Experimental Evaluation of Implant UWB-IR Transmission With Living Animal for Body Area Networks

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Abstract—One of promising transmission technologies in wireless body area networks (BANs) is ultra-wideband (UWB) communication, which can provide high data rate for real-time transmission, and extremely low power consumption for increasing device longevity. However, UWB signals suffer from large attenuation in a wireless communication link, especially in implant BANs. Although several investigations on channel characterization have been far thus conducted for evaluating the UWB transmission performance, they have been limited to either computer simulations or experiments with biological-equivalent phantoms. Experimental evaluation with a living body has rarely been conducted, i.e., the performance in real implant BANs has been scarcely discussed. In this paper, therefore, we focus on a living animal experimental evaluation on the UWB transmission performance. To begin with, we develop an ultra-wideband impulse radio (UWB-IR) communication system with a multipulse pulse position modulation scheme, and then analyze the fundamental characteristics of the developed UWB-IR communication system by a liquid phantom experiment. Finally, we evaluate the performance of the developed UWB-IR communication system via the living animal experiment. From the experimental results, although we have observed that the path loss is more than 80 dB, the developed system can achieve a bit error rate of $10^{-2}$ within the communication distance of 120 mm with ensuring a high data rate of 1 Mb/s. This result first time gives a quantitative communication performance evaluation for the implant UWB transmission in a living body.

Index Terms—Implant body area networks (BANs), living animal experiment, ultra-wideband impulse-radio (UWB-IR) transmission.

I. INTRODUCTION

WIRELESS body area networks (BANs) have attracted a lot of attention as a future technology for wireless networks. Typical applications of wireless BANs include healthcare, medical treatment, and medical monitoring [1]–[3]. Generally, wireless BANs are classified into two groups: wearable BANs and implant BANs. Wearable BANs are mainly used to monitor a person’s healthy condition in daily life [2], whereas wireless capsule endoscopy (WCE) has been one of the most important applications in implant BANs [4], [5]. WCE involves swallowing a small capsule by a patient, which contains a color camera, light source, and battery and transmits images to the outside receiver in order to assist in diagnosing gastrointestinal conditions such as obscure malabsorption, gastrointestinal bleeding, chronic diarrhoea, and abdominal pain. In this paper, we focus on implant BAN applications. Such a medical application requires a reliable wireless communication channel, and extremely low power consumption for increasing device longevity.

To realize the implant communications, the 400-MHz band and 2.4-GHz band are usually chosen. For example, a commercially available implant communication chip for cardiac pacemaker employs the 400-MHz band for data transmission and the 2.4-GHz band for waking up and control. References [6] and [7] have reported that all of the WCE techniques employ 400 MHz, 2.4 GHz, or dozens of megahertz bands with narrow-band modulation schemes, such as frequency shift keying (FSK) or binary phase-shift keying (BPSK). The data rate is limited to several hundred kilobits per second. However, in view of the implant communication application, for instance, WCE requires a higher data rate for a real-time image and video transmission. In order to fulfill the above requirements, this paper pays attention to ultra-wideband (UWB) transmission. As UWB transmission schemes, ultra-wideband impulse radio (UWB-IR), direct sequence ultra-wideband (DS-UWB), and multiband orthogonal frequency-division multiplexing (multiband-OFDM) have been proposed [8]–[10]. Of the all UWB schemes, UWB-IR is a technique that iteratively transmits extremely short pulses on the nanosecond time duration per bit. Therefore, it has a merit in respect of low power consumption. Furthermore, a coherent detection, namely a correlation detection, claims to be one of the most suitable solutions for the UWB-IR communication system. Although the coherent detection needs to generate a template signal in a receiver side, the reliability of the coherent detection is generally superior to that of a non-coherent detection.

