signal was too weak to be accurately measured, the signal attenuation showed similar trends to the results in the simulation: the receiver's electrode contacting condition determined the level of received signal, as shown in Fig. 3.13.

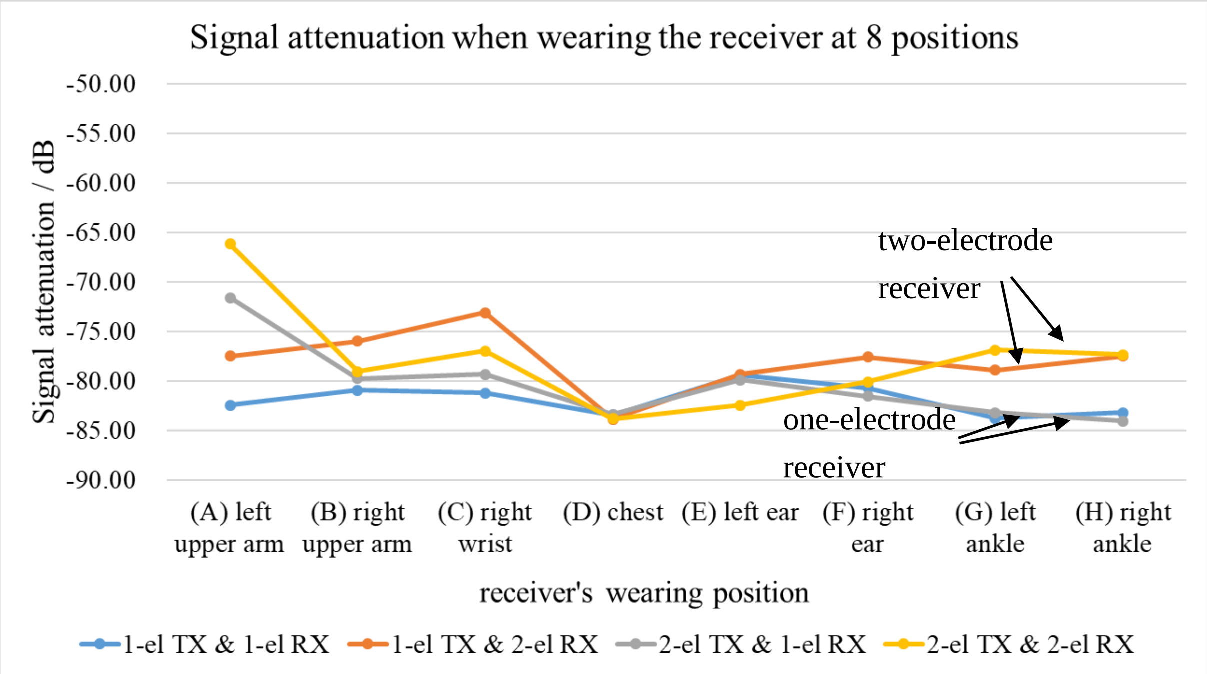


Fig. 3.13 Signal attenuation when wearing the receiver at 8 positions

3.4 Conclusion

The transmission characteristic of the one-electrode and two-electrode devices according to the wearing position was investigated, since the couplings among the wearable devices and the human body would change when wearing the receiver at different parts of the body.

In this chapter, signal attenuation of the transmission according to different wearing positions was calculated in simulation and measured in experiment.

In simulation, the two-electrode receiver worked better at the middle part of the body, and the one-electrode receiver worked better at the extremity of the body. It was because that the ground electrode attached to the skin made part of the human body function as the ground, and promoted the signal return to the body. Thus, the performance of the two-electrode receiver was closely related with the distance between the devices, and the one-electrode receiver was less affected by the wearing position.

In experiment, though the actual received voltage was too weak to be accurately measured, the results showed that the receiver's electrode contacting condition determined the level of the received signal, which met the conclusion in simulation.

Chapter 4 Evaluation of the number of devices' contacting electrodes according to the posture

4.1 Purpose of studying the influence of the posture

In daily life, users do not always stand still when they use the intra-person HBC to monitor the physical health conditions. The situation that people are moving should be involved in the study to meet the needs of practical use.

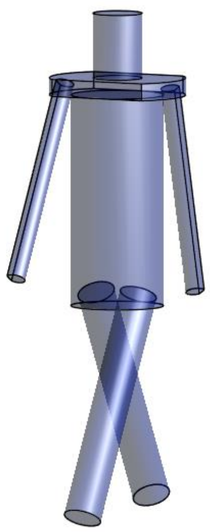
In this chapter, postures such as walking, swinging the arm sideways and frontward are studied by both simulation and experiment.

4.2 Influence of walking posture according to the simulation

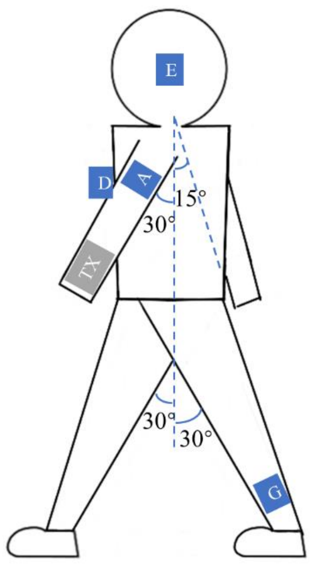
4.2.1 Model of the walking human

Model of the walking user used in simulation is shown in Fig. 4.1 (a), and the detail is shown in Fig. 4.1 (b). Model of the walking human is built based on how people actually walk. The left arm is swinging 30 º forward, and the right arm is swinging 15 º backward. The left foot is tilted 30 º backward, and the right foot is tilted 30 º forward.

The user is wearing the transmitter at the left wrist, and wearing the receivers at (A) left upper arm, (D) chest, (E) left ear, and (G) left ankle.



(a) Model used in simulation



(b) Side view of the walking human

Fig. 4.1 Model of the walking human

4.2.2 Results when the user is walking

Signal attenuation when the user is walking is shown in Table. 4.1 and Fig. 4.2.

The results of the walking situation and the standing situation were in good agreement. Two-electrode receiver worked better at the middle part of the body, such as (A) left upper arm and (D) chest. One-electrode receiver worked better at the extremity of the body, such as (E) left ear and (G) left ankle.

Table 4.1 Signal attenuation when the user is walking

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	-64.49 dB	-66.29 dB	-59.74 dB	-59.03 dB
D	chest	-91.07 dB	-97.72 dB	-93.21 dB	-88.14 dB
E	left ear	-91.95 dB	-104.67 dB	-95.34 dB	-99.18 dB
G	left ankle	-83.78 dB	-110.46 dB	-80.10 dB	-106.73 dB

