SAR Reduction in Implant Body Area Networks with Spatial Diversity Reception

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ABSTRACT

This paper investigates the impact of spatial diversity reception on specific absorption rate (SAR) reduction at 400 MHz medical implant communication service (MICS) band. First, in order to calculate the bit error rate (BER) performance under this implant propagation channel and derive the required transmit power to secure a permissible BER, we perform finite-difference time-domain (FDTD) simulations for implant BAN channel modeling with a numerical human body model. Then, we calculate the local peak SAR under the required transmit power when the implant transmitter moves along the digestive organs. Consequently, our simulation results demonstrate that the use of spatial diversity reception can significantly reduce SAR in implant body area networks.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Measurement

1. INTRODUCTION

A concept of wireless body area networks (BANs) is becoming a reality due to the breakthrough of semiconductor technologies and wireless communications in recent years. Typical applications of wireless BANs include healthcare, medical treatment and medical monitoring [1–3]. Generally, 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, 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 WCE as an implant BAN application.

Since the human body may have a high energy absorption in microwave frequency band, it is necessary to satisfy the regulation of specific absorption rate (SAR) which is an indicator of human safety. Therefore, we need to comply with the safety guideline of SAR in realizing a wireless capsule endoscope transmission. The SAR is the amount of power absorbed per unit mass of human tissue. Since the implant transceiver of capsule endoscope has a very small size, the induced SAR would be highly localized so that we only need to pay attention to the local peak SAR. According to the ICNIRP guideline [6], a local SAR as averaged over any ten grams should never exceed 2 W/kg (or 10 W/kg for occupational exposure). We therefore must satisfy the safety guideline at the same time of realizing a high reliability communication performance. However, the wireless communication performance depends much on the transmit power. This is because more transmit power leads to higher signal-to-noise power ratio (SNR) at a receiver side. Hence, it is important to evaluate the communication performance, i.e., bit error rate (BER) performance when the transmit power is limited by the safety guideline of SAR.

On the other hand, spatial diversity reception is well known as a technique to improve the wireless performance without any temporal and spectral resource expansion. Furthermore, in this paper, we pay attention to the feasibility that spatial diversity reception can not only improve the communication performance but also reduce SAR. As a spatial diversity reception technique, maximal-ratio combining (MRC) provides the best performance improvement in terms of maximizing the SNR, as compared with other combining techniques. However, MRC has the largest complexity of all combining techniques since it requires knowledge of channel state information (CSI) in each branch. From this viewpoint, equal gain combining (EGC) has an advantage in practice because they can be realized with less knowledge of CSI relative to the optimal MRC scheme [7]. Indeed, EGC usually does not require estimation of the channel fading amplitudes. So, from the above reason, our focus in this paper shall be on EGC diversity reception.

In order to investigate the effect of spatial diversity reception on SAR reduction, we need to evaluate the transmit power to secure a permissible BER. For this purpose, the model of the

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propagation characteristics in the implant BANs at the 400 MHz medical implant communication service (MICS) band is required. Although several studies have so far been conducted to establish a path loss model for the capsule endoscope [8,9], no one has related it to the SAR. Therefore, this paper first performs a finite-difference time-domain (FDTD) simulation for implant BAN propagation characteristic and local peak SAR calculation with a numerical human body model. In place of the difficulty in actual measurement of propagation characteristics for living humans, FDTD simulation has a merit to provide high-quality propagation data by using an anatomically based on high-resolution human body model [10]. Then, we derive an implant BAN channel model, and then calculate the BER performance under this implant propagation channel to determine the required transmit power for securing a permissible BER. Finally, we derive the local peak SAR and its statistical characteristic under the required transmit power. Such an approach can provide a threshold transmit power used to ensure that the local peak SAR never exceed the safety guideline.

The remaining of this paper is organized as follows. Section II presents the system model of the spatial diversity receiver. Then, Section III describes the implant propagation channel model for capsule endoscope, and Section IV explains the SAR evaluation procedure under required BER performance. Next, Section V demonstrates and discusses the SAR evaluation results in the cases with and without the spatial diversity reception. Finally, Section VI concludes this paper.

