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UWB diversity performance in correlated lognormal-sum-distributed in-body to on-body channel

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Abstract: Ultra wideband (UWB) technology in low band has being attracted considerable attention for high-speed and real-time transmission from inside to outside human body. However, it suffers from large attenuation and shadow fading in human tissues. A diversity technique is expected to provide effective improvement on its communication performance. This study aims to derive an approximate model for correlated in-body to on-body diversity channel and clarify the diversity effect. First, correlated statistical distribution between each two single signals is approximated as a lognormal sum distribution. Then two flexible parameters s_1 and s_2 in the lognormal sum approximation are optimized to obtain the probability density function (PDF) of the diversity channel. Finally the average bit error rates (BERs) are calculated theoretically to clarify the diversity effect, and its validity is verified by computer simulations.

Keywords: ultra wideband (UWB), in-body to on-body communication, spatial diversity, lognormal sum distribution, bit error rate (BER)
Classification: Antennas and Propagation

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1 Introduction

Ultra Wideband (UWB) technology in low band has being attracted considerable attention particularly for implant body area network (BAN) application on account of its inherent features for high-speed and real-time image transmission. However, the in-body to on-body transmission undergoes severe signal decay and shadow fading inside the human body. This feature makes it necessary to adopt diversity reception for improving communication performance. Based on our previously-derived in-body to on-body channel characteristics using finite difference time domain (FDTD) numerical simulation technique [1], we found that the received on-body signals follow lognormal distribution and are correlated between different receiver branches. So a diversity signal with maximal ratio combining (MRC) or equal gain combining (EGC) follows a correlated lognormal sum distribution. However, few researches have addressed the diversity performance for such an in-body to on-body correlated lognormal sum distributed channel. In this paper, in order to clarify the average bit error rate (BER) performance for diversity reception in the in-body to on-body transmission, we employ a moment generation function (MGF) based lognormal sum approximation method to derive the probability density function (PDF) of the combined diversity channel. After optimizing the corresponding parameters in the PDF derivation, we derive a theoretical average BER performance and clarify the diversity effect in the in-body to on-body transmission. The validity of the proposed theoretical approximation is also verified by computer simulations.

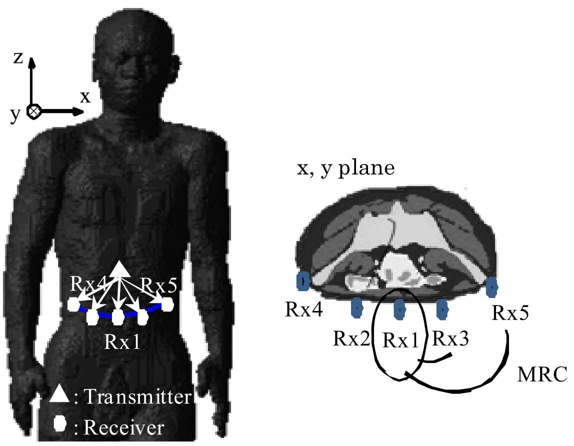

Fig. 1. Analysis model with spatial diversity reception for capsule endoscope

2 Spatial diversity reception model

Fig. 1 shows an anatomical human body model with spatial diversity reception for capsule endoscope application. The transmitting antenna was assumed to move in the small intestine to take 33 locations with three polarization directions, x, y, and z. The transmitted UWB signal was limited

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at low band from 3.4 – 4.8 GHz. The receiving antennas (Rx) were arranged at five locations with a spatial interval of 6.5 cm in front of the abdomen based on the consideration of spatial diversity reception. At each on-body receiver location, we calculated the received signal energy using the FDTD numerical method incorporated with an anatomical human body model, and then extracted the path loss and shadow fading characteristics. The path loss was obtained from the ratio of the transmitted and received signal energies between each transmitter and receiver, and the instant variation from the average path loss was regarded as the shadow fading.