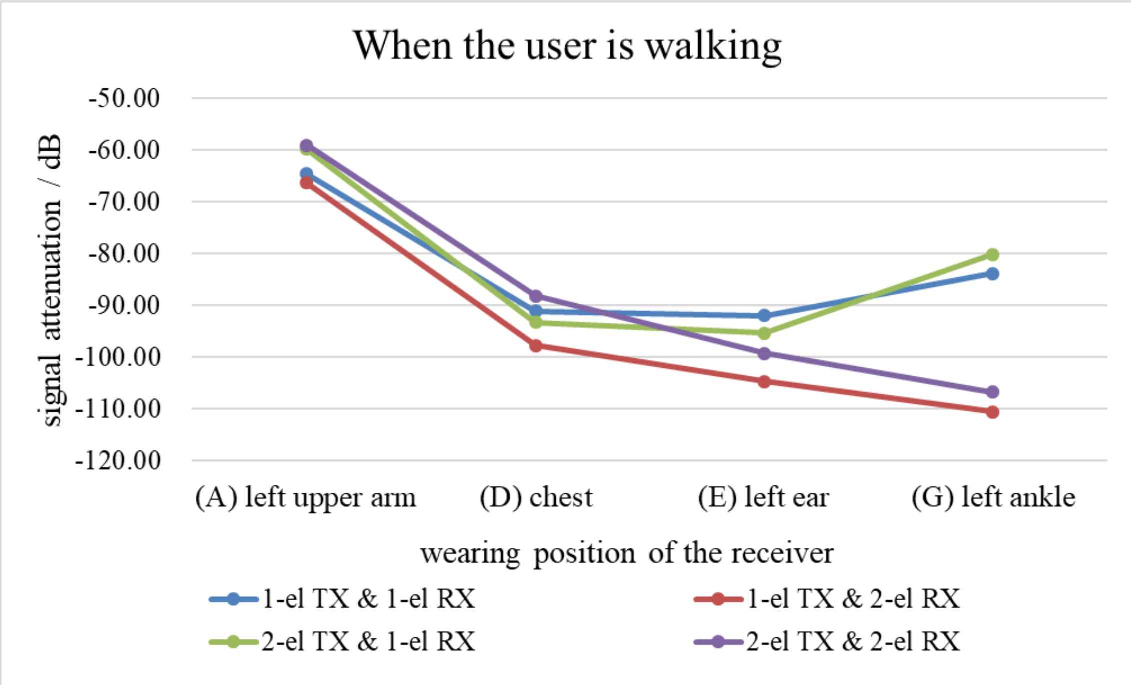


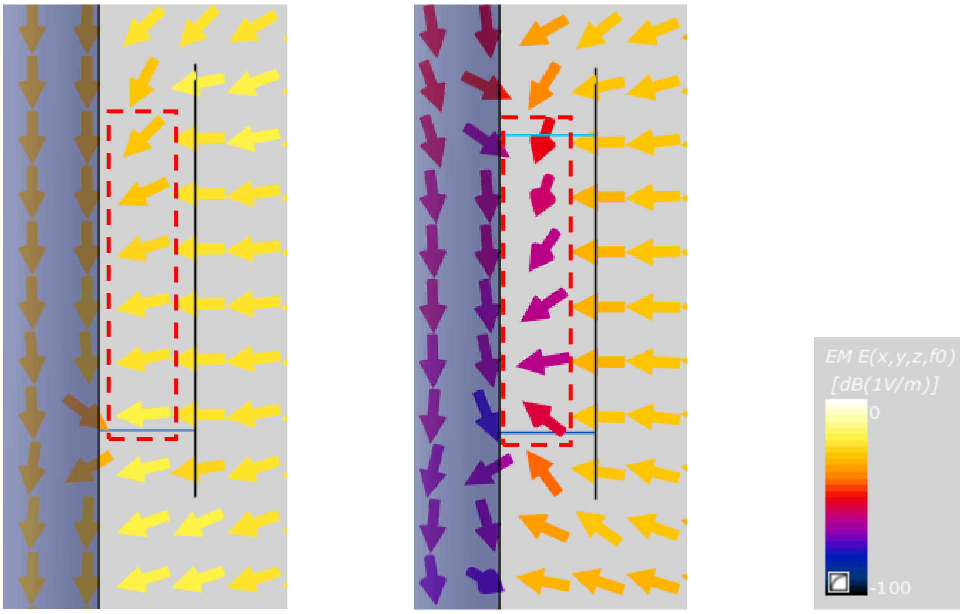
Fig. 4.2 Signal attenuation when the user is walking

Besides, the signal attenuation was 4.3 dB and 4.6 dB smaller than the standing posture when wearing the two-electrode receiver at (A) left upper arm and (D) chest respectively. However, the signal attenuation was almost the same with the standing posture when wearing the two- electrode receiver at (E) left ear and (G) left ankle, which verified the conclusion in chapter 3.

4.2.3 Analysis on electric field distribution

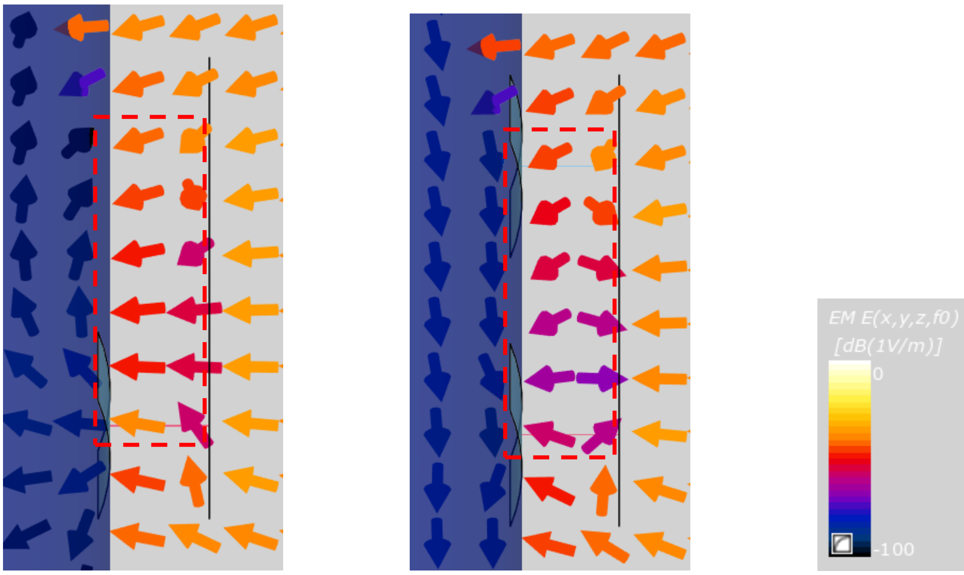
The results of the experiment were in good agreement with the results of the simulation. In addition, similar results were indicated in the electric field distribution diagrams as well.

Firstly, the ground electrode attached to the skin made part of the body be the ground when wearing the two-electrode receiver, as shown in Fig. 4.3 and Fig. 4.4. Thus, it was easier for current to flow from the wire and ground electrode to the body, and made the capacitive coupling between the ground electrode and floating ground weak.



(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

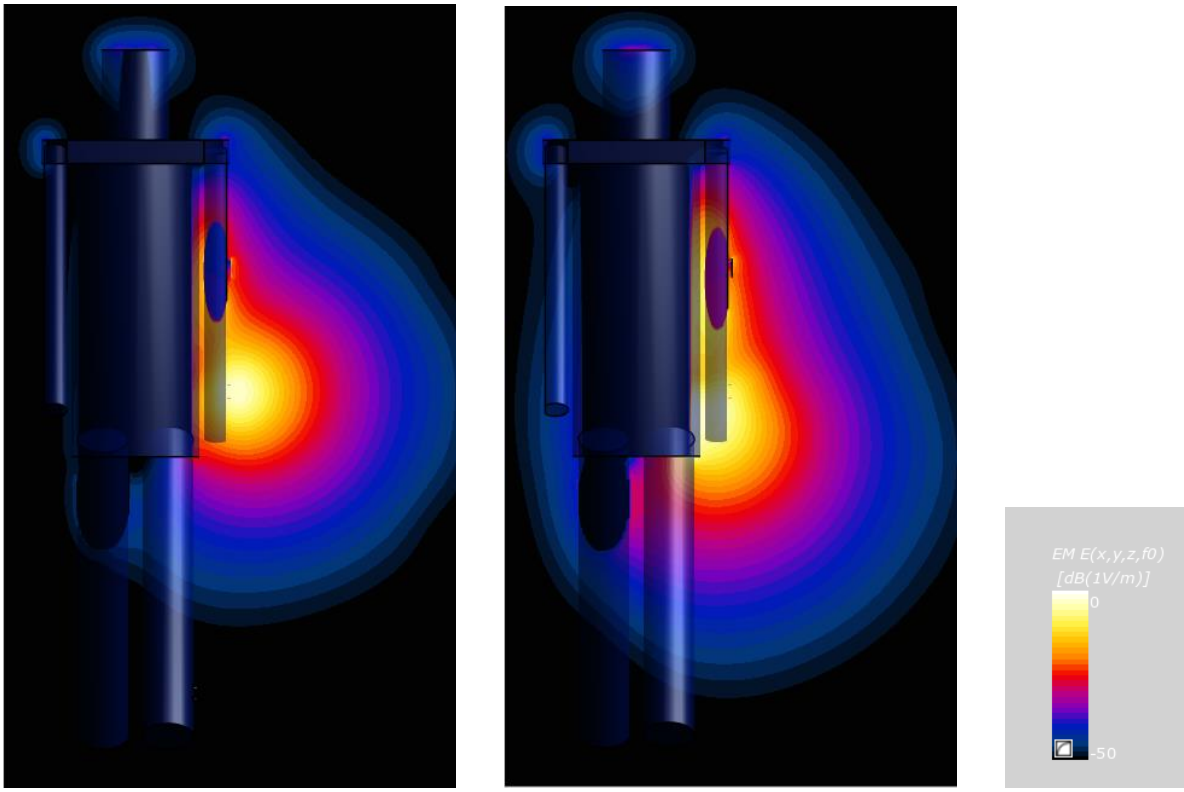
Fig. 4.3 When wearing the receiver at the left upper arm (with two-electrode transmitter)



(a) One-electrode receiver **(b) Two-electrode receiver** **(c) Scale of the color bar**

Fig. 4.4 When wearing the receiver at the left ankle (with one-electrode transmitter)

Secondly, the ground electrode attached to the human body made part of the body function as the ground when wearing the two-electrode transmitter. Thus, the signal tended to return to the body and the coupling around the body increased. As shown in Fig. 4.5, the signal returned to the human body promoted the transmission from the transmitter to the receiver worn at the left upper arm.



