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Path-loss Estimation of Wireless Channels in Capsule Endoscopy from X-ray CT images

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Abstract— **The paper describes an estimation method of path-loss for capsule endoscopy using wireless communications to send images from digestive tract. This method is based on the use of a set of X-ray computer tomography (CT) images of the patient. In order to evaluate this method, we conducted a measurement of received signal strength (RSS) by introducing a signal generator (SG) in esophagus and duodenum of a participant. As a result of comparisons, the method provides estimates on path-loss for the participant with estimation errors of less than 6 dB in 75% measurement positions.**

I. INTRODUCTION

Capsule endoscopy is one of promising applications [1] of wireless body area networks (WBANs) in which a wireless device going thorough digestive tract is included [2]. The capsule endoscopy gives diagnosis in less-invasive because of the use of wireless transmission of taken images from the in-body wireless device. The quality of images taken by capsule endoscopy depends on conditions of wireless channels between the capsule device and body-worn antenna. The channel condition is characterized by path-loss, which is defined as its signal attenuation during radio propagation. In order to evaluate wireless communications, a link budget is generally introduced, in which the number of its path-loss is crucial information to calculate expected signal-to-noise ratio (SNR) at its receiver's antenna. In capsule endoscope, GMSK modulation has been employed as wireless communications. The SNR to satisfy bit error rate of 10^{-3} is around 10 dB; assuming that its transmission power is -16 dBm and noise level at the receiver is -100 dBm, its acceptable path-loss to maintain the BER of 10^{-3} becomes 84 dB. A common approach for evaluating path-loss is to carry out an electromagnetic (EM) field simulator [3]; however, this method requires massive computer resources for the simulations.

In this paper, a method to estimate the path-loss is presented using a set of X-ray computed tomography (CT) images. In this estimation method, a set of X-ray CT images are used to assign dielectric parameters of the participant's tissues. Path-loss is simply calculated through a layer model that consists of two layers representing air and body. The dielectric parameters for the body-layer are obtained from the CT images. The estimates obtained from this method are compared with measurement results for a participant by the use of a capsule-sized signal generator (SG).

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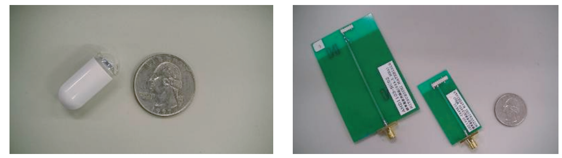


Fig. 1. The outlook of the signal generator (left) to be swallowed and antennas used in the measurement (right). The larger one is for the 403 MHz, the other one is for 2450 MHz.

II. MEASUREMENT OF RADIO SIGNALS RADIATED FROM AN IMPLANTED SIGNAL GENERATOR

A. Measurement setup

Received signal strength (RSS) is measured radiated from a capsule-sized SG to a body-worn antenna. The SG is placed in either esophagus or duodenum of a participant. Ethics statement is as follows: this measurement was approved by Yokohama City University Institutional review Board, and informed consent was obtained from the participant for all procedures prior to the measurement.

In the measurement of RSS, a fabricated small-size SG is used which has its diameter of 11 mm and the length of 18 mm. This SG was swallowed by an introducer to control its position or direction of the SG. The outlook of the SG and body-worn antenna is shown in Fig. 1. This measurement was carried out in two different frequencies; one is 403 MHz, which is in the frequency band of medical implantable communication system (MICS), and the other one is 2450 MHz, which is in the 2.4 GHz ISM band. A specific body-worn antenna was prepared for each frequency. In the measurement, a separation of 15 mm is kept between the antenna and the body surface by using a dielectric block (formed polystyrene) in order to maintain its VSWR characteristic of the out-body antenna. Fig. 2 shows an X-ray image that the SG with its introducer is located in the duodenum.

B. Measurement results

Table I lists the measurement results on RSS for various positions of the body-worn antenna around the human body. In these RSS, the antenna gain is removed. In this table, distances between SG and the body-worn antenna are also listed. The distances are measured by CT images taken during the measurement. Fig. 3 shows the measured RSS versus the distance d. The results show that the slope of

Fig. 2. An X-ray image to show the swallowed signal generator with an introducer is shown in the case of the duodenum.

