Ear Canal Insertable Size Wireless Transceiver for Hearing Aid

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Abstract

The aim of this study was to test the feasibility of a wireless transceiver that can be inserted into the ear canal. The wireless technology could minimize the cosmetic problems of patients, and it can be applied to binaural hearing aids for improving speech perception. In order to implement the ear canal insertable transceiver, simple finite-difference time-domain (FDTD) simulations were carried out to determine the feasibility, and the hardware of the transceiver was implemented within the ear shell. The size of the implemented transceiver was only 7 x 7 mm, and it could successfully transmit signals to external devices. In order to measure the radiation pattern, a simple RF phantom was used, and the maximum attenuation from the phantom was observed to be 23 dB when the reference antenna was placed at a distance of 2 m from the transmitter.

Key words: Wireless, Hearing aid, Ear canal, 2.4 GHz, RF link

Ⅰ. INTRODUCTION

In recent years, use of the digital signal processor (DSP) has become widely spread in the hearing aid devices to improve sound perception. Many researchers have suggested that it could improve the sound perception when an array of microphones was used for adaptive signal processing [1]. The most popular type of the array microphone in the hearing aid is a necklace type which was proposed by Dr. Bernard Widrow [2]. In the necklace, the array microphone and the DSP are embedded and transmit the filtered signal to the hearing aid using a magnetic field communication. Therefore, the hearing aid must be equipped with a telecoil, which is a small induction coil contained within the hearing aid to generate sound from the magnetic field power. Dr. Widrow's system could dramatically improve speech perception, particularly in the presence of background noise, reverberation, and feedback. One drawback of the previous necklace system is a cosmetic problem, because the necklace type is easily visible due to its wires and microphones, and the patients want to hide their hearing aid devices. Further, the magnetic communication has error when transmitting distance is long, and previous system transmits the signal from the necklace to the ear that is too long distance for the magnetic communication.

In order to improve cosmetic problem, a binaural hearing aid technique is one of method [3]; The binaural hearing aid requires two hearing aids and communicating each other for improving the speech perception. Therefore, a low power transceiver is a fundamental hardware for the binaural hearing aid and it could increase its working time. Behind the ear (BTE) size hearing aids were already made as binaural hearing aid; However, there was technical barrier to implementing the ear canal insertable size due to limited space and the battery power problem.

In order to insert the transceiver into the ear canal insertable size hearing aid, reducing size and power consumption of a transceiver are important points. A. Deiss et al. proposed a low power 200 MHz low frequency RF receiver for the hearing aid system, and it can be activated by an average of 667 μA [4,5]. The implemented system used a direct modulation method, which uses only one mixer, to reduce power consumption and was implemented with 0.8 mm bipolar complementary metal

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oxide semiconductor (BiCMOS) technology. The problem of this technique is using the low carrier frequency (200 MHz) that requires a large antenna for the communication. When the small antenna is used for a low frequency carrier, a high RF power amplifier is required to transmit to the external receiver and that increases the overall power consumption.

In this paper, an RF transceiver that could be inserted into the ear canal was implemented to determine the feasibility of the RF link system. A simple simulation was conducted by using a finite-difference time-domain (FDTD) method to determine the feasibility, and a 2.4 GHz transceiver was chosen. The transceiver was assembled on the 7 × 7 mm size printed circuit boards (PCB) and assembled into an ear shell with a controller, an antenna, and a battery. The implemented system was tested by using a simple RF phantom and it showed a feasibility to communicated with external system.

II. METHODS

A. RF band selection and FDTD simulation

Fig. 1 illustrates the proposed hearing aid device is inserted into the ear canal and does the RF communication. Unfortunately, the RF power is attenuated by the human head, because the human head has high permittivity and conductivity when it is exposed to the high frequency carrier. There are various researches about the RF relationship between the cell phones and the head [6], and the proposed method is different than previous researches because the RF source is slightly inserted into the car canal. When the antenna is deeply implanted inside of the human body and have moderate size, the 402~405 MHz band is recommended by the federal communications commission (FCC) [7]. When using the 402~405 MHz band, it is hard to implement small and efficient antenna when the antenna size is smaller than 2 cm^2 that is larger than the ear canal. A higher frequency band such as the ultra-wideband (UWB, 3.1 ~ 10.6 GHz) [8] is not suitable because of its high attenuation from the human head. The attenuation value is increasing when RF frequency is increasing, and the receiver have to overcome huge RF power difference from 3.1 to 10.6 GHz [9]. Therefore, the UWB communication is not suitable for the hearing aid, and the proposed system used a 2.4 GHz band from other industrial, scientific and medical (ISM) band for two reasons; First, there are many high efficient antenna designs or commercial antennas. Second, various transceivers present for the 2.4 GHz band and it could be easily used for the low power communication. Because of the above reasons, the FDTD simulation was conducted with 2.4 GHz, and the Maxwell's curl equations were used in the time domain as