2. SYSTEM MODEL FOR SPATIAL DIVERSITY RECEPTION

We assume a transmitter with a single antenna inside a human body and an EGC diversity receiver with L antennas (branches) on the human body. The transmitter sends a BPSK modulated signal $s(t)$. The receiver is equipped with L diversity branches, hence the wireless channel is decomposed into L fading sub-channels. Defining the received signal at the l-th diversity branch as $r_l(t)$ $(l = 1, 2, \cdots L)$, $r_l(t)$ is given by

$$r_l(t) = h_l(t) \otimes s(t) + n_l(t). \tag{1}$$

In Eq. (1), $h_l(t)$ and $n_l(t)$ denote the impulse response of the l-th sub-channel and the additive Gaussian noise at the l-th diversity branch, respectively, and $\otimes$ denotes the convolution. Here, we assumed that $n_1(t), n_2(t), \cdots, n_L(t)$ are independent with the same power.

Then, the combined received signal $r(t)$ is represent as

$$r(t) = \sum_{l=1}^{L} w_l r_l(t) \tag{2}$$

where w_l denotes the diversity weight of the l-th branches. Since the EGC diversity receiver equally weighs them, the EGC diversity receiver obtains w_l as $e^{-j2\pi\theta_l}$, where θ_l is the phase of $h_l(t)$.

3. PROPAGATION CHARACTERISTICS

We employed FDTD simulation to analyze the propagation characteristic and SAR. The employed numerical human body model, which was developed by National Institute of

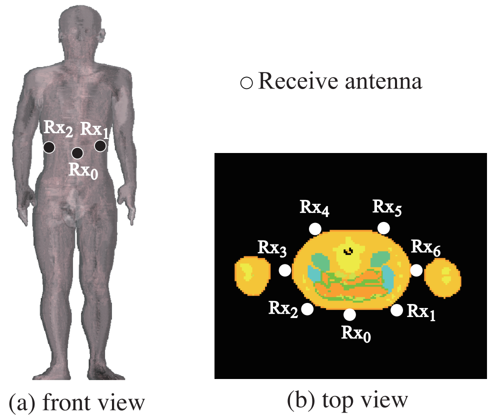

Figure 1: Positions of receive antennas

Information and Communication Technology, Japan [11], is shown in Fig. 1. The human body model is 1.73 m tall and 65 kg weight, and is composed of 51 kinds of biological tissues with a spatial resolution of 2 mm. The transmit antenna of capsule endoscope was assumed inside the digestive organs of the human body, and the receive antennas were placed at seven locations on the body surface around the abdomen and back. In the FDTD simulation, a 4-mm long dipole as the transmit antenna was moved to have 30 locations inside the human body: 4 locations in esophagus, 4 locations in stomach, 9 locations in small intestine and 13 locations in large intestine, with three directivities. The seven receive antennas, denoted as in Fig. 1 with Rx_i $(i = 0, 1, \cdots, 6)$, were 20-mm long dipoles fixed at the body surface.

For the above-described simulation model, we calculated the received power at the seven receive antennas by using the FDTD method. Then, from the following equation

$$PL_{dB} = 10 \log_{10} \frac{P_t}{P_r} \tag{3}$$

where P_t and P_r are the transmit power and receive power, respectively, we obtained the instant path loss in unit of dB as a function of distance d between the transmitter and each receiver. According to an empirical formula that the power decays in proportional to d^n, the average path loss $PL_{dB}^{average}$ can be expressed as

$$PL_{dB}^{average} = PL_{0,dB} + 10n \log_{10} \frac{d}{d_0} \tag{4}$$

where d_0, $PL_{0,dB}$ and n are a reference distance, the path loss at the reference distance d_0 and the path loss exponent, respectively. Fig. 2 shows an example of the path loss characteristic and a fitted curve given by (4) at the receive antenna of Rx_0. The parameters in (4) were estimated by the least squares method. From this figure, we can see that the average path loss is well approximated by (4), and it is indeed proportional to d^n. Table I shows the fitted parameters in (4) for each receive antenna.

Next, we consider a shadowing effect caused by different organs surrounding the transmit antenna, namely, a shadow fading characteristic in the implant BAN channel. With the

