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Performance Evaluation of Wireless Communications through Capsule Endoscope

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Abstract— **This paper presents a performance evaluation of wireless communications applicable into a capsule endoscope. A numerical model to describe the received signal strength (RSS) radiated from a capsule-sized signal generator is derived through measurements in which a liquid phantom that has equivalent electrical constants is used. By introducing this model and taking into account the characteristics of its direction pattern of the capsule and propagation distance between the implanted capsule and on-body antenna, a cumulative distribution function (CDF) of the received SNR is evaluated. Then, simulation results related to the error ratio in the wireless channel are obtained. These results show that the frequencies of 611 MHz or lesser would be useful for the capsule endoscope applications from the view point of error rate performance. Further, we show that the use of antenna diversity brings additional gain to this application.**

I. Introduction

In the filed of medical applications, the use of wireless communication technology has been paid attention in order to not only reduce costs related to the workload in the case of medical staffs but also improve the quality-of-life in the case of patients. One promising use of such wireless communications is capsule endoscope. In this procedure, patients are freed from the pain by introducing wireless capsule; this capsule wirelessly transmits the image from inside the digestive tract to body-worn devices [1].

Current versions of such a capsule endoscope are equipped with one-directional communication for image transmission; however, advanced capsule endoscopes are expected. These advanced endoscopes are expected to deploy some drug delivery or simple operation functions by monitoring the transmitted image data. In order to realize such an advanced capsule endoscope, a highly reliable broadband wireless transmission is required.

In this paper, we focus on the design of physical layer for wireless communications that would be applicable to such an advanced capsule endoscope. The wireless communication in this case should maintain a low error rate performance even in channels of high attenuation due to radio propagation through human tissue and antenna impairments. Thus, we derive a numerical model to describe the attenuation of radio signals in human tissue. This model is obtained by measuring the received signal strength (RSS) radiated from a capsule-sized signal generator (SG) put into a liquid phantom, which has electrical constants close to those of the human tissue. Further, antenna impairments caused by the movement of a capsule device with a typical dipole antenna are stochastically modeled. Then, based on the usage scenario of a capsule endoscope, performance from the viewpoint of wireless communication is evaluated.

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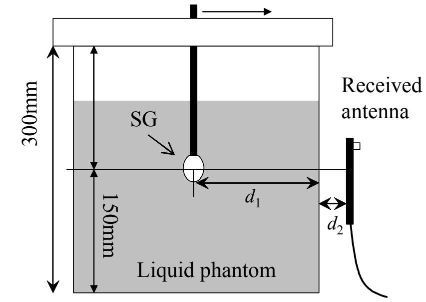

(a) Measurement setup.

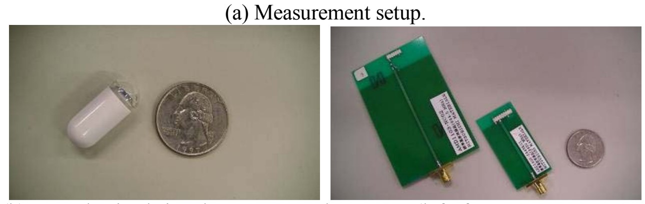
(b) Capsule-sized signal generator and antennas (left: for except 2450 MHz, right: for 2450 MHz) used in the measurements.

Fig. 1. Measurement setup on measurements of RSS to obtain a numerical model of path attenuation trough the human tissue.

II. Numerical Modeling of RSS

In this section, a model that provides RSS corresponding to a certain thickness of the human tissue is shown.

A. Measurement setup

The measurement setup is shown in Fig. 1. A capsule-sized SG (length: 18 mm, diameter: 10 mm) radiates continuous waves (CWs) of 403 MHz, 611 MHz, 953 MHz, and 2450 MHz. The use of such an SG, which has no cables connected to it, is useful for avoiding the influence of radiation from cables on measured results. The liquid phantom (IEC 6220909-1 HT430) imitates electrical constants of the human tissue. Measured electrical constants of the liquid phantom at measured frequencies are listed as complex permittivity in Table I. This liquid phantom is stored in a cylindrical vessel (diameter: 150 mm) made by polycarbonate. The antenna to receive signals that radiate from the capsule-sized SG is set at an outside of the vessel at a distance of 15 mm from the wall of the vessel. This antenna is a chip antenna that provides an omnidirectional pattern in the horizontal plane. The gain of the antenna is around 0 dBi. We prepare an antenna for each frequency to be measured. During all the measurements, we