$$\nabla \times H = \frac{\partial}{\partial t}\varepsilon E + \sigma_E E \tag{1}$$

$$\nabla \times E = \frac{\partial}{\partial t}\mu H + \sigma_H H \tag{2}$$

Where ε and μ are the permittivity and permeability of the material, σ_E and σ_H are electric and magnetic conductivity. In order to reduce computational complex, the transverse magnetic (TM) mode, which is composed of E_x, E_y, and H_z, is chosen and the Maxwell's equation can be reduced into two dimensions as

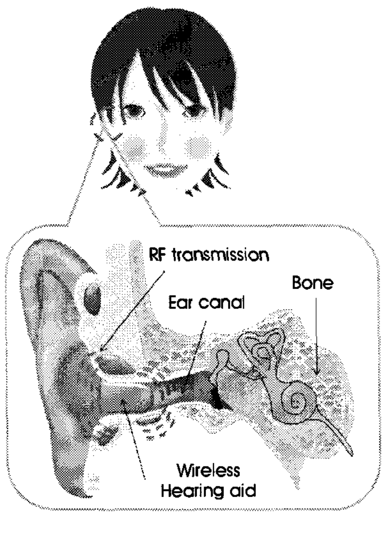


Fig. 1. Concept of the proposed system.

$$\frac{\partial}{\partial t}H_x = -\frac{1}{\sqrt{\varepsilon_0\mu_0}}\frac{\partial}{\partial y}E_z \quad (3)$$

$$\frac{\partial}{\partial t}H_y = -\frac{1}{\sqrt{\varepsilon_0\mu_0}}\frac{\partial}{\partial x}E_z \quad (4)$$

$$\frac{\partial}{\partial t}E_z = -\frac{1}{\varepsilon_r\sqrt{\varepsilon_0\mu_0}}\frac{\partial}{\partial z}H_y - \frac{\sigma_E}{\varepsilon_r\varepsilon_0}E_Z \quad (5)$$

Where ε_0, μ_0, and ε_r are the permittivity of vacuum, the permeability of vacuum, and the relative permittivity, respectively. The equations were solved by using a finite-difference approximation in both space and time, where the E and H were calculated at alternating discrete points in time using a leap-frog algorithm [10]. From the simulation, the minimum cell size was chosen as 1.8 mm, because it is 10 times shorter than the minimum wavelength of the 2.4 GHz frequency with the maximum dielectric constant of the human head. And the time step was chosen as 3 picoseconds, and it satisfied the Courant condition that is the stability condition of the FDTD simulation [11]. Further, the eight depth perfectly matched layer (PML) was programmed to prevent reflection.

Fig. 2 illustrates shape of the head used for the simulation, and it consisted of a simple circle for the head and a cylinder for the ear canal to reduce complexity of the calculation. The conductivity (σ) and relative static permittivity (ε_r) were chosen as 2.09 S/m and 54.7 on the basis of dielectric properties research from P. O'Rourke Ann et al. [12]. A point source was used for the antenna, and it was placed at middle of the ear canal that is 10 mm inside from the ear. In order to perform the simulation, a MATLAB program was used and the result is discussed in the experiment parts.

B. Implementation of transceiver

Fig. 3 shows a block diagram of the system and dotted lines indicate future improvements for the hearing aid system. Current implementation was focused to determine the feasibility of the RF link system, and a periodic pattern generator was used to send the data for testing the RF link system. A boost converter was used to boost a single cell zinc battery (ZA10, TOSHIBA), and overall operating system voltage was fixed at 2.0 V.

In order to implement a small and low power wireless transceiver, a chip from Nordic Semiconductor was used [13]. This chip has excellent performance about fast locking that could reduce overall transmission time. In order to control the transceiver, a simple 8051 controller from Silicon Labs [14] was used to communicate with the transceiver throughout the serial peripheral interface (SPI) protocol.