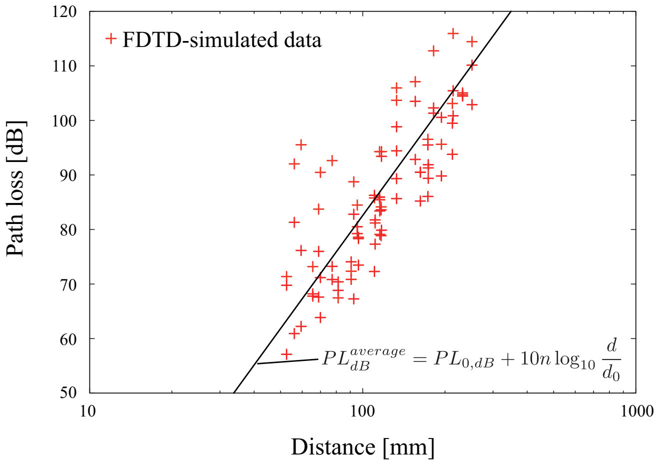

Figure 2: Path loss characteristic

Table 1: Fitted Parameters of Propagation Characteristics

	d_0[m]	$PL_{0,dB}$	n	σ
Rx_0	0.05	49.67	5.533	2.04
Rx_1	0.05	37.81	5.997	2.20
Rx_2	0.05	37.99	6.663	1.80
Rx_3	0.1	59.74	6.421	2.17
Rx_4	0.1	44.24	13.75	2.08
Rx_5	0.1	50.96	11.01	1.73
Rx_6	0.1	58.62	5.793	2.17

definition

$$S_{dB} = PL_{dB} - PL_{dB}^{average} \tag{5}$$

we have found that the statistical distribution of the shadow fading in decibel S_{dB} can be well approximated by normal distribution [12]. That is to say, the lognormal distribution fits well the shadow fading data S at each receive antenna location. The probability density function (*pdf*) of lognormal distribution is given by

$$p(S) = \frac{1}{\sqrt{2\pi}\sigma S} \exp\left[-\frac{(\log S)^2}{2\sigma^2}\right] \tag{6}$$

where σ denotes the standard deviation in log domain. Furthermore, the standard deviation is also shown in Table 1 for each receive antenna.

Finally, we explain correlation coefficients between received signals of two branches, which determine the communication performance of the spatial diversity reception. From our investigation of the correlation coefficients, it is found that the correlation coefficients range from 0.076 to 0.867, which suggests the feasibility of spatial diversity reception, if we adequately choose the receive antenna locations.

4. SAR EVALUATION PROCEDURE UNDER REQUIRED BER PERFORMANCE

4.1 BER Performance Analysis

Table 2: Parameters for deriving transmit power from SNR

T_0 [K]	296
B [MHz]	1
N_F [dB]	6
K	1.36×10^{-23}

In order to derive the required transmit power to ensure a BER performance for capsule endoscope application, we need to calculate the BER performance of the EGC diversity reception under the derived implant shadow fading channel. Defining the average SNR at each branch and the average SNR vector ($L \times 1$) as $\overline{\gamma_l}$ ($l = 1, \cdots, L$) and $\overline{\mathbf{\Gamma}} = [\overline{\gamma}_1, \cdots, \overline{\gamma}_L]^T$, respectively, the average BER for the EGC diversity receiver is given by

$$P_b^{EGC}(\overline{\mathbf{\Gamma}}) = \int_0^{\infty} P_b^{AWGN}(\gamma_{EGC}) p(\gamma_{EGC}|\overline{\Gamma}) d\gamma_{EGC}. \tag{7}$$

where, $P_b^{AGWN}(\gamma_{ECG})$ and $p(\gamma_{ECG}|\overline{\Gamma})$ are the average BER under additive white Gaussian noise when the SNR is γ_{ECG} and the probability density function (*pdf*) on the SNR γ when $\overline{\Gamma}$ is given, respectively. In the case of multiple branches ($L \geqq 2$), we can not analytically derive the $p(\gamma_{EGC}|\overline{\mathbf{\Gamma}})$. This is because γ_{EGC} includes the sum of Log-Normally distributed random variables ($|h_l(t)|$ is Log-Normally distributed), and furthermore, the received signals at all receive branches are uncorrelated with each other. Hence, we derive the $p(\gamma_{EGC}|\overline{\mathbf{\Gamma}})$ by a numerical analysis based on Monte Carlo simulation (a theoretical analysis of the BER performance is our future work).

4.2 Calculation of Required Transmit Power and SAR

Next, we link the SNR and the transmit power. Let us assume that the only noise source at the receiver is AWGN. This noise is typically thermal, introduced by the receive antenna and the front-end circuit of the receiver. The thermal noise power is given by

$$N = kT_0BN_F \tag{8}$$

where k, T_0, B and N_F denote the Boltzmann constant, the environment temperature, the communication bandwidth or data rate and the noise figure of receiving device, respectively. Then, the transmit power can be calculated as

$$\begin{aligned} P_{t,dBW} &= P_{r,dBW} + PL_{dB} \\ &= \gamma_{dB} + 10\log_{10}[kT_0B] + N_{F,dB} + PL_{dB}. \end{aligned} \tag{9}$$

Table 2 gives the parameters for deriving the transmit power from the SNR γ_{dB}.