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TABLE I
COMPLEX PERMITTIVITY OF THE LIQUID PHANTOM FOR MEASURED FREQUENCIES

Frequency [MHz]	ε'	ε''
403	42.27	39.40
611	40.20	29.78
953	37.28	23.04
2450	31.00	17.98

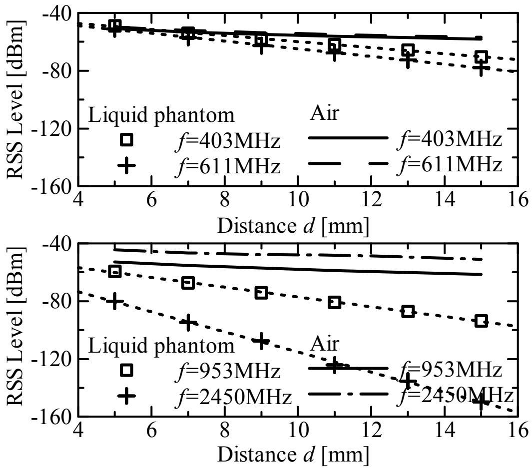

Fig. 2. Measured RSS in dBm for distance d_1 in 403, 611, 953, and 2450 MHz.

TABLE II
COEFFICIENTS VALUES FOR A NUMERICAL MODEL OF RSS

Frequency f [MHz]	Coefficients $a(f)$ and $b(f)$
403	$a(f) = -0.21$, $b(f) = -38.95$
611	$a(f) = -0.27$, $b(f) = -38.12$
953	$a(f) = -0.34$, $b(f) = -43.17$
2450	$a(f) = -0.69$, $b(f) = -45.66$

set the angle of the SG such that the SG faces the direction providing the maximum gain with the horizontal plane of the chip antenna. RSS received by the chip antenna is measured by a spectrum analyzer. All these measurements are carried out in an anechoic chamber.

B. Modeling a numerical model

Fig. 2 displays measured RSS in the setup shown in Fig. 1. As a reference, RSS measured in the air is also plotted for each measured frequency. Based on the measured results, a numerical model of the RSS is derived. The model of RSS, $S(d, f)$, is given by the following equation.

$$S(d, f)\,[\mathrm{dB}] = a(f)\cdot d\,[\mathrm{mm}] + b(f) \tag{1}$$

where $a(f)$ and $b(f)$ are coefficients obtained from least square fitting and d stands for the thickness of the human tissue which is the same as d_1 of Fig. 1. Table II lists the coefficients $a(f)$ and $b(f)$ in the case of each measured frequency. The linear curves on the RSS obtained from these coefficients are also plotted in Fig. 2. It is shown that the attenuation is well fitted by a linear curve. Further, the coefficients values are show that the $a(f)$ in the case of 2450-MHz signal is around three times the value of that in the case of 403-MHz signal. This implies that the increase in the frequency of a radio signal causes an increase in the attenuation during propagation in the human tissue.

The frequency dependency of the RSS level is also

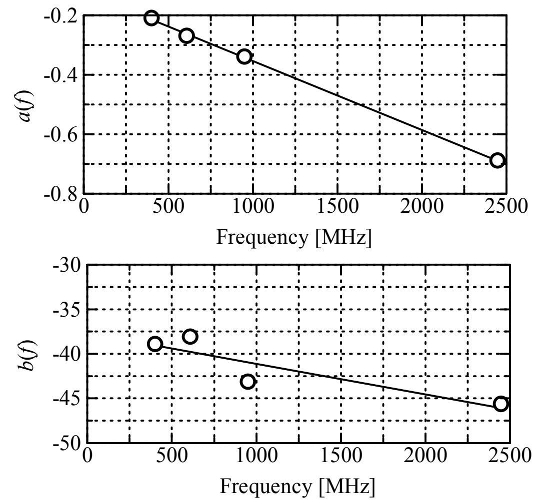

Fig. 3. Fitting of the coefficients in Eq.(1), $a(f)$ and $b(f)$,to describe frequency dependency of them.