The transmitter mode was programmed to save the data in the buffer, and transmit 256 bits data within 0.289 ms. The receiver mode was programmed to lock the carrier within 0.128 ms and then received the data. After the data was received, the baseband processor verified the received data by using the cycle redundancy check (CRC) and the address. After the data were verified, the receiver sends the acknowledgement command within 0.033 ms to the transmitter for the handshake protocol. If the transmitter does not received the acknowledge command within 0.250 ms, then it regards the signal lost and re-transmitted. Output RF power was reduced to -21 dBm for power saving. The transceiver can send 32 Kbits/second with average power consumption of 0.986 mW.

Fig. 4 shows the implemented system and the 0201 size (0.6

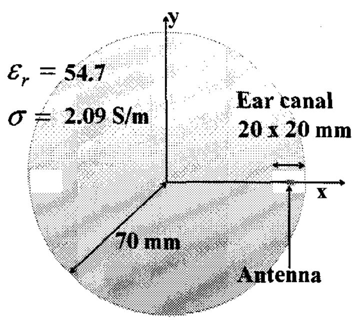


Fig. 2. Structure of the head and ear canal that is used in the simulation.

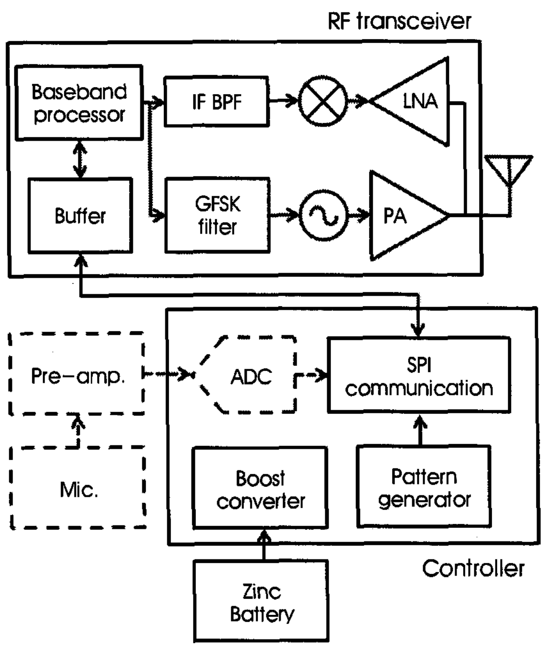


Fig. 3. Block diagram of the implemented transmitter part.

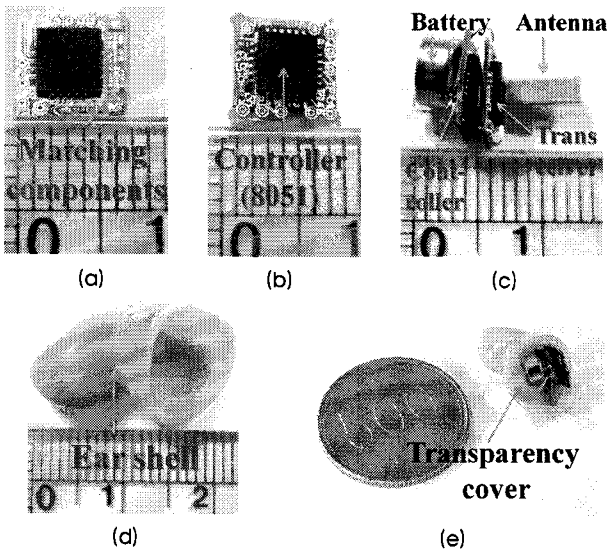


Fig. 4. Implemented system. (a) Transceiver. (b) Controller. (c) Assembled circuits. (d) Ear shell. (e) Assembled circuits and shell.

mm × 0.3 mm) surface mount device (SMD) was used to reduce size of the transceiver. The small antenna was chosen (ANT-2.4, Antenna Factor) and its size was only 8.5 × 2.2 mm. The ear shell was custom designed from a hearing aid company, GShearing. Fig. 4 (c) shows assembled modules and the antenna is closely placed at the right side of the circuit. The problem of placement causes the power attenuation to left side of the antenna.

