Material property based analysis of Electro-Quasistatic Human-Structure Interactions

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***Abstract*—Identification of an energy-efficient communication channel for information exchange between humans and the web-enabled 'smart' devices that are present in the surroundings has been the topic of interest over the last few decades. Energy-efficient and physically secure Human Body Communication (HBC)-based capacitive Human-Structure Interaction (HSI) in Electro-Quasistatics (EQS) regime calls for an analysis of the material property of the structure that has a decisive influence on the HSI channel characteristics. This paper, for the first time, addresses the effect of electrical properties (permittivity and conductivity) of the communicating structure's material on channel loss variation, and develops an equivalent circuit model highlighting its distributed nature. Finite Element Method (FEM) based simulations are performed to study the variations in channel behavior with the structure's material properties. Results are analyzed to build up an understanding of the electrical properties of a communication medium that can provide low loss interface for applications involving Human-Machine Interactions (HMI).**

***Index Terms*—Electro-Quasistatic (EQS), Human Structure Interaction (HSI), Human Body Communication (HBC), Human-Machine Interface (HMI)**

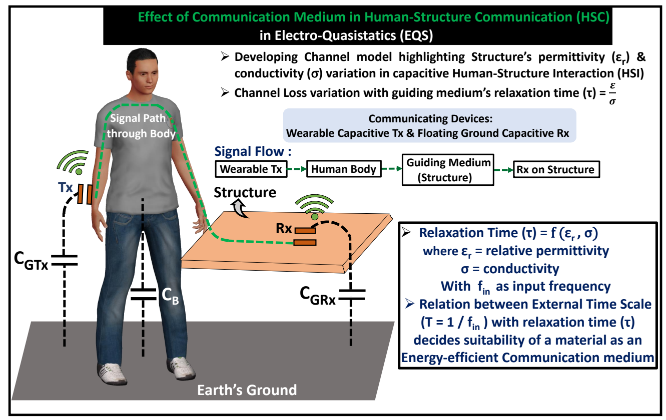

Fig. 1. Studying effect of electrical properties of the structure that is present in capacitive coupling-based Human-Structure Interaction (HSI): Schematic Diagram, representing the signal path through body and structure. Conceptualizing charge relaxation time in communication medium for energy-efficient interface design for Human-Machine Interactions.

I. Introduction

The increasing trend in the ubiquitous use of 'smart' electronic devices, powered by the Internet of Things (IoT) [1]–[3] and the proliferation of the Internet of Bodies (IoB) (in terms of wearables, implantable, ingestible, etc.) [4], [5], as an augmentation for the extensive IoT, motivates the exploration of a low-loss communication channel between the human body and its surrounding objects. With its emergence as a promising alternative to wireless communication for higher energy-efficiency ($\sim$ 10 pJ/bit) and physical security (signal leakage constrained within $\sim$5-10 cm around the body) [6], [7] in Electro-Quasistatics (EQS), Human Body Communication (HBC) prompted us to analyze the communication channel in Human-Structure Interaction (HSI). To achieve an energy-efficient interface for HSI, intuitively one can think of the involved structure as a communication medium, offering lower path loss during signal transmission. Hence, the communication medium's electrical properties i.e., relative permittivity (ϵ_r) and conductivity (σ) decide the energy efficiency of the HSI communication channel. The proposed study of the HSI channel dependency on the structure's material will facilitate exploring the suitable communication medium that can support an energy-efficient Human-Machine Interface (HMI) for physiological signal monitoring in 'smart' hospitals or developing assisted technologies for augmented living.

II. Relaxation Time and its Relation with Excitation Frequency

The metric that collectively captures the effect of material's relative permittivity and conductivity in deciding the path loss in a communication channel, is charge carrier relaxation time (τ), defined as follows:

$$\tau = \frac{\epsilon}{\sigma} \tag{1}$$

which represents the amount of time it takes the charges inside a material to redistribute themselves and to eventually attain nearly same potential throughout the medium (i.e., the time when charge density inside a material drops to 36.8% of its initial value). Besides the intrinsic time scale of the charge relaxation time (τ), there exists an external time scale (T = 1/f_{in}) or observation time, which depends upon the frequency (f_{in}) of the applied excitation. Thus, the material properties together with the relation between these two-time scales decides the type of physics interface required to study the charge relaxation process in different time-scale regimes.