However, in implant BANs, the UWB-IR signals suffer from large attenuation, which may lead to undesired performance...
degradation. Therefore, it is important to investigate the transmission performance of the implant BANs. Although several papers have so far investigated the channel characteristics [11]–[15], the investigations have been performed by either computer simulations or experiments with biological-equivalent phantoms. An experimental investigation with a living body has been rarely conducted. In other words, the performance evaluation in real BANs has been scarcely discussed. This paper aims to perform an experimental evaluation for UWB-IR transmission performance with a living body. For this purpose, we develop a UWB-IR communication system with a multipulse pulse position modulation (MPPM) scheme. The reason why we employ the MPPM scheme is to control the tradeoff relationship between the data rate and the reliability, namely, the bit error rate (BER) performance. This paper then analyzes the basic characteristics of our developed UWB-IR communication system by a liquid phantom experiment and evaluates the experimental results with theoretical ones. Finally, the UWB-IR communication system is evaluated in the living animal experiment.

The remainder of this paper is organized as follows. Section II presents the design of the developed UWB-IR communication system. Section III then describes the fundamental performance of the developed UWB-IR communication system by a biological-equivalent liquid phantom experiment, and Section IV demonstrates and discusses the results of the living animal experiment. Finally, Section V concludes this paper.

II. DESIGN OF UWB COMMUNICATION SYSTEM

A. Antennas

In the developed UWB-IR communication system, we chose the UWB low band (3.4–4.8-GHz band) because the higher transmitting frequency has a smaller penetration depth in biological tissues. For the transmit and receive antennas, we employed three types of UWB low-band antennas. Fig. 1 shows the transmit and receive antennas. The transmit antenna in Fig. 1(a) is a trapezoid strip excited broad band hemispherical dielectric resonator antenna (DRA), which was designed for medical capsule endoscope [16]. A PVC material with dielectric constant of around 3 is chosen to build the hemisphere. A conformal taper copper strip was mounted on the hemisphere surface, and a circular ground plane with the same diameter was set at the base of the hemisphere. This structure allows the whole electric current to flow on the DRA surface and is able to broaden the impedance bandwidth. The antenna has been experimentally confirmed to exhibit an $S$-parameter $S_{11}$ smaller than $-10$ dB within a biological-equivalent liquid phantom, and a broad beam directivity at the excitation side. The total radiation gain of the trapezoid strip excited hemisphere DRA at 4 GHz in the liquid phantom is $-24$ dB toward the maximum radiation direction. The detailed radiation pattern can be referred in [16]. On the other hand, we used two kinds of receive antennas, as shown in Fig. 1(b) and (c). One was a Vivaldi antenna [17], which has a linear polarization, and the other was a helical antenna, which has a circular polarization. The Vivaldi antenna consisted of two exponentially tapered slot lines arranged on the upper surface of a dielectric substrate with a dielectric constant of 10.2. The feeding radial stub microstrip was arranged on the lower surface of the dielectric substrate, and the corresponding ground microstrip was connected to one Vivaldi taper. To achieve expected radiation characteristics, a metallic reflector plate is added at the back of the Vivaldi side. The helical antenna acted at its axial mode. It had a strong radiation along its axial direction so that a high gain was obtained in this direction. Fig. 2 shows the measured $S_{11}$ for the helical antenna. Both antennas were developed for on-body applications, and the $S_{11}$’s were less than $-10$ dB in the range of 3.4–4.8-GHz band. Fig. 1 also shows the sizes of transmit and receive antennas. As can be seen from this figure, the transmit antenna is much smaller than the receive antennas because the transmit antenna should be implantable to a human body.