3 Sum of correlated lognormal signals

The shadow fading has been found to follow lognormal distribution but a correlation between each two channels exists [1]. The correlation coefficient between each two received UWB signals was obtained from:

$$\rho(i,j) = \frac{\sum_{m=1}^{M}(A_{ri,m} - \overline{A_{ri}})(A_{rj,m} - \overline{A_{rj}})}{\sqrt{\sum_{m=1}^{M}(A_{ri,m} - \overline{A_{ri}})^2 \sum_{m=1}^{M}(A_{rj,m} - \overline{A_{rj}})^2}} \tag{1}$$

where $M(=99)$ is the data number corresponding to different transmitting locations and polarizations, $A_{ri,m}$ and $A_{rj,m}$ are the root of instant FDTD-calculated received energies at any two receivers among five receivers shown in Fig. 1, $\overline{A_{ri}}$ and $\overline{A_{rj}}$ indicate their averages, respectively. The calculated correlation coefficient between each two receivers is tabulated in Table I. Generally, the realization of a significant diversity requires a smaller correlation. As can be seen in Table I, the correlation coefficients range from 0.1 to 0.5, which suggests that the dependency of each two received signals is not so strong. This also means that a diversity effect can be expected even though the received signals are correlated in the in-body to on-body wireless communication.

Table I. Correlation coefficients between each two received signals

	Rx1	Rx2	Rx3	Rx4	Rx5
Rx1	1				
Rx2	0.10	1			
Rx3	0.24	0.34	1		
Rx4	0.13	0.52	0.28	1	
Rx5	0.18	0.44	0.49	0.51	1

In order to derive the theoretical BER performance for diversity reception, we have to know the PDF of the sum of two correlated lognormal-distributed signals. However, any exact closed-form expressions for such a PDF are unknown. A usual method to approximate the sum of correlated lognormal-distributed variables is to use a single lognormal distribution. With this approximation, we here employed a MGF-based method to determine the corresponding parameters in the approximated single lognormal distribution. As proposed in [2], this method is very analytical and flexible. It matches

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a short Gauss-Hermit approximation of the MGF of the sum of correlated lognormal-distributed variables with that of a single lognormal distribution. That is to say, the parameters μ_{dB} and σ_{dB} in the approximated single lognormal distribution were solved by the following nonlinear equation:

$$\sum_{n=1}^{N} \frac{w_n}{\sqrt{\pi}} \exp\left[-s_i \exp\left(\frac{\sqrt{2}\sigma_{dB}a_n + \mu_{dB}}{\xi}\right)\right]$$
$$= \sum_{n1=1}^{N}\sum_{n2=1}^{N} \frac{w_{n1}w_{n2}}{\pi} \exp\left(-s_i\left[\exp\left(\frac{\sqrt{2}\sigma_{1,dB}a_{n1} + \mu_{1,dB}}{\xi}\right)\right.\right.$$
$$\left.\left. + \exp\left(\frac{\sqrt{2}\rho\sigma_{2,dB}a_{n1} + \sqrt{2}(1-\rho^2)\sigma_{2,dB}a_{n2} + \mu_{2,dB}}{\xi}\right)\right]\right),$$
$$\text{for } i = 1 \text{ and } 2. \quad (2)$$

In equation (2), $\xi = 10\log_e 10$ is a scaling constant. ρ is the correlation coefficient between any two received signals. w_n and a_n are the weights and abscissas respectively for the Gauss-Hermit series expansion, and are tabulated in [3]. The Hermit integration order N is suggested as 6. s_i $(i = 1, 2)$ indicate the parameters for adjusting the weighted integrals of the short Gauss-Hermit integration. It should be highlighted here that the pair of parameters (s_1, s_2) is a key point and needs to be optimized for realizing a more accurate approximation in different applications. How to choose an appropriate pair of s parameters is therefore of great importance. For the in-body to on-body UWB transmission, we determined the s parameters by comparing the accuracy of the approximated lognormal sum PDF with that of the simulated one. The PDF accuracy is defined by:

$$A_{pdf} = \sum_{m=1}^{M} e_m \frac{|F_{(s_1,s_2)(x_m)} - H(x_m)|}{H(x_m)} \quad (3)$$