evaluated. The coefficients $a(f)$ and $b(f)$ are linearly fitted using least square fitting. As a result, each coefficient is given by a function of frequency as follows:

$$a(f) = -2.32\times10^{-4}\cdot f\,[\mathrm{MHz}] - 0.121 \tag{2}$$

$$b(f) = -3.42\times10^{-3}\cdot f\,[\mathrm{MHz}] - 37.69 \tag{3}$$

Fig. 3 shows the coefficient values versus the frequency to confirm the agreement between the values shown in Table II and values obtained by Eq.(2) and (3).

III. MODELING ON CAPSULE ENDOSCPE

This section describes characteristics of antenna impairment and propagation distance based on a usage model of capsule endoscope. Here, the antenna impairment describes power loss due to a mismatch in antenna plane between the capsule and the body-worn antenna. The propagation distance determines the distribution of human tissue in which a radio signal propagates to convey information from or to the capsule device.

A. Antenna impairment

In the RSS measurement, the antenna is fixed to measure the maximum RSS in each frequency band. However, since the capsule device moves along with the digestive tract, its antenna plane is randomly changed during the movement. Thus, the antenna impairment due to such a movement should be taken into account while evaluating the performance. Note that the antenna has some frequency dependency on its directional pattern; however, in this discussion, such frequency dependence is ignored.

A cumulative distribution function (CDF) of the antenna loss on a dipole antenna over whole angles (i.e., x–y, y–z, and z–x planes) is shown in Fig. 4. The loss is normalized by the maximum gain of this antenna. Since a dipole antenna has deep nulls in the directional pattern, CDF of the antenna gain widely spreads from 0 dB to around 30 dB. At 99% of the CDF, the antenna loss reaches 21 dB. In medical applications including such an advanced capsule endoscope, reliable

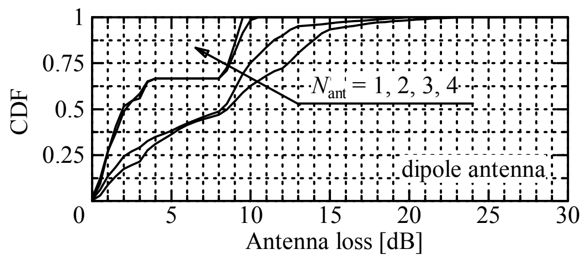

Fig. 4. CDF of the antenna loss for a single dipole antenna and multiple antenna systems to achieve antenna diversity gain.

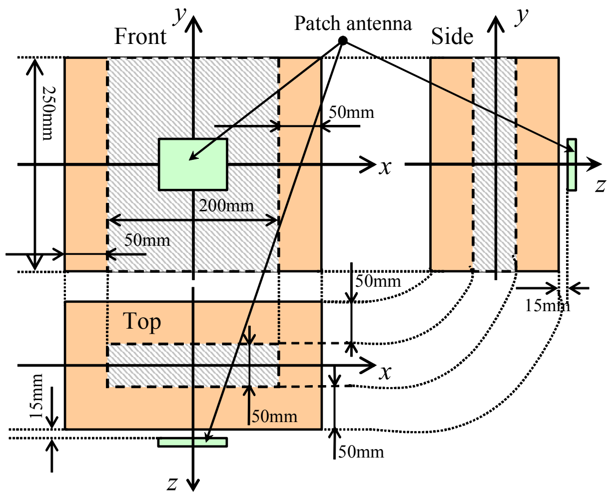

Fig. 5. Cubic model to evaluate the performance of wireless connection in capsule endoscope. The moveable area is colored by gray.

communication is required in which a wireless connection is maintained with a probability of 99% or more. Therefore, a link margin of more than 21 dB to mitigate such an antenna loss is required.

The use of an antenna diversity, in which a couple of body-worn-devices with a single antenna are attached to capture the signal from the capsule at each device, or a couple of antennas connected to a single device are attached to the body surface, is beneficial to mitigate the effects of such a deep null. Fig. 4 also shows the CDF on antenna gain for a selective antenna diversity in which the smallest antenna loss among the antennas is selected. In this evaluation of the antenna diversity, we assume that each antenna is attached to the body surface around human body with the angle between the adjacent antennas is set to $90/N_{ant}$ deg where N_{ant} indicates the number of antennas. The number of antennas is set to 2, 3, or 4 antennas. By introducing such a selection combining, the antenna loss to reach 99 % CDF becomes 18.5 dB, 10.8 dB, and 9.6 dB for a 2-, 3-, and 4-antenna system, respectively.