B. Transmitter

The structure of the transmitter is shown in Fig. 3. As a UWB-IR pulse, we employ the first-order Gaussian monocycle pulse, and this transmitter uses an MPPM scheme, which can control the tradeoff relationship between the data rate and the reliability of the transmission. Assuming $K$ as the total number of transmitted bits, the MPPM signal $s(t)$ can be expressed as

$$s(t) = \sum_{k=1}^{K} b_k^T \mathbf{p} \{t - (k - 1)T_s\}$$  (1)
where $\mathbf{b}_k$ is the $k$th transmitted bit information vector, namely, $\mathbf{b}_k \in \{\mathbf{b}_0, \mathbf{b}_1\}$ ($k = 1, 2, \ldots, K$), $T_s$ is the symbol duration, and the operator $(\cdot)^T$ represents transpose of $(\cdot)$. Defining $L$ as the number of chip slots in a symbol, $\mathbf{b}_0$ and $\mathbf{b}_1$ denote a chip sequence vectors corresponding to transmitted bits of 0 and 1, respectively, which are $L \times 1$ vectors and the $l$th components of the both vectors $b_{0l}$ and $b_{1l}$ ($b_{0l}, b_{1l} \in \{0, 1\}$) represent the pulse existence in the $l$th chip slot of the corresponding symbols, respectively. In (1), $p(t)$ is defined as $C \times 1$ vector
\[
p(t) = \begin{bmatrix} p(t); p(t-T_c); \ldots; p(t-(L-1)T_c) \end{bmatrix}^T
\] (2)

where $T_c$ denotes the chip duration. Fig. 4 shows an example of MPPM signals when $L$ is set to 4, in which two UWB-IR pulses are assigned to each transmitted symbol. It is possible to control the data rate by changing the number of chip slots $L$. We note that the IR-type transmitter does not need a carrier signal and amplifiers. It employs a clock generator and some CMOS gates to produce pulses and a bandpass filter (BPF) for spectrum forming. Since CMOS gates consume low power and the passive BPF does not consume power, the total power consumption in the transmitter can be expected at a quite low level.

C. Receiver

Fig. 5 shows the structure of the receiver. In our previous study [18], we have found that the power delay profile can be well represented as a two-path model with a very small mean time interval in the order of nanoseconds. This means that the multipaths are almost indistinguishable in the received signal and the multipath fading effect is not dominant. Thus, in this study, we try to investigate the communication performance without channel estimation to confirm whether our proposed UWB transmission system can work well in a real living body environment. As mentioned previously, we pay attention to the correlation detection as the receive detection scheme. In the correlation detection, since the binary MPPM chooses one from two location assignments in the $k$th symbol, we calculate two kinds of $k$th energies for the corresponding pulse locations from the received signal $r(t)$ as follows:

\[
E_k^0 = \sum_{l=1}^{L} b_{0l}^T \int_{(k-1)T_s+(l-1)T_c+T_d}^{(k-1)T_s+lT_c+T_d} r(t)\hat{s}_0(t)dt
\] (3)

\[
E_k^1 = \sum_{l=1}^{L} b_{1l}^T \int_{(k-1)T_s+(l-1)T_c+T_d}^{(k-1)T_s+lT_c+T_d} r(t)\hat{s}_1(t)dt.
\] (4)

where $T_d$ denotes the integration time, and $\hat{s}_0(t)$ and $\hat{s}_1(t)$ are the template signals for each symbol, respectively. Note that $T_d$ is much smaller than the symbol duration $T_s$ and the chip slot duration $T_c$ in UWB-IR transmission. Comparing $E_k^0$ and $E_k^1$, the received bit information $\hat{b}_k$ can be decided as

\[
\hat{b}_k = \begin{cases} 0, & \text{if } E_k^0 > E_k^1 \\ 1, & \text{otherwise.} \end{cases}
\] (5)

We note that as can be seen from the above equation, the MPPM requires no threshold. Furthermore, the symbol timing in Fig. 5 is synchronized with pilot signals.