(a) One-electrode transmitter **(b) Two-electrode transmitter** **(c) Scale of color bar**

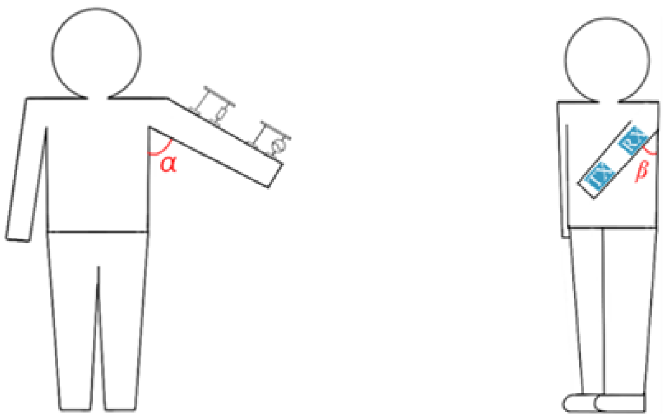
Fig. 4.5 when wearing the two-electrode receiver at the left upper arm

4.3 Influence of posture of the arm

4.3.1 Assessment according to the simulation

4.3.1.1 Swinging the arm sideways and frontward

People swing the arm sideways and frontward as shown in Fig. 4.6 when they are walking or reaching something. In chapter 3, it has been shown that the two-electrode transmitter works better when wearing the receiver at the left upper arm. Therefore, the two-electrode transmitter and two kinds of receivers are used in the situation of swinging the arm sideways and frontward.



(a) Swinging the arm sideways **(b) Swinging the arm frontward**

Fig. 4.6 Swinging the arm

The signal attenuation of the transmission when wearing the two-electrode transmitter at the left wrist and swinging the arm sideways is shown in Table. 4.2 and Fig. 4.7.

Table. 4.2 Signal attenuation when swinging the arm sideways

Angle α	one-electrode receiver	two-electrode receiver
0 °	-56.3 dB	-54.7 dB
10 °	-60.8 dB	-59.4 dB
20 °	-61.5 dB	-60.2 dB
30 °	-61.5 dB	-60.3 dB
40 °	-61.6 dB	-60.4 dB
50 °	-61.5 dB	-60.6 dB
60 °	-61.6 dB	-60.7 dB
90 °	-63.0 dB	-61.1 dB

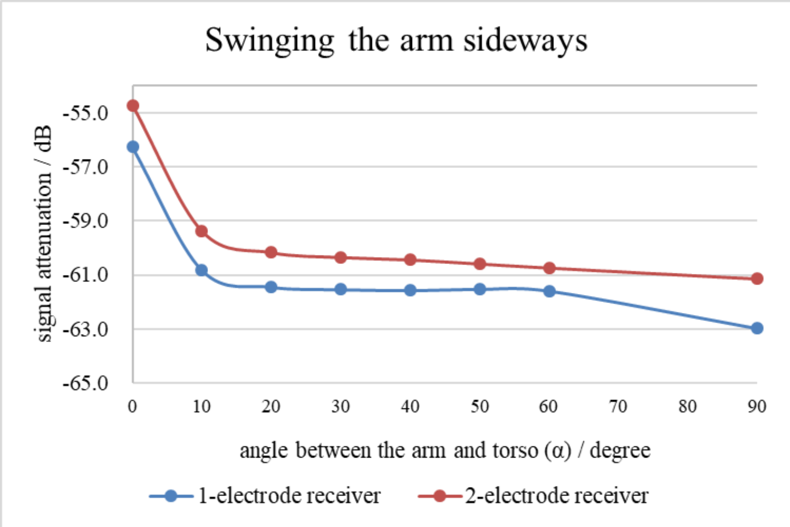


Fig. 4.7 Signal attenuation when swinging the arm sideways

The signal attenuation of the transmission when wearing the two-electrode transmitter at the left wrist and swinging the arm frontward is shown in Table. 4.3 and Fig. 4.8.

Table. 4.3 Signal attenuation when swinging the arm frontward

Angle β	one-electrode receiver	two-electrode receiver
0 º	-56.3 dB	-54.7 dB
10 º	-59.1 dB	-57.6 dB
20 º	-60.3 dB	-59.1 dB
30 º	-61.0 dB	-59.8 dB
40 º	-61.4 dB	-60.1 dB
50 º	-61.7 dB	-60.3 dB
60 º	-62.1 dB	-60.3 dB
90 º	-63.0 dB	-60.6 dB

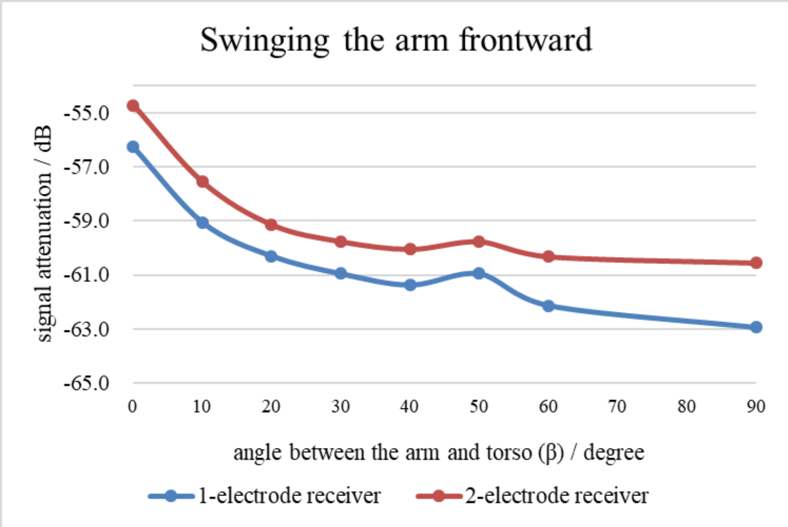


Fig. 4.8 Signal attenuation when swinging the arm frontward

From the results of the simulation, three characteristics were found:

(a) The received signal decreased as the angle between the arm and torso increased when swinging the arm sideways or frontward.

(b) The received signal attenuated slower when swinging forward compared to swinging sideways.

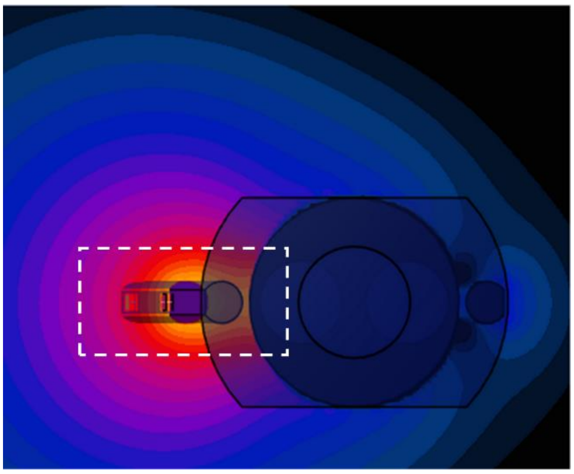
(c) Signal attenuation did not change much with the angle between the arm and torso when it was over 40 º.

The reasons why these phenomena show are explained in next section by analyzing the electric field distribution around the arm and the torso.

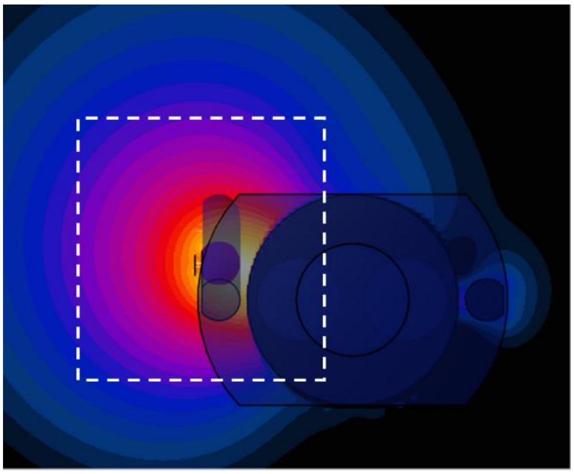
4.3.1.2 Analysis on electric field distribution

Firstly, the coupling between the arm and the torso also decreased as the angle between the arm and the torso increased. Thus, the received signal got weaker. Fig. 4.9 shows the electric field distribution when wearing the two-electrode transmitter and the two-electrode receiver. The electric field distribution was almost the same when wearing the two-electrode transmitter and the one-electrode receiver. As shown in Fig. 4.9 (a), (c), (e) and Fig. 4.9 (b), (d), (f), the electric field around the arm and the torso decreased as the angle between the arm and torso increased when swinging the arm sideways or frontward.

