Sensitivity of Galvanic Intra-Body Communication Channel to System Parameters

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Abstract. In this paper, we investigate the sensitivity of the galvanic coupling Intra-Body Communication (IBC) channel to the variation of the basic parameters - being them electrical, geometrical or biological - of the main blocks of the IBC system; the transmitter and receiver nodes, the electrodes used, and the communication channel itself being the human body in this case. The study is performed over the frequency range 100 kHz–100 MHz, providing the system designer with a unique guide for the relationship between the system parameters, thus facilitating the design of an efficient and better matched system components.

Keywords: Body Area Networks · Intra-Body Communication · Galvanic coupling · Channel modeling · Circuit model

1 Introduction

Wearable devices are rapidly being adopted as means of augmenting and improving health care services. In order to provide a cable-free biomedical monitoring system, new wireless technologies associated with sensor applications have been promoted as the next biomedical revolution, yet the size and power requirements of wireless sensors which are typically dominated by the Radio Frequency (RF) section of the associated transceivers, have limited their adoption. To overcome such concerns, system architects proposed designing the system in a way that would allow more than one sensor to share the same wireless gateway, providing a distributed solution, with less power consumption. That approach paved the way for adopting IBC systems where data transmission is carried out through the body (mostly skin layers), rather than through air [1, 2]. This emerging technology would ultimately lead to Body Area Networks (BANs) that operate at extremely low power, with minimal foot print by replacing expensive, power consuming RF front ends, for each individual node with simpler interfaces. IBC can be categorized into two main types; capacitive coupling (near field coupling method) and galvanic coupling. In capacitive coupling, only the signal electrodes of the transmitter and the receiver are attached to the body while the ground (GND) electrodes are left floating in the air. The conductive body forms the forward path while the signal loop is closed through the capacitive return path between the transmitter and the receiver

L. Mucchi et al. (Eds.): BODYNETS 2019, LNICST