Ⅲ. EXPERIMENT

Fig. 5 depicts the simulation result, and the output power of the source was programmed to -21 dBm that is same as the implemented transmitter. The point source was inserted into the ear canal, and fig. 5 (a) shows the shadow fading due to the head. Fig. 5 (b) is a transversive view of the fig. 5 (a), and the lowest power was observed in the middle of the head. The RF power at the opposite side of the ear canal was -72.5 dBm, which has 10.5~12.5 dB power margin on the basis of sensitivity of the general receiver (-83~85 dBm). Fig. 5 (c) depicts the radiation pattern when 2 m distance from the antenna source, and the shadow fading is easily observed.

In order to measure the radiation pattern, a phantom with ear canals was used and it is illustrated in fig. 6. The material used to implement the phantom was polypropylene (PP) that satisfied the RF phantom container (loss tangent < 0.05 and relative permittivity < 5). In side of the phantom was filled with the liquids that had similar dielectric properties of the

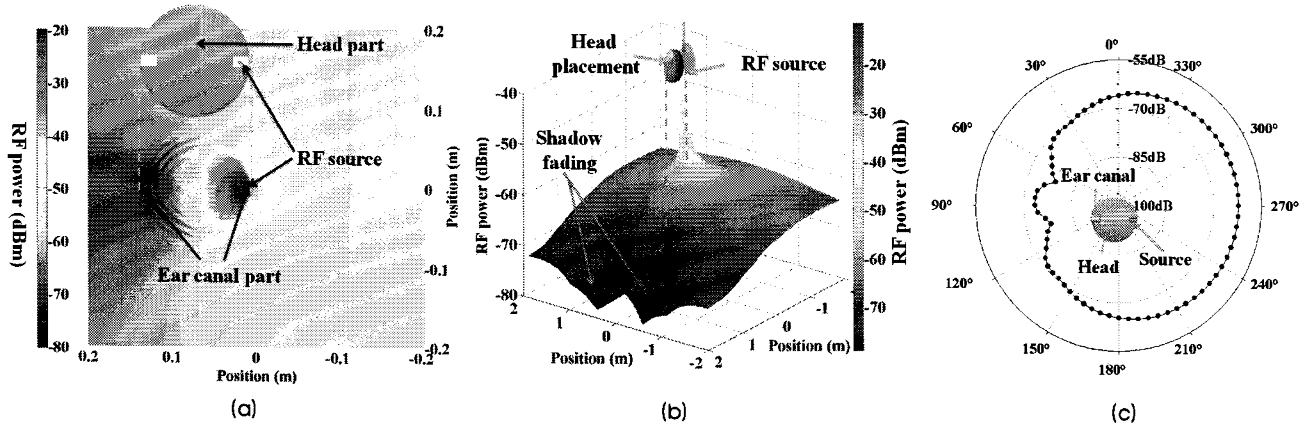


Fig. 5. Simulation results. (a) Surface curve. (b) Transverse view. (c) Radiation pattern from 2 m distance from the source.

Table 1. Ingredients for tissue equivalent liquid

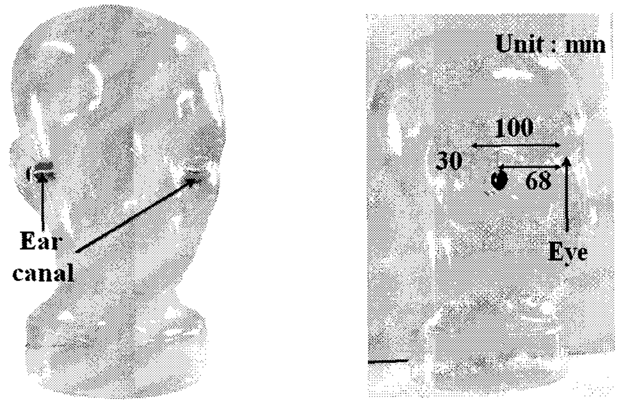
Target frequency (MHz)	Ingredients (%)			
2550	Water	Diethylene glycol mono- buthyl ether (DGBE)	Trition	NaCl
	71.89	7.99	19.97	0.15

human [15] and the table 1 summarized ingredient for the liquids. The distilled and non-ionized water was used and the NaCl was dried 5 minutes from about 60℃ before measuring its weight. A precision scale (HR-200, A&D Company) was used to measure the weight of the NaCl and 10 L liquid was mixed at one time in order to reduce error from the scale.

The position of the ear canal was taken from the kemar manikin [16] that is widely used in the application for the hearing aid measurement, and it has well-defined specifications of the auricle which is the external part of the ear. On the basis of the ear canal position information from the kemar manikin, the ear canals (20 x 20 mm) were placed in the phantom and black sponges was inserted in the canal to hold the ear shell. The RF power attenuation from the sponges was empirically tested, and there was no significant difference with and without the sponges.