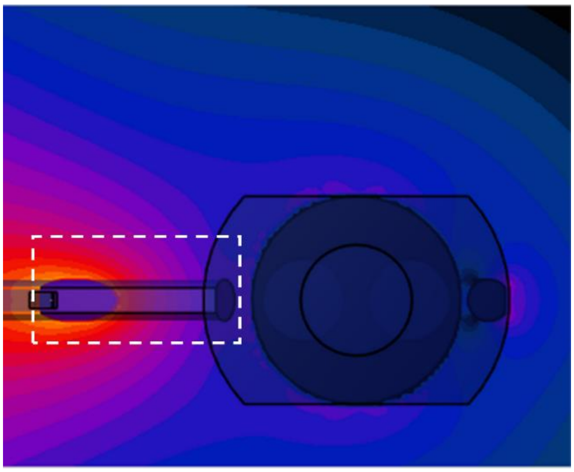
Secondly, the coupling occurred not only around the side part of the torso, but also the front part of the torso when swinging the arm frontward. So the received signal attenuated slower when swinging frontward compared to when swinging sideways. As shown in Fig. 4.9 (a), (b) and Fig. 4.9 (c), (d) and Fig. 4.9 (e), (f), the strong electric field was generated around the front part of the torso when the angle between the arm and the torso was the same.



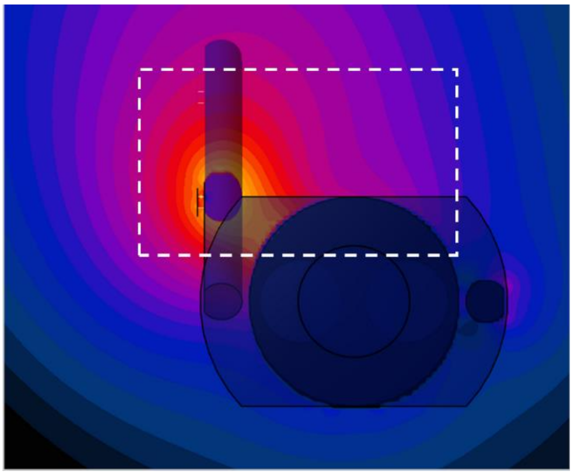
(a) α = 10°



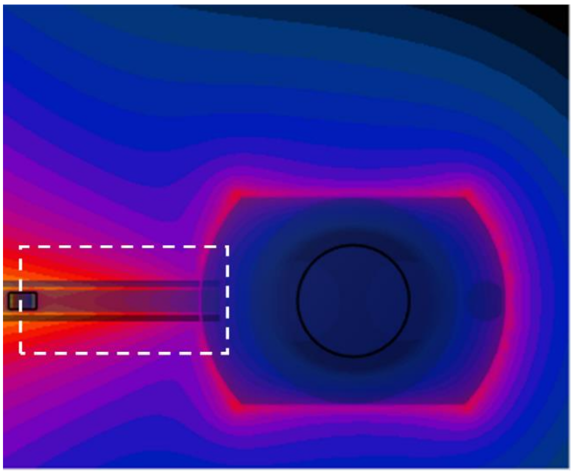
(b) β = 10°



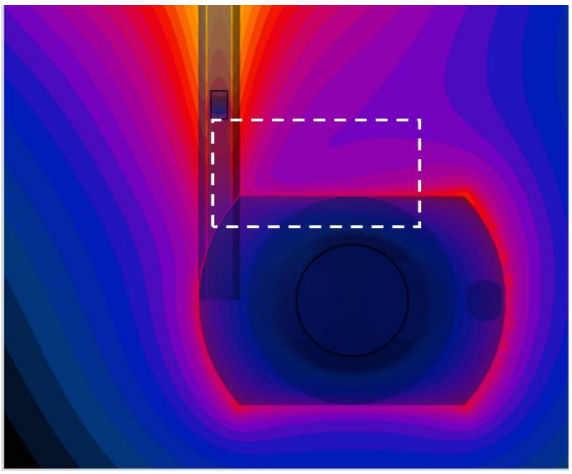
(c) α = 60°



(d) β = 60°



(e) α = 90°



(f) β = 90°

Fig. 4.9 Electric field distribution when swing the arm sideways and frontward

Thirdly, the coupling between the torso and the wearable devices was weak, when the angle was over 40°, as shown in Fig. 4.9 (c), (d), (e), (f). Thus, the signal attenuation did not change much with the angle when the angle between the arm and torso was big.

4.3.2 Assessment according to the experiment

In experiment, the two-electrode transmitter was worn at the left wrist and the one-electrode and two-electrode receivers were worn at the left upper arm. As shown in Fig. 4.10, situations that swinging the arm sideways and frontward were included in experiment.

(a) Swinging the arm sideways **(b) Swinging the arm frontward**

Fig. 4.10 Overview of the experiment

The signal attenuation when swinging the arm sideways and frontward are shown in Table 4.4 and Table 4.5 respectively.

Table 4.4 signal attenuation when swinging the arm sideways

Angle α	one-electrode receiver	two-electrode receiver
0 º	-71.63 dB	-66.19 dB
30 º	-72.85 dB	-67.68 dB
60 º	-72.91 dB	-67.70 dB
90 º	-72.91 dB	-67.72 dB

Table 4.5 signal attenuation when swinging the arm frontward

Angle β	one-electrode receiver	two-electrode receiver
0 º	-71.59 dB	-66.19 dB
30 º	-72.89 dB	-67.34 dB
60 º	-72.96 dB	-67.54 dB
90 º	-72.95 dB	-67.67 dB

As shown in Fig. 4.11, the experiment results were in good agreement with the simulation results:

(a) The electrode contacting condition of the receiver determined the level of received signal.

(b) The received signal decreased when the angle between the arm and torso increased when swinging the arm sideways or frontward. However, the signal attenuation did not change much with the angle when the angle was large.

Different from the characteristics shown in simulation, the received signal did not apparently attenuate slower when swinging forward compared to swinging sideways. It was supposed to be the influence of the environment.

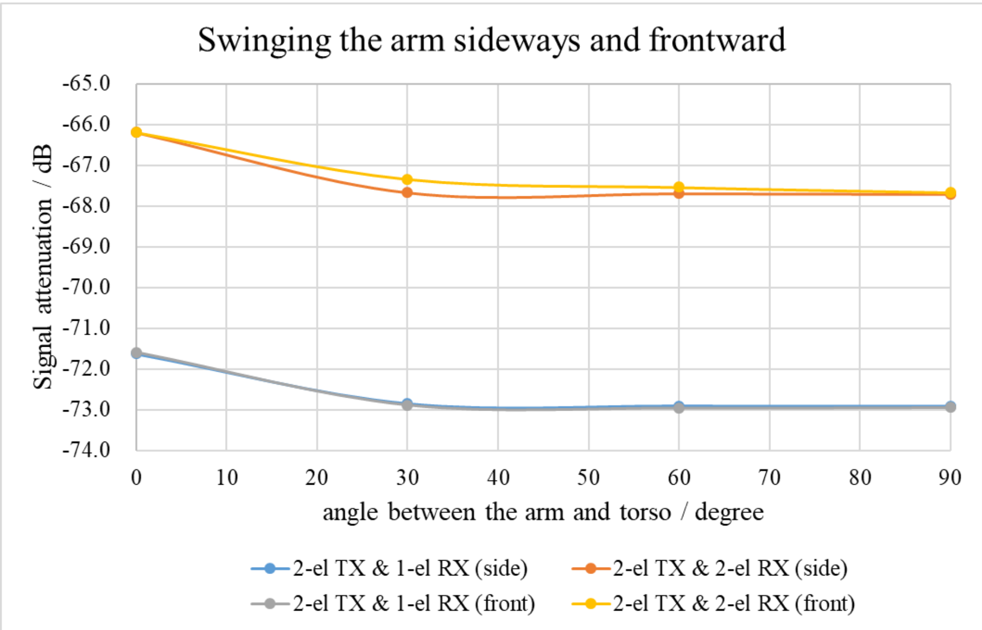


Fig. 4.11 Swinging the arm sideways and frontward

4.4 Conclusion

In this chapter, the influence of the posture including walking and swinging the arm sideways and frontward was discussed.

When the user was walking, the two-electrode receiver worked better at the middle parts of the body and the one-electrode receiver worked better at the ends of the body, which meeted the conclusions in chapter 3.

The coupling between the torso and the wearable devices determined the performance of the transmission when wearing the receiver at the left upper arm. The signal attenuation increased as the angle between the arm and torso increased.

Chapter 5 Evaluation of the number of devices' contacting electrodes according to the anti-noise ability

5.1 Purpose of studying the ability of anti-noise

Security problem is what people pay great attention to when using intra-person HBC. people only want to send information to the person or organization that get their permission. Human body may act as an antenna, and receive a signal which is a signal from another intra-person HBC or an electro-magnetic wave from the environment. So, the signal from the intra-person HBC will be affected when another signal is nearby and is at the same frequency with the transmitted signal which cannot be filtered. The ability that makes the transmission not be easily affected is called anti-noise ability. The ability of anti-noise of the devices with different number of the contacting electrodes is studied in order to improve the safety performance of the intra-person HBC.

In this chapter, evaluation of the number of devices’ contacting electrodes according to the anti-noise ability is conducted by simulation.