On the other hand, the safety to human body is evaluated in terms of the SAR as averaged over any ten gram of tissue. The SAR is expressed as

$$SAR = \frac{\sigma}{\rho}E^2. \tag{10}$$

In (10), σ, ρ and E are the the conductivity of tissue, the mass density of tissue and the electric field rms value inside

Table 3: Average and maximum transmit power at BER = 10^{-3} in the case without spatial diversity reception.

	Maximum transmit power [mW]	Average transmit power [mW]
Rx_0	37.60	3.80
Rx_1	34.46	1.50
Rx_2	8.35	0.41
Rx_3	40.07	6.69
Rx_4	222.24	8.81
Rx_5	10.63	1.43
Rx_6	100.09	8.09

tissue, respectively. To calculate the SAR, we employ FDTD simulation with the numerical human model shown in the section III. The transmit power of the capsule endoscope is determined based on the above procedure for ensuring a BER of 10^{-3}. As mentioned previously, the ICNIRP safety guideline requires 2 W/kg (or 10 W/kg for occupational exposure) to be satisfied.

5. SAR EVALUATION RESULTS

5.1 Case without Spatial Diversity Reception

First, we demonstrate the results for the case of a single branch, namely, no spatial diversity reception case. To begin with, the required transmit power was calculated. Table. 3 shows the required transmit power for obtaining an average BER of 10^{-3}, and the required transmit power for obtaining a BER always below 10^{-3}, respectively. We name the transmit power in the former case as the required average transmit power and that in the latter case as the required maximum transmit power. We can see that the average and maximum transmit powers are different at different receiver locations. Note that the average transmit power is always smaller than 10 mW, and such a transmit power can never induce a 10-gram average SAR exceeding 2 W/kg. In this sense, the safety guideline is always satisfied. However, if we require a higher communication quality to ensure the BER smaller than 10^{-3} in any capsule location, the SAR will be determined by the maximum transmit power in Table 3. As can be seen, when the receiver antenna is located in the front of the human body, the path loss is relatively small so that the required transmit power is also small.

5.2 Case with Spatial Diversity Reception

Next, this paper shows the results for the case of multiple branches, and investigates the effect of spatial diversity reception on SAR reduction. In this paper, we consider only the case of two branches ($L = 2$), however, the SAR evaluation for the case of more than three branches ($L \geqq 3$) can be realized by the similar way in the case of two branches. In the same similar way to the single branch case, the required transmit power for the case with the spatial diversity reception was calculated at first. Tables 4 and 5 show the required average transmit power and the required maximum transmit power, respectively. As compared with the results for the case without spatial diversity reception in Table 3, we can see that applying spatial diversity reception to the receivers can significantly reduce both the required average and maximum transmit powers. Furthermore, similarity to the single branch case, the required average transmit power is also less than 10 mW at all selections of the receive antennas, namely, the 10-gram average SAR exceeding 2 W/kg can not occur. In addition, generally, the performance of the spatial diversity reception is linearly dependent on the correlation coefficient between the received signals, that is, less correlation coefficient leads to better communication performance of the spatial diversity reception. If we can choose the best receive antenna positions, for example Rx_0 and Rx_2, the achievable required maximum transmit power is 2.36×10^{-1} mW, and it is around 3% of 8.35 mW, which is the minimum value in the case without the spatial diversity reception.

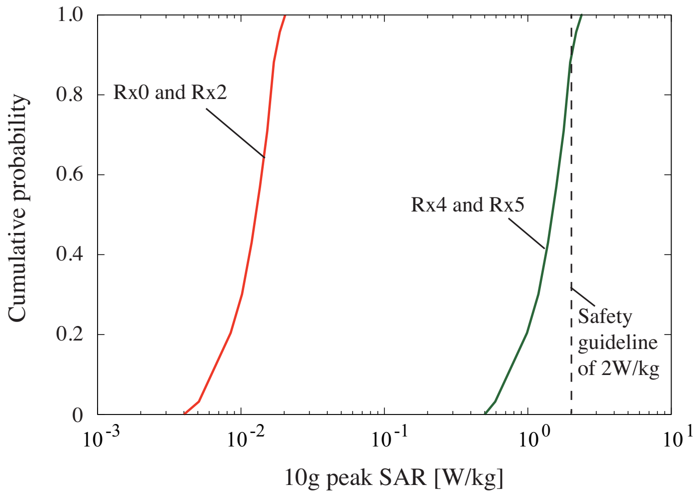

Figure 3: Cumulative probability of 10g peak SAR in the case with spatial diversity reception.