A. Relaxation Time in Electro-Quasistatics

In EQS, with f_{in} lying in the range from 100 kHz to 10 MHz makes T (ranges from 100 ns to 10 μs) being twelve-to-fourteen orders of magnitude (i.e., $\sim 10^{12}$ to 10^{14} times) larger than τ ($\sim 10^{-19}$s) in good conductors like copper [8] and around eight-to-ten orders of magnitude (i.e., $\sim 10^8$ to 10^{10} times) smaller than τ ($\sim 10^3$s) in good dielectrics like silica glass. This makes the structure's electrical behavior to be either purely resistive in conductors or purely capacitive in dielectrics. However, by creating artificial materials with τ being four orders of magnitude (i.e., $\sim 10^4$ times) smaller than T, the behavioral switching of channel characteristics i.e., from resistive to capacitive, can be appreciated in EQS.

B. Equivalent Circuit Model

In the EQS-regime (f $\leq$ 10 MHz), where the operating signal wavelength ($\lambda \geq 30$ m) in air, is orders of magnitude larger than the dimensions of a human body ($\leq$ 2 m), and the employed communication devices (transmitter and receiver $\leq$ 0.03 m), the lumped approximation of the distributive nature of the bio-physical model of the human body is consistent. From the understanding of the previously proposed lumped-elements-based bio-physical model for capacitive HBC in EQS [9]–[11], this paper presents an equivalent circuit model for capacitive coupling-based HSI that potentially captures the electrically distributive nature of the structure's material, shown in Fig. 2 (a). With the lumped approximation of the human body in EQS, the structure as a guiding communication medium can be thought of as a distributive RC network, depicted in Fig. 2 (b). The intrinsic resistances, (R_{11}, R_{22}, $\ldots$, R_{NN}) present in the proposed circuit model vary with material's conductivity (σ) whereas the intrinsic capacitance (C_i) has a dependence on material's relative permittivity (ϵ_r) (i.e., $C_i \propto \epsilon_r$).

Now, the equivalent circuit model can be analyzed for three different classes of materials as follows:

(a) Conductors: Due to their σ being several orders of magnitude higher than their ϵ, conductors possess very small relaxation time (τ) which typically lies in the order of 10^{-19} s for good conductors like copper. This causes an almost instantaneous redistribution of excess charge carriers inside conductors when subjected to an external electrical stimulus. Hence, for the conductors, the proposed distributed circuit model can be fairly approximated as a lumped capacitance (C_{SG}) between the conducting structure and the earth's ground,

$$\text{i.e., } C_{11} + C_{22} + ... + C_{NN} = C_{SG}$$

Hence, the approximated capacitive HSI-channel transfer function can be reduced into the following form:

$$\frac{V_{out}}{V_{in}} \approx \frac{C_{GTx}}{C_B + C_{SG}} \times \frac{C_{GRx}}{C_{L(eff.)}} \tag{2}$$

where C_{SG} varies with the structure's dimension, its distance from the ground, and the permittivity ($\epsilon = \epsilon_0\epsilon_r$) of the surrounding medium.

(b) Dielectrics: With their σ being several orders of magnitude smaller than ϵ, dielectrics have larger relaxation time. For a good dielectric like silica glass, τ ranges in the order of 10^3 s. Thus, their electrical behavior can be approximately modelled by the intrinsic material capacitance (C_i), which depends upon its ϵ_r and the receiver's orientation relative to the transmitter. Eventually, the HSI-channel transfer function can be represented as

$$\frac{V_{out}}{V_{in}} \approx \frac{C_{GTx}}{C_B} \times \frac{C_{GRx}}{C_{GRx} + C_{L(eff.)} + \frac{C_{L(eff.)} \times C_{GRx}}{C_i}} \tag{3}$$

(c) Lossy Dielectrics: Materials with σ smaller than conductors but more than dielectrics behave as lossy dielectrics and can provide a communication channel that can offer frequency dependence variation in channel behavior in EQS, i.e., with a change in frequency its characteristic changes from resistive to capacitive or vice-versa.