5.2 Evaluation according to the simulation

5.2.1 Model of the human body with the noise

Model of the human body with the noise in the environment is shown in Fig. 5.1. The noise is 500 mm away from the transmitter. The frequency of the noise is 21 MHz, which is same with the frequency of the signal sent out by the transmitter. Two metal bars are attached to the noise to help send out the noise. The length of the bar is 300 mm.

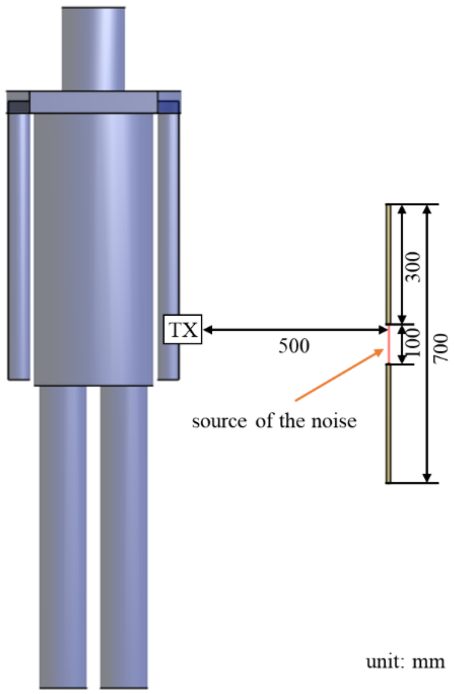


Fig. 5.1 Model of the human body with the noise

5.2.2 Results when the noise is nearby

Evaluation of the number of devices' contacting electrodes according to the anti-noise ability was conducted by the simulation. Meanwhile, the receivers' wearing position was also taken into account.

In order to study the influence of the noise close to the human body, the signal attenuation of the transmission when only the noise was working should be known for comparison. Thus, the situations when only the transmitter was working and when only the noise was working were simulated. The results are shown in Table. 5.1 and Table 5.2 respectively.

Table 5.1 Signal attenuation when the noise is nearby but not working

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	-64.80 dB	-68.14 dB	-56.27 dB	-54.73 dB
B	right upper arm	-87.70 dB	-97.47 dB	-88.92 dB	-87.69 dB
C	right wrist	-86.68 dB	-107.14 dB	-84.20 dB	-94.52 dB
D	chest	-86.90 dB	-98.10 dB	-89.91 dB	-83.53 dB
E	left ear	-90.82 dB	-105.57 dB	-93.02 dB	-99.01 dB
F	right ear	-90.56 dB	-111.90 dB	-96.09 dB	-101.44 dB
G	left ankle	-82.75 dB	-115.55 dB	-79.62 dB	-106.29 dB
H	right ankle	-84.83 dB	-111.98 dB	-83.51 dB	-110.59 dB

From the results in the Table 5.1, it was indicated that the influence of the metal object close to the user could be ignored. As shown in Fig. 5.2, the signal attenuation with and without the switched-off noise were almost overlapped.

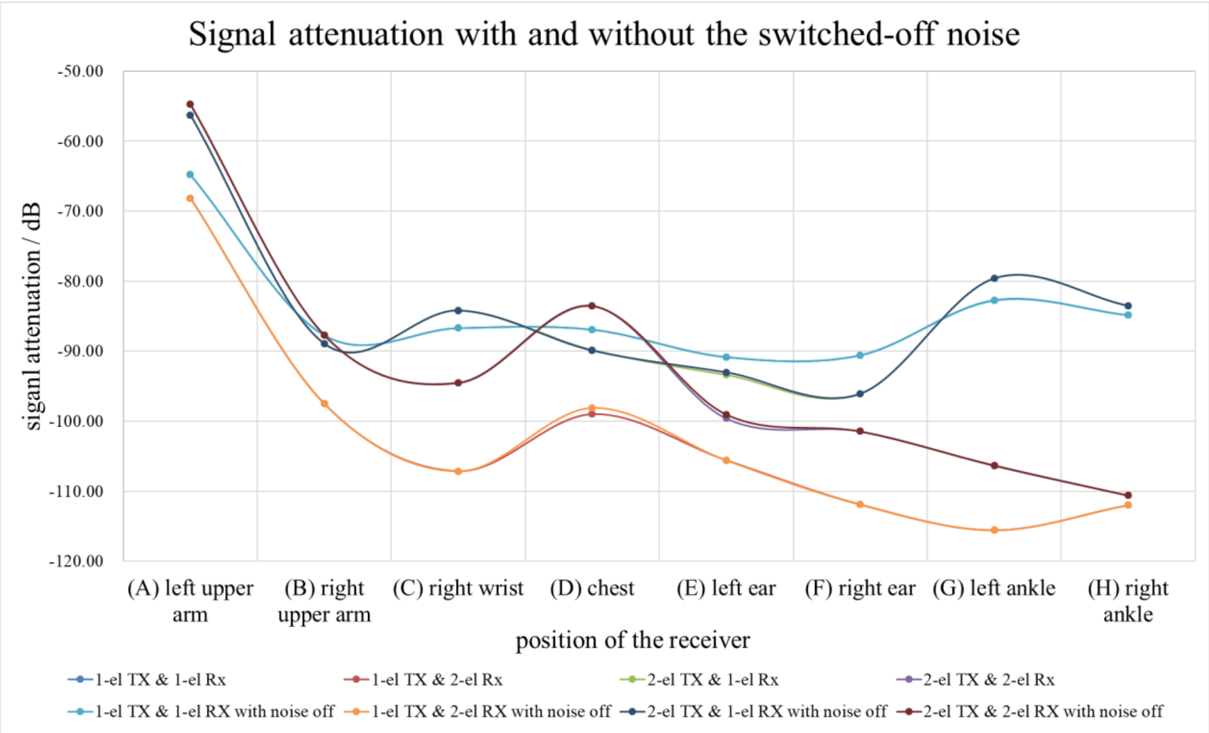


Fig. 5.2 comparison of the signal attenuation with and without the switched-off noise

Table 5.2 Signal attenuation when the noise is nearby and working

label	position of the receiver	1-el TX & 1-el RX	1-el TX & 2-el RX	2-el TX & 1-el RX	2-el TX & 2-el RX
A	left upper arm	-62.43 dB	-85.29 dB	-62.43 dB	-85.28 dB
B	right upper arm	-113.98 dB	-98.79 dB	-113.98 dB	-98.79 dB
C	right wrist	-90.83 dB	-105.41 dB	-90.83 dB	-105.41 dB
D	chest	-81.74 dB	-97.32 dB	-81.74 dB	-97.32 dB
E	left ear	-76.91 dB	-101.02 dB	-76.91 dB	-101.01 dB
F	right ear	-93.99 dB	-102.28 dB	-93.99 dB	-102.28 dB
G	left ankle	-67.67 dB	-108.28 dB	-67.67 dB	-108.26 dB
H	right ankle	-81.02 dB	-103.66 dB	-81.02 dB	-103.66 dB

The results when the nearby noise was working or not in four situations according to the devices' number of contacting electrodes are shown in Fig. 5.3, Fig 5.4, Fig. 5.5 and Fig. 5.6 respectively.

Three phenomena were shown:

(1) The electrode contacting condition of the receiver determined the level of the received signal from the noise when considering the receiver's wearing position.

(2) The two-electrode transmitter and two-electrode receiver situation performed best when there was noise near the user. However, it only worked when the distance between the transmitter and receiver was close.

(3) It was more reasonable to wear the receiver on the right judging by the anti-noise ability when wearing the one-electrode receiver. Right upper arm was the best position, where the signal attenuation was 26.28 dB higher when the noise was switched off. Left ankle and left ear were worst positions, where the signal attenuations were 13.91 dB and 15.09 dB lower when the noise was switched off.

The reasons why these phenomena occurred are explained by the distribution of electric field in next section.

