Experimental Assessment of Human-Body-Like Tissue as a Communication Channel for Galvanic Coupling

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***Abstract*—The recent surge of implantable and wearable medical devices have paved the way for realizing intra-body networks (IBNs). Traditional RF-based techniques fall short in wirelessly connecting such devices owing to absorption within body tissues. A different approach is known as galvanic coupling, which employs weak electrical current within naturally conducting tissues to enable intra-body communication. This work is focused on channel characterization of the human body tissues considering the propagation of such electrical signals through it that carry data. Experiments were conducted using porcine tissue (in lieu of actual human tissue) with skin, fat and muscle layers in the frequency range of 100 kHz to 1 MHz. By utilizing single-carrier BPSK modulated Pseudorandom Noise Sequences, a correlative channel sounding system was implemented, leading to the following contributions: (1) measurements of the channel impulse and frequency response, (2) a noise analysis and capacity estimation, and (3) the comparison of results with existing models.**

I. INTRODUCTION

The demand for continuous patient monitoring and preventive treatment has resulted in the development of new healthcare technologies. With the help of body sensor networks (BSN), physiological data can be gathered in normal living conditions, and the information can be used to either perform medical treatments like drug delivery and electrical stimulation, or alerting the proper personnel upon a critical health event. Such body-area networks can utilize sensors either on or implanted within the human body, the latter, resulting in the so called intra-body networks (IBNs). There is a growing concern for providing reliable intra-body communication between a multitude of sensors and implanted actuators. Several commercial devices that facilitate such intra-body communications exist, but they require wired connectivity, where leads can extend anywhere within the human body. Such is the case for current methods of alleviating chronic pain through spinal cord stimulation [11]. These methods are typically very intrusive from a surgical standpoint. Moreover, for the on-body cases, wired implementations of BSNs limit the use of monitoring the patient's activity to only areas within medical facilities, or at a high cost of personal inconvenience (e.g., wired ECG). For IBNs, a plethora of different communication enabling methods exist, the most common of which utilizes RF-based communication (ultra-wide band and narrow band) and ultrasound. However, the utilization of RF causes drawbacks in the form of limited penetration of human tissue (high attenuation), increased risk of tissue heating through signal absorption, and a concern about the risk of eavesdropping that could compromise security in the transfer of patient-physician information [1]. Ultrasound as a means of intra-body communication faces its own set of drawbacks in the form of severe multi-path fading and high delay (caused by slow propagation speeds), which in turn, may require the need for more complex system designs.

We investigate the use of a technique called as Galvanic Coupling (GC) that is able to mitigate the above-mentioned issues. GC works by coupling weak electrical current (~ 0.5 mA) into the body through electrodes for the purpose of data communication [5]. In order to understand how these signals will behave using the body as a medium, extensive work has been done to model the human body channel as a complex network of impedances representing the different layers of human tissue and their boundaries. For example, in [5], the human body tissue layers are represented in the form of black boxes in a 2-port circuit model for computation of channel gain and capacity estimation. Each tissue layer (skin, fat, muscle and cortical bone) takes into account tunable dimensions and the electrical properties of the human body. The implementation of this 2-port circuit model allows for easy modification of parameters (center frequency, electrode separation, electrode dimensions, etc.) and flexibility in terms of transmitter and receiver location. The model also takes into account several paths that the current can travel within the layered human body model, enabling the observation of the scattering parameter and boundary reflection at the electrode-tissue interface. Similarly, in [10], an equivalent circuit representation is used to model the behavior of the human body under the influence of galvanic coupling, and experiments are done on a human upper arm to validate the model. In [3], mathematical modeling and simulation of galvanic coupling with different transmission paths is presented, where the human body (abstracted as concentric cylinders) was transformed into a model represented by the head, arm, torso, and leg, for the layers of skin, fat, muscle, cortical bone, and bone marrow. The mathematical model, an IBC circuit, and its corresponding transfer function were developed to take into consideration the internal resistances of the devices used in IBC. Experiments (to validate the models created) of the galvanic coupling IBC were carried out in the frequency range of 100 kHz to 5 MHz in two different subjects, with various communication paths for skin-to-skin electrode contact. These methods of channel modeling, although highly complex and well inclusive of the dielectric properties of human tissue that may affect signal propagation, do not make mention of the fundamental properties of wireless channels (e.g., amplitude-fading statistics and multi-path delay spread) that need to be considered in the eventual design of a communication system.

