# A Distributed-Parameter Approach to Model Galvanic and Capacitive Coupling for Intra-body Communications

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**Abstract.** In this paper, we propose a simple, but accurate propagation model through the skin based on a *RGC* distributed-parameter circuit that leads to the obtaining of simple and general attenuation expressions for both galvanic and capacitive coupling methods that could assist in the design of Intra-body Communications (IBC) systems. The objective of this model is to study the influence of the skin impedance in the propagation characteristics of a particular signal. In order to depict that skin impedance, the model is based on the major electro-physiological properties of the skin, which also allows a personalized model. Simulation results have been successfully compared with several published results, thus showing the tuning capability of the model to different experimental conditions.

**Keywords:** Attenuation, capacitive coupling, distributed parameter circuit, electrophysiological properties, galvanic coupling, intra-body communication, skin admittance.

## 1 Introduction

Intrabody Communication (IBC) is a technique that uses the human body as a transmission medium for electrical signals to connect wireless body sensors [1]. Therefore, it is a human-centric connectivity technology that exhibits interesting advantages over conventional RF standards such as Bluetooth and Zigbee. Specifically, low frequency bands without large antennas can be used and there is no need to transmit high-power signals, thus considerably reducing energy consumption and the interference with external devices [2]. These features make IBC a promising alternative for the communication among sensors in biomedical monitoring systems, where minimally-invasive, small size and power-saving devices are required, which provides the basis of pervasive computing technologies with personal health systems [3]. These advantages have led many research groups to improve their IBC prototypes [4], [5]. However, no criteria have been

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proposed yet that allow achieving an optimal electronic design for an IBC system (in terms of power consumption, data rate, carrier frequency, modulation scheme, etc.) probably due to the lack of knowledge about the IBC propagation mechanisms. For this reason, a model of the human body and in particular the skin (where the signal is mainly confined) as a transmission medium is needed. In the literature there are several modeling approaches: FDTD electromagnetic simulations [6], liquid and solid phantoms [7] and propagation theoretical models that use simple geometries such as cylinders and planes to model the human body [8], as well as circuital models that emulate it as a set of impedances. In [9], a four-port lumped circuit model of the IBC galvanic coupling up to tens of MHz is introduced. As frequencies increase, the previous model becomes more imprecise. In this sense, a distributed $RC$ circuit model of the IBC capacitive coupling was proposed in [10] based on three T-shaped cylinders that simulate the trunk and the arms. Nevertheless, the human body impedance values were discrete and neither physiological characteristics of skin nor the frequency dependence of their dielectric properties were addressed. Only in [11] several electrophysiological considerations were taken into account, but the attenuation study was limited up to 1 MHz for the galvanic coupling technique. The authors of this work have already proposed in [12], [13] a general transmission model through the skin from the cascade, along a longitudinal axis, of basic electrical cells that emulate the skin transcutaneous admittance, forming a $RGC$ distributed-parameter circuital structure, whose elements depend on the frequency up to 1 GHz. In this paper, we propose an improved version of this $RGC$ distributed parameter model, which is able to account for the major electrophysiological properties of the skin, with the added value that it can easily reproduce both galvanic and capacitive coupling, by considering as many longitudinal axes as needed to reproduce the experimental conditions for both coupling techniques as well as the coupling capacitance with the air, which were considered negligible in the previous model. This paves the way for the comparison between both techniques, which has not been yet theoretically undertaken in the literature. Notice that IBC mechanism is based on the fact that the signal is confined to the body surface, with a negligible electromagnetic energy component radiated into the air. For this reason, the frequency of our study only ranges from the hundreds of kHz to 1 GHz, which is the frequency band in which most IBC applications have been developed. Nevertheless, we agree that the most suitable frequency band for IBC performance is below 100 MHz, because the human body does not act as an antenna and communication is limited to the human body surface, without radiation into the air [2]. The ultimate objective of the proposed model is to obtain some insight about the communications performance, through simple expressions of signal attenuation that could assist in the identification of the main IBC design parameters. The simulations have been successfully compared with several published results, thus showing the validity and tuning capability of the model to different experimental conditions.