D. Theoretical Analysis of BER Performance

When the transmitter sends a signal $s(t)$, we assume the received signal $r(t)$ is expressed as $r(t) = s(t) + n(t)$. Whereas the $n(t)$ is not a narrowband noise (in other words, it is not a Gaussian noise) due to the BPF of the receiver designed for UWR-IR signals, the UWB signal can be decomposed into $M = 2BT_d$ narrowband signals [19], where $B$ denotes the bandwidth of the UWB-IR signals. Therefore, we take into consideration that the number of UWB pulses in each symbol is $L/2$, and we
finally obtain \((k\) is dropped without loss of generality so \(E_0^k\)

is replaced by \(E_0^{\text{detected}}\)) \[20\]

\[
E_{\text{detected}} = \sum_{l=1}^{L} \int_{t=0}^{T_d} \left[ n(t) + n(t); \hat{s}_0(t) \right] dt
\]

\[
= \sum_{l=1}^{L/2} \int_{t=0}^{T_d} \left[ 2M \left( s_i^1 + n_i(t)^1 \right) \sum_{j=1}^{2M} \hat{s}_j^1 \phi_j(t) \right] dt
\]

\[
= \sum_{l=1}^{L/2} \sum_{i=1}^{2M} \left( s_i^1 + n_i(t)^1 \right) \hat{s}_j^1
\]

where \(\phi_i(t)\) represents an orthogonal function over the pulse interval. In (6), \(n_i\) is a zero mean independent Gaussian random variable with variance \(N_0/2\), and \(s_i\) is defined to satisfy \(E_i = \sum_{i=1}^{2M} (s_i^2)^2\), where \(E_i\) represents the energy of the transmitted pulse. As a result, from (6), the detected energy \(E_{\text{detected}}\) is a sum of \(ML(= 2M \times L/2)\) independent variables with a chi-square distribution. According to the Central Limit Theorem, the probability distribution of \(E_{\text{detected}}\) can be approximated as Gaussian distribution when \(ML\) is getting large. Finally, from the Gaussian approximation, defining \(E_b\) as the energy per bit, the bit error probability \(P_e\), i.e., BER, is given by \[21\]

\[
P_e \left( \frac{E_b}{N_0} \right) = Q \left( \sqrt{\frac{LE_b}{2N_0}} \right)
\]

where

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \exp \left( -\frac{t^2}{2} \right) dt.
\]

III. EXPERIMENT FOR FUNDAMENTAL PERFORMANCE EVALUATION WITH LIQUID PHANTOM

Before conducting the living animal experiment, we performed a preliminary experiment for evaluation of the fundamental performance of the UWB-IR communication system. For this purpose, we measured the fundamental characteristics of the UWB-IR transceivers in a liquid phantom simulating a human body. In this experiment, we used the helical antenna as an on-body receive antenna put on the liquid phantom surface with a spacing of 1 cm. For the in-body transmit antenna, we employed a modified version of the antenna described in Section II, which has an antenna performance similar to the DRA antenna designed for the living body experiment. The modification was because of the use of the liquid phantom. We coated a type of glue to the antenna and feeding part for preventing a direct contact of the antenna to the liquid. Figs. 6 and 7 show the measurement setup with the liquid phantom and a picture of the phantom experiment, respectively. The transmit antenna was inserted in the liquid phantom. The liquid phantom was produced to simulate muscle-like dielectric properties. We have measured its dielectric properties between 3–5 GHz. The measured results show that the relative permittivity ranges from 40 to 35, somewhat smaller than that of muscle, whereas the conductivity ranges from 2.2 to 4.2 S/m, almost the same as that of muscle, within this frequency band. We used the vessel made from a plastic material in the liquid phantom experiment. We have checked the dielectric properties of the vessel and found that its loss is almost ignorable. The transmit and receive antennas were connected to a network analyzer with coaxial cables. The two coaxial cables were arranged at right angle to each other for removing possible direct coupling between them. Fig. 8 shows examples of shapes of the transmitted and received UWB signals. Moreover, Fig. 9 shows the spectrum of the UWB signal. We measured the \(S_{21}\) performance, namely, the path-loss characteristic, as a function of the distance from the implant transmit antenna to the phantom surface at the frequency band of 4 GHz. The measured path-loss characteristics are shown in Fig. 10. Furthermore, Fig. 11 shows the frequency characteristic of the measured path loss. It is found that at a depth of 70 mm from the body surface, the path loss is around 80 dB. Such a path-loss level may be acceptable in present transceiver design technology.

