A Simulation Platform to Study the Human Body Communication Channel

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Abstract— Human Body Communication (HBC) is an attractive low complexity technology with promising applications in wearable biomedical sensors. In this paper, a simple parametric model based on the finite-element method (FEM) using a full human body model is developed to virtually emulate and examine the HBC channel. FEM allows better modeling and quantification of the underlying physical phenomena including the impact of the human body for the desired applications. By adjusting the parameters of the model, a good match with the limited measurement results in the literature is observed. Having a flexible and customizable simulation platform could be very helpful to better understand the communication medium for capacitively coupled electrodes in HBC. This knowledge, in turn, leads to better transceiver design for given applications. The platform presented here can also be extended to study communication channel characteristics when the HBC mechanism is used by an implant device.

Keywords- Human body communication, Computational human body models, Capacitive coupling

I. Introduction

Human Body Communication (HBC) is one of the wireless technologies defined by the IEEE 802.15.6 standard on body area networking [1]. In HBC, the human body is used as a communication medium between a pair of transmitter and receiver electrodes that are placed on the body surface. The low complexity and energy consumption are among the reasons that make this technology attractive for wearable and implantable devices. Also, as the transmitted data is mostly confined to the human body area, there is less chance of unauthorized access; and therefore, better security is expected compared to other wireless technologies used for body area networks. In the literature, the general technology has also been referred to as Body Channel Communications (BCC) or Intra-Body Communications (IBC). These non-RF communication mechanisms include capacitive (or equivalently electric field) and galvanic signal coupling.

In the capacitive coupling method, the electrical signal that is applied to the human body (i.e. forward path) is capacitively coupled through the air or the environment where the body is located (i.e. return path). Alternatively, in the galvanic coupling method, the human body would act as a waveguide for the signal that is injected by the alternating current into the body. The term HBC, as outlined in the IEEE802.15.6, mainly refers to the capacitive coupling methodology. The underlying concept behind HBC is the fact that in the presence of a weak electric field, the human body can act as a signal guide to capacitively couple two electrodes that are in contact with the body surface. The coupling through the body is achieved with much less attenuation compared to the free space. There have been several studies by researchers to better understand and characterize the HBC channel in the past 10 years. These studies are mostly in the form of measurement campaigns considering different scenarios. As the environment around the human body (and possibly the body posture) directly affects the wireless link between two HBC electrodes, some discrepancies are often observed among the physical measurement results reported in the literature. Also, due to the variables and parameters that could impact the return path, developing a comprehensive simulation platform that can adequately model the HBC channel is quite challenging. Methodologies that have been used to investigate the electric field propagation mechanism and modeling the underlying body channel include RC circuits, Finite-Element Method (FEM), Circuit-coupled FEM as well as FDTD (Finite Difference Time Domain) method to model the communication link [3 - 8].

Circuit models representing the HBC channel have been developed in [5, 6]. The reported results for the channel gain (or equivalently pathloss) in the range of 1 to 100 MHz show a bandpass profile with a peak somewhere in the 40-60 MHz interval. In [7], the authors have developed a circuit-coupled finite-element method (FEM) model of the HBC channel. A multi-layer FEM model was used to represent the human forearm. The parasitic effects of the printed circuit board (PCB) and the return path were modeled as circuit elements. While measurement results for the channel attenuation versus frequency still showed a bandpass profile, simulation results show monotonically increasing with a much milder bandpass profile for various parameters values. In [8], the authors concluded that measurements of the pathloss in HBC systems strongly depend on the instrumentation configurations. Using a small battery-powered transmitter and receiver to measure pathloss, they showed that inclusion of any additional ground plane, even isolated by baluns, serves to underestimate the resulting path loss by up to 33.6 dB. Their pathloss results again showed a bandpass profile with a peak around 70-75 MHz.

The common element in most of the results published in the past several years is the passband profile shape of the channel attenuation in HBC within the range 1-100 MHz. As pointed out earlier, depending on the instrumentation or methodology that was used for channel measurement, the location of the peak frequency in the passband profile varies from 40 to 70 MHz. In addition, discrepancies are also observed on the average magnitude of the forward transmission coefficient. This is due to the specifics of the model used for the parasitic return path in the HBC system. Our objective in this research was to develop a simple parametric FEM-based model that 1) can capture the fundamental concept of HBC operation/channel; 2) can be adjusted to emulate a specific measurement scenario; and 3) can be easily extended to study implant HBC channel.

The rest of the paper is organized as follows. Section II describes a computational 3D human body model that is used for this study along with a simple model of the HBC electrodes and communication links. Section III provides simulation results for several on-body scenarios and a brief discussion on comparison with existing physical measurements in the literature. Finally, conclusions and our plans for future work are described in section IV.