Fig. 3 shows the cumulative probabilities of the 10-gram average peak SARs in the case with the spatial diversity reception at the required maximum transmit powers for the best selection (Rx_0 and Rx_2) and the worst selection (Rx_4 and Rx_5). From this figure, in addition to the required transmit power, the SARs are also remarkably reduced as compared with those for the single branch case. Even if the two receive antennas are set to Rx_4 and Rx_5 (the worst selection), a transmit power of only 27.5 mW is required to ensure a BER not exceeding 10^{-3}. We can see from Fig. 3 that such a transmit power yields a local peak SAR ranging under around 2.4 W/kg and the local peak SAR can not exceed the 2 W/kg with the cumulative probability of 0.8. This result means that the maximum transmit powers for the case with the spatial diversity reception can never exceed 10 W/kg. Moreover, if we can optimally select the diversity branches, for example the selection of Rx_0 and Rx_2, the 10-gram average SAR has 10^2 times safety margin of the safety guideline of 2 W/kg.

6. CONCLUSION

This paper has investigated the impact of spatial diversity reception on SAR reduction in implant BANs. In order to evaluate the transmission performance and the local peak SAR in a WCE scenario, we have performed the FDTD

Table 4: Average transmit power at BER = 10^{-3} in the case with spatial diversity reception

	Average transmit power [mW]						
	Rx_0	Rx_1	Rx_2	Rx_3	Rx_4	Rx_5	Rx_6
Rx_0	–						
Rx_1	4.32×10^{-2}	–					
Rx_2	1.62×10^{-2}	2.10×10^{-2}	–				
Rx_3	5.61×10^{-2}	4.11×10^{-2}	3.35×10^{-2}	–			
Rx_4	1.27×10^{-1}	8.04×10^{-2}	4.09×10^{-2}	6.20×10^{-1}	–		
Rx_5	2.02×10^{-1}	2.05×10^{-1}	4.87×10^{-2}	5.21×10^{-1}	9.94×10^{-1}	–	
Rx_6	2.65×10^{-1}	2.52×10^{-1}	4.66×10^{-2}	3.50×10^{-1}	6.82×10^{-1}	2.43	–

Table 5: Maximum transmit power at BER = 10^{-3} in the case with spatial diversity reception.

	Maximum transmit power [mW]						
	Rx_0	Rx_1	Rx_2	Rx_3	Rx_4	Rx_5	Rx_6
Rx_0	–						
Rx_1	6.81×10^{-1}	–					
Rx_2	2.36×10^{-1}	4.93×10^{-1}	–				
Rx_3	5.57×10^{-1}	3.92×10^{-1}	3.44×10^{-1}	–			
Rx_4	4.23	3.56×10^{-1}	1.76	21.9	–		
Rx_5	1.94	2.62	6.03×10^{-1}	5.06	27.5	–	
Rx_6	3.69	5.22	9.06×10^{-1}	4.98	21.7	24.7	–

simulation for a numerical human body model in the 400 MHz MICS band. Based on the simulation results, we have derived an implant shadow fading channel model, and then calculated the BER performance of the EGC diversity receiver under the derived channel.

In the case with the spatial diversity reception (two branches case), we have seen from the numerical analyses that the required average power is less than 10 mW at all selections of the receive antennas, and in terms of both the required average and maximum transmit powers, the 10-gram average SAR exceeding 10 W/kg will never be induced. This result means that the receiver without spatial diversity reception must choose an optimal receive antenna location in order to satisfy the safety guideline of 10 W/kg, whereas the spatial diversity receiver can choose any receive antenna locations. Furthermore, even if we choose the worst receive antenna locations, for example Rx_4 and Rx_5, the local peak SAR can not exceed the 2 W/kg with the cumulative probability of 0.8. Additionally, by choosing the best receive antenna locations, for example Rx_0 and Rx_1, we have also confirmed that the 10-gram average SAR has 10^2 times safety margin of the safety guideline of 2 W/kg. It should be noted that the SAR is largely dependent on the transmit antenna. Although, in this study, we employed a dipole which may be a different from a typical capsule endoscope, the demonstrated approach is valid to any types of transmit antennas.

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