In addition to the path-loss measurement, we then also evaluated the communication performance of the UWB-IR transceivers based on the path-loss measurement results in the liquid phantom experiment. In this experiment, we assumed that the transmitter and the receiver were connected with an attenuator in order to accurately control the path loss according to the distance between transceivers. The transmitter sent 10 000 bits, and then we calculated the BER from comparison between the transmitted bit sequence and the received bit sequence. As for the symbol timing and sampling clock synchronization, we have confirmed that it is almost perfectly performed with a proper length of pilot signals. Moreover, we have also determined the
optimal integration time $T_{\text{int}}$ before conducting the experiment. The parameters of the UWB-IR transceivers are summarized in Table I.

Fig. 12 shows the average BER performances by the experiment and the theoretical analysis against the distance between transceivers. The theoretical results were derived from (7) by linking the $E_b/N_0$ to corresponding distance via the measured path loss in Fig. 10. From Fig. 12, we observe good agreements between the results of the experiment and the theory. Hence, it can be said that we properly set the parameters of the transceivers and the theoretical analysis given by (7) can reasonably explain the developed UWB-IR communication system. Furthermore, as seen from Fig. 12, the BER performance is improved as the data rate decreases (namely, $L$ increases). This is because, from (7), we can accomplish $L/2$ times higher $E_b/N_0$ after demodulation in the receiver. Note that the BER performance of $10^{-2}$ is accomplished at the distance of around 70 mm when $L = 16$ (namely, the data rate is 1 Mb/s). The achievement of the BER performance of around $10^{-2} - 10^{-3}$ means that it is possible to obtain an error-free BER ($< 10^{-10}$) if we adapt an adequate forward error correction code [22]. This error-free BER satisfies the requirement for almost all implant BAN applications. Therefore, the developed UWB-IR communication system can establish a reliable communication link at the maximum distance of 70 mm in the biological-equivalent liquid phantom.

**TABLE I**

<table>
<thead>
<tr>
<th>UWB-IR TRANSCEIVER PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average transmitted power transceiver</td>
</tr>
<tr>
<td>Peak transmitted power</td>
</tr>
<tr>
<td>Pulse width $\tau$</td>
</tr>
<tr>
<td>Bandwidth after front-end processing</td>
</tr>
<tr>
<td>Chip time $T_c$</td>
</tr>
<tr>
<td>Bit rate</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Forward error correction</td>
</tr>
<tr>
<td>Length of pilot signal</td>
</tr>
</tbody>
</table>
Fig. 12. Effect of attenuation on BER performance.

Fig. 13. Living animal experimental model.

IV. LIVING ANIMAL EXPERIMENT

A. Experimental Setup

Fig. 13 shows the overview of the living body experiment with the developed UWB-IR system. In the living body experiment, we used a living animal (pig) instead of a human body because it is difficult to conduct an experiment with a living human body in our environment. The transmit antenna was implanted into the pig, and the receive antenna was put on the pig-body’s surface. The transceivers and each antenna were connected with coaxial cables. For the received data capture, a laptop computer was connected to the receiver. The insertion points of the transmit antenna and the positions of the transmit antennas are shown in Fig. 14, where Fig. 14(a) and (b) show the transmit antenna positions when the insertion point was in the center of the abdomen and the thorax (chest), respectively. In the animal experiment, the transmit antenna was covered with a vinyl material for insulation. The receive antenna was just above the transmit antenna on the body surface. Moreover, Table II summarizes the detailed information of the implanted transmit antenna position [23] and the distance between transmit and receive antennas, which was measured by a magnetic tracker system. Fig. 15 shows a photograph of the living animal experiment.