II. Simulation Platform

Modeling of a HBC channel is a challenging task due to the many parameters that can possibly affect the characteristics of the communication link. Among those, we can point to size and shape of the electrodes, locations and the distance between the RX/TX electrodes, separation between the signal and ground plates of each electrode, body posture, dielectric properties of the human tissues that are in contact with the electrodes and possibly the environment surrounding the human body.

A novel 3D immersive platform to study wireless channels in body area networks has been developed at the Information Technology Laboratory of the National Institute of Standards & Technology (NIST) [2]. A 3D computational human body model is one of the main components of this platform that can be customized for the desired application. The body model includes frequency dependent dielectric properties of 300+ parts in a male human body. These properties are also user-definable if specific changes or modifications are desired. The human body model has a resolution of 2 mm. To study HBC, this computational model has been augmented with a skin shell that fits over the exterior body mesh. In addition, variable fat shells (reflecting skinny, average and obese persons) have been added to the model. This will allow us to study the potential impact of the fat layer on the forward path attenuation of a HBC channel.

The electrodes were modeled as two metal plates; one in contact with the skin and the other located directly above and floating in the air. To ensure the full contact of electrodes with the skin tissue in the body model, a small patch (i.e. brick) of skin material has been added directly underneath the electrode to unite the signal plate with the skin exterior. This ensures that the surface of the electrode and the skin are fully coincident. Size, plate separation, distance between the receiver/transmitter electrodes are design variables; and therefore, the impact of each one of these parameters can be easily investigated in our model. Figure 1 shows an example of two electrodes placed on the right arm of the human body model in our platform.

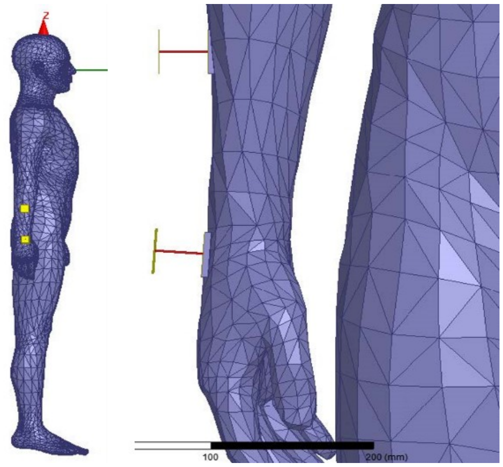

Figure 1. HBC electrodes on the right arm

The biggest complexity in modeling the HBC channel is incorporating the impact of the parasitic return path and characteristic impedances of the electronic circuits generating the signal (or in case of physical measurement, parasitic of the probe PCB). In our FEM-based model, the coupling of the electrodes through the air (i.e. return path) is modeled by a capacitor (C_{Ret}). This is similar to the circuit or circuit-enabled models proposed in [7]. However, we have implemented the capacitive return path using RLC boundaries methodology in ANSYS. The signal leakage path between the electrode plates has also been modeled with capacitor C_L. The characteristic impedance of the source has been modeled by a cascade of resistor R_T and inductor L_T. These elements are schematically shown in Figure 2.

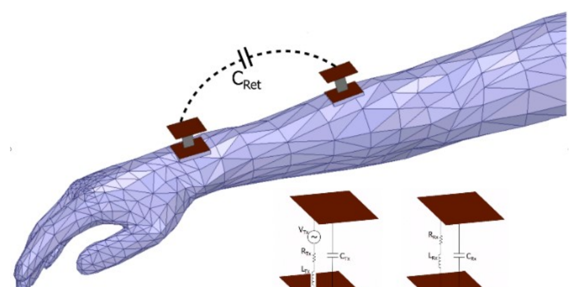

Figure 2. System schematic

Using ANSYS HFSS[1] electromagnetic solver, a variety of different quantities such as the magnitudes of the electric field (inside, on the surface and outside of the body) and the Scattering parameters (e.g. S_{21}) between the two electrodes can be calculated. For example, Figure 3 highlights the basic principle of HBC by displaying the electric field distribution. Fig. 3(a), on the left, shows the distribution of the magnitude of the electric field when the transmitting electrode is not in contact with the human body (i.e. operating in the air). On the other hand, when the electrode is place on the human arm (as

[1] HFSS is a product of ANSYS, Inc. HFSS has been used in this research to foster research and understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that this product is necessarily the best available for the purpose.

seen in Fig. 3(b)), the electric field extends over the entire body surface. This ensures much higher received signal strength; and therefore, better communication channel between the two electrodes. A signal frequency of 50 MHz has been used for the result shown in Figure 3.