TABLE I
MEASUREMENT RESULTS OF RSS RADIATED FROM THE IMPLANTED SIGNAL GENERATOR.

(1) 403 MHz

Position	Esophagus		Duodenum	
	distance d	RSS R	distance d	RSS R
Front	121.5 mm	-65.3 dBm	104.5 mm	-70.0 dBm
Right	161.1 mm	-83.1 dBm	192.1 mm	-77.0 dBm
Left	170.1 mm	-70.2 dBm	128.9 mm	-71.2 dBm
Back	98.9 mm	-59.9 dBm	105.8 mm	-87.1 dBm

(2) 2450 MHz

Position	Esophagus		Duodenum	
	distance d	RSS R	distance d	RSS R
Front	122.6 mm	-93.0 dBm	110.3 mm	-88.0 dBm
Right	169.0 mm	-91.5 dBm	197.8 mm	-84.7 dBm
Left	180.8 mm	-91.6 dBm	119.2 mm	-84.6 dBm
Back	89.8 mm	-91.3 dBm	114.9 mm	-86.4 dBm

the decrease of the RSS level in 2450 MHz is steeper than that in 403 MHz. It shows that 2450 MHz faces larger attenuation during its propagation in the human tissue. This is one reason why 403-MHz frequency band is allocated into MICS services. Another observation is that the attenuation in the 2450 MHz highly depends on its propagation medium since the curve of the RSS corresponding to the distance does not agree with that in air. This observation is comes from that its propagation medium is constituted by complicated tissues such as muscle, water, bones, fat, air and so on. The fitting results in Fig. 3 are useful to evaluate its radio propagations; however, it is not easy way to obtain this curve since tests like this measurement is required for each patient in order to provide a model for each patient because every patient has different composition of the tissue. Thus, a simple estimation method of its radio propagation in implanted WBANs is required to reduce pain for patients.

III. ESTIMATION METHOD OF PATH-LOSS USING CT IMAGES

A. Estimation method

The path-loss is estimated by using a set of X-ray CT images. The CT values, which take signed integer from -1000 to 1024, represent their characteristics of human tissues. For example, -1000 stands for that the medium is air, and the

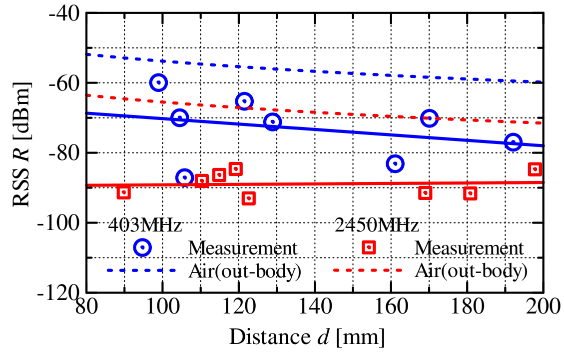
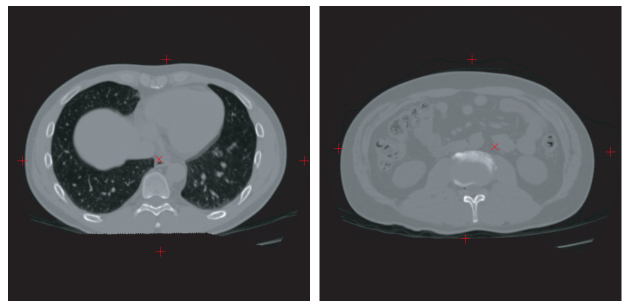


Fig. 3. The measured RSS corresponding to the distance d are plotted in the frequency of both 403 MHz and 2450 MHz.



(a) Esophagus (b) Duodenum

Fig. 5. Positions of the SG and the body-worn antenna are marked by '+' for the measurements in the frequency of 400 MHz.

1024 means metallic material. Based on this property, human tissues are categorized into five groups as shown in Table II. In this table, typical values of two electric constants, a relative permittivity ϵ_{r_j} and a conductivity σ_j, are also listed for the frequencies. The values on these electrical constants are obtained from equations shown in FCC's Gabriel report [4].

Categorization results on tissues are shown in Fig. 4. The results are histograms on the five category labels shown in Table II. These histograms are obtained from a set of X-ray CT images of the participant in the measurement by counting CT values by pixel along with a line between the positions of the SG and body-worn antenna. The locations of them are shown in Fig. 5. As shown in these histograms, the content of the tissues depends on the positions.

