RF Transmission Characteristics In/Through the Human Body

Xianming Qing, Zhi Ning Chen, Terrence Shie Ping See, Chean Khan Goh and Tat Meng Chiam

RF and Optical Department
Institute for Infocomm Research, Singapore
1 Fusionopolis Way, #21-01 Connexis, South Tower, Singapore 138632
{qingxm, chenzn, spsee, ckgoh, tmchiam}@i2r.a-star.edu.sg

Abstract— In this paper, the RF transmission characteristics in/through human body are investigated experimentally and numerically. An experimental methodology to characterize the RF transmission of human body is presented. The proposed method addresses the challenge to characterize the RF transmission accurately and reliably without the body tissue effect on the antennas under test. The proposed methodology of using tissue-embedded antennas is validated at 403 MHz band (Medical Implant Communication Service, MICS).

Keywords—RF transmission, MICS, biomedical applications

I. INTRODUCTION

The last decade has witnessed a rapid surge of interest in new sensing and monitoring devices for healthcare and the use of wearable/wireless devices for clinical applications. There has been a strong tendency to use implanted electronic devices for therapeutic and diagnostic purposes. Recently, the Medical Implant Communication Service (MICS) technologies have been investigated with great interest. The MICS system is able to transmit information from an antenna embedded inside the human body to the external device by using a wireless communication link. Using the MICS, a healthcare provider can set up a wireless link between an implanted device and a base station, which allows physicians to establish high-speed, ease of use, reliable, and short-range access to the patient's health data in real time. The MICS system is able to reduce the frequency of diagnosis by the doctor and to alleviate the physical or mental burden of the patients. Furthermore, it is non-invasive as communication can be established without wire piercing of the skin, which reduces the risk of infection during a medical diagnosis.

The MICS band, which was allocated by the Federal Communication Committee (FCC) on a shared and secondary basis in 1999, refers to a specification for using a frequency band between 402 to 405 MHz in communication with medical implants [1, 2]. The maximum transmit power is limited to 25 μW, or −16 dBm, in order to reduce the risk of interfering with other users within the same band. The maximum usable bandwidth at any instant is 300 kHz. Figure 1 shows the typical scenarios for MICS applications. The implanted radios are wirelessly connected to external controllers using radio wave transmission. The external controller can be either attached onto the human body or positioned at a distance away from the body. The lossy and dispersive human tissues not only affects the electrical characteristics of the implanted antenna but also results in large transmission loss when the lossy and inhomogeneous human body is the main part of the RF channel. Furthermore, the transmission of the RF signals through the human body is strongly dependent on the operating frequency and the application scenarios where the antennas may be positioned differently inside the human body with varying orientation. Therefore, characterizing the RF transmission of the human body is essential for the link budget calculation of a communication system [3, 4].
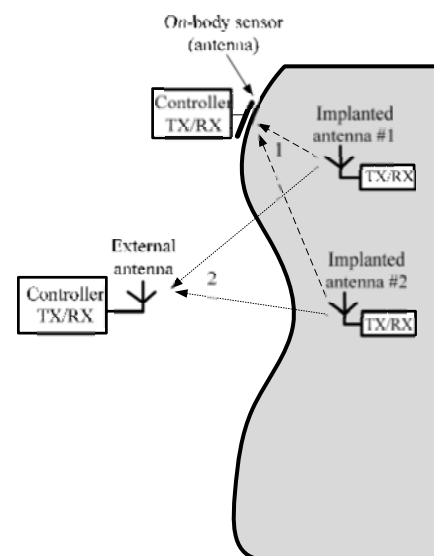

Figure1 Typical MICS application scenarios.

II. PROPERTIES OF HUMAN TISSUES

Unlike the typical wireless communication through the air, the various tissues and organs within the body have their own unique conductivity, dielectric constant, and thickness. In order to construct a reliable wireless communication link in/through the human body, the body has to be characterized as a medium for wave propagation. Thus, the electrical properties of the body tissues at the frequency of interest should be known. Table I shows the electrical properties of muscle, fat, and skin at 403 MHz [5]. It is noted that the body tissues have a high

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dielectric constant and electrical conductivity, which results in a large path loss in the RF transmission from the implant to free space. Furthermore, the dielectric constant and conductivity of the tissues vary substantially with frequency and can therefore only be considered constant over a narrow range of frequencies.