This paper aims to address experimental characterization of a human-body-like channel using a correlative channel sounding method. The rest of the paper is organized as follows: Section II gives insight into the type of channel sounding method used in this work. Section III describes the system in which the channel sounding method was implemented. Section IV provides the channel characterization, portraying the measured channel impulse and frequency responses, Section V presents an analysis of the noise and the achievable capacity. Section VI describes how galvanic coupling can be used in commercial medical applications, and Sections VII and VII conclude and outline future work, respectively.

II. Channel Modeling Method

When designing and simulating wireless communication systems, it is imperative that accurate channel models are created to fully understand how the signals of interest propagate through the medium. Different types of channel modeling methods are available for use, and each with their own unique way of uncovering the properties that have an effect on signal performance. The method of channel modeling conducted in the context of this work is known as a Stored Channel Impulse Response method [2]. In this method, a correlative channel sounder (explained below), measures, captures and records the channel impulse response. This approach has two distinct advantages: (1) the measured and stored channel impulse responses are realistic and (2) the stored responses are reproducible, reusable for as long as needed, allowing for the simulation and optimization of different communication systems to take place.

Conceptually, a channel sounding signal is composed of a pulsed transmission that takes places with pre-specified repetition intervals and upon reception of the signals, filters for storage and processing off-site. The type of sounding signal sent is determined by the specific method of channel sounding used [2]. In the rest of this paper, the term 'channel' exclusively implies the human body channel.

A. Correlative Channel Sounders

Specific to this work, correlative channel sounders are implemented for the sake of exposing channel behavior. These sounders belong to the general category of pulse compression techniques [4].

When a white noise signal $n(t)$ is applied to the input of a linear system, the output $w(t)$ can be cross-correlated with a delayed replica of the input $n(t-T)$, yielding a cross-correlation coefficient that represents a scaled version of the impulse response of the system, $h(t)$, evaluated at T. Following [4], this can be shown from the definition of the auto-correlation function of the noise $R_n(\tau)$, as

$$R_n(\tau) = E[n(t)\ n^*(t-\tau)] = N_0\delta(\tau) \tag{1}$$

where N_0 is the single-sided noise-power spectral density. In the time domain, the system output is given by $w(t) = h(t) * n(t)$ and it is then cross-correlated with the input to yield

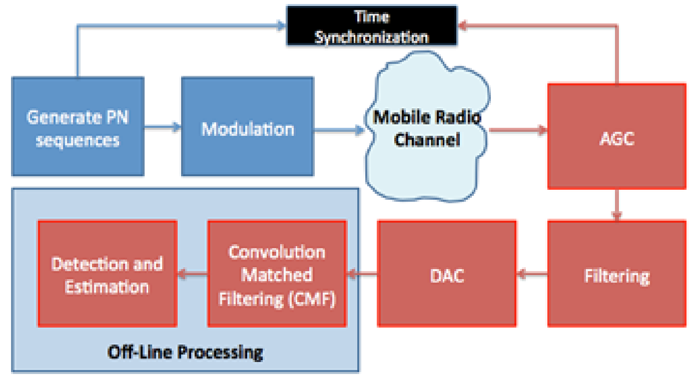

Fig. 1. Channel sounding generic block diagram.

$$\begin{aligned} E[w(t)\ n^*(t-\tau)] &= E\left[\int h(\zeta)n(t-\zeta)n^*(t-\tau)\mathrm{d}\zeta\right] \\ &= \int h(\zeta)R_n(t-\zeta)d\zeta \\ &= N_0 h(\tau) \end{aligned} \tag{2}$$

which is proportional to the channel impulse response.