## 2 Proposed Distributed *RGC* Model

The methodology used in this work consisted in obtaining a transmission model through the skin by means of the cascade of basic $RGC$ blocks, along a longitudinal axis, which forms a distributed parameter circuital structure. The objective of this model is to study the influence of the skin cross-sectional admittance $Y_{skin}$ and the skin longitudinal impedance $Z_{skin}$ in the propagation characteristics of a particular signal. Specifically, $Y_{skin}$ is a $GC$ shunt circuit where the conductance $G$ represents the conductive pathways of the skin, which are mainly the sweat glands and the ionic channels that cross the cell membrane, and the conductance $C$ represents the keratinized cells of the stratum corneum (SC) and the lipid bilayer, which are respectively more or less negligible depending on the frequency range [14]. In addition, the impedance $Z_{skin}$ is reduced to a resistance $R$ parameter that emulates the signal propagation between the basic $GC$ cells, that are repeated along the propagation axis, thereby obtaining a distributed parameter circuit model. These parameters were easily obtained from the equations $G = A\sigma/d$, $R = 1/G$ and $C = \varepsilon_r\varepsilon_0 G/\sigma$ where $d$ and $A$ are the skin depth and the cross-sectional area of the $GC$ cell, respectively. The permittivity $\varepsilon$ and the conductivity $\sigma$ dielectric properties of the skin where taken from [15]. It can be noticed that this circuit configuration can correspond to the equivalent electrical circuit model of a lossy transmission line without the inductive element $L$, i.e $L = 0$. In this way, we can obtain the propagation constant $\gamma$ and subsequently the attenuation constant $\alpha$ of the skin. Once we have modeled the skin as a transmission medium, we only have to introduce the electrodes configuration of both galvanic and capacitive coupling, as well as the coupling capacitance with the external ground in the latter case. Both circuital model schemes are shown in Fig 1. $Z_e$ represents the electrode impedance, whose values were taken from [16] for two kinds of materials (AgCl and copper). $\mathrm{R_L}$ is the load impedance, which was set to $50\,\Omega$. In Figs. 1c-d, the $C_a$ coupling capacitance with the air has been added in order to model the IBC capacitive coupling. Its value strongly depends on the environment, and it further increases with the presence of interfering devices. We have chosen values about tens of $pF$, as reported in [9]. $C_{ad}$ is the distributed coupling capacitance that appears between each point of the skin and the nearby space towards the external ground. In order to estimate it, a 1m-distance between the person and the floor was considered.

The propagation constant $\gamma$ of both models can be found by means of

$$\gamma = \sqrt{Z_{skin} Y'_{skin}} \tag{1}$$

where $Z_{skin} = R$ and $Y'_{skin}$ depends on the coupling type.

- For galvanic coupling,

$$Y'_{skin} = Y_{skin} = 2(G + j\omega C) \tag{2}$$

  where (2) is multiplied by a constant factor equal to 2, due to the differential configuration of the galvanic coupling. Therefore, a virtual ground line

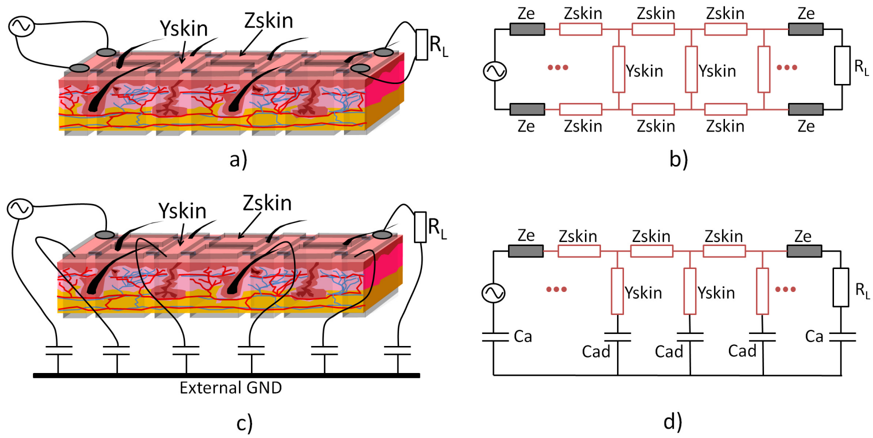


**Fig. 1.** a) Galvanic coupling IBC method. b) Galvanic coupling IBC equivalent circuital model. c) Capacitive coupling IBC method. d) Capacitive coupling IBC equivalent circuital model.

appears in the middle of the distributed circuit, thus dividing $C$ into $2C$-value capacitors and $G$ into $2G$-value conductances.

- For capacitive coupling, $Y'_{skin}$ is the serie circuit of $Y_{skin}$ and $C_{ad}$,

$$Y'_{skin} = \frac{1}{\frac{1}{G+j\omega C} + \frac{1}{j\omega C_{ad}}} \tag{3}$$

Thus, this model allows to obtain the propagation constant $\gamma$ related to both electrophysiological properties of the skin, which is modeled by means of $R$, $G$ and $C$ parameters; as well as the coupling type, through the two different expressions of $Y'_{skin}$. Once we have the propagation constant $\gamma$ we can calculate its real part in order to find the $\alpha$ attenuation constant of the skin and predict the behavior differences between both capacitive and galvanic coupling approaches. Then, the electrodes effect have been introduced in order to obtain the total pathloss of the IBC system. Thus, the introduction of the electrodes might cause an impedance mismatch, represented by the reflection coefficient $\Gamma_l$,

$$L(\text{dB}) = 20\log_{10}\frac{1+\Gamma_l e^{-2\gamma l}}{(1+\Gamma_l)e^{-\gamma l}} \tag{4}$$

where $l$ is the length between the electrodes.

