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Signal Transmission through Human Muscle for Implantable Medical Devices using Galvanic Intra-body Communication Technique*

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Abstract—**Signal transmission over human tissues has long been the center research topic for biomedical engineering in both academic and industrial arenas. This is particular important for implantable medical devices (IMD) to communicate with other sensor devices in achieving health care and monitoring functions. Traditional Radio Frequency (RF) transmission technique suffers from not only high attenuation but also potential interference & eavesdropping. This paper has examined the alternate galvanic type Intra-Body Communication Technique (IBC) in transmitting signal across the body tissue (mainly muscle) in both analytical electromagnetic model with simulation results. Comparisons of these results with traditional RF data in literatures show a high promising potential (saving over 10 dB or more in path loss) for IBC transmission. Concrete discussions and several further research directions are also given out at the end of this paper.**

I. INTRODUCTION

In recent years, wearable electronics for personal health care using Body Area Network (BAN) technique have started from research arena and migrated into applications [1] with gradual wide popularity. It is expected to provide personalized assistants anywhere at any time on-user-demand fashion to monitor the human's mind and body health status. There are many applications regarding on wearable electronics, which can involve both external (on-body) and internal (in-body) devices as shown in Figure 1. For examples, a pacemaker sends electrical impulses to restore the normal heart's rhythm. ECG provides valuable information in the diagnosis of cardiac diseases, which have been investigated by much effort from various researchers throughout the years. Hence, it is the most commonly-used physiological signal for monitoring purpose in various health care systems. The sensors used in BAN can be wearable (on surface or implantable) devices that are capable of monitoring or restoring the vital cardiac signs continuously.

Current wearable systems usually include wired connections between the various distributed network components. Even for non-invasive (wearable external) devices, the wires between physiological sensors cause unwieldy inconvenience to users. This is particular troublesome for implanted medical devices (wearable internally) due to induced complications (such as infection at the surgical site and/or sensitivity to the device material, wire breakage) of wired implants [2][3].

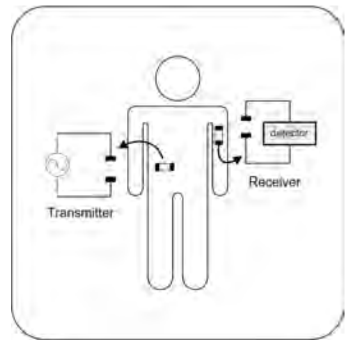

Fig. 1. General overview of BAN with both implants and surface devices

Replacing the cables with wireless communications will enable enhanced performance of the wearable system. For implantable devices, traditional wireless (RF) methods have been used but suffer from poor transmission through biological tissues using electromagnetic fields. Threats from potential interference & eavesdropping on RF communication channels shared by multiple devices pose other issues to RF methods. A relatively new wireless communication technique, called Intra-Body Communication (IBC) [4], can be used to provide solution to these problems. IBC directly employs the electrical conducting property of human body to transmit signal all over the body. Hence, it can provide natural connections among diverse physiological sensors on/in the human body and belongs to "built-in wireless" mode.

The authors have previously developed a mathematical model for on-body IBC with verifications by both *in-vitro* and *in-vivo* experiments [5]. This paper presents preliminary results of in-body IBC communication channel characteristics through muscle and investigates the effects of the body path-loss versus thickness. The next section gives an overview of medical implanted communications. Section III describes our mathematical IBC and simulation approaches and Section IV gives our model results and make comparisons with other technologies. Finally, the conclusion of the paper is drawn and future directions are given.

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II. OVERVIEW OF MEDICAL IMPLANTED COMMUNICATION

Medical implanted communication is generally inspired by the emerging of common data communication technologies, though it is not intuitive from those technologies. Considering an implant placed deep inside the human body and sometime near the vital organs, the method should be designed for the sake of infection immune, reliability, and security. Based on these reasons, wired connection used in the earlier stage is merely expedient because of possibly infection and lack of durability [6].

Nowadays, the feasible technologies for the implanted communication are mainly inductive coupling and RF telemetry. The former is the most commonly adopted technology [7][8]. The basic principle of a transcutaneous inductive link resembles a normal transformer with core made by human tissues. The mutual coupling of magnetic flux between windings can facilitate electrical energy and data exchanged. To put it simply, a pair of coil is needed to simultaneously perform power and data transmission [7]. This is an attractive technology for the implant, which requires compact and power efficient. The inductive link generally operates in low frequencies, with data rates up to 512kbps [8], although some recent researches explored the possibility of high frequencies [9][10][11][12]. Accurate alignment and short separation distance between internal and external coil are the major drawbacks of the inductive link technique. These pose serious problem for establishing reliable link with the implants as locating the device deep inside the human body is difficult, not mentioning simple movement can easily jeopardize the coupling efficiency [8].

RF telemetry has been evolving as an more favorable technology for the medical implant communication since the rapid development of the microelectronic industry and the commission of the Medical Implanted Communications Service (MICS) band in 1999 [13]. Higher bandwidth and longer range are expected with RF telemetry, but with the expense of additional antenna size and power consumption. Therefore, many research groups applied the microelectronics technique to improve the overall circuit efficiency and performance[14][15][16]. The RF telemetry also suffers from conductive properties of the human tissues, which introduces Ohmic loss in the near-zone of the antenna [17]. Interference is another serious drawback of RF telemetry, even with MISC band. It is overlapped with the Meteorological Aids Service (METAIDS) which is used for weather balloons transmitting data down to the Earth[8].

III. METHODOLOGIES

A. MATHEMATICAL MODELLING

For the sake of analytical handling, similar to our previous work [18], we first focus on solving galvanic type coupling IBC on human limb by using a regular hollow cylinder with inside and outside radii of a and b, respectively, as shown in Figure 2. Because of the much smaller conductivity of bone

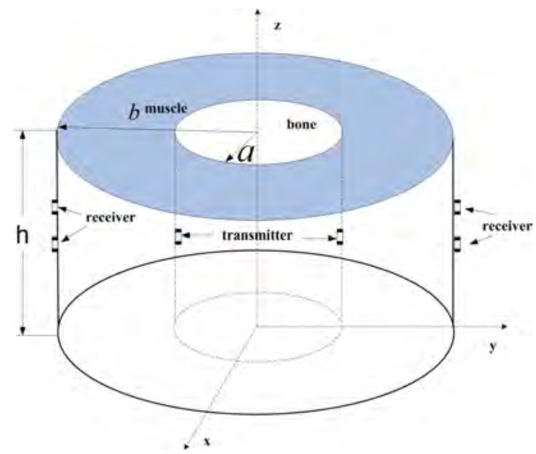

Fig. 2. Cylindrical model for the limb with IMDs

in comparison with muscle's [19], we again neglect the bone conductivity at this initial investigation as the center hollow part. Nevertheless, instead of injecting and extracting signal via 2 + 2 band-type electrodes on the outer surface of the limb, we supply current signal via 2 band-type electrodes in the inside surface of the muscle to represent IMD devices there. A pair of band-type electrodes is applied on the limb surface to extract the transmitted signal differently. Applying the quasi-static approximation similar to another previous work [5] on the hollow muscle cylinder, we come up with the following equation,

$$\nabla \sigma_{Eq} \nabla V \cong 0 \tag{1}$$

where

$$\sigma_{Eq} = \sigma + j\omega\epsilon_r\epsilon_0 \tag{2}$$

and σ represents the conductivity of muscle, ϵ_r dipicts the relative permittivity of muscle and ϵ_0 is the permittivity of free space. Note that σ_{Eq} has included the displacement-current effect this time and the following confinement flow boundary conditions,

$$\begin{aligned} V(r,\phi,z=0) &= 0 \\ V(r,\phi,z=h) &= 0 \\ \frac{\partial V}{\partial r}(r=b,\phi,z) &= 0 \\ \frac{\partial V}{\partial r}(r=a,\phi,z) = \frac{J_n(\phi,z)}{\sigma_{Eq}} &= g(\phi,z) \qquad (3) \\ & \qquad (4) \end{aligned}$$

where V is the potential within the human limb.

$$J_n(\phi,z) = \begin{cases} A & z_1 \le z \le z_1+\Delta, |\phi| \le \delta \\ -A & z_1 \le z \le z_1+\Delta, |\phi-\pi| \le \delta \\ 0 & otherwise \end{cases} \tag{5}$$

where A is the input current density magnitude and Z_1, Z_2, Δ, and δ are coordinate parameters for band type electrodes.

Applying the above boundary conditions, similiar to [18], we come up with the following general solution of IBC model.

$$V(r,\phi,z) = \sum_{m=1}^{\infty}\sum_{n=0}^{\infty}[I_n(k_m r) + \beta K_n(k_m r)] \\ [C_{mn}cos(n\phi) + D_{mn}sin(n\phi)]sin(k_m z) \tag{6}$$

where

$$C_{mn} = \begin{cases} \frac{1}{\alpha\pi h}\int_{-\pi}^{\pi}\int_0^h g(\phi,z)sin(k_m z)cos(n\phi)\mathrm{d}z\mathrm{d}\phi \\ \qquad n = 0 \\ \frac{2}{\alpha\pi h}\int_{-\pi}^{\pi}\int_0^h g(\phi,z)sin(k_m z)cos(n\phi)\mathrm{d}z\mathrm{d}\phi \\ \qquad n = 1,2,\ldots\infty \end{cases} \tag{7}$$

$$D_{mn} = \frac{2}{\alpha\pi h}\int_{-\pi}^{\pi}\int_0^h g(\phi,z)sin(k_m z)sin(n\phi)\mathrm{d}z\mathrm{d}\phi \\ n = 1,2,\ldots\infty \tag{8}$$

$$\beta = -\frac{[I_n'(k_m r)]_{r=b}}{[K_n'(k_m r)]_{r=b}} \tag{9}$$

$$\alpha = [I_n'(k_m r)]_{r=a} + \beta\,[K_n'(k_m r)]_{r=a} \tag{10}$$

$$k_m = \frac{m\pi}{h} \tag{11}$$

where I_n is the nth order modified Bessel function of the first kind and K_n is the nth order modified Bessel function of the second kind.

B. EDA SIMULATION

In addition to develop a mathematical model for the galvanic IBC, we have also selected the COMSOL Multiphysics [20] as the simulation tool to simulate the status of a 100 kHz signal transmission across the human tissue, using the same geometry described in III-A. The specific values are chosen as listed in Table I so that the model can be close to real human subject.

TABLE I
PHYSICAL PARAMETERS FOR SIMULATED LIMB

Symbol	Value
a	1 cm
b	2.5 cm
h	30 cm
σ[19]	0.36 S/m
ϵ_r[19]	8100
A	0.1 mA/cm^2
$z_1 = z_2$	14.75 cm
Δ	0.5 cm
δ	14.32°

As indicated in Figure 3 and Figure 4, the mean square error between model calculation and simulation results is about 0.01%. Their results match very well.

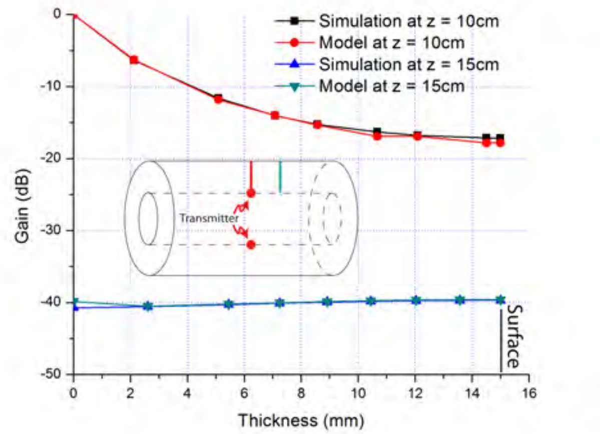

Fig. 3. Signal gain versus outward radial distance

IV. RESULTS AND PATH LOSS COMPARISON OF TRADITIONAL TECHNIQUES VS. IBC

Figure 3 shows the signal gain versus outward radial distance both along the applied source region & 5 cm away. One can observe that the signal reaching to the limb surface pays the price of 16-17 dB attenuation while 5 cm off at z = 15 cm the loss can be around 40 dB.

Figure 4 displays path loss along the limb surface from center to the end with respective to the source. As expected, rapid decay occurs whenever far from transmission side.

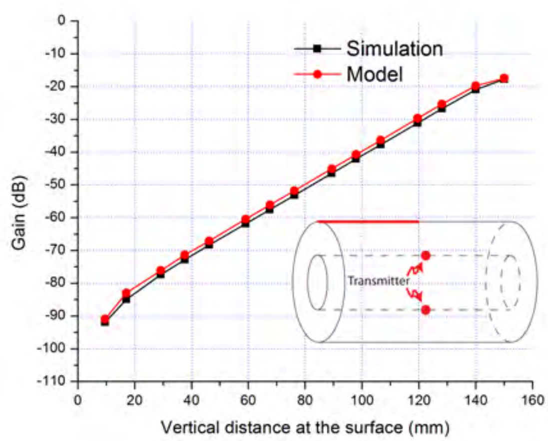

Fig. 4. Path loss along the limb surface from center to the end

In order to compare with the performance of other technologies, we have constructed several thicker (up to b = 8 cm) limb muscle models in simulations with the interior radius fixed at a = 1 cm. From Figure 5, we can tell galvanic IBC coupling is better than (several dB to 20 dB advantage) the models [21] by RF frequency at 2.4 GHz. For another example, according to the channel models [22] using MICS frequency band, the path loss is about 50dB for the implanted device 50mm deep from the body surface while the expected IBC loss is only ∼33 dB, showing a 17 dB advantage.

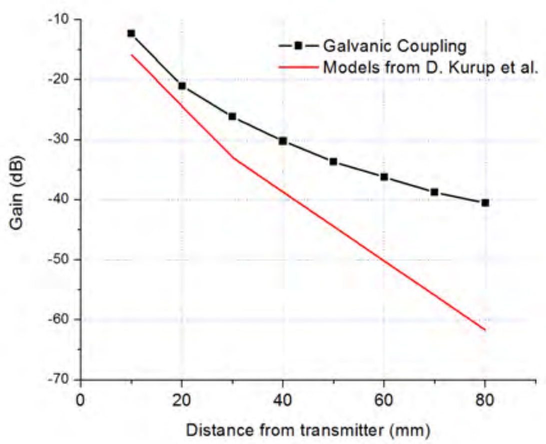

Fig. 5. Path loss along the limb surface from center to the end

V. CONCLUSION & DISCUSSION

So far, we have developed a quasi-static mathematical IBC model for IMD devices communications. With the simulation results and comparisons with the state of the art technologies, we can conclude that galvanic coupling IBC owns a high potential advantage in path loss over MICS and regular RF techniques. IBC shows even larger benefit for thicker tissue. This is particular important because it can save power and hence enhance longer implantable devices battery life (such as pace maker entrenched in chest). In another point of view, it needs less power to transmit in ensuring various safety concerns. Our model and results can provide important information for system-level modeling of wearable system employing low-power and low-cost transceivers in the body-centric WLAN.

In this paper, we have so far investigated the signal transmission from inside tissue to human surface. We will shortly inspect the reverse signal transmission path so that to provide a full duplex communication channel investigation for coordination among various sensor devices in BAN. Also, we plan to study the multilayer structure and frequency response of IBC channel with wider frequency band say from 10 kHz to 10 MHz. The last but not the least, appropriate experiment will be carried out to validate these IBC analytical and simulation results.

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