In practice, the behavior of noise signals, which are added to the channel, must be known at the receiver. Therefore, experimental systems employ deterministic waveforms with characteristics that resemble noise-like behaviors. A widely known type of such a signal is known as binary maximal length pseudorandom noise sequences, or PN sequences, typically generated using shift registers with the appropriate logic. Using maximal length PN sequences as the signal of interest should yield an auto-correlation function with a high correlation peak at $R_{P_{TX}}$ ($\tau = 0$, or zero-shift point), and very low side lobes (high peak-to-off-peak ratio). This property allows for the detection of each multi-path component due to the convolution matched-filter (CMF) in the receiver, correlating the channel output with the originally transmitted PN sequence. Figure 1 presents a block diagram depicting a traditional channel sounding architecture.

III. System Overview and Experimental Method

In order to measure the channel impulse responses, PN sequences were transmitted in a single carrier BPSK modulated fashion. The chip duration of the linear generated polynomial PN Sequence of degree $m = 14$, using a linear-feedback shift register, was set to the value of .909 microseconds (for a bandwidth of approximately 1.1 MHz). This number allows for measurements to take place in the frequency range used in the galvanic coupling system described in [5], beginning and ending at 100 kHz and 1 MHz, respectively. The lower bound was chosen to avoid interference with medical telemetry devices and human body signals, while the upper bound was set at the frequency where the effects of the human body behaving as a radiating antenna become noticeable, drastically reducing the gain. The carrier frequency of 550 kHz was

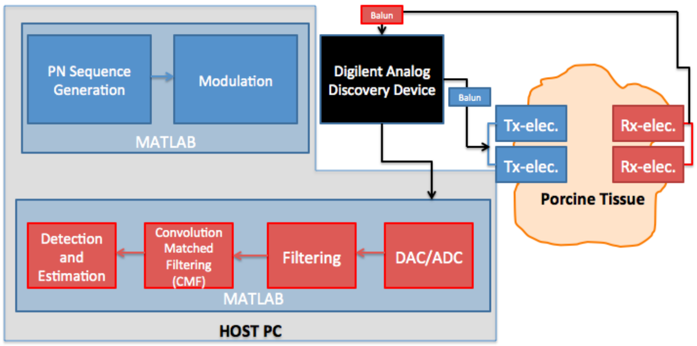

Fig. 2. Correlative channel sounding system block diagram.

chosen for modulation as a middle point, in order to observe the entire bandwidth of interest when measuring the channel impulse response. The correlative channel sounding test bed implemented can be seen in Figure 2.

The experiment was carried out on a tissue of a freshly slaughtered swine consisting of skin, fat and muscle layers, with a length of 25.5 cm, a width of 23.5 cm and a varying thickness between 2.5 and 5 cm. The rationale for using a porcine tissue for human-body-like behavior stems from an understanding that the dielectric properties of human skin and porcine skin are very similar [9]. The entire experimental setup, including the porcine tissue, is pictured in Figure 3.

The Analog Discovery™, by Digilent, Inc., was used to generate the signals used in this study. At its base there is a Spartan-6 Xilinx FPGA. The device uses its own in-house signal generation software, known as WaveForms™, with a sampling rate up to 100 MHz. The device is also enabled to work directly with MATLAB®, but the sampling rate was deemed too low for use in this test. In order to utilize some of the custom signal generation capabilities of WaveForms, all signals were generated in MATLAB, saved into `.csv` file format, and loaded to WaveForms for generation. The baluns (Schaffner IT239), are used to isolate the common ground return paths of the transmitter and receiver. It is important to note that experiments were conducted with the use of alligator clips to allow for better contact with the porcine tissue, instead of the electrodes. For power and off-site processing, a personal computer was directly connected with the Analog Discovery device. The received signals are captured in WaveForms in `.csv` file format and then stored for post processing in MATLAB. Within MATLAB, a band pass filter is used to restrict measurements to solely the frequency range of interest. This stage is followed by the convolution matched-filter, then the detection and estimation of the parameters of concern. Transmitter and receiver location, distance and orientation are modified to test received signal strength in various positions. Measurements were taken at distances of 5, 10 and 15 cm in each of the locations and orientations, while keeping a constant electrode separation distance of 5 cm.