## 3 Results

The attenuation constant of the skin was found by means of the real part of (1) for both coupling methods using $RGC$ model parameters values detailed in Section 2. The result is shown in Fig. 2. It can be seen that there is a significant difference between both couplings techniques mainly at low frequencies. This behaviour could be explained by the fact that at low frequencies in the galvanic coupling approach the signal penetrates transversely across the skin into the muscle, therefore muscle conductivity is higher at such frequencies [17]. On the other hand, the capacitive coupling is based on the near-field coupling mechanism that ensures the signal to be confined in the body surface, mainly through the skin, which acts as a signal guide that couples the signal electrostatically without penetrating across it, and which does not cause losses as high as those of galvanic coupling. As a proof of the validity of the model, the IBC pathloss in (4) has been simulated and the theoretical results have been successfully compared with experimental measurements reported by other authors in the literature. We remark that the same parameters used for the simulation results presented in Fig. 1 have been applied, together with the inclusion of the corresponding electrode models. For the sake of representation, in Fig. 3 we have chosen an author that works with galvanic coupling with three different commercial electrodes [7] and two authors that work with capacitive coupling but with different material electrodes [10],[18] in Fig. 4, in order to illustrate the adaptability of the model to different frequency ranges, electrode types and coupling methods. In all these cases it is evidenced a good agreement between the attenuation predicted by the model and the measurement data, notwithstanding that there is a large variability with the values reported in the literature, as a consequence of the different test set-ups and measurement conditions under which the authors carried out their experiments. In addition, skin admittance varies considerably between different people and environmental conditions. Changes in hydration mechanisms due to sweat gland activity and temperature can be manifested in large variations of skin admittance [14]. Thus, we show the tuning capability of our model, which besides retains an electrophysiological significance.

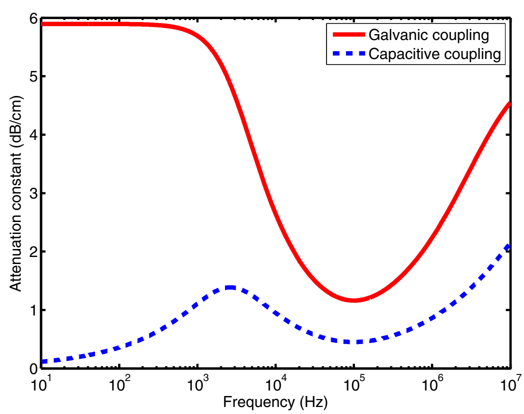


**Fig. 2.** Attenuation constant (dB/cm) for both galvanic and capacitive coupling between 10 Hz and 10 MHz

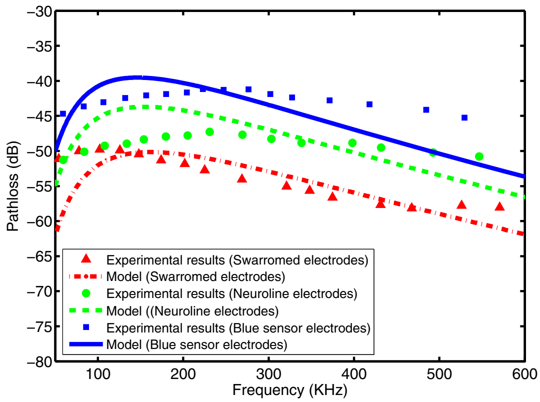


**Fig. 3.** Pathloss results for galvanic coupling and three different types of commercial electrodes. Comparison between simulated results from model and experimental results in [7].

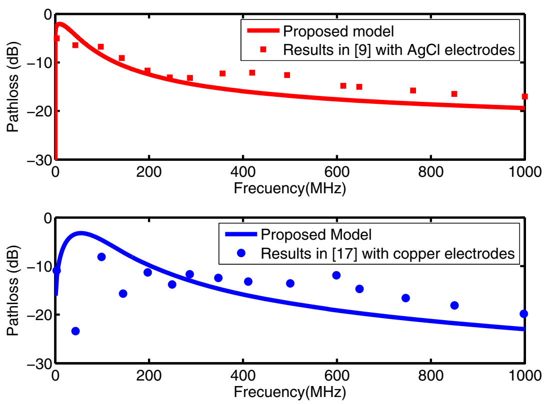


**Fig. 4.** Pathloss results for capacitive coupling and two different electrodes material: copper and Agcl. Comparison between simulated results from model and experimental results in [10] and [18].

## 4 Summary and Conclusion

We have proposed a simple but accurate model based on an *RGC* distributed parameter circuit that combines its simplicity with the flexibility to approximately match diverse experimental results, regarding both IBC galvanic and capacitive coupling methods. Notice that model validation is not aimed at an accurate prediction of the characteristics of attenuation, but to approach the trends and behavior observed in practice, because of the large variability of the measurement conditions under which IBC results have been carried out. In conclusion, a helpful tool to guide IBC designs has been obtained. In addition, we accounted for the main electrical properties of the skin. Moreover, $RGC$ parameters can be derived from bioimpedance measurements, thus obtaining a personalized model. Our next work will be focused on the practical implementation of both IBC coupling techniques in order to obtain different experimental measurements with which the model data could be fitted.

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