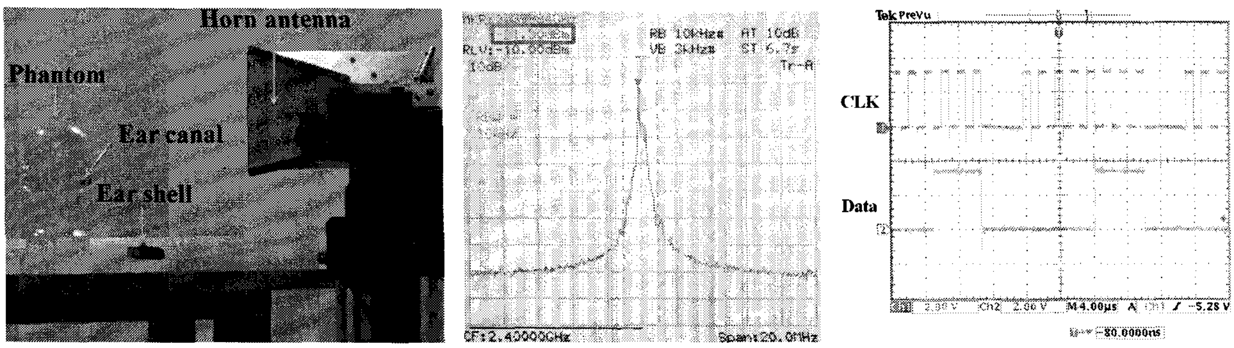
Fig. 7 (a) shows the test environment of the RF enclosure chamber (Lindgren) that could shield 110 dB at the 2.4 GHz range. A horn antenna (11966E, HP) which has 8.3 dBi gain was used to measured the signal from 2 m distance from the implemented transmitter. A spectrum analyzer (MS2651B, Anritsu) was used to measure the environment temperature which was controlled at 23~24 ℃ to satisfy the condition of the RF measurement temperature variation.

Fig. 7 (b) shows the -21 dBm RF output power from the transceiver that was directly measured by the spectrum



(a) (b)

Fig. 6. The phantom. (a) Shape of the phantom with ear canal. (b) Lateral view.



(a) (b) (c)

Fig. 7. Test environment. (a) Measurement setup in the RF enclosures chamber. (b) Output power from the transmitter (directly connected to the spectrum). (c) Waveform of command and data from the 8051 controller to the transceiver by using SPI protocol.

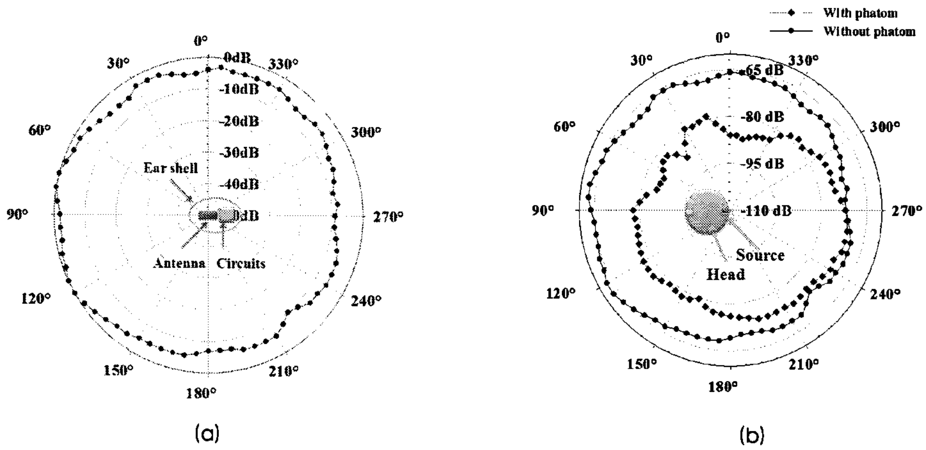


Fig. 8. Measured radiation patterns in horizontal plane. (a) Normalized pattern with circuits. (b) Pattern with and without phantom.

analyzer (MS2651B, Anritsu). Fig. 7 (c) shows sending command and data from the 8051 controller to the transceiver, and the SPI protocol was used to communicate each other.

Fig. 8 depicts the result of the measurement and the polar plot shows the average value from four time measurements. Fig. 8 (a) shows the normalized radiation pattern of the horizontal plane with the antenna and the circuits. When the ear shell was inserted into the phantom, the antenna part was inserted deeper into the ear canal and the circuit was placed to the outsize. The fig. 8 (b) shows the radiation pattern with and without the phantom, and the maximum attenuation cause by the phantom was 23 dB.

The measured data show larger attenuation than the simulation result, and it is assumed that efficiency of the antenna caused power attenuation. Fig. 9 shows average packet error rate for 10 minutes when the both hearing aid was place in air and ear canal. The result shows that there was no packet error from the air and 1.1 x 10-5 % error was observed from each ear canal. The transmitter automatically retransmit the data when there was no acknowledgement signal; therefore, the packet error rate (PER) was counted as when the data were not received within 8 ms that is maximum delay between communication packets.

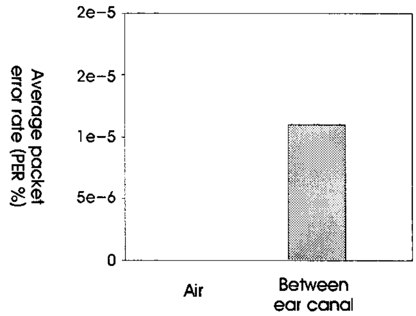


Fig. 9. Average packet error rate (PER).

The table 2 summarizes the specification of the proposed system and A. Deiss's system [4,5]. The data rate of the proposed system was slower than a. deiss's system, and size of the proposed system was smaller and it could act as transceiver that could prevent data lost by using the handshaking protocol and CRC. The operating voltage of A. deiss's system was not clearly mentioned; Therefore, comparing overall power consumption was impossible.

Ⅳ. CONCLUSION AND DISCUSSION

In this paper, a wireless transmitter that can be inserted into

Table 2. Specification of the proposed transceiver and A. Deiss's receiver.

	Data rate (Kbit/s)	Size (mm)	Current consumption	Power consumption	antenna size (mm)	Channel coding	Number of channel
Proposed system	30	7 × 7	0.493 mA (transceiver, strobe ratio = 0.03)	0.986 mW	8.5 × 2.2	O	Max. 126
A. Deiss's receiver [4,5]	336	20 × 40	0.667 mA (receiver only)	Unknown	Unknown	X	Unknown

the ear canal was designed and implemented. The implemented system showed the feasibility to communicate with external devices, and it could minimize cosmetic problems. In order to use the proposed system, the following issues have to be considered. First, the specific absorption rate (SAR) problem should be considered. Although the current system's RF power is too low (-21 dBm) to cause the problem of high SAR, it requires to measure the SAR whether the current transceiver violates the regulation. According to IEEE guidelines, the SAR should be below 1.6 mW/g [17].

Second, the size and shape of the antenna should be optimized. In this study, the controller and the transmitter was easily inserted into the ear mold, while the antenna was place at the speaker place which is called as a receiver in hearing aids devices. Further, the antenna was covered with the hearing aid circuit that reduced the overall performance of the transceiver. In order to place the speaker in the ear mold and increase performance of the transceiver, the antenna have to be placed at external side of the ear canal. Fortunately, the completely-in-the-canal (CIC) type hearing aid devices use a small rigid string to pull the device out of the ear canal. This string could be used as an antenna, and further research is required to implement a thin, invisible, and well-packaged antenna.

Third, power consumption from the transceiver is still high to be used for clinical application. The power consumption from the receiver is approximately 1 mW and the capacity of the zinc battery, which is used in this study, is 105 mW. Therefore, the transceiver could maximumly working about 105 hours (4 days). Furthermore, considering power consumption from the aiding aid devices such as a mike, amplifier, and speaker, the working time of the hearing aid device could be reduced as twice or third times. Therefore, the power consumption of the transceiver have to be reduced.

Fourth, when both ear canal insertable type hearing aid devices require to communicate with each other to use binaural effect, the RF power should be increased when the diameter of the human head is larger than that considered in the current study (14 cm). Even though the current study showed acceptable errors, it could be a problem when the human head is much larger than the our research. This problem could be overcome by increasing the RF power or employing other technology such as a body area network (BAN). The BAN uses the human body as a communication channel [18]; therefore, it could reduce output power of the transceiver because the human body is better channel than the air. When the reliable BAN communication is implemented in hearing aids, both hearing aids could communicate with each other as long as they are attached to the human body.

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