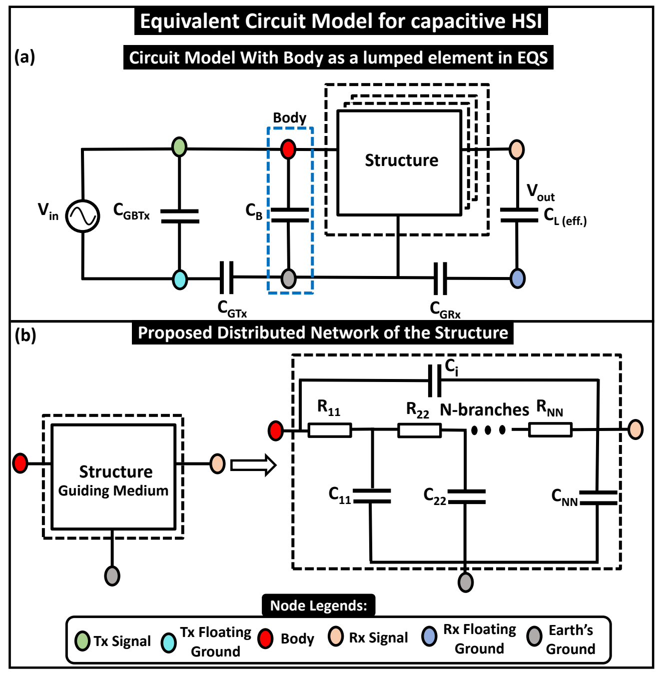

Fig. 2. Equivalent Circuit Model for the communication channel in capacitive HSI with a wearable (floating ground) transmitter (Tx) and a structure-mounted floating ground receiver (Rx): (a) Circuit model with human body as an approximated lumped capacitance (C_B) in EQS, and the structure (guiding medium) as a multistage distributive network, (b) Distributed network for the structure with intrinsic resistances (R_{11}, R_{22}, $\ldots$, R_{NN}), capacitance (C_i) that changes with structure's relative permittivity (ϵ_r) and conductivity (σ) and capacitances (C_{11}, C_{22}, $\ldots$, C_{NN}) that varies with the relative permittivity of the surrounding medium and distance of the structure from ground

III. SIMULATION MODEL & RESULTS

In capacitive coupling-based HSI, the transmitter (Tx) together with the human body and receiver (Rx) form the forward path for signal transmission, and the existing parasitic capacitances between the devices floating ground and the earth's ground form the return path. Now, to study the effect of the structure's electrical properties on HSI channel characteristics, Finite Element Methods (FEM) based EM simulations are executed in EQS frequency regime (1 MHz $\leq$ f $\leq$ 10 MHz) using a Finite Elements Analysis (FEA) based EM solver- Ansys High-Frequency Structure Simulator (HFSS).

A. Simulation Setup

This section presents the description of the FEM simulation setup for HSI.

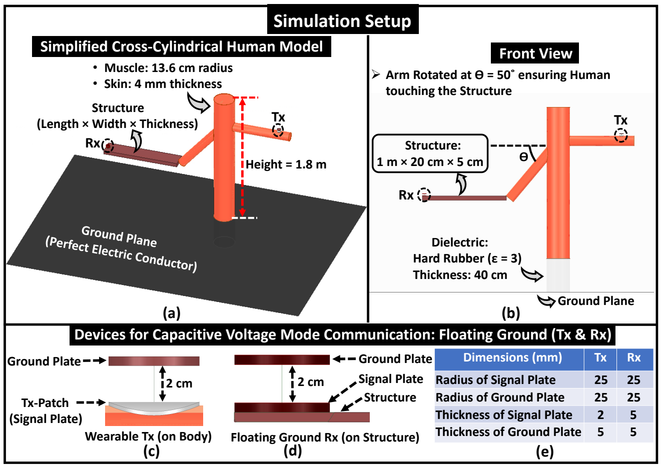

Fig. 3. Simulation Setup: (a) Simplified cross-cylindrical human model used for HFSS simulations and its dimensions with the position of wearable Tx and structure-mounted Rx shown, (b) Front View, Communicating Devices: (c) Capacitive Tx, (d) Capacitive Rx, (e) Summary of dimensional parameters of the devices.