In order to calculate its propagation loss in the medium during the radio propagation, we introduce a simple 2-layer model that consists of an in-body part and out-body part. The out-body part is simply considered as air layer. And, the values for the electric parameters of the in-body layer are obtained as follows:

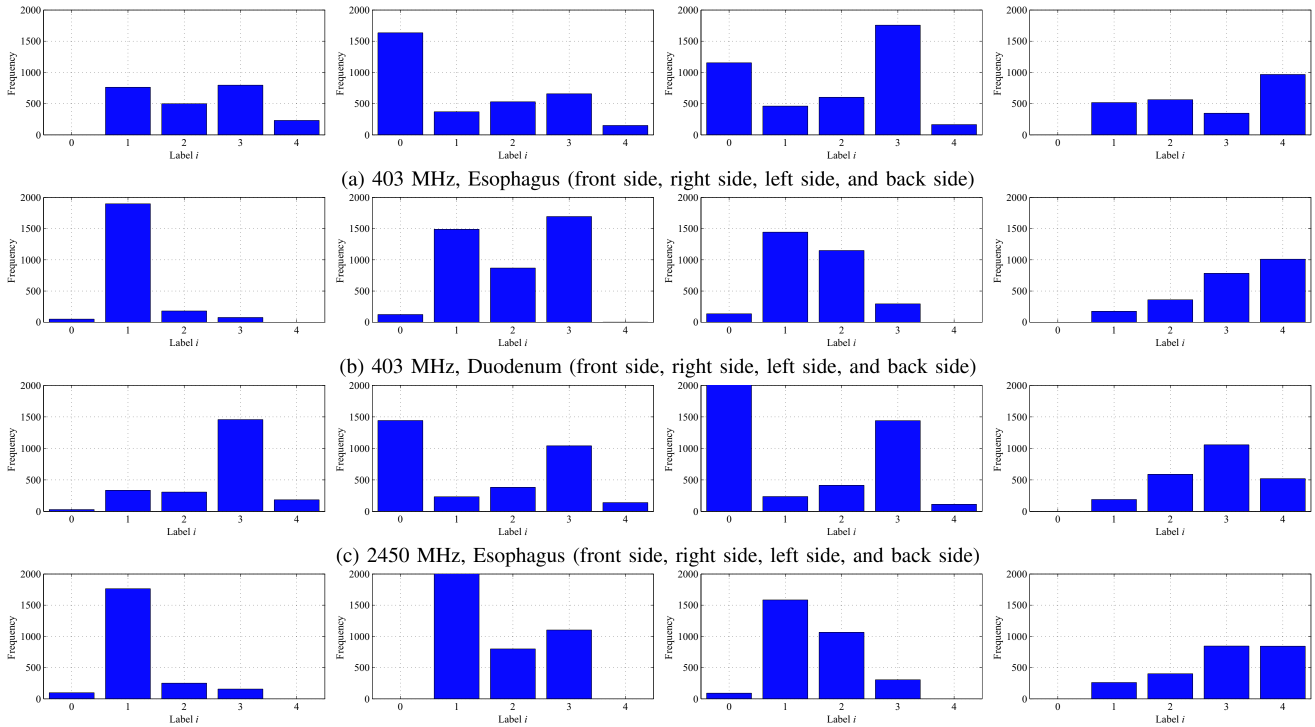
$$\bar{\epsilon_r}(f,p) = \frac{1}{N}\sum_{i=0}^{4}\epsilon_{r_i}\cdot N_i(f,p) \quad (1)$$

$$\bar{\sigma}(f,p) = \frac{1}{N}\sum_{i=0}^{4}\sigma_i\cdot N_i(f,p) \quad (2)$$

TABLE II

CATEGORIZATION OF THE HUMAN TISSUE BASED ON THE CT VALUES. ON THE ϵ_{r_i} AND σ_i, THE LEFT VALUE IS FOR 403 MHZ, AND THE RIGHT ONE IS FOR 2450 MHZ.