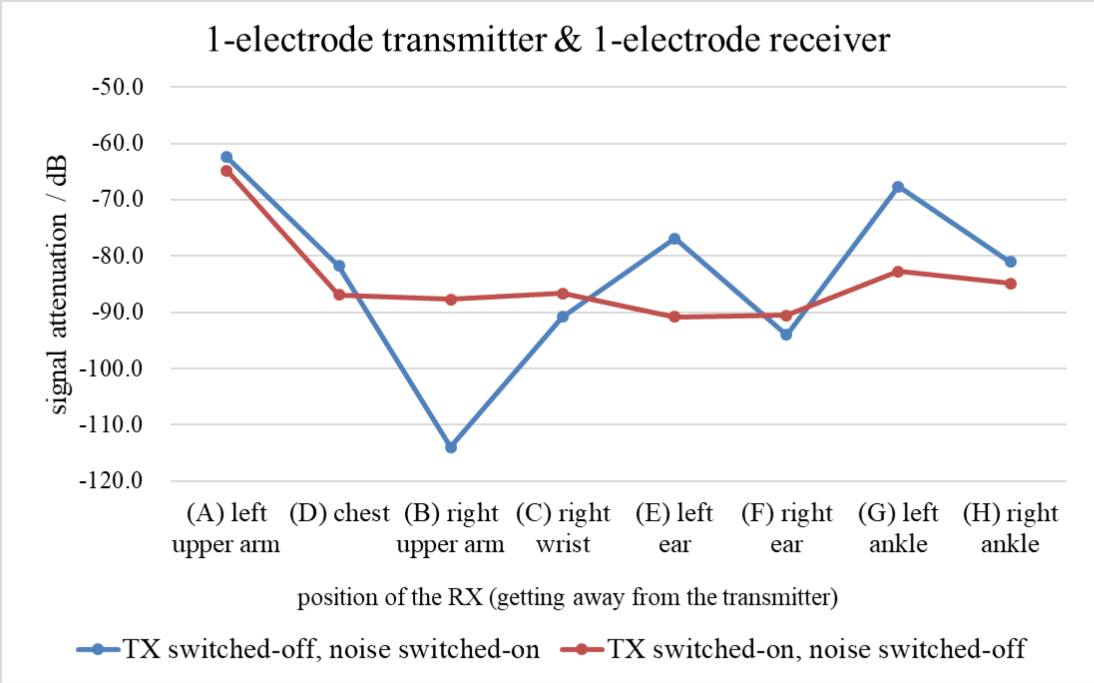


Fig. 5.3 Signal attenuation when wearing the one-electrode transmitter and one-electrode receiver with and without the noise

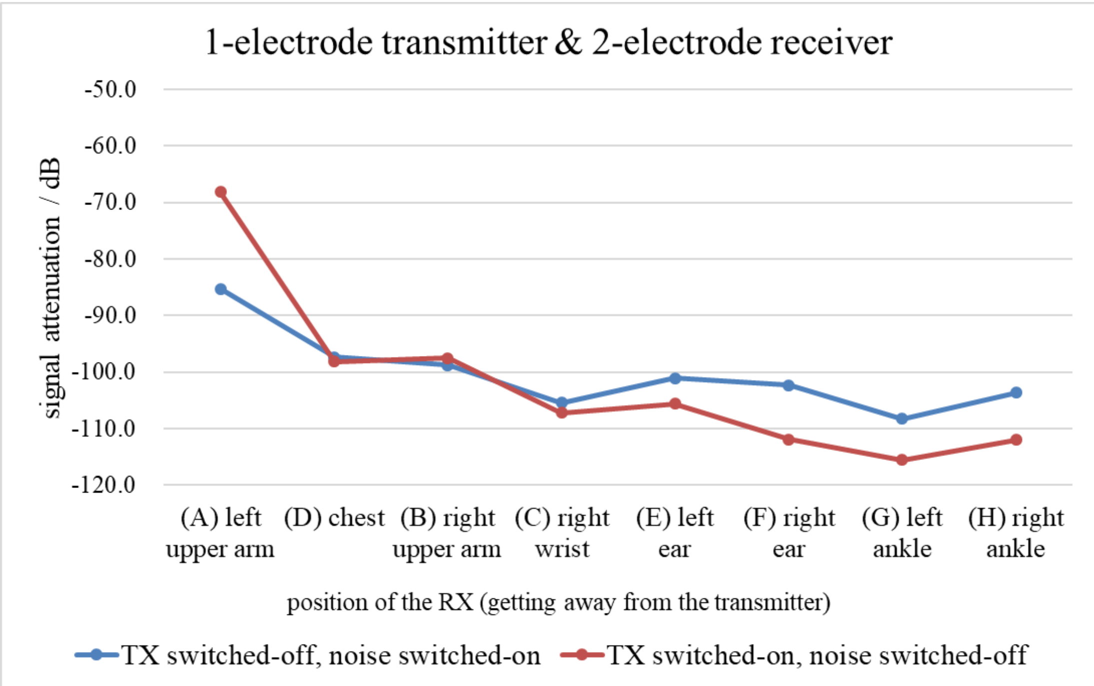


Fig. 5.4 Signal attenuation when wearing the one-electrode transmitter and two-electrode receiver with and without the noise

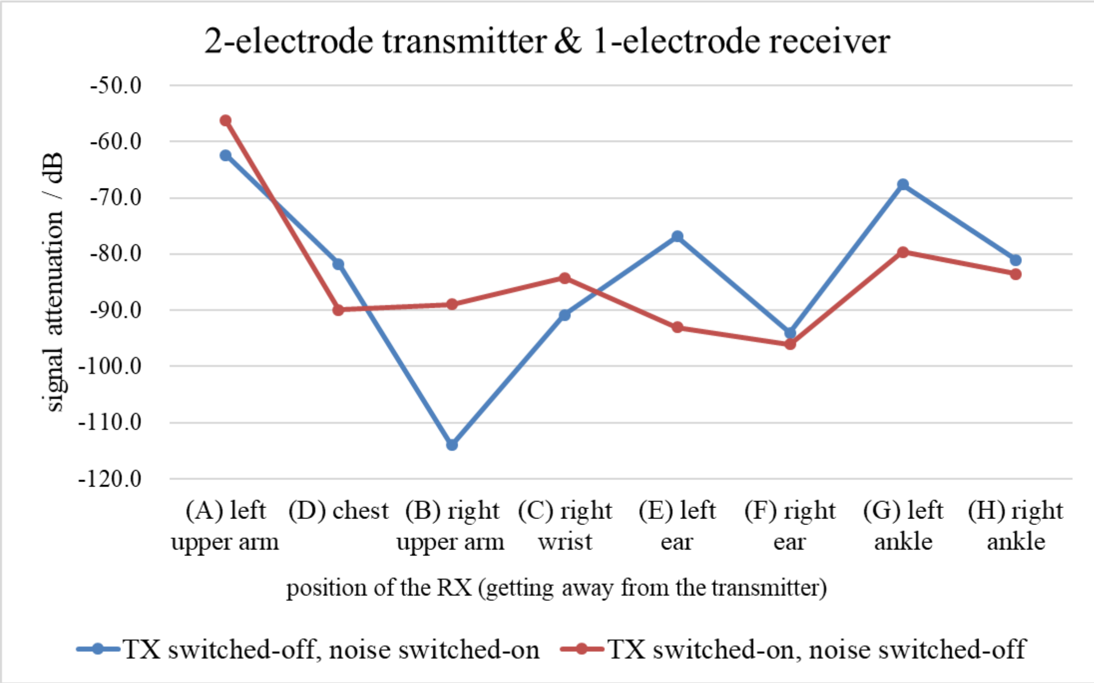


Fig. 5.5 Signal attenuation when wearing the two-electrode transmitter and one-electrode receiver with and without the noise