B. Experimental Results

Figs. 16 and 17 show the BER performance against the distance between transmit and receive antennas in the case of the Vivaldi-type receive antenna and the helical-type receive antenna, respectively. In these figures, the antenna position IDs are also indicated. Note that, in the both antenna cases, we observed no bit error at the distance of 22 mm (Position ID: A), and moreover, in the helical antenna case, also no bit error was observed at the distance of 33 mm (Position ID: D). As for the reason that there is a sharp drop after $10^{-3}$ at 2 and 1 Mb/s, it is because that the transmitted data number is not sufficient for giving an average BER in this order. Similarly to the result of the basic characteristic investigation in the previous section, we can see from these figures that the BER performances are inversely proportional to the data rate. Furthermore, as the distance between the antennas increases, the BER performance is getting worse due to the corresponding path loss in the biological tissues. However, as can be seen in Figs. 16 and 17, the BER at a distance of 80 mm exhibited a worse performance compared to that at 120 mm, which means that the BER performances are not always getting worse when the communication distance increases. This is because of the difference in the types and thickness of tissue between the transceivers. A high water-content tissue such as muscle and peritoneal fluid has a larger path loss, whereas a low water-content tissue such as fat and bone has a smaller path loss. The implant communication performance is therefore dependent on not only the distance, but also the types and thickness of tissue between the transceivers, which explains why the results for the antennas placed in the five positions exhibit such distance dependence.

As also pointed out in [24]–[26], the transmission path is influenced by different tissue types which possess different dielectric properties. Therefore, we should consider not only the distance between the transceivers, but also the penetrated tissues. To specify the effect of the penetrated tissues in detail, more investigation is required. In total, the developed UWB-IR communication system can achieve the BER performance of around $10^{-2}$ at the data rate of 1 Mb/s up to a distance of 120 mm.
As compared between the results in the case of the Vivaldi antenna and the helical antenna, the BER performance of the helical antenna is better than that of the Vivaldi antenna. The difference of the BER performance may be attributed to the beam patterns of antennas and the polarization mismatch. Half-power beamwidth of the circular polarized helical antenna is smaller than the beamwidth of the linear polarized Vivaldi antenna. This results in a higher gain and in a lower polarization dependency of the signal received by the helical antenna.

On the other hand, to investigate the polarization of the implantable transmit antenna, we conducted a computer simulation. In the computer simulation, the polarization of transmit antenna was aligned along each 3-D axis direction at the center of a muscle-simulating cylinder phantom, whose relative permittivity and conductivity were 51.1 and 3.2 S/m, respectively. We employed the Vivaldi antenna as a receive antenna, which was put on a side surface of the cylinder phantom. Fig. 18 shows the effect of the transmit antenna polarization on the path-loss characteristics. From this result, the transmit antenna needs to be aligned to ensure a good polarization, but it is not easy to realize in reality for the implant applications. In the living animal experiment, the transmit antenna alignment was limited inside the animal body, so that the transmit antenna and the receive antenna were not aligned on the best polarization condition. This could result in a significant degradation on the path loss and BER. In our experiment, the Vivaldi antenna at the receiver was always put along the animal body surface so that its polarization was not optimized. As opposed to this, since the helical antenna acted at its axial mode, it was easy to adjust its axial direction to have the polarization be optimized at each receive antenna position. As a result, even though the transmit antenna polarization was not optimized, better BER performance with the helical antenna has been obtained than that with the Vivaldi antenna.

TABLE II
TRANSMIT ANTENNA POSITION AND DISTANCE BETWEEN TRANSMIT AND RECEIVE ANTENNAS

<table>
<thead>
<tr>
<th>Position ID</th>
<th>Transmit Antenna position</th>
<th>Range (mm)</th>
<th>Organs and Tissues along the Propagation Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Left quadrant</td>
<td>22</td>
<td>Jejunum, peritoneal fluid, muscle, fat, skin</td>
</tr>
<tr>
<td>B</td>
<td>Under liver</td>
<td>47</td>
<td>Liver, peritoneal fluid, muscle, fat, skin</td>
</tr>
<tr>
<td>C</td>
<td>Under liver</td>
<td>81</td>
<td>Liver, peritoneal fluid, muscle, fat, skin</td>
</tr>
<tr>
<td>D</td>
<td>Behind sternum</td>
<td>33</td>
<td>Cartilage, bone, fascia, muscle, skin</td>
</tr>
<tr>
<td>E</td>
<td>Behind heart</td>
<td>120</td>
<td>Heart, cartilage, bone, fascia, muscle, skin</td>
</tr>
</tbody>
</table>