Label i	0	1	2	3	4
Range of CT values	-1000 – -151	-150 – -31	-30 – +30	+31 – 90	+91 – +1024
Composition	Air	Fat	Water	Tissues	Bones
Relative permittivity ϵ_{r_i}	1.00 / 1.00	5.27 / 5.58	77.0 / 77.0	52.6 / 57.1	18.5 / 22.4
Conductivity σ_i	0 / 0	0.11 / 0.04	0.10 / 0.10	1.78 / 0.80	0.87 / 0.23



(a) 403 MHz, Esophagus (front side, right side, left side, and back side)

(b) 403 MHz, Duodenum (front side, right side, left side, and back side)

(c) 2450 MHz, Esophagus (front side, right side, left side, and back side)

(d) 2450 MHz, Duodenum (front side, right side, left side, and back side)

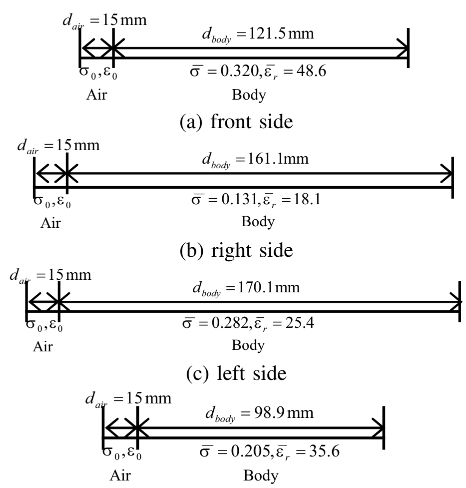
Fig. 4. Histograms of the labels representing the content of the human tissue between the SG and body surface.

where $N_i(f,p)$ shows the number of pixels categorized into the i th label shown in Table II at the position $p(\in \{\text{front}, \text{right}, \text{left}, \text{back}\})$ and frequency $f(\in \{403\text{MHz}, 2450\text{MHz}\})$. N is the total number of the pixels in CT image between the SG and body-worn antenna. Fig. 6 shows the 2-layer models corresponding to the histograms in Fig. 4. The thickness of the in-body layer is obtained from the CT images. On the other hand, the thickness of the out-body layer is fixed into 15 mm in the measurement since a 15-mm dielectric block is inserted between the on-body antenna and body surface. Based on these models, we can obtain the path attenuation as follows if its signal wave is assumed to be a plane wave. The path-loss in each layer L_{air} and L_{body} are given by [5]

$$L_{\text{air}} = 20 \log_{10} \exp(-\alpha_{\text{air}} d_{\text{air}}) \tag{3}$$

$$L_{\text{body}} = 20 \log_{10} \exp(-\alpha_{\text{body}} d_{\text{body}}) \tag{4}$$

where α_{air} and α_{body} represents the attenuation constant for the air layer and the human tissue layer, respectively, and



(a) front side

(b) right side

(c) left side

(d) back side

Fig. 6. Simple 2-layer models used in the estimation of RSS levels for 403 MHz at the position the esophagus.

given by

$$\alpha_{\text{air}} = \text{Re}\left[j\omega\sqrt{\mu\epsilon_0}\left(1 + \frac{\sigma_0}{j\omega\epsilon_0}\right)\right] \tag{5}$$

TABLE III
AVERAGE VALUES ON $\bar{\sigma}(f,p)$ AND $\bar{\epsilon_r}(f,p)$ FOR EACH POSITION AND FREQUNECY.

(1) 403 MHz

Position	Esophagus		Duodenum	
	$\bar{\sigma}(f,p)$	$\bar{\epsilon_r}(f,p)$	$\bar{\sigma}(f,p)$	$\bar{\epsilon_r}(f,p)$
Front	0.320	48.6	0.054	13.4
Right	0.131	18.1	0.419	43.1
Left	0.282	25.4	0.134	40.0
Back	0.205	35.6	0.454	46.5