Aiming to execute FEM simulations at reduced time and complexity, a simplified cross-cylindrical human body model, made up of skin and muscle tissues (dielectric (ϵ) and conductive properties (σ) of tissues, are taken from the works of Gabriel et al. [12]), is used, whose accuracy was confirmed from the fact that it possesses identical electric and magnetic field distributions inside-around the body as the complex human body model - VHP Female v2.2 from Neva Electromagnetics [13], shown by Maity et al. [14]. The simulation model, along with its structural parameters, are delineated in Fig. 3. Human with a wearable transmitter on one arm touches the structure (Dimension: 1 m $\times$ 20 cm $\times$ 5 cm) (envisioned to serve the purpose of a guiding communication medium) with the other arm (rotated at an angle θ to mimic the touch), while the floating ground Rx, is mounted on the other end of the structure, shown in Fig. 3 ((a), (b)). Though, to emulate the more realistic scenario, the structure can be mounted on a supporting table, however, to emphasize the effect of the electrical properties of the structure's material and subsequently to avoid the effect of the supporting table's material on the HSI channel behavior, the structure is kept being floating. The communicating devices (Tx, Rx), used for capacitive voltage mode communication, have disc-shaped signal and ground electrodes with their dimensions specified in Fig. 3 ((c), (d), (e)).

B. Simulation Results

This section delineates FEM simulation results in EQS.

1) Channel characteristics in EQS: The effect of variation in HSI channel behavior with change in the material of the communicating structure is portrayed in Fig. 4.

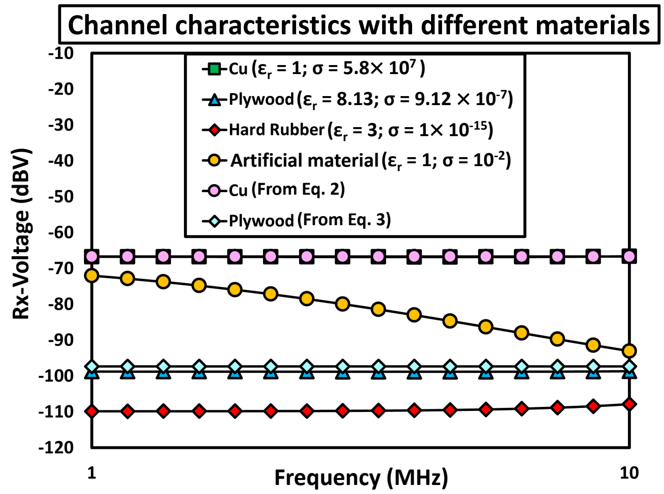

Fig. 4. Human-Structure Interaction channel behavior in EQS with different materials: Copper (Cu) with smaller τ ($\sim 10^{-19}$s) than T, offers higher V_{out}, i.e., lower channel loss. However, materials like Plywood, Hard rubber etc., owing to their higher τ compared to T, provide a highly lossy communication channel with path loss $\geq$ 100 dB .