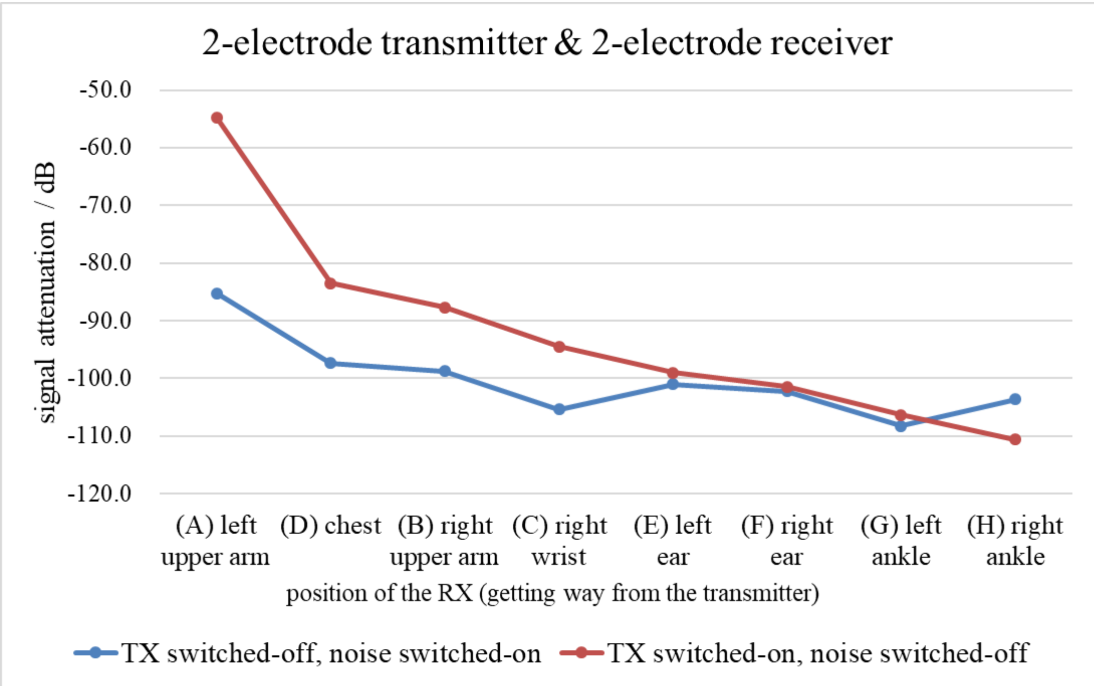
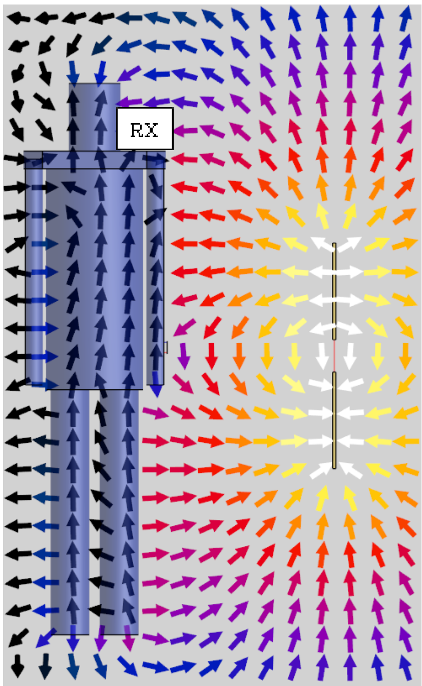
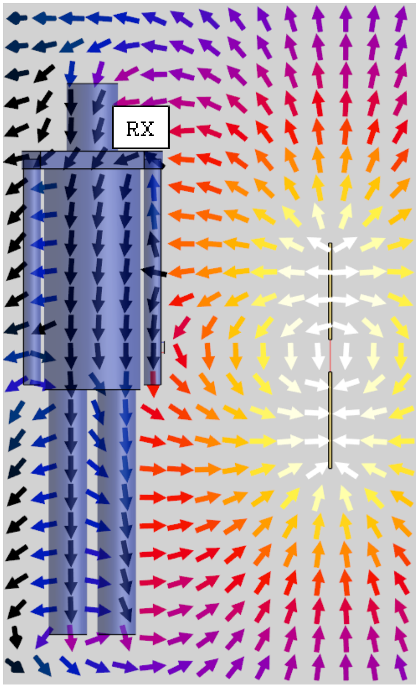


Fig. 5.6 Signal attenuation when wearing the two-electrode transmitter and two-electrode receiver with and without the noise

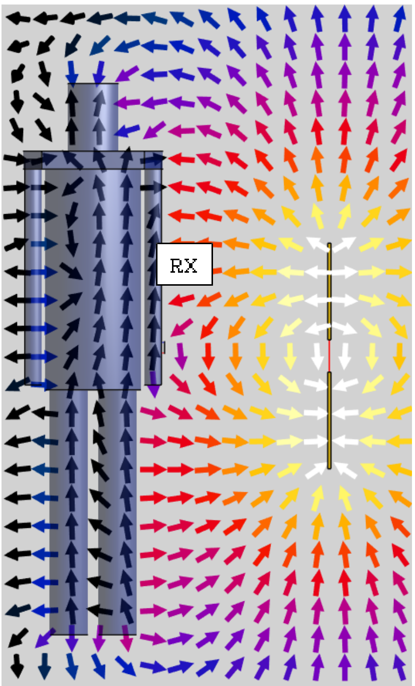
5.2.3 Analysis on electric field distribution

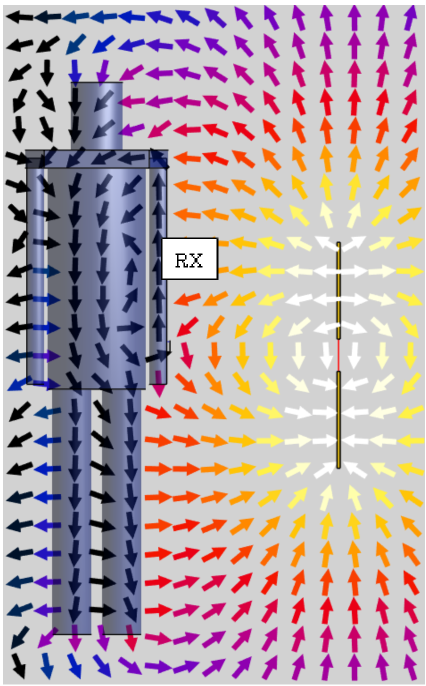
Firstly, the noise was transmitted through the air regardless of the wearing position of the receiver and the electrode contacting condition of the devices, as shown in Fig. 5.7.

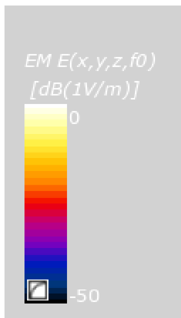




(a) 1-el transmitter and 1-el receiver **(b) 1-el transmitter and 2-el receiver**







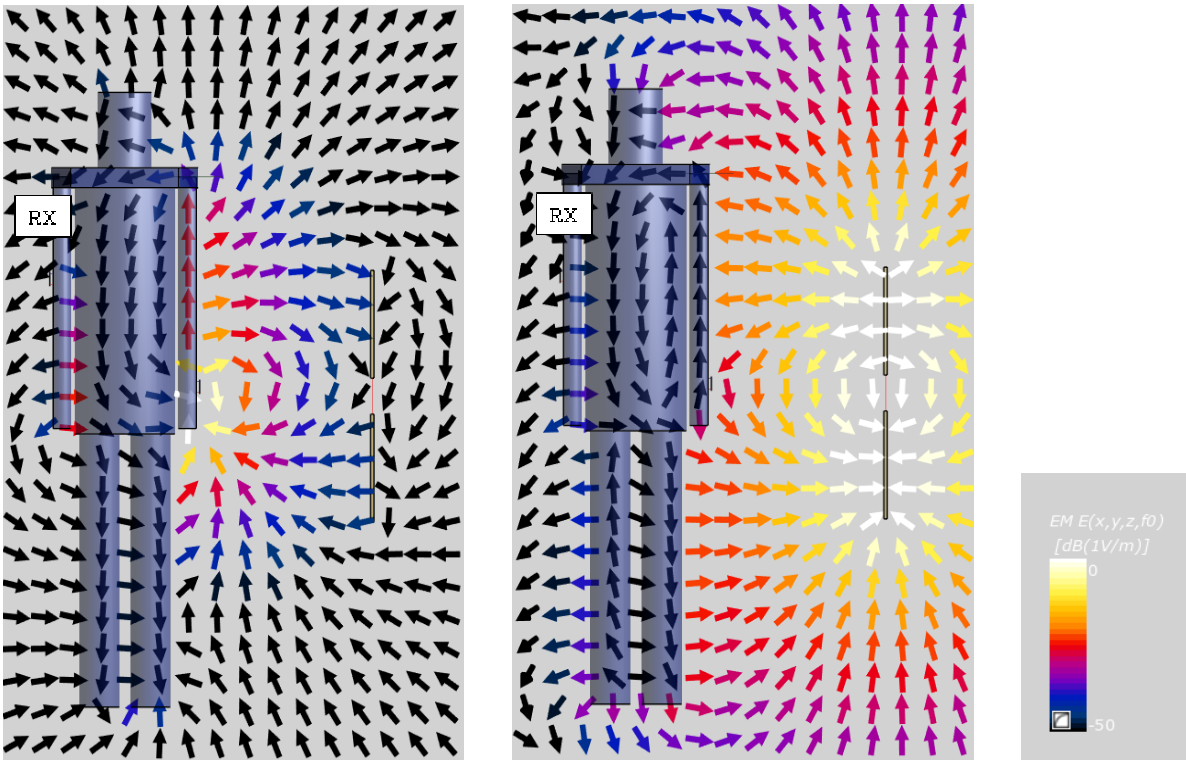
(c) 1-el transmitter and 1-el receiver **(d) 1-el transmitter and 2-el receiver** **(e) Scale of color bar**

Fig. 5.7 Electric field distribution when the noise is nearby

Besides, the two-electrode receiver received more signal from the body compared to the one-electrode receiver. As mentioned in chapter 3, when wearing the two-electrode receiver, the ground electrode attached to the skin made part of the body function as the ground. Thus, the electrode contacting condition of the receiver determined the level of the received signal from the noise when considering the receiver's wearing position.