(2) 2450 MHz

Position	Esophagus		Duodenum	
	$\bar{\sigma}(f,p)$	$\bar{\epsilon_r}(f,p)$	$\bar{\sigma}(f,p)$	$\bar{\epsilon_r}(f,p)$
Front	1.122	46.3	0.243	26.1
Right	0.392	31.0	0.534	34.1
Left	0.278	20.7	0.276	30.5
Back	0.758	36.2	0.852	40.6

$$\alpha_{\text{body}} = \text{Re}\left[j\omega\sqrt{\mu\epsilon_0\bar{\epsilon_r}}\left(1+\frac{\bar{\sigma}}{j\omega\epsilon_0\bar{\epsilon_r}}\right)\right] \quad (6)$$

where ω, which is given by $2\pi f_c$, means the angle frequency, ϵ_0 and σ_0 denotes the permittivity and conductivity in the air, respectively, and μ is the magnetic permeability. In addition to the loss due to going through each layer, the loss due to a reflection by the boundary is occurred. The loss L_r due to the reflection is given by [6]

$$L_r = 10\log_{10}\left|\left(\frac{2\alpha_{\text{air}}}{\alpha_{\text{body}}+\alpha_{\text{air}}}\right)^2\frac{Z_{\text{body}}}{Z_{\text{air}}}\right| \quad (7)$$

where the parameters Z_{air} and Z_{body} are given by $Z_{\text{air}} = j\omega\mu/\alpha_{\text{air}}$ and $Z_{\text{body}} = j\omega\mu/\alpha_{\text{body}}$. As a result, the total loss L is given by

$$L = L_{\text{air}} + L_{\text{body}} + L_r \quad (8)$$

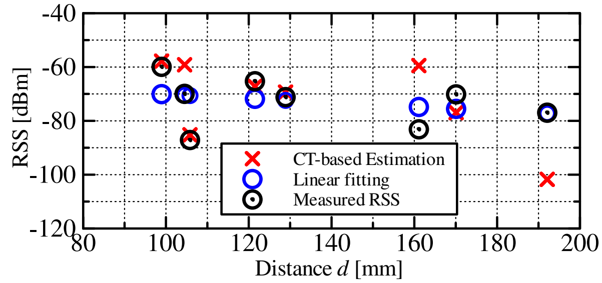
When equivalent transmission power from an implanted device is denoted as P_t, the received signal strength R_{est} is obtained by

$$R_{\text{est}} = P_t - L \quad (9)$$

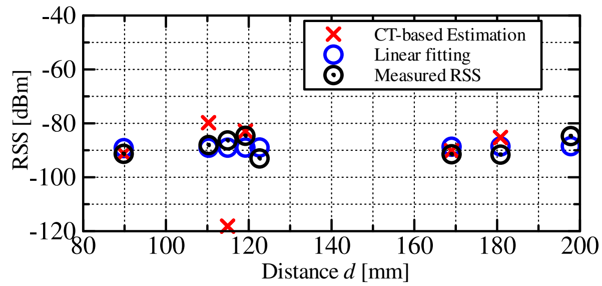
This procedure to estimate the RSS from a set of X-ray CT images is implemented in MATLAB.

B. Evaluation of estimation results

We evaluate the estimation method through comparison with measured results. In this estimation, P_t in the Eq.(9) is set to -36 dBm, which is obtained from a measurement result over the air between SG and body-worn antenna. Also, this value is determined based on specifications of introduced implanted WBANs. Table III lists its average values of the electrical constants for the in-body layer in the 2-layer models. These values are derived from a set of CT images through implemented MATLAB code. Fig. 7 plots estimated RSS, also displays measured RSS and RSS obtained from the fitting curves shown in Fig. 3. The results show that the estimation method provides estimates agree with measured results in most cases; however, we can find a couple of cases where huge estimation error is observed. These cases are conditions where their propagation mediums include a plenty of "Tissues" in Table II. In the estimation method, a unique value of the electrical constant is introduced for the "Tissues" although this category label includes variety of tissues which have different values on the electrical constants. Except such irregular points, the difference between the measured results and estimates is less than 6 dB.



(a) 403 MHz



(b) 2450 MHz

Fig. 7. Comparisons between measured and estimates of RSS based on the CT images.

IV. CONCLUSION

This paper presents path-loss estimation though a simple layer model from a set of X-ray CT images. The X-ray CT images are employed in order to assign electric constants of the tissues and to calculate the thickness of the layer. This procedure is implemented in MATLAB, in which a set of X-ray CT images based on DICOM is loaded, then an estimate on its path-loss is provided by setting both transmit (capsule) and receive (out-body) positions. This estimation is applicable into evaluation of its channel quality in capsule endoscopy. A comparison was given between measured RSS and their estimates through presented method. The result shows that difference is less than 6 dB except two positions where the component given by "Tissue" occupies the medium mainly. Thus, future works include improvement of its estimation accuracy.

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