B. Propagation distance

The propagation distance, which is equivalent to the thickness of the human tissue in the wireless channel, is estimated through a simple human body model. The shape of a human body and the movable part of a capsule device are modeled by cubic as shown in Fig.5. The moveable part is colored; it has a height (y-axis) of 250 mm, width (x-axis) of 200 mm, and depth (z-axis) of 50 mm. In this model, the thickness of human tissue between the body surface and movable part is set to 50 mm. We assume that each body-worn antenna is placed at a distance of 15 mm from the body surface.

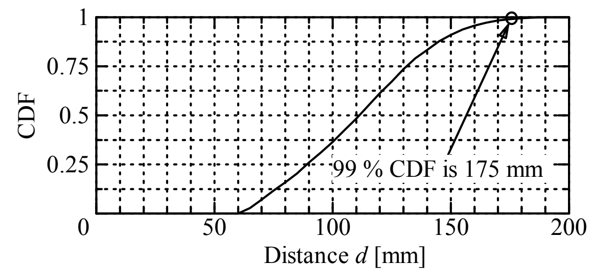

Fig. 6. CDF of the propagation distance which is equivalent to the thickness of the human tissue in the wireless channel along with the line-of-sight.

Based on this model, the histogram of the propagation distance is estimated as shown in Fig. 6. The propagation distance is equivalent to d in Eq.(1). It is shown that the distance ranges from 50 to 200 mm, and 135 mm is the most frequent distance. A CDF value of 99% is achieved at a distance of 175 mm.

IV. Performance Evaluation

This section demonstrates performance evaluation of wireless communication enabled by a capsule endoscope by using the obtained RSS model and stochastic models of antenna impairment and propagation distance.

A. CDF of the SNR at the receiver

The received SNR for a frequency f, $\gamma(f)$, is estimated using the obtained model and CDF characteristics as follows:

$$\gamma(f)=\int\int\{S(d,f)-L_{ant}-N(f)\}p(L_{ant})p(d)\cdot dd\cdot dL_{ant} \quad (4)$$

where $N(f)$ denotes the noise level for the frequency f that includes the thermal noise and the noise figure, and L_{ant} denotes antenna loss, as shown in Fig. 4. The noise figure is set to 7 dB and the bandwidth is 4 MHz. $p(L_{ant})$ and $p(d)$ describe the probability density functions (PDFs) for antenna loss L_{ant} and propagation distance d. The CDF of the RSS for various conditions on antenna loss and frequency are derived from the PDF of the received SNR, which is obtained by the following equation.

$$p(\gamma(f))=p(d)\otimes p(L_{ant}) \quad (5)$$

Fig. 7 shows the CDF curves of the received SNR for 1-, 2- and 3-antenna systems at 403, 611, 953, and 2450MHz. Here, 403 MHz is the assigned frequency band for medical implantable communication systems (MICS) [2, 3], 611 MHz is for wireless medical telemetry systems (WMTS) in the US [4], 953 MHz is dedicated for sensor networks in Japan, and 2450 MHz is the international ISM band. The SNRs required to achieve 90 %, 99 %, and 99.9 % CDF are displayed in Fig. 8, in which $S(d,f)$ in (4) is obtained by using the (2) and (3). It is shown that frequencies of 1200 MHz or more bring no positive SNR even though the required CDF is set to 90 % under the use of three antennas. On the other hand, frequencies of less than 403 MHz provides SNR of 10 dB or more even in 99.9 % CDF under the use of 3-antenna