where e_m is the relative error weight and the sum until M can be normalized by 1. $F_{(s_1,s_2)}(x_m)$ denotes the PDF of the approximated lognormal sum distribution with parameters derived by Eq. (2), while $H(x_m)$ indicates the PDF of the corresponding simulated lognormal sum. To determine the parameters (s_1, s_2) in Eq. (3), we made s_1 be a fixed parameter such as 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, and changed s_2 to make it have a proportional relationship with s_1 ($s_2/s_1 = 1 \sim 10$). In this way, we obtained some typical pairs of smaller s values and also some typical pairs of relative larger s values.

Fig. 2 (a) is plotted to show the PDF accuracy versus the ratio of s_2 to s_1. For smaller s values such as $s_1 = 10^{-4}$ or $s_1 = 10^{-3}$, the PDF accuracies are almost in the same level with different pairs of (s_1, s_2). Nevertheless, the highest achievable accuracy was found when $(s_1, s_2) = (10^{-3}, 4\times10^{-3})$. While for larger s values such as $s_1 = 10^{-2}$ or $s_1 = 10^{-1}$, the PDF accuracy seems not so good in comparison with smaller s values even if there is a comparable PDF accuracy at $(s_1, s_2) = (10^{-1}, 3\times10^{-1})$. As a result, we decided to fix the s parameters as $(s_1, s_2) = (10^{-3}, 4\times10^{-3})$ for deriving a good approximation of lognormal sum PDF. With such an optimized s parameters, we derived the parameters μ_{dB} and σ_{dB} in left hand of Eq. (3) by using the FDTD-derived

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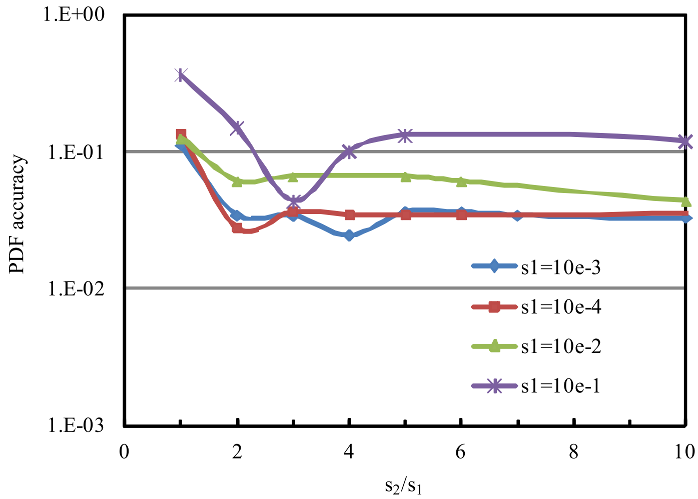
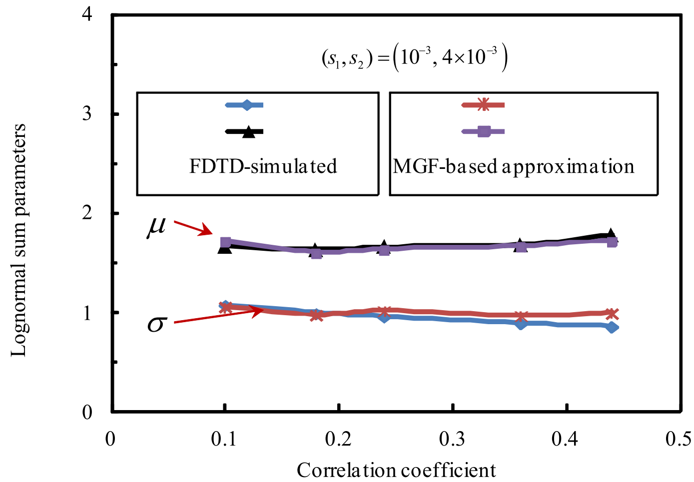
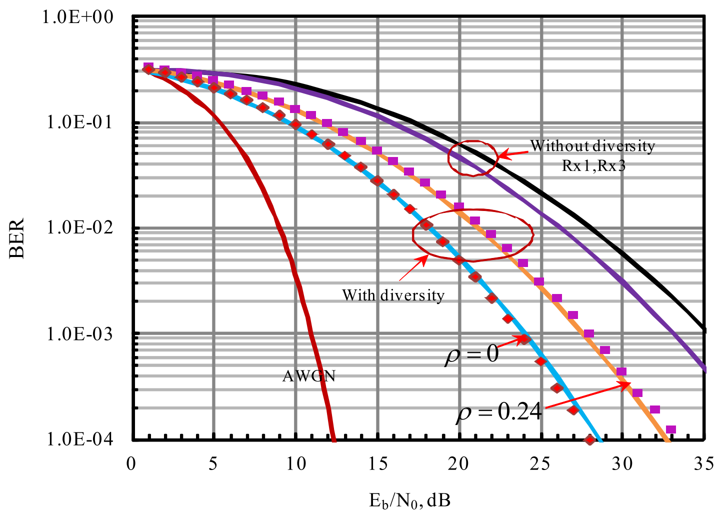