Fig. 16. Experimental results of BER (Vivaldi antenna).

Fig. 17. Experimental results of BER (helical antenna).

Fig. 18. Effect of antenna polarization on path-loss characteristics. (a) Computer simulation setup. (b) Results.
antenna. This result suggests a possibility to ensure a good polarization by manually adjusting the receive antenna directivity on the body surface.

Furthermore, in our previous study, we measured \( S_{11} \) when the transmit antenna was inserted in a liquid phantom [16]. The result has shown \( S_{11} \) smaller than \(-10\) dB in the UWB low band. Since the liquid phantom was a high water-content one simulating the average torso tissue properties, the measured \( S_{11} \) characteristic can be considered as a representative of torso. Since the surrounding tissues were almost high water-content ones in our animal experiment, as shown in Table II, there was no large degradation on \( S_{11} \) from that designed in the liquid phantom. If the transmit antenna is implanted in a low water-content tissue, a large degradation on \( S_{11} \) may occur and some special considerations are necessary.

Finally, we also investigate the path loss between the transceivers. From (7), we can roughly estimate \( E_b/N_0 \) from the BER measured in the experiment as

\[
E_b/N_0 = P_x^{-1}\{\text{BER}_{\text{measured}}\}. \tag{9}
\]

Here, \( P_x^{-1}(\cdot) \) means the inverse function of (7). Defining \( R_s \) as the spectral efficiency ratio, \( E_b/N_0 \) can be expressed as

\[
\frac{E_b}{N_0} = \frac{P_L}{P_n R_s} \tag{10}
\]

where \( P_L, P_x, \) and \( P_n \) denote the path loss, transmitted power, and noise power, respectively. Consequently, substituting (10) into (9), we obtain

\[
P_L = \frac{P_x^{-1}(\text{BER}_{\text{measured}}) P_n R_s}{P_x}. \tag{11}
\]

Fig. 19 shows the path loss estimated by the measured BER against the distance between the transmit and receive antennas. We note that the estimated path loss includes the gains of the transmit and receive antennas. Therefore, as can be seen from Fig. 19, the path losses for the case of the Vivaldi antenna and the helical antenna are different from each other. Although the estimated path loss includes the antenna gain, the path loss is around 80 dB in the both antenna cases. However, we again emphasize that despite the large path loss of more than 80 dB, the developed UWB-IR communication system can ensure the BER performance of around \( 10^{-2} \) at a bit rate of 1 Mb/s in the living animal experiment.

V. CONCLUSIONS

This paper has aimed on experimental evaluation of the UWB-IR transmission performance in a living animal. For this purpose, to begin with, we have developed a UWB-IR communication system with an MPPM scheme, and then analyzed the fundamental characteristics by a liquid phantom experiment. Finally, we have conducted the living animal experiment with the developed system in order to evaluate the UWB transmission performance in a real implant BAN environment. From the experimental result, although it has been observed that the path loss is more than 80 dB, the developed system can achieve the BER performance of \( 10^{-2} \) at a depth up to 12 cm with ensuring a high data rate of 1 Mb/s. This result is the first time that the feasibility of a UWB transmission for implant BAN applications in a real living body has been shown.

There is still room for further improvement of our prototype UWB-IR communication system. One of our future subject is to optimize the transmit and receive antennas for the developed UWB-IR transceiver. Another is to incorporate some biological sensors into the UWB-IR transceiver for real in-body information transmission.

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