Structure, made up of materials with higher conductivity (σ), i.e., σ comparable to metals like copper ($\sim 10^7$ S/m), supports guided communication at path loss of $\sim$67 dB. Substituting the obtained capacitance values as follows: $C_{GTx} \approx 0.27$ pF, ($C_B + C_{SG}$) $\approx$ 70 pF, $C_{GRx} \approx 0.31$ pF, and $C_{L(eff.)} \approx 2.67$ pF from Ansys Maxwell in Eq. 2, the validity of the equivalent circuit model with copper structure has been confirmed. Change in the structure's material from conductors to dielectrics (like plywood, hard rubber, etc.) results in a considerable increase in channel loss ($\sim$ 97 dB for Plywood, $\sim$ 110 dB for hard rubber). This increase in channel loss can be attributed to an increase in charge carrier relaxation time (τ) inside the dielectric (i.e., $\tau_{Cu} << \tau_{Plywood}, \tau_{hard-rubber}$). The capacitance values for the structure's material to be wood: $C_{GTx} \approx 0.27$ pF, $C_B \approx 55$ pF, $C_{GRx} \approx 0.31$ pF, $C_i \approx 0.008$ pF and $C_{L(eff.)} \approx 2$ pF, when substituted in Eq. 3, confirm the proposed circuit model. Aiming to observe the effect of variation in structure's conductivity when its material's conductivity is artificially changed to a lower value (σ = 0.01 S/m), we observe channel characteristics to be electrically low pass in nature where the cut-off frequency (f_c) of the low pass channel decreases with an increase in τ (i.e., decrease in σ).

2) Variation in Channel Loss with Conductivity (σ): The effect of variation in the structure's electrical behavior as a communicating channel with the change in its conductivity is represented in Fig. 5. In the region of lower conductivity ($\sigma \leq 10^{-5}$ S/m), the dependency of received voltage (V_{out}) on the medium's relative permittivity (ϵ_r) (i.e., capacitive behavior) is dominant over medium's conductivity. However, in the region of higher conductivity, the structure's conductive behavior mostly decides V_{out}.

3) Variation in Channel Loss with Relative Permittivity (ϵ_r): The variation in the structure's relative permittivity on channel loss is presented in Fig. 6. For a material with higher

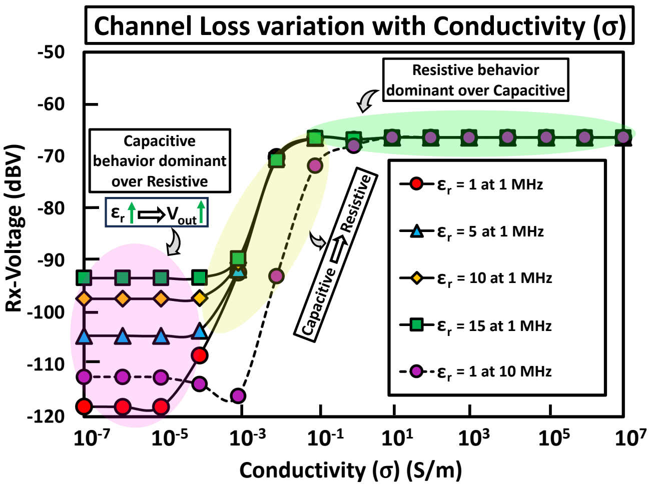

Fig. 5. Effect of variation in structure's conductivity (σ) on HSI channel loss at operating frequency = 1 MHz: Keeping the relative permittivity (ϵ_r) at a fixed value, an artificial increase in σ causes variation in received voltage(V_{out}), i.e., medium with lower σ offers lower V_{out} whereas the one with higher σ provides higher V_{out}. Furthermore, an increase in structure's ϵ_r, leads to an increase in static channel loss in the region of lower σ. Increasing frequency to 10 MHz leads to an increase in σ that causes the change in channel behavior from capacitive to resistive.

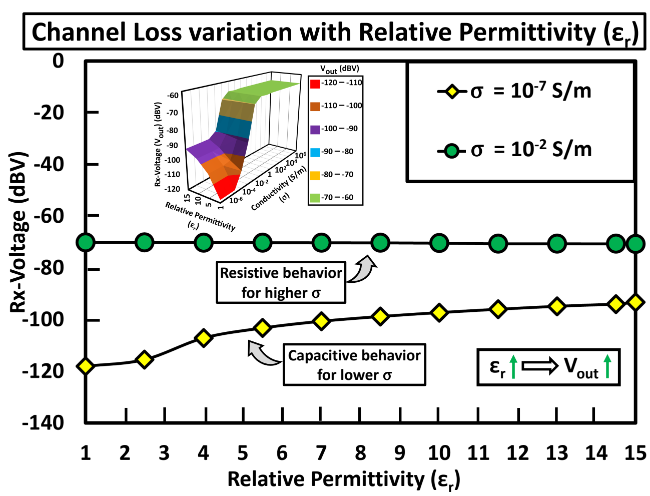

Fig. 6. Channel loss variation with relative permittivity (ϵ_r) for different values of conductivity (σ) at operating frequency = 1 MHz. Resistive behavior is predominant with higher σ i.e., V_{out} is almost independent from the variation in ϵ_r for higher σ whereas capacitive behavior persists as V_{out} changes with variation in ϵ_r for lower σ.