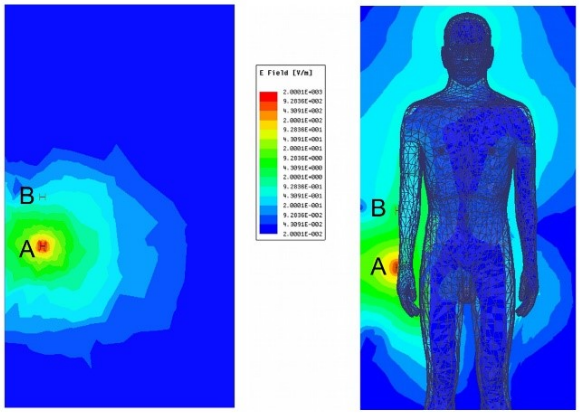

Figure 3. Electric field distribution around the transmitter electrode (a) without the human body (b) with the human body

The HBC platform mentioned above enables us to run different parametric studies to find the matching values of the parasitic elements as well as investigate the impact of electrodes size, location, and body placement for various applications. In the next section, we point out to some of these results.

III. RESULTS

The frequency range of interest in HBC is typically 1-100 MHz. Higher frequencies could result in the human body acting as an antenna and are also susceptible to external radiation [9]. Therefore, for frequencies higher than 100 MHz, significant channel variation and lower efficiency of the communication system can be expected. Using the simulation platform discussed in the previous section, the HBC channel attenuation can be measured by the forward transmission coefficient S_{21} for various scenarios. As mentioned earlier, limited measurement results in the literature indicate a bandpass profile with varying location of the peak frequency. The bandpass profile is mostly influenced by the capacitive leakage path as well as the parasitic inductance L_{Tx}.

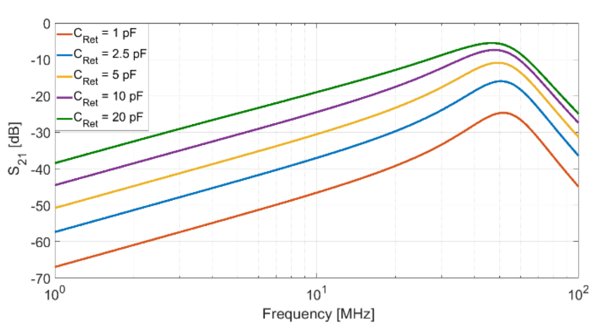

Figure 4. Forward transmission coefficient for various C_{Ret}

To show the impact of these parameters, consider the scenario depicted in Figure 1 with a distance of 15 cm between the two electrodes on the arm. Figure 4 displays the simulation results for various values of the capacitive return path (C_{Ret}) when L_{Tx}=225 nH. Similarly, Figure 5 reflects the impact of varying L_{Tx} while C_{Ret} is fixed. As observed, the bandpass profile shape and values for the S_{21} can be tuned and optimized to match the physical measurement results published in the literature. In fact, for 15 cm separation between the electrodes, C_{Ret}=5 pF, L_{Tx}=220 nH and C_L=35 pF, the simulation results match well with the reported physical measurement results in [5, 6]. The source and load impedances were assumed to be 50 Ohms. We also investigated the S_{21} results for distances of 30 cm and 45 cm as the receiver electrode was moved further up the arm and closer to the shoulder. The same values for the parasitic capacitance and inductance resulted in the best match with the reported measurements in [3, 4].

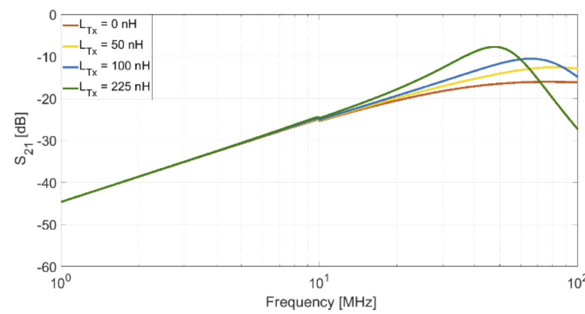

Figure 5. Forward transmission coefficient for various parasitic inductance

Looking at the results for electrode separations of 15, 30 and 45 cm, a slight degradation of the S_{21} versus distance is observed (see Fig. 6). However, the parasitic capacitance representing the return path seems to be the same. The S_{21} degradation is due to the higher attenuation of the forward path, i.e. the path through the body. For the three scenarios considered so far, the forward and return path distances are approximately the same as the receiver electrode is moved away from the transmitter along the straight human arm. It is worth noting that there could be scenarios where the forward and return path distances are quite different, for example, when the electrodes are located on the left and right wrists, and the arms are held straight down along the body (or even close to each other in front of the body).