(a) PDF accuracy versus s_1/s_2 ratio



(b) Parameters of the correlated lognormal sum distribution



(c) BER performance for MRC diversity with Rx1 and Rx3

Fig. 2. Approximation results of lognormal sum distribution and BER performance

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data ($\mu_{1\,dB}$, $\sigma_{1\,dB}$, $\mu_{2\,dB}$, $\sigma_{2\,dB}$). The parameter μ and σ in logarithm region versus the correlation coefficient for different MRC diversity combination are shown in Fig. 2 (b). As can be seen, the approximated parameters μ and σ with MGF-based approximation method can reach a good agreement with the FDTD-simulated results. That is to say, the optimized s parameters may not be dramatically influenced by different correlation coefficients for different channel combinations. Moreover, the PDF combining the receiver Rx2 and Rx4, which possesses the highest correlation coefficient in this study, also exhibits good agreement between the MGF-based approximation and the FDTD-simulated result.

4 Diversity performance

By using the derived PDF of correlated lognormal sum, theoretical BER performance of MRC diversity for the in-body to on-body transmission was analyzed in terms of on-off keying (OOK) and pulse position modulation (PPM) schemes in impulse radio (IR)-UWB system with the energy detection. Fig. 2 (c) shows the average BER performance of MRC diversity for Rx1 and Rx3 combination ($\rho = 0.24$) with OOK-IR-UWB system. Also shown in the figure with symbols are computer-simulated BERs, which agree well with the theoretical curves and ensure the validity of the proposed approximation. From Fig. 2 (c), the possible diversity improvement was found to be around 5 dB at BER of 10^{-3}. It degrades about 4 dB in comparison with that of independent diversity channel ($\rho = 0$). With the decrease of the correlation coefficient from 0.24, the diversity effect would be better than 5 dB and close to 9 – 12 dB. If we choose a combined diversity channel such as Rx1 and Rx2 which is in the front of human abdomen and has a lower correlation coefficient, a more significant diversity improvement can be expected. In addition, the average BER performance with PPM-IR-UWB system has also been calculated and shown a similar tendency with that of the OOK-IR-UWB system.

5 Conclusion

A theoretical approximation to correlated lognormal-sum-distributed in-body to on-body diversity channel has been proposed and used to analyze UWB diversity reception performance. With a MGF-based method to approximate the sum of two correlated lognormal signals as a single lognormal distribution, we have optimized the corresponding parameters (s_1, s_2) as $(10^{-3}, 4 \times 10^{-3})$ for deriving the PDF in the in-body to on-body diversity channel, and clarified the diversity effect via average BER analysis. We have also verified the validity of this theoretical approximation by computer simulations. Based on this approach, we can choose an appropriate combination of the on-body receivers in order to achieve a significant improvement on the in-body to on-body communication performance.

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