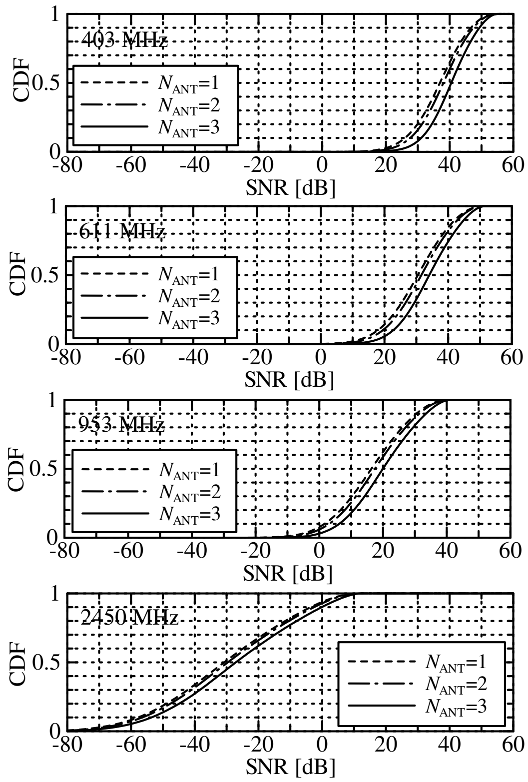

Fig. 7. CDF of the received SNR for each frequency and the number of antennas.

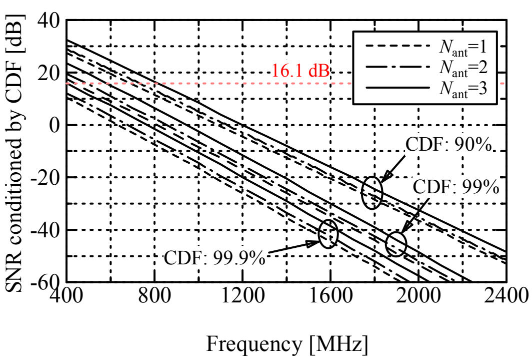

Fig. 8. SNR conditioned by CDF (90, 99, and 99.9%) for various numbers of antennas versus frequencies.

reception. The use of 3 antennas provides SNR of 10 dB or more in the frequencies of less than 960 MHz, 720 MHz, and 540 MHz for 90 %, 99 % and 99.9 % CDF, respectively.

B. Error rate performance

We use Gaussian frequency shift keying (GFSK) for wireless communication since GFSK enables to implement cost-effective transceiver with low power consumption. Fig. 9 shows the bit and packet error ratio of GFSK in the reception by a frequency discriminator. The horizontal axis, E_b/N_0, indicates the SNR per information bit. The packet size is set to 128 bytes. The modulation index and BT product of GFSK are set to 1.0 and 0.5, respectively. The bit rate under the bandwidth of 4 MHz reaches around 1.2 Mbps. By setting the target PER of 10^{-2}, we determine that the required SNR is 16.1 dB. Thus, as shown in Fig.8, the use of a 400-MHz signal results in a 99 % probability of successful wireless

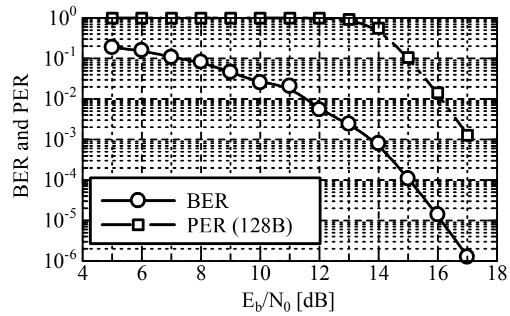

Fig. 9. Bit error ratio (BER) and packet error ratio (PER) vs. E_b/N_0 of GFSK modulation with modulation index of 1.0 and BT of 0.5 in the reception by a frequency discriminator.

transmission with a single antenna. In a CDF of 90 %, by using the 3-antenna systems, results demonstrate that the applicable frequencies range up to 800 MHz.

V. Conclusion

This paper gave a performance evaluation of wireless communication for an advanced capsule endoscope. A numerical model of the RSS was derived from the measured RSS. In this measurement, a liquid phantom and capsule-sized signal generator were used. We also provided stochastic models of both the antenna impairment and propagation distance based on a typical usage model. By using these models, we showed CDF of the received SNR for 1-, 2-, and 3- antenna reception. The results showed that the use of a lower frequency with antenna diversity makes implantable wireless connection for a capsule endoscope reliable and robust.

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