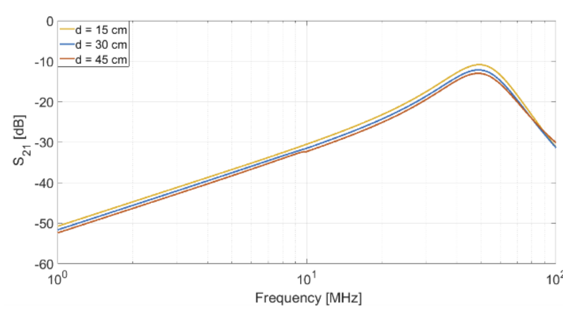

Figure 6. Forward transmission coefficient for various electrodes distances

To the best of our knowledge, there are no results in the literature that highlights the impact of this discrepancy between forward and return path distances. Our conjecture is that the parasitic capacitance could be a function of the return path distance. For example, if the electrodes are located on the separate wrists, the magnitude of S_{21} will change as the person under experiment move his hands closer or farther away from each other. Also, another ambiguity regarding the forward path distance is whether this distance is considered as the shortest path through the human body (i.e. in-body distance) or on the body surface. For example, consider two HBC electrodes, one located on the chest area while the other is on the back side of the body. Depending on how the electric field is distributed, the length of the forward path could be the straight line through the body connecting the electrodes or the distance around the body surface separating the two electrodes. To better understand this issue, we first need to eliminate the impact of the return path which can be accomplished by short-circuiting the ground plates of the electrodes with a perfect conductor. This was first done for the scenario in Figure 1 and the resulting S_{21} versus frequency (which is now representing only the attenuation through the forward path) is shown in Figure 7.

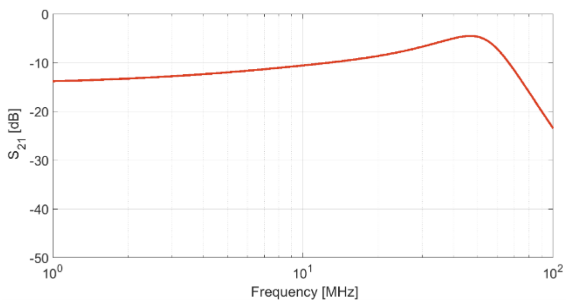

Figure 7. Forward path attenuation for the scenario shown in Fig. 1

As observed, the body seems to be a uniform attenuator (for frequencies below 100 MHz) with approximately 10-15 dB loss when the distance between TX and RX electrodes is about 15 cm. This level of attenuation was also observed through physical measurement in [7].

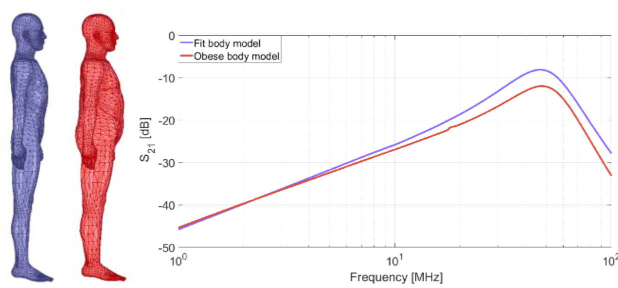

Figure 8. Forward transmission coefficient for various body shapes

The material properties of the body tissues that are along the forward path of the HBC channel can also impact the signal attenuation. To observe this, we conducted a simulation using two body models representing a fit versus obese person (see Fig. 8). The electrodes were placed on the stomach area where a heavier concentration of fat exists. The electrode separation was chosen to be 20 cm. The S_{21} for the two human body models are shown in Figure 8. The result indicates higher attenuation for the obese person, which can be explained by the lower conductivity of the fat tissue versus muscle for the frequency range of 10 to 100 MHz.

IV. Conclusions and Future Work

A FEM-based parametric simulation platform including a full 3D computational human body model has been presented in this paper. The S_{21} results match the bandpass HBC channel attenuation profile reported in the literature with appropriate adjustment of the model parameters. The platform allows researchers to further study the HBC channel by considering variable electrode size and plate separation, placement on the body, as well as designing virtual experiments to better understand the impact of variable return path distance for a fixed forward path through the human body. The authors also intend to continue this research by further extending the computational human body model to include various postures. Further studies on the distribution of the electric field inside the body would also be necessary to investigate the potential impact of using HBC on implant devices such as pacemakers.

Also, as mentioned earlier, low complexity and energy consumption of HBC will also make this technology an attractive alternative for implantable devices. Since implants are completely located inside the human body, physical measurements are no longer possible to examine the channel. Therefore, a simulation platform including a full human body model will be very useful to study and characterize the implant HBC channel. The implant communication link is less affected by the environmental variables as both forward and return paths are confined within the human body. Development of the platform discussed in this paper is the first step toward a comprehensive study of the implant HBC channel.

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