IV. Channel Characterization

Following the acquisition through the WaveForms software, the received signals were post-processed in MATLAB to obtain the channel frequency response and channel impulse response. Channel characterization work done in [6] concluded from

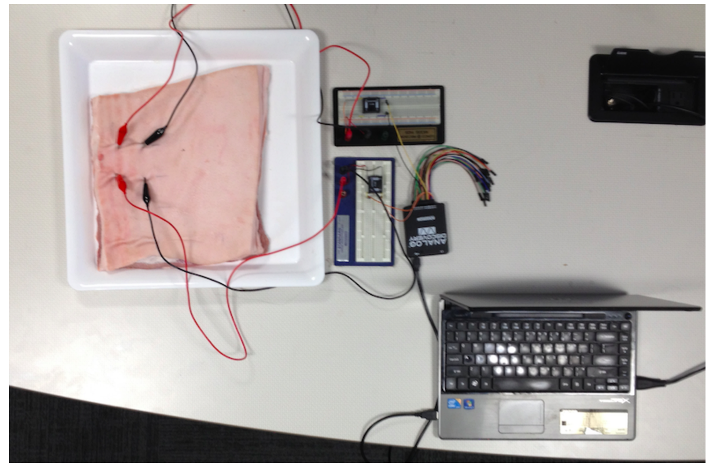

Fig. 3. Experimental setup, including porcine tissue

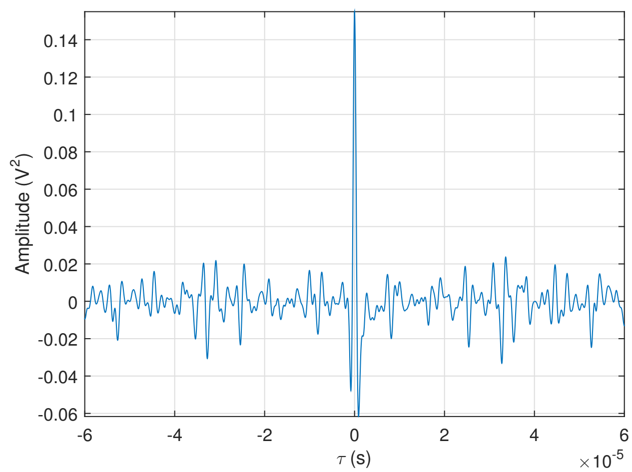

Fig. 4. The measured channel impulse response (CIR) for the Muscle to Muscle tissue communication scenario.

preliminary simulations that the channel of a galvanic coupling based communication scheme is non-frequency selective. In order to verify this claim and that of many other works, the channel impulse and frequency response are presented in this section. Each of the following channel characteristics will be displayed for different tissue communication scenarios, specifically Muscle to Muscle (MM), Skin to Skin (SS), Muscle to Skin (MS) and Skin to Muscle (SM), with the first layer representing the placement of the transmitter and the second layer mentioned the placement of the receiver. This nomenclature will be used to present results throughout the duration of this work. The measured channel impulse response (CIR) for one tissue communication scenarios (MM) can be seen in Figure 4. It can be seen that the high peak-to-off-peak ratio (discussed in Section II) exists, providing good correlation results from the experiments. All of the CIRs from each communication scenario obtained from the experiments, show a very similar impulse response, indicating the presence of no multi-path in the channel environment.

The corresponding frequency domain representation (Channel Frequency Response), for an assumed transmitter band-

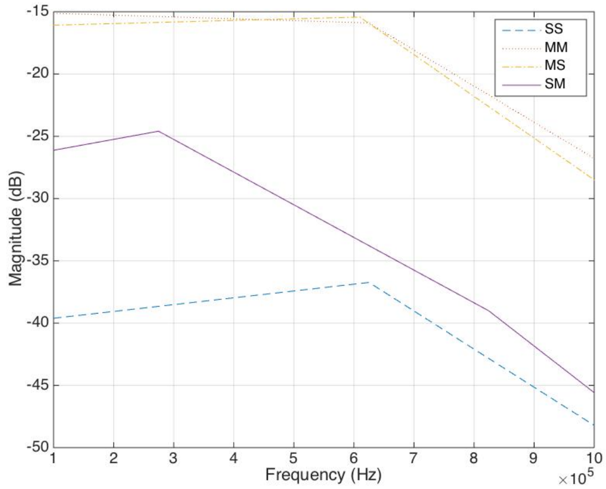

Fig. 5. Channel Frequency Response (CFR) for all tissue communication scenarios for $d = 10$ cm.