TABLE I.   HUMAN TISSUE PROPERTIES AT 403 MHZ

	Relative permittivity	Conductivity [S/m]	Loss tangent
Fat	5.57	0.004	0.328
Muscle	57.10	0.797	0.622
Skin	46.71	0.689	0.658

III.   MEASUREMENT SET-UP

It is known that the radiation characteristics and the impedance matching of an antenna are significantly degraded when it is embedded in the human body tissue or placed directly on or near the surface of a human body. The antennas designed in free space are thus not adequate for the measurement of RF transmission in/through the human body. A reliable measurement methodology should ensure that the antennas used in the measurements are not affected by the human body tissues.

A.   Characterization of the RF transmission in the human body tissue

Figure 2 shows the proposed measurement set-up, where two antennas were separately embedded in two boxes filled with lean meat (pork) in order to restrain the effect of the measured tissue on the antenna characteristics. The two antennas were respectively connected to the two ports of a vector network analyzer.

The procedure for characterizing the RF transmission of body tissue is as follows: the two boxes of lean meat with the embedded antennas were put together and the $|S_{21}|_{ref}$ was recorded. Next, a piece of tissue was placed in between the two boxes of lean meat with the embedded antennas. The inserted piece of tissue can either be lean meat, fat, or lean meat with fat of a certain thickness. The $|S_{21}|_{tissue}$ with the inserted tissue was then recorded. The attenuation of the measured tissue, Δ (in dB), can be obtained by taking the difference of the $|S_{21}|_{ref}$ and $|S_{21}|_{tissue}$, i.e. $\Delta = |S_{21}|_{ref} - |S_{21}|_{tissue}$. From this, the attenuation coefficient α(dB/mm) of the measured tissue can be calculated by:

$$\alpha = \frac{\Delta}{t} = \frac{|S_{21}|_{ref} - |S_{21}|_{tissue}}{t} \qquad (1)$$

where t is the thickness of the measured tissue (in mm).

B.   Characterization of the RF transmission through the body tissue

In order to characterize the RF transmission in air through the body tissue, the measurements were conducted using the setup as shown in Figure 3. An antenna (dipole or loop) was embedded in the box filled with lean meat and connected to an RF signal generator. A probe was positioned at a certain distance away the surface of the measured tissue and connected to a spectrum analyzer. This measurement set-up is conducive to measure very weak signals, especially when the probe was placed far away from the surface of the tissue. This is because the spectrum analyzer is able to offer a larger system dynamic range. In the measurement, the probe was first placed on the surface of the lean meat and the reference received power P_{ref} was recorded. Next, with the measured tissue positioned on the top of the lean meat and the probe placed directly ($d = 0$ mm) and at different distances from the surface of the measured tissue, the received power P_{tissue} was recorded. The RF transmission loss through the tissue to air can be calculated by:

$$L = P_{tissue} - P_{ref} \qquad (2)$$

where L is in dB, P_{ref} and P_{tissue} are in dBm.
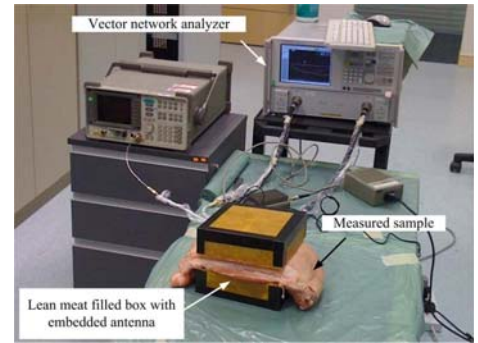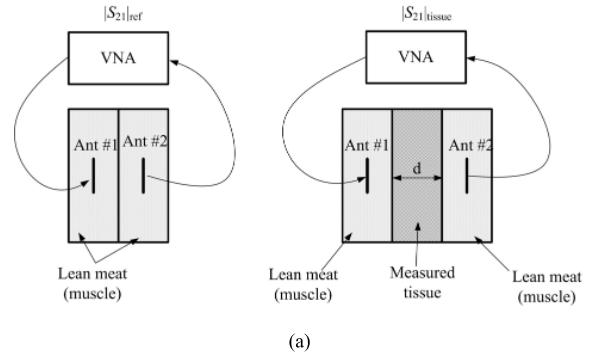

(a)

(b)

Figure 2 Characterization of the RF transmission in the body tissue: (a) schematic view, (b) photo of the measurement set-up.