conductivity ($\sigma \geq 10^{-2}$ S/m), an increase in relative permittivity doesn't offer significant variations in V_{out}. However, the change in the material's ϵ_r can be appreciated for lower values of σ. This can be attributed to the fact that in the materials with higher conductivity, resistive behavior is dominant, and in those with lower conductivity capacitive nature persists.

4) Dimensional variation of structure's with different materials: Aiming to observe the channel loss dependency on the structure's dimension for different materials, keeping the receiver at a fixed distance away from the body, the width of the structure is varied, shown in Fig. 7. For the structure's

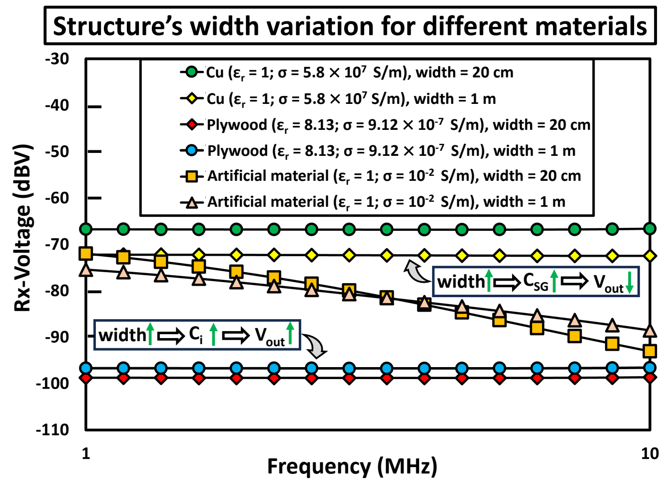

Fig. 7. Variation in HSI-channel behavior with width variation of the structure for different materials. Increase in width of Cu structure reduces V_{out} whereas increase in structure's width for dielectrics like plywood, increases V_{out}.

material to be copper, an increase in the width of the structure gives rise to an increase in C_{SG} and eventually, causes a reduction in V_{out} as per the eq.2. With the structure's material as plywood, an increase in its width results in an increase in V_{out} owing to an increase in C_i, from the eq. 3. However, for an artificial material with (ϵ_r = 1 and $\sigma = 10^{-2}$ S/m), channel characteristic switches from resistive to capacitive with a change in frequency, and this switching frequency depends upon the dimension of the structure which decides the distributive network inside it.

Conclusion

Analysis of the material properties of the incorporated communicating structure in capacitive-coupling-based Human Structure Interaction (HSI) in the EQS, is presented. Together with the lumped-element-based biophysical model for capacitive HBC, the proposed resistor-capacitor (RC) network (envisioned to emulate the structure's electrically distributed behavior) captures the effect of material properties on channel loss. Simulation results illustrate the variation in channel characteristics with change in charge carrier relaxation time (τ), which varies with relative permittivity (ϵ_r) and conductivity (σ) of the structure. For a fixed operating frequency (f_{in}), with the incorporated structure's material to be sufficiently conductive (σ being 10^{-2} S/m or higher), the channel loss becomes independent of the variation in relative permittivity, making the structure's electrical characteristic to be resistive. However, with an increase in f_{in}, the limit of σ that makes the structure electrically resistive also increases while achieving low loss. These understandings of proposed equivalent circuit model, incorporating material property-based analysis for communication medium can be extended further, while quantitatively relating the structure's electrical parameters with the lumped circuit elements to facilitate design of energy-efficient interfaces for HMI applications.

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