width of 50 kHz, indicates that the channel is relatively flat within the frequency range of interest. In Figure 5, for each tissue communication scenario, the Channel Frequency Response (CFR) exhibits a decreasing gain with frequency. The best channel gain takes place for the communication of MM, with SS having the worst performance in terms of channel gain. It is important to note that within this figure, the CFR for a communication range of 10 cm is presented. Equivalent trends with higher magnitudes for channel gain are presented in the CFRs of each tissue communication scenario captured at shorter distances between the transmitter and receiver. In Figure 6, a comparison of the model and experiments used in [5] is presented for center frequency values of 100 kHz and 1 MHz. The difference in channel gain, ΔG, which equals the absolute value of the difference between the experimental channel gain and model channel gain from [5]. The model parameters in this work were tailored to mimic the experimental setup as best as possible. The results, presented for all tissue layer communication scenarios except SM (an experimental outlier in this comparison), indicate that a good matching exists between model and experiments (no more than 10 dB of difference among the different scenarios explored). This difference can be attributed to the lack of the 2-port circuit model's ability to account for the exposed muscle tissue in the experiments. The Skin to Skin based communication comparison has a very low difference, which may be due the model accounting for the loss at the Skin to Air interface. For the other layers, perfect isolation is assumed. Though this cannot be avoided in our experimental setup, comparison in terms of channel gain show promising results.

A. Path Loss Model Fitting

The human tissue can be characterized as a lossy dielectric propagation medium [7]. As such, the energy of the wave attenuates by a factor $e^{2\alpha d}$, and specifically, the power per unit area flowing past the point d is given [8] by

$$\mathcal{P}(d) = \mathcal{P}(0)e^{-2\alpha d} \quad (3)$$

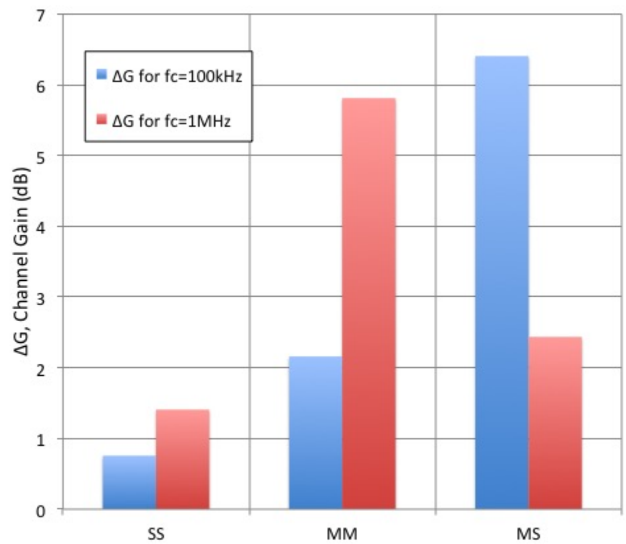

Fig. 6. Comparison between channel gain measurements obtained from experiments and the model created in [5] for $d = 10$ cm

TABLE I. MODEL PARAMETERS

	$\mathcal{P}(0)$	95% confidence bounds	α	95% confidence bounds
MM	0.03961	(0.02348, 0.05574)	24.2450	(29.6850, 18.8100)
MS	0.06061	(0.02769, 0.09353)	24.1250	(31.3650, 16.8800)
SM	0.01177	(0.007756, 0.01578)	22.9400	(27.4100, 18.4750)
SS	0.01297	(0.006081, 0.01985)	29.5050	(37.0200, 21.9950)

where d is the linear distance between transmitter and receiver, in our case. The magnitude $\mathcal{P}(0)$ is the power per unit area flowing at $d = 0$.