C.   Antennas/probe used for the measurement

Two types of antennas, namely a balanced dipole antenna and a balanced loop antenna were used in the measurement. The antennas were co-designed with the lean meat to ensure good impedance matching when the antennas were embedded in the tissues. The configurations and the detailed dimensions of the antennas designed at 403 MHz are exhibited in Figure 4.

The Langer EMV-Technik LF-R 400 probe was used in the measurement as shown in Figure 4(c) [6].
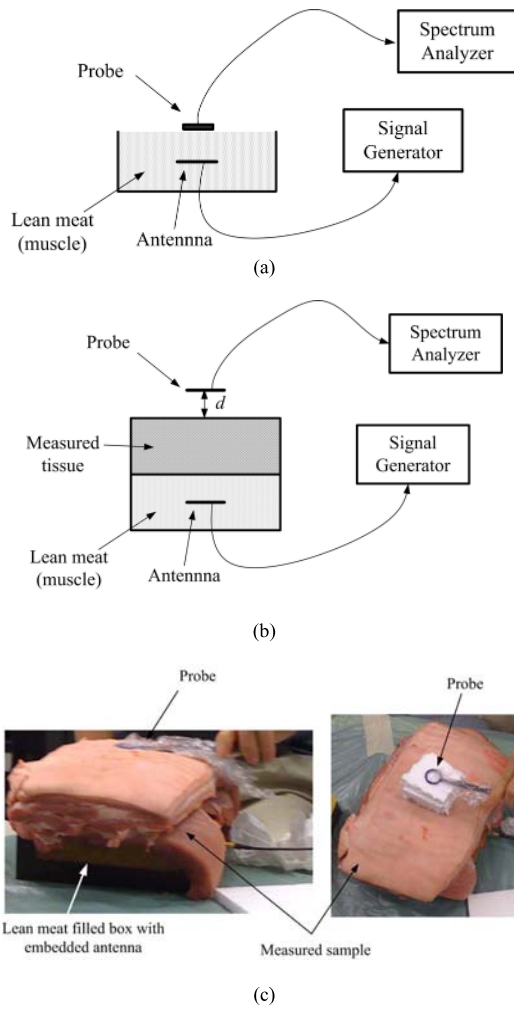

(a)

(b)

(c)

Figure 3 Characterization of the RF transmission through the body tissue: (a) reference measurement (b) measurement with inserted tissue, and (c) photo of the measurement set-up.

IV. RESULTS AND DISCUSSIONS

A. Impedance matching of the antennas in the body tissue

Figure 5(a) exhibits the measured return loss of the dipole antennas embedded in the body tissue (pork lean meat). The return loss is around 10 dB for both antennas. With the insertion of the measured tissue, the return loss is slightly degraded to around 7–9 dB, which is acceptable for the measurement.

Figure 5(b) shows the measured return loss of the loop antennas embedded in the body tissue (pork lean meat). The return loss at 403 MHz is greater than 15 dB for both antennas. With the insertion of the measured tissue, the antennas have

maintained the good impedance matching, with return loss to be larger than 10 dB, which is desirable for the measurement.
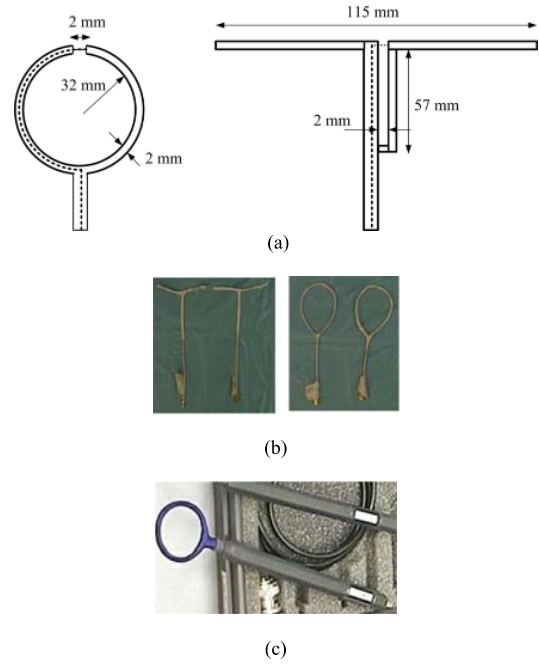

(a)

(b)

(c)

Figure 4 Antennas/probe used for measurement: (a) antenna configurations and dimensions of the balanced dipole and loop antennas, (b) photo of the antenna prototypes, and (c) photo of the probe.
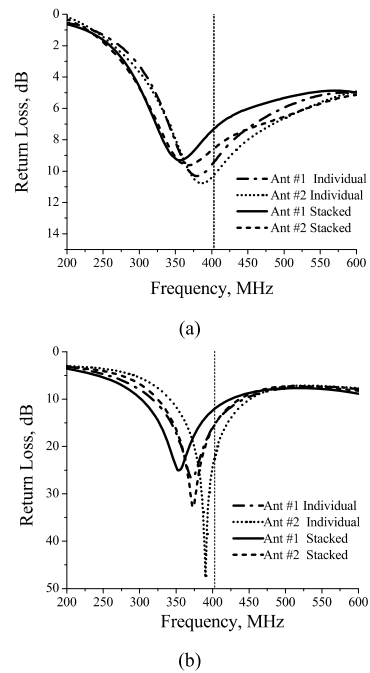

(a)

(b)

Figure 5 Measured return loss of the antennas in the body tissue: (a) dipole antenna and (b) loop antenna.

B. Attenuation coefficient of the body tissue

Figure 6 illustrates the measured $|S_{21}|$ for two different pork tissue samples, which shows an obvious reduction in the transmission response with the presence of the tissues. The corresponding attenuation coefficients of the tissues were calculated using Equation (1) and tabulated in Table II. Desirable agreement is observed between the measurement and the simulation by Zeland IE3D [7]. It is to be noted that in the simulation, the body was modeled using homogenous layers of skin, muscle (lean meat), and fat tissues.
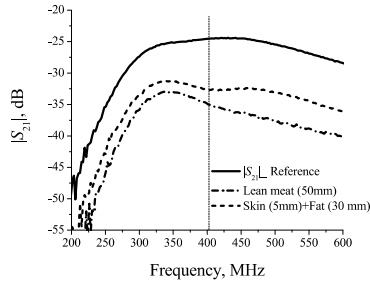

Figure 6 Measured $|S_{21}|$.

TABLE II.   ATTENUATION COEFFICIENT (α, dB/mm) OF THE TISSUES AT 403 MHz

	Lean meat (50 mm)		Skin (5mm)+ Fat (30 mm)	
	Measured	Simulated	Measured	Simulated
Dipole	0.211	0.232	0.234	0.237
Loop	0.223	0.171	0.198	0.194

C. Transmission loss through the tissue

The measured RF transmission loss through the tissue (skin/5 mm + fat/20 mm) to air is tabulated in Table III. Generally, the loss increases with the d. It is found that the field attenuation in air demonstrates near-field characteristics and does not attenuate proportionally with distance. The simulated results are not provided because it is difficult to accurately model the probe used in the measurement. Furthermore, the loop antenna features lower transmission loss than that of the dipole, which may suggest that the loop antenna is more suitable to be used in biomedical applications such as microcapsule endoscopy.

V. CONCLUSIONS

The transmission characteristics of the RF signals through the human body are strongly dependent on the operating frequency and the application scenarios. The characterization of the RF transmission characteristics of the human body is essential for the link budget calculation of a communication system.

In this paper, the RF transmission characteristics in/through human body have been investigated experimentally and numerically. The proposed experimental methodology is able to characterize the RF transmission in/through human body accurately and reliably. The proposed methodology of using tissue-embedded antennas has been validated to offer the accurate results at 403 MHz.

TABLE III.   MEASUREDTRANSMISSION LOSS THROUGH THE TISSUES AT 403 MHz

Skin (5 mm) + Fat (20 mm)	L (dB)	
	Dipole	Loop
$d = 0$ mm	-12.02	-14.20
$d = 5$ mm	-16.80	-14.38
$d = 12$ mm	-19.09	-14.46
$d = 24$ mm	-19.91	-17.90
$d = 36$ mm	-22.95	-21.10
$d = 48$ mm	-24.87	-24.25
$d = 60$ mm	-28.48	-26.59
$d = 72$ mm	-31.48	-27.15

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