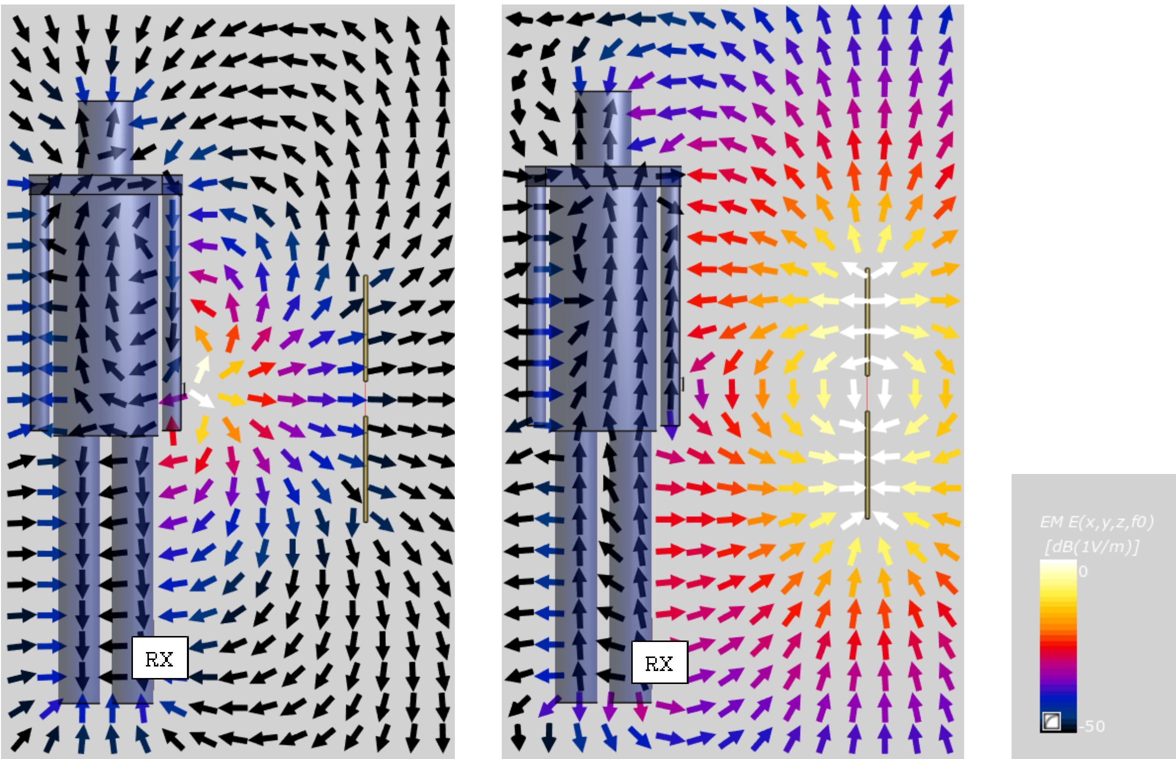
Secondly, it was more difficult to tell apart the signal from the noise and the signal from the one-electrode receiver. When wearing the two-electrode transmitter, the signal tended to return to the body. While, when wearing the one-electrode transmitter, the signal partly dispersed to the air around the human body. Therefore, the situation when wearing two-electrode transmitter and two-electrode receiver performed best when there was noise near the user.

Thirdly, the signal of the noise decreased as the transmission distance increased. In intra-person HBC, the transmitter and the receiver were attached to the human body, and the body was utilized to transmit the signal. However, the noise from the environment was 500 mm away from the transmitter worn at the left wrist, and it was further away from the right part of the body. Thus, the right part of the body was less vulnerable to the noise, as shown in Fig. 5.7 and Fig. 5.8.



(a) Noise is switched off **(b) Noise is switched on** **(c) Scale of the color bar**

Fig. 5.7 When wearing the one-electrode receiver at the right upper arm



(a) Noise is switched off **(b) Noise is switched on** **(c) Scale of the color bar**

Fig. 5.8 When wearing the one-electrode receiver at the left ankle

5.3 Conclusion

In this chapter, the evaluation of the number of devices' contacting electrodes according to the anti-noise ability was discussed.

The situation when wearing the two-electrode transmitter and two-electrode receiver had the best anti-noise ability. Signal sent out from the two-electrode transmitter tended to return to the body, which decreased the attenuation of intra-person HBC. And the two-electrode receiver was more dependent of the coupling between the body and the device. Therefore, it was less affected by the noise when wearing the two-electrode transmitter and two-electrode receiver.

The communication was easily affected by the noise when it was close to the receiver when wearing the one-electrode receiver. Signal of the noise was decreased as the transmission distance increased. Thus, the one-electrode receiver was less vulnerable to the noise when it was far away from the noise.

Chapter 6 Conclusion and future work

6.1 Results and conclusion

In this study, analysis and evaluation of transmission characteristics of the intra-person HBC was conducted. The influence of the number of contacting electrodes of the transmitter and the receiver was discussed by the electric field analysis according to the devices' wearing position, user's posture and the anti-noise ability.

Conclusions are as follows.

(1) Wearing position of the receiver

- Influence of wearing position

Comparison of the received signal levels at 8 wearing positions has shown that the influence of the wearing position on the one-electrode receiver was less than that on the two-electrode receiver. The maximum received signal difference was 39.82 dB for the one-electrode receiver and 55.86 dB for the two-electrode receiver.

- Body shape of the wearing position

One-electrode receiver worked better at the extremity of the human body such as right wrist, left ear, right ear, left ankle, and right ankle. On the other hand, two-electrode worked better at the middle part of the human body, such as left upper arm, right upper arm, and chest.

- Received signal variation

When wearing the two-electrode receiver, the received signal decreased as the distance between the transmitter and the receiver increased. On the other hand, variation of the received signal was small for one-electrode receiver.

(2) User's posture

Influence of the user's posture such as walking and swinging the arm was evaluated.

- Body shape of the wearing position

The characteristics were the same as that of the standing situation. The two-electrode receiver worked better at the middle part of the body and the one electrode receiver worked better at the extremity of the body.

- Influence of the swinging direction of the arm

The received signal was more dependent of the coupling between the arm and torso when swinging the arm sideways or frontward. The received signal decreased as the angle between the arm and torso increased, but it did not change much when the angle was over 40 º. Besides, the received signal attenuated slower when swinging forward compared to swinging sideways.

(3) Anti-noise ability

The electrode contacting condition of the receiver determined the level of the received signal from the noise when considering the receiver's wearing position.

The two-electrode transmitter and two-electrode receiver situation performed best when there was noise near the user. However, it only worked when the distance between the transmitter and receiver was close.

It was more reasonable to wear the receiver on the right judging by the anti-noise ability when wearing the one-electrode receiver. Right upper arm was the best position, where the signal attenuation was 26.28 dB higher when the noise was switched off. Left ankle and left ear were worst positions, where the signal attenuations were 13.91 dB and 15.09 dB lower when the noise was switched off.

Electric field distributions around the human body, transmitter and receiver were analyzed to explain the results above.

The ground electrode contact with the body made part of the human body function as the ground. Thus, the signal tended to return to the body close to the transmitter when wearing the two-electrode transmitter.

The ground electrode and the wire contacting the floating ground made the transmission dependent on the coupling between the body and the receiver. Therefore, the two-electrode receiver is more affected by the wearing position.

The situation when wearing the two-electrode transmitter and two-electrode receiver had the best anti-noise ability because of the characteristics above.

In previous research, the influence of the wearing position was not investigated. In this study, it was found that the transmitter and receiver with different numbers of contacting electrodes did have various characteristic according to the wearing position. Devices of higher efficiency and higher security for intra-person HBC were found by this research. The conclusions of this paper are useful to the design of the transmitter and receiver.

6.2 Future work

In this study, transmission characteristic of intra-person HBC by the number of contact electrodes of transmitter and receiver was analyzed and evaluated. Simulations and experiments showed that the contacting electrode condition of the receiver determined the level of the received signal: one-electrode receiver was suitable for the extremity of the body; two-electrode receiver was suitable for the middle part of the body. Considering the anti-noise ability, wearing the two-electrode transmitter and two-electrode receiver had the best performance.

However, not only the number of the contacting electrodes of the devices for intra-person HBC needs to be studied, that for the HBC among several users and HBC between the user and stationary device also need further investigation.

Moreover, in this study, the influence of the noise from the environment is only investigated by the simulation. Therefore, the experiment such as artificially producing 21 MHz noise during the measurement needs to be included. Additionally, electrode arrangement which can resist the noise from other HBC users or devices needs to be investigated.

Furthermore, measurement method needs to be improved for measuring weak signals.

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Research achievements

(B-) Domestic Conferences

(1) Senlian Sang, Kentaro Yamamoto, Ken Sasaki, Hiroshi Hosaka, 'Electromagnetic Field Analysis of Electrode Conact Conditions and Transmission Characteristics in Human Body Communication', Transdisciplinary Federation of Science and Technology 9^{th}, Tokyo, Oct. 2018.

(2) Senlian Sang, Ken Sasaki, Kentaro Yamamoto, 'Research of wearing position and equipment condition of intra-person human body communication for low power consumption', The Japan Institute of Electronics Packaging 34^{th}, 3C3-03, Kanagawa, Mar. 2020.

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