If both transmitter and receiver have the same effective area, then the gain can be computed as

$$\begin{aligned} A_{dB}(d) &= -10\log_{10}\left(\frac{\mathcal{P}(d)}{\mathcal{P}(0)}\right) \\ &= 20\log_{10}(e)\alpha d = 8.686\alpha d \end{aligned} \quad (4)$$

Based on several measurements in the porcine tissue, we were able to determine the parameters for an exponential fit as in (3). This model provides with a simple approximation that is suited for most system design problems. Figure 7 presents the set of measurements and their fitting model, that have been constrained to the range of 3 to 15 cm, where it shows a better adherence and is also the scope of our system.

The parameters $\mathcal{P}(0)$ and α, the attenuation coefficient, were obtained for different layers and are summarized in Table I.

V. NOISE ANALYSIS AND CAPACITY ESTIMATION

Another set of measurements were taken in the porcine tissue for the assessment of the noise characteristics, including probability distribution and spectral power.

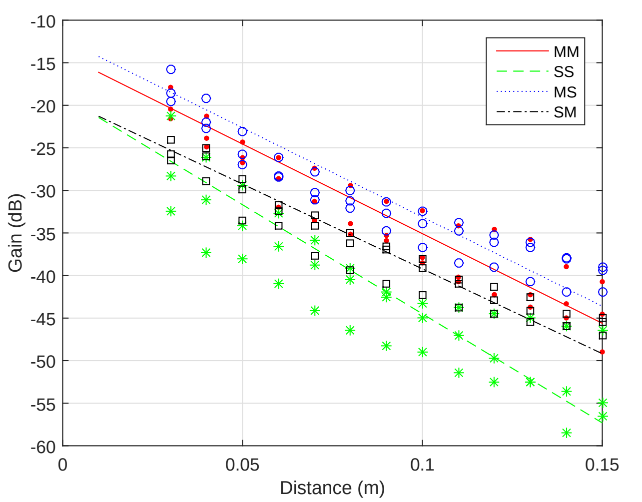

Fig. 7. The measurements and the fitted exponential model for the gain on different layers.

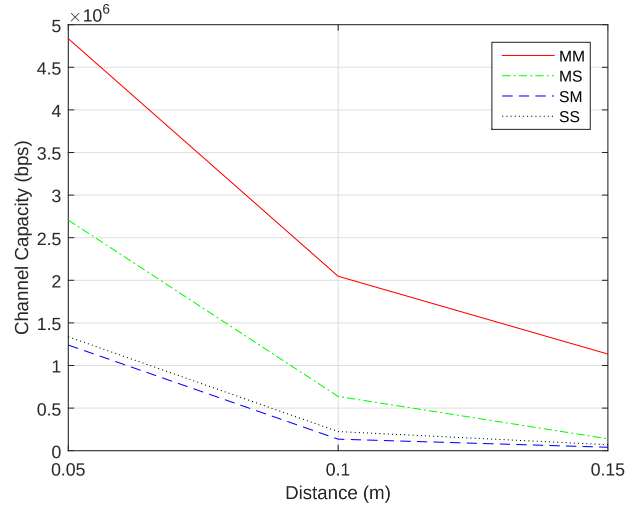

Fig. 8. Channel capacity estimate for different layers and distances.

a) Noise Characteristics: The results show that the noise's probability density function fits well as a normal distribution. The frequency analysis presents a fairly flat power spectral density with a noise power spectral density dependent on the layer of tissue and in the order of $N_{0,MM} = -107.0$ dBm, $N_{0,SS} = -105.5$ dBm, and $N_{0,MS} = N_{0,SM} = -102.4$ dBm. Therefore, the channel is taken as a zero-mean Additive White Gaussian Noise (AWGN) and treated as such for channel capacity estimation.

b) Channel Capacity: For an AWGN channel we employ the well known Shannon-Hartley formula given by (5) to make an estimate of the maximum achievable capacity of the system. The calculations are made using the measured received power P_{RX} for several locations and for a signal covering the whole 900 kHz bandwidth.

$$C = BW \cdot \log_2 \left(1 + \frac{P_{RX}}{N_0 \cdot BW}\right) \quad (5)$$

Figure 8 shows the results for different Tx–Rx combinations whereas Figure 9 presents one comparison example of the channel capacity estimation from the experimental data and results from the 2-port circuit model, presented for a center frequency of 100 kHz and the noise levels mentioned previously. Results indicate a similar range of values for capacity estimation, even in the presence of the differences among tissue exposure to the environment that was not modeled in [5].

