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Study on the Transmission Mechanism for Wearable Device Using the Human Body as a Transmission Channel

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SUMMARY Recently, wearable devices which use the human body as a transmission channel have been developed. However, there has been a lack of information related the transmission mechanism of such devices in the physical layer. Electro-magnetic communication trials using human body as transmission media have more than a decade's history. However, most of the researches have been conducted by researchers who just want to utilize the fact and practically no physical mechanisms have been researched until recently. Hence, in previous study, the authors proposed calculation models of the wearable transmitter and the receiver attached to the arm using the FDTD method. Moreover, the authors compared the calculated received signal levels to the measured ones by using a biological tissue-equivalent phantom. However, there was little analysis on each component of the propagated signal. In this paper, the authors clarified the transmission mechanism of the wearable device using the human body as a transmission channel from the view point of the interaction between electromagnetic wave and the human body. First, the authors focused their attention on measuring the each component of the propagated signal using a shielded loop antenna. From these results, the favorable direction of electrodes of the transmitter was proposed to use the human body as a transmission channel. As a result, longitudinal direction is effective for sending the signal to the receiver, compared to the transversal direction. Next, the authors investigated the dominant signal transmission channel, because the question of whether the dominant signal channel is in or around the arm had remained unsettled. To clear this question, the authors proposed the calculation model of an arm wearing the transmitter and receiver placed into a hole of a conductor plate. The electric field distribution and received signal voltage was investigated as a function of the gap between the hole of the conductor plate and the surface of the arm. The result indicated that the dominant signal transmission channel is not inside but the surface of the arm because signal seems to be distributed as a surface wave.

key words: *personal area network, intra-body communication, human body, phantom, FDTD*

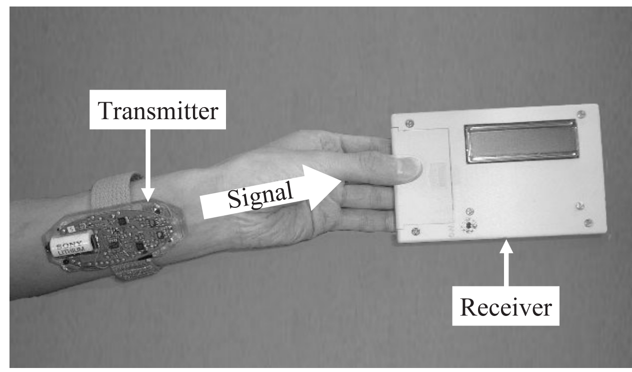

Fig. 1 Transmission system using the human body as a transmission channel.

1. Introduction

As cellular phones, personal digital assistants (PDAs), digital video cameras, pocket video games, and other information and communication devices become smaller and more widespread, we have begun to adorn our bodies with these appliances and the opportunities to use these small computers have been increased in our everyday lives. We can say with fair certainty that miniaturization of these devices will evolve, and we will meet the ubiquitous computing society [1]. However, currently there is no method for these personal devices to exchange data directly. If these devices are wire-connected, it is clearly impractical because they easily become tangled, so some sort of short-range wireless technology is required. The concept for networking these personal devices has been proposed as Personal Area Networks (PANs) which uses the human body as a transmission channel [2]. Although many studies have been made on the development of wearable devices using the human body as a transmission channel, little is known about the transmission mechanism of such devices in the physical layer [2]–[9].

Figure 1 shows an example of communication system of the PANs. When a user wearing the transmitter touches the electrode of the receiver, a transmission channel is formed using the human body. In this case, the receiver recognizes the user's ID and it can be personalized. The merit of this system is that the data is exchanged through daily natural actions, such as simply touching the receiver. This communication system uses the near field region of the electromagnetic wave generated by the device which is eventually coupled to the human body by electrodes. Hence, the structure of electrodes is one of the key issues for the transmission using human body.

In previous study, the authors proposed some calculation models of the transmitter and the receiver attached to the arm using the FDTD method to clarify the transmission

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mechanism [10], [11]. From them, the authors estimated the difference in the received signal level due to the electrode structures of the transmitter under various conditions. Moreover, in order to verify the validity of these calculation models, the calculated received signal levels were compared to the measured ones by using a biological tissue-equivalent phantom. The result showed a good agreement between calculated and measured received signal levels. In addition, it was found that the GND electrode of the transmitter attached to the arm strengthens the generated electric field around the arm. However, there was little analysis on each component of the propagated signal.

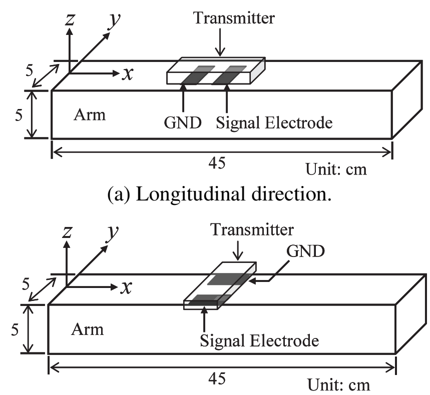
In this paper, the authors clarified the transmission mechanism of the wearable device using human body as a transmission channel from the view point of the interaction between electromagnetic wave and the human body. First, the authors focused their attention on measuring the each component of the propagated signal using a shielded loop antenna. Moreover, in order to clarify the validity of the measurement, the authors compared the measured data to the calculated ones. Then the authors considerated the current distribution inside the arm from each component of the distributed signal. From these results, the favorable direction of electrodes of the transmitter for using the human body as a transmission channel was proposed.

After the validity of this calculation model was demonstrated, the authors clarified the dominant signal transmission channel, because the question of whether the dominant signal channel was in or around the arm still remained unsettled. To clear this question, the authors proposed the calculation model of an arm wearing the transmitter and receiver placed into a hole of a conductor plate. The electric field distribution and received signal voltage was investigated as a function of the gap between the hole of the conductor plate and the surface of the arm when signal passed through the hole made in the conductor plate. If the dominant signal channel is around the arm, the received signal is not generated when the gap between the conductor plate and surface of the arm does not exist. On the other hand, if the dominant signal channel is inside the arm, the received signal is generated in the same condition.

2. Investigation of the Signal Propagation in Relation with the Direction of the Electrodes of the Transmitter

2.1 Measurement of the Magnetic Field Distributions

In this part, the authors investigate each component of magnetic field around the arm in relation with the direction of electrodes of the transmitter. The reason of measuring the magnetic field is that it is difficult to measure the each component of the electric field around the arm precisely. For the measurement, a shielded loop antenna with a diameter of 1 cm is used. Figure 2 shows the condition of the measurement for the various components of the magnetic field distribution. The transmitter has two electrodes. One is the signal electrode to feed an excitation signal (3 V_{p-p}, Sine wave of 10 MHz), and the other is GND electrode which is connected to the ground level of the electrical circuit [11]. The direction of the transmitter is changed according to two patterns to compare the magnetic field distributions. One is the longitudinal direction shown in Fig. 2(a), the other one is the transversal direction shown in Fig. 2(b). In addition, the conventional distance between signal electrode and GND electrode was 4 cm [11]. However, the distance between signal electrode and GND electrode is closed up to 1 cm not to stick out of the width of the arm. The experimental muscle-equivalent phantom used for the arm, which is modeled by a rectangular parallelepiped (5 cm × 5 cm × 45 cm) has the relative permittivity ε_r set to 81 and the conductivity σ set to 0.62 S/m. Although, the relative permittivity of the muscle at 10 MHz equals 170.73 [12], the authors have verified that they can use this phantom from the reference [11]. Because the received signal voltage is almost same. The reason of using the phantom whose relative permittivity ε_r equals 81 as a substitute for the ε_r equals 170.73 comes from the difficulty of making a phantom with such a high relative permittivity. Moreover, in the same reference, the authors investigated the electric field distribution around the whole body model wearing the transmitter and found electric field concentrates around the arm. Hence, only arm model can be evaluated in this paper.



(a) Longitudinal direction.

(b) Transversal direction.

Fig. 2 Direction of the transmitter attached to the arm.

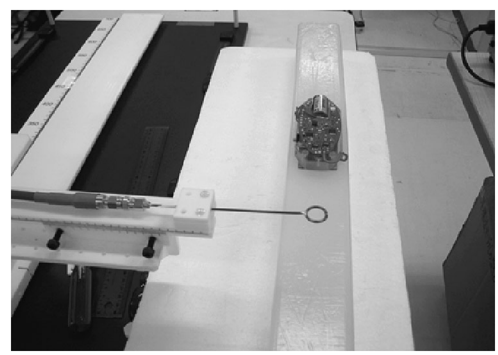
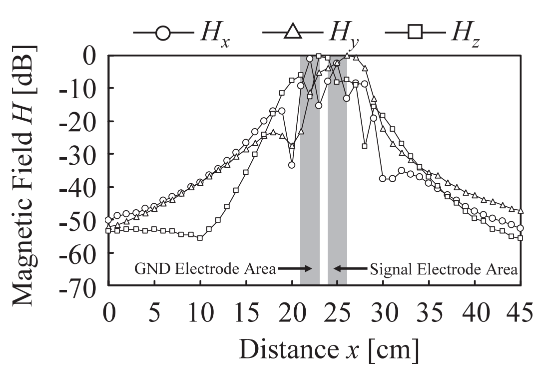


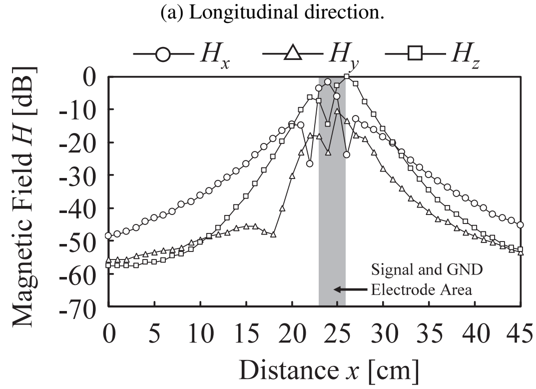
Fig. 3 Setup for measurement.

Figure 3 shows the experimental setup for measurement to enhance the accuracy of the measurement position. For the shielded loop antenna, a coaxial cable and copper wire with a diameter of 1.6 mm are used. At the tip of the antenna, a 0.5 mm gap is constructed to generate the received signal voltage. A spectrum analyzer and a power amplifier are also used. The shielded loop antenna is set 3 cm above the surface of the arm and the magnetic field distributions are measured along the x axis at y=0 and z=3 cm.

Figure 4 shows the various components of the magnetic field distribution around the arm with the transmitter. The level of each point is normalized by the value of H_z at x=26 cm in Fig. 4(b), which is the maximum value of all measured data in Fig. 4. In the case of the transmitter set to the longitudinal direction in Fig. 4(a), from Ampère's law, the dominant current distribution inside the arm is the x component because H_y component is stronger compared to the H_x and H_z components near the tip of the arm (x=30 to 45 cm). On the other hand, in the case of the transmitter attached to the transversal direction in Fig. 4(b), the dominant current distribution inside the arm is the y component because the H_x and H_z components are stronger than the H_y components near the tip of the arm (x=30 to 45 cm). From what has been discussed above, it can be concluded that the direction of the dominant current distribution inside the arm is the same as the direction of the electrodes of the transmitter, because the current is formed between signal electrode and GND electrode.



(a) Longitudinal direction.

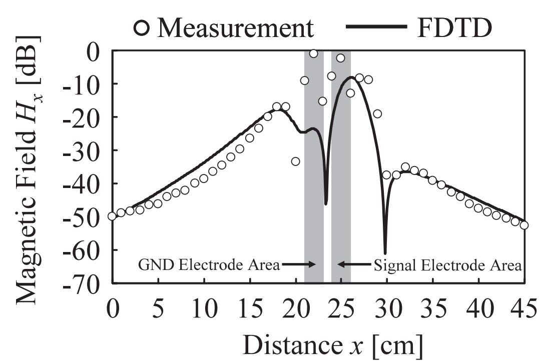


(b) Transversal direction.

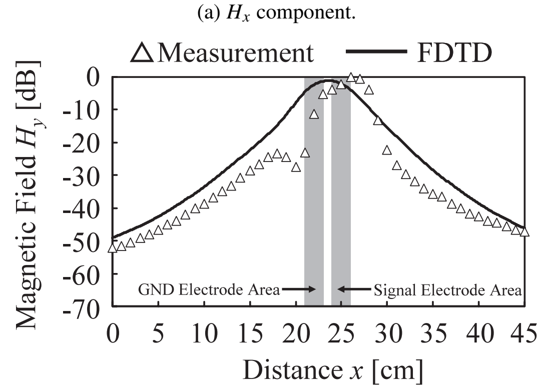
Fig. 4 Measured magnetic field distributions around the arm with the transmitter.

2.2 Comparison between Measured and Simulated Magnetic Field

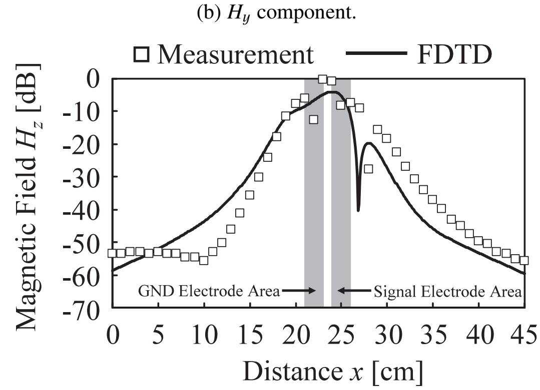
Figures 5 and 6 indicate the comparison between measured and simulated magnetic field by the use of the FDTD method to show the validity for the measurement. These figures show the transmitter set to the longitudinal direction and transversal direction, respectively. In the FDTD calculation, two electrodes and circuit board of the transmitter are modeled as perfect conductor sheets [11]. The sizes of the electrodes are 2 cm × 3 cm and the size of the circuit board is 8 cm × 3 cm. The numerical muscle-equivalent phantom used for the arm has the relative permittivity ε_r set to 81 and the conductivity σ set to 0.62 S/m. The size of the cells is $\Delta x = \Delta y = \Delta z = 1$ mm. The absorbing boundary condition is the Liao, and the time step is 1.92 ps to satisfy the



(a) H_x component.

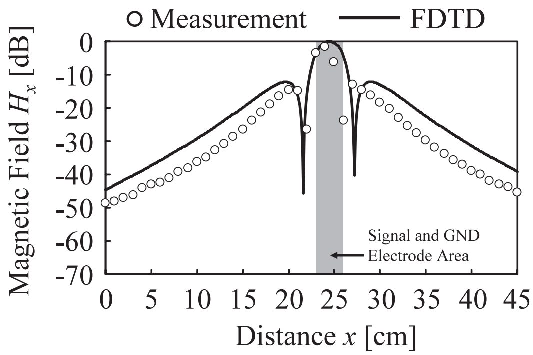


(b) H_y component.

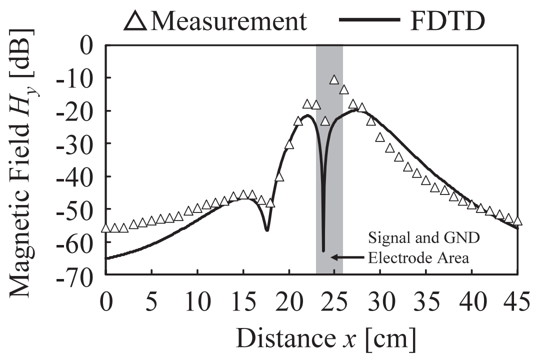


(c) H_z component.

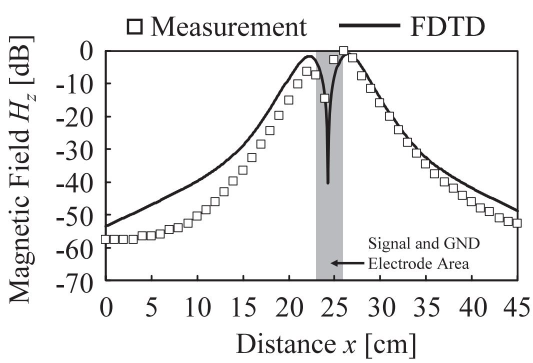
Fig. 5 Longitudinal direction.



(a) H_x component.



(b) H_y component.



(c) H_z component.

Fig. 6 Transversal direction.

Courant stability condition. In Fig. 5 and 6, all the simulated data are normalized by the value of H_x at x=24.5 cm in Fig. 6(a), which is the maximum value of all the simulated data in Fig. 5 and Fig. 6.

To discuss the difference between measured and calculated magnetic field, Eq. (1) is defined

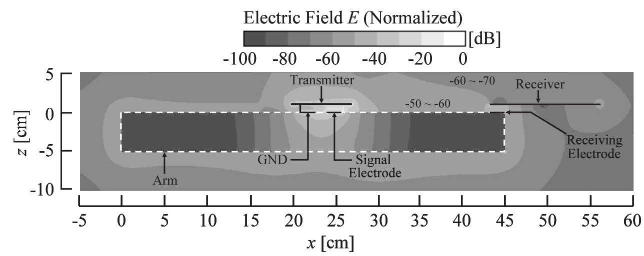
$$Difference = \sqrt{\frac{1}{x_2 - x_1}\int_{x_1}^{x_2}\{H_{Meas.}(x) - H_{FDTD}(x)\}^2 dx} \quad (1)$$

where the $H_{Meas.}(x)$ and $H_{FDTD}(x)$ indicate the measured and calculated magnetic field, respectively. x_2 and x_1 equal 45 cm and 0 cm, respectively. Table 1 shows the difference between $H_{Meas.}(x)$ and $H_{FDTD}(x)$ by using Eq. (1).

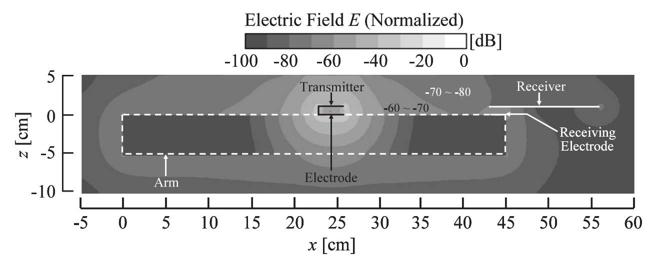
From Table 1, all the differences of Fig. 5 and Fig. 6 are almost less than 7 dB. As the dynamic range for the measurement is about −55 dB, these differences is arisen. However, the rate of decrease and the null point as a function of the distance x is generally fit. From this view point, the authors can relatively compare the each component of the magnetic field distribution that indicates validity in both the FDTD and measurement.

Table 1 Difference between measured and calculated magnetic field distributions.

	Fig. 5			Fig. 6		
	(a)	(b)	(c)	(a)	(b)	(c)
Difference [dB]	6.7	7.0	7.2	7.0	5.4	6.5



(a) Longitudinal direction.



(b) Transversal direction.

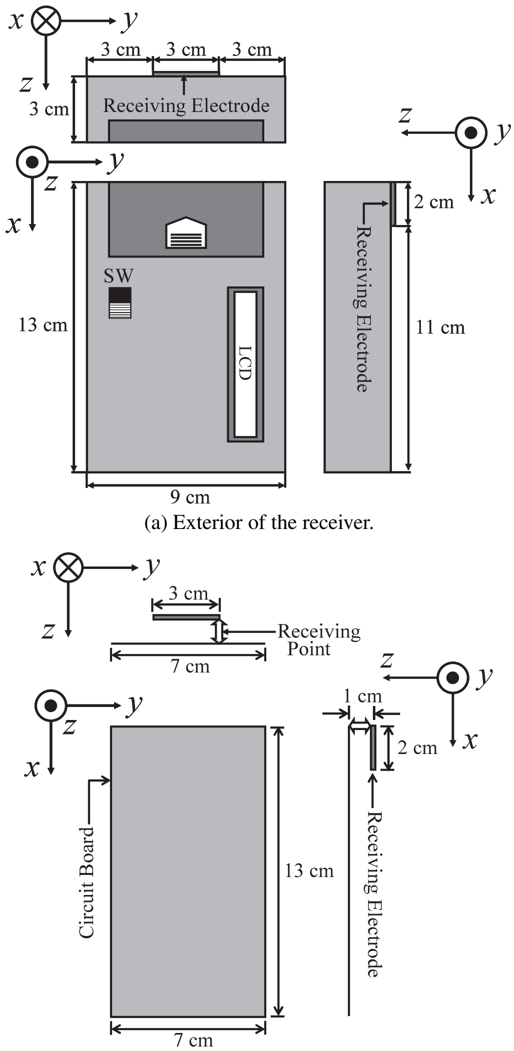
Fig. 7 Electric field distributions in and around the arm with the transmitter and receiver.

2.3 Electric Field Distributions in and around the Arm

Figure 7 illustrates the electric field distributions (root-sum-square) of both directions of the electrodes of the transmitter. The reason of discussing the electric field distribution is that the received signal voltage of the receiver is calculated from the electric field. Thus, the argument from the view point of the electric field is essential.

The structure of the receiver is illustrated in Fig. 8. The receiver has a receiving electrode and LCD that can indicate the received signal voltage directly [11]. The reason of no GND electrode is that the existence of the GND electrode for the receiver reduces the received signal voltage [10]. Hence, there is no optimal direction of the receiver because the receiver has only one electrode. Figure 8(b) is the FDTD calculation model of the receiver. The receiving electrode and the circuit board are modeled as perfect conductor sheets. The received signal voltage is calculated from the electric field at the receiving point. Therefore, this receiver does not detect the magnetic field but the electric field.

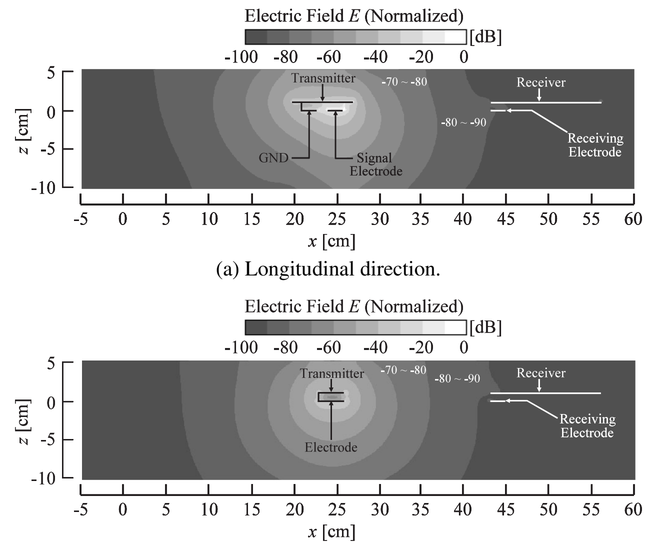
The distance between the transmitter and receiver is



(a) Exterior of the receiver.

(b) FDTD calculation model.

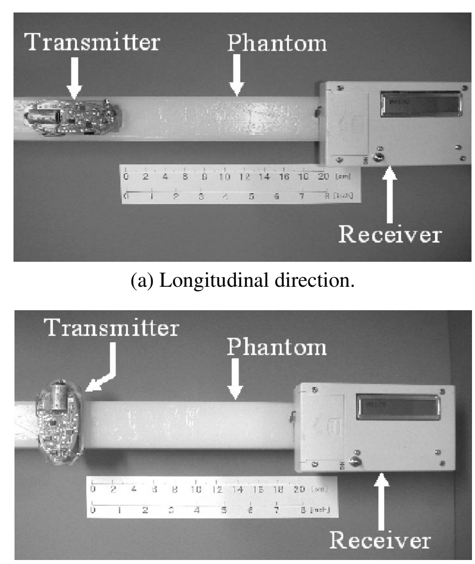
Fig. 8 Structure of the receiver.



(a) Longitudinal direction.

(b) Transversal direction.

Fig. 9 Electric field distributions without arm.



(a) Longitudinal direction.

(b) Transversal direction.

Fig. 10 Measurement condition of the received signal voltage.

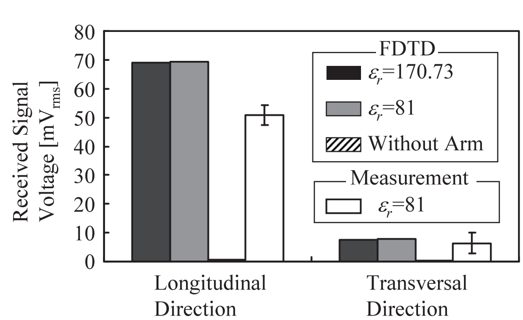


Fig. 11 Received signal voltage.

fixed to 17 cm because the transmitter is located at the center of the arm and the receiver is also located at the tip of the arm. The observation plane is the x-z plane including the receiving point of the receiver. The electric field is normalized to the value at the feeding gap. In the case of the longitudinal direction of the transmitter in Fig. 7(a), the electric field is propagated along the surface of the arm (−50 to −60 dB). However, in Fig. 7(b), the level of the electric field on the surface of the arm seems low (−60 to −70 dB) and the electric field is not propagated along the surface of the arm and it is radiated on the upper side of the arm. So, this result means disadvantage for practical use compared to the Fig. 7(a) in terms of the higher signal reception. In addition, Fig. 9 indicates the electric field distribution without the arm to show the validation of using human body as a transmission channel. The loss of the electric field at the receiving point is quite large (less than −80 dB) compared to the Fig. 7. The authors can conclude that this transmission system uses the human body as a transmission channel.

Below is a physical meaning of the difference between Fig. 7(a) and Fig. 7(b). As shown in Fig. 4(a), dominant current distribution is the x component when the transmitter is set to the longitudinal direction. Hence, electric field is distributed along the length of the arm (x direction). On the other hand, as shown in Fig. 4(b), dominant current distribution is the y component when the transmitter is set to the transversal direction. Hence, electric field is not distributed along the x direction. Consequently, the difference of the current distribution causes the difference of the electric field distribution.

2.4 Received Signal Voltage of the Receiver

The pictures shown in Fig. 10 are the measurement conditions of the received signal voltage according to the direction of the electrodes of the transmitter. In order to verify the validity of the calculation models, we compared the received signal voltages by the calculation to the measured ones by using a biological tissue-equivalent phantom. In Fig. 10(a), the transmitter is attached in the longitudinal direction. On the other hand, Fig. 10(b) indicates the transversal direction.

Figure 11 shows the comparison between the measured received signal voltages and the calculated ones. The result shows a good agreement of the calculated and measured received signal levels that indicates a considerable validity in both the FDTD and measurement. When compared to the received signal voltage of the longitudinal direction, the one of the transversal direction drops of nearly 10 percents. Moreover, the received signal voltages without arm is almost zero. So, the transmission system using the human body as a transmission channel has advantage over those using airborne radio waves. Regarding the difference of the relative permittivity, the received signal voltages are almost same. Hence, it is appropriate to use the phantom with ε_r set to 81 as a substitute for the ε_r set to 170.73.

As a conclusion, longitudinal direction is effective for sending the signal to the receiver, compared to the transversal direction. These investigations have made it clear that we can use the human body as a transmission channel effectively by flushing the current along the length of the arm.

3. Investigation of Dominant Signal Transmission Channel

3.1 Calculation Model

In this section, the authors investigate the dominant signal transmission channel, because the question of whether the dominant signal channel is in or around the arm still remains unsettled. To clear that question, the authors proposed a calculation model of an arm wearing the transmitter and receiver placed into a hole of a conductor plate. Figure 12 shows the calculation model of the arm with the transmitter and receiver using the FDTD method. The size of the conductor plate d is infinity because it is attached to the absorbing boundary of the FDTD. The size of the cells is $\Delta x = \Delta y = \Delta z = 1$ mm. The absorbing boundary condition is the Liao, and the time step is 1.92 ps to satisfy the Courant stability condition. The distance between signal electrode and GND electrode was set to the conventional size (4 cm) [11]. By using this model, the electric field distribution and the received signal voltage is investigated as a function of the gap g between the hole of the conductor plate and the

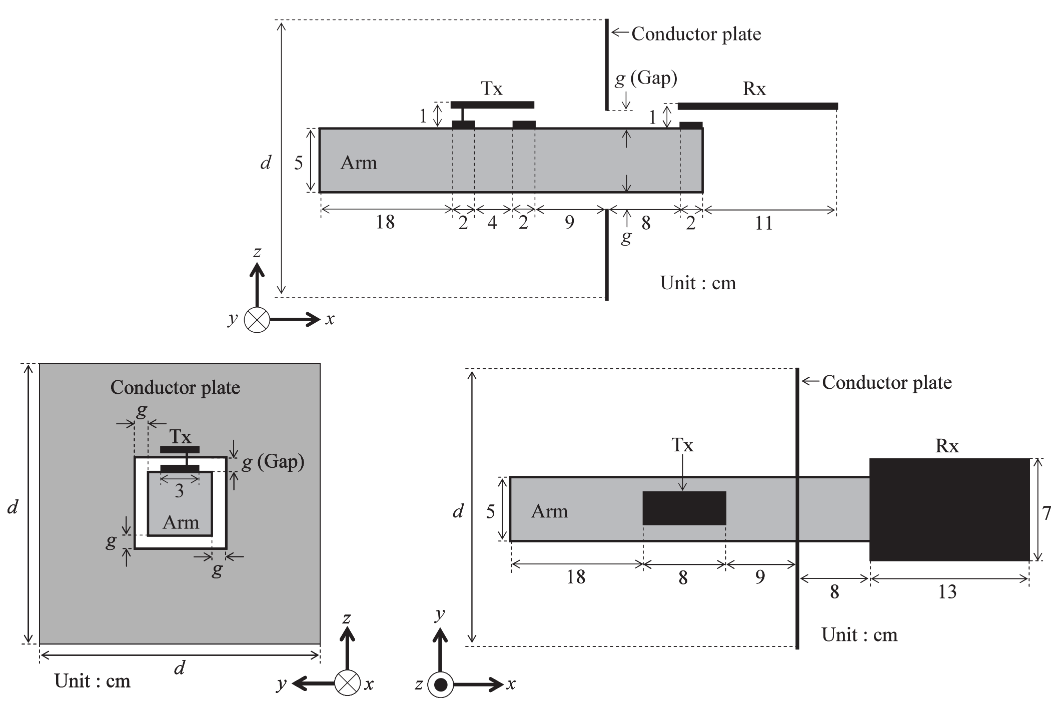


Fig. 12 Calculation model.

surface of the arm. The reason of discussing the electric field distribution in this section is that the received signal voltage of the receiver is calculated from the electric field. Thus, the argument from the view point of the electric field is essential.

3.2 Electric Field Distributions and Received Signal Voltage

Figure 13 illustrates the electric field distributions (root-sum-square) in and around the arm. The observation plane is the *x*-*z* plane and *y* plane includes the receiving point. The electric field is normalized to the value at the feeding gap. Figs. 13(a), (b) shows the distributions when the gap g is -1 mm and 0 mm, respectively. It can be seen that the electric field is not propagated toward the receiver but reflected at the point of the conductor plate. However, in Figs. 13(c)–(f), as the gap g between conductor plate and the surface of the arm becomes wider, the electric field is more propagated toward the receiver.

Figure 14 shows the comparison between the measured received signal voltages and the calculated values as a function of the gap g. To measure the received signal voltages, the conductor plate with a size of 200 cm × 200 cm is used (d = 200 cm). When the size of the gap g is -1 mm and 0 mm, the received signal voltage is almost zero. However, as the gap g between conductor plate and surface of the arm becomes wider, the received signal voltage rises sharply. Moreover, the result shows a good agreement of the calculated and measured received signal levels that indicates a considerable validity in both the FDTD and measurement. The reason of the difference of the received signal voltage between longitudinal direction in Fig. 11 and w/o conductor in Fig. 14 is come from the difference of the distance between the signal electrode and GND electrode. In

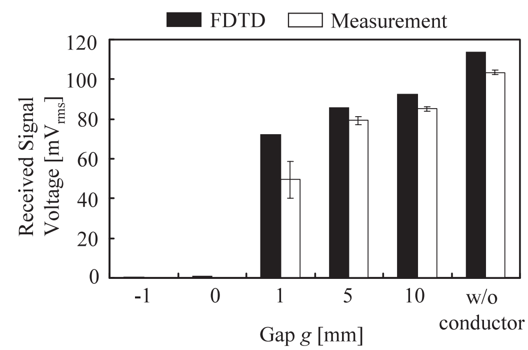
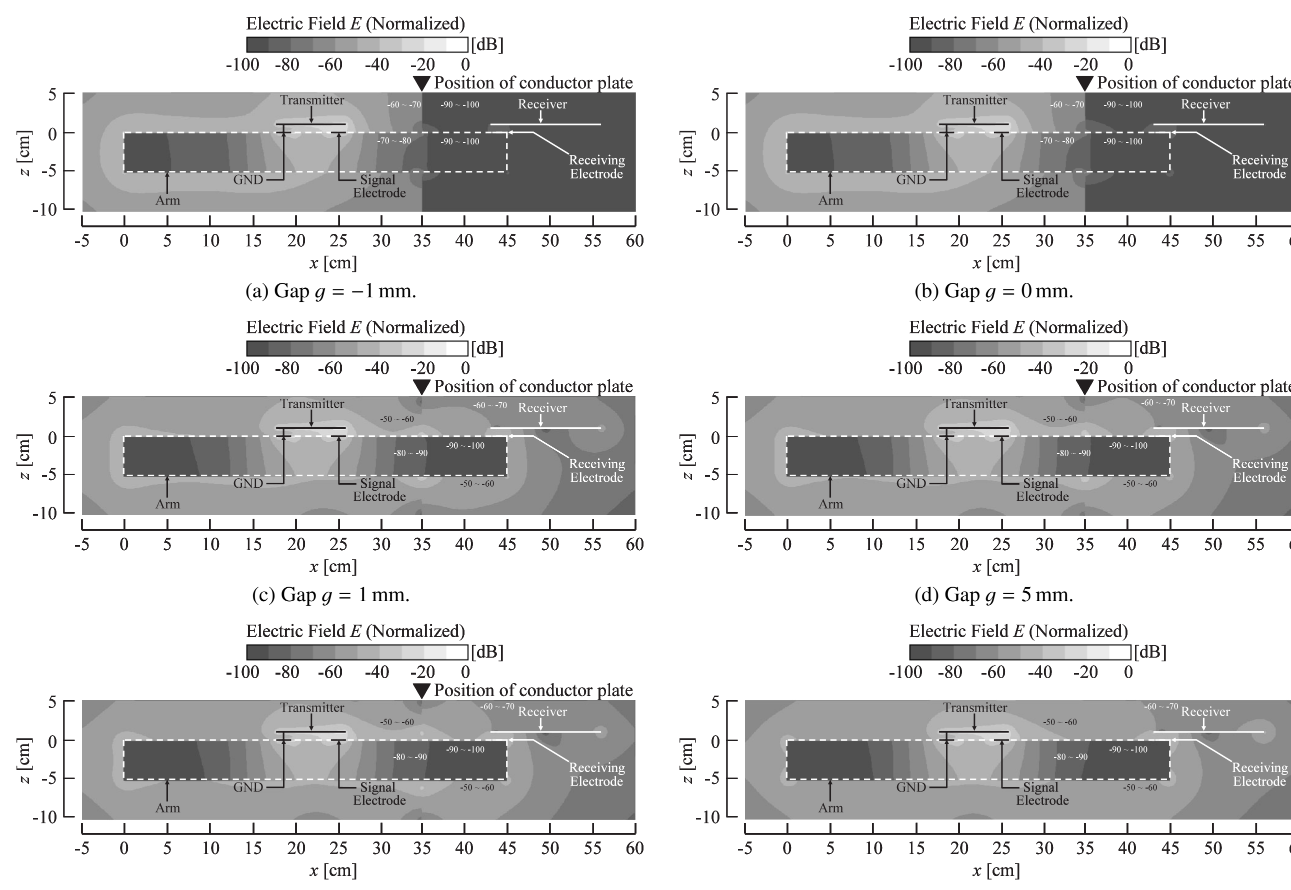


Fig. 14 Received signal voltage as a function of the gap between conductor plate and surface of the arm.



(a) Gap $g = -1$ mm.

(b) Gap $g = 0$ mm.

(c) Gap $g = 1$ mm.

(d) Gap $g = 5$ mm.

(e) Gap $g = 10$ mm.

(f) Without conductor plate.

Fig. 13 Electric field distributions in and around the arm with the transmitter and receiver.

Fig. 11, the distance between the signal electrode and GND electrode is 1 cm. The circuit of the transmitter is almost shorted. Hence, electric field generated from the transmitter is lower than the conventional size.

On the basis of these results, dominant signal transmission channel using the human body as a transmission channel is not inside but the surface of the arm, because signal seems to be distributed as a surface wave.

4. Conclusions

In this paper, the authors clarified the transmission mechanism of the wearable device using the human body as a transmission channel from the view point of the interaction between electromagnetic wave and the human body. First, in order to investigate desirable direction of the electrodes of a transmitter using the human body as a transmission channel, the magnetic field distributions around the arm with the transmitter was measured by the use of the shielded loop antenna and biological tissue-equivalent phantom. Then, in order to verify the validity of these measured data, the authors compared the calculated magnetic field distribution to the measured ones by using the FDTD method. The result showed a good agreement of both the calculated and measured magnetic field distribution. As a conclusion, longitudinal direction is effective for sending the signal to the receiver, compared to the transversal one. These investigations have made it clear that we can use the human body as a transmission channel effectively by flushing the current along the length of the arm.

Next, the dominant signal transmission channel was investigated, because the question of whether the dominant signal channel was in or around the arm remained unsettled. To clear the question, the authors proposed the calculation model of running the arm wearing the transmitter and receiver into the hole of the conductor plate. Then, the electric field distribution and received signal voltage was investigated as a function of the gap between the hole of the conductor plate and the surface of the arm. The results lead us to the conclusion that the dominant signal transmission channel of a wearable device using human body as a transmission channel is near the surface of the arm because the signal seems to be propagated as a surface wave. However, there has been still room for theoretical argument about surface propagation of this result, for further study. In the future, real human model will be applied to this study.

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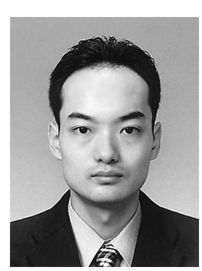

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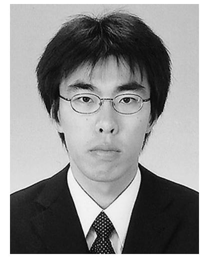

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