VI. Potential Applications

The relatively flat nature of a galvanic-coupled human body communication channel can lead to simplistic communication system designs. The potential promise of such systems can provide many benefits in the medical and commercial application space. In the realm of medically implantable devices, many current health care systems that utilize a wired implementation of applications that provides a means to combat epilepsy and chronic pain [11]. Other applications exist in the form of a drug delivery network, where an actuator controls the release

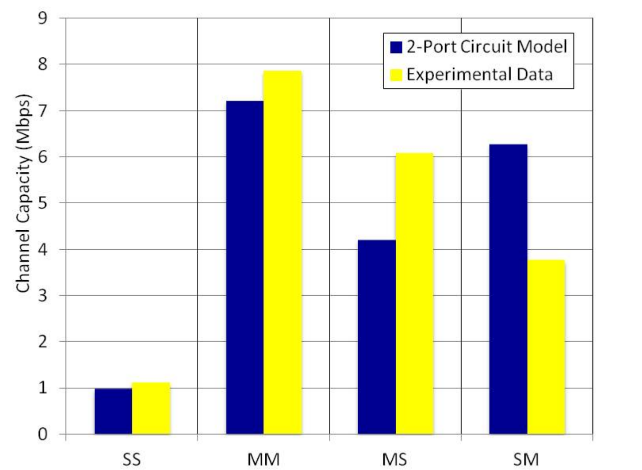

Fig. 9. Experimental channel capacity estimate comparison with 2-port circuit model by [5] for $d = 10$ cm and a center frequency of 100 kHz.

of some form of medicine, based on a particular biological marker sensed within this network. The specific nature of galvanic coupling may allow for it to replace parts of these systems, in order to make the application less intrusive and allow for a more scalable network.

An example of such a system is the RNS® System by NeuroPace, Inc. This close-loop device acts as a neurostimulator to aid against the causes of epilepsy. This device requires that the body house a small microprocessor and battery in a small cavity in the skull. This device is then connected to two leads, surgically implanted within the brain. The position of the leads is based on where the seizures originate, and each lead is composed of four electrodes with the functionality of recording neural activity and delivering electrical stimulation.

This is one form of a system in which a galvanic coupling interface can provide an enhanced and less intrusive solution. By equipping the microprocessor with a set of transmitting electrodes, and developing stand alone leads that can sense, communicate, and stimulate, the need for wires can be removed. Galvanic coupling would allow the microprocessor to communicate with the leads, alerting them when to provide stimulation. Similarly, neural information picked up by the leads can be forwarded to the microprocessor for data extraction. An implicit benefit from the implementation of a galvanic-coupled communication system in this case, lies in the possibility of introducing no additional electrodes into the system. The same electrodes used for stimulation and sensing, can also be used for communication purposes. Medtronics adaptive SCS device, for combating chronic pain [11], is another example of a similar system in which the implementation of galvanic coupling can provide benefit.

VII. Conclusion

A channel probing system was implemented to uncover the behavior of a human body-like communication channel. Results indicate that the channel response is relatively flat for the frequency ranges of interest, the noise can be approximated as additive white Gaussian, and the achievable capacity lies in the range of Mbps. The comparison of these experimental results with currently existing analytic channel models and experiments, shows a similar range of achievable capacity, but the channel frequency responses differ in the range of ±5 dB for particular center frequency values. The differences are likely to stem the use of different mediums under study. Taking into account all of the comparisons presented in this study, results lead us to believe that the performance of the existing models, though advantageous when estimating channel parameters, may not be able to provide a complete notion of channel behavior for the human body.

VIII. Future Work

After the characterization of the channel and the derivation of appropriate high-level parameters for design purposes, the necessary steps in the pursuit of the establishment of a practical system for galvanic coupling intra-body networks should include the selection and testing of proper signals and modulation techniques. Likewise, other elements of the communication system design (namely, medium access control, and uplink/downlink schemes) have to be addressed. Finally, an actual implementation with dedicated hardware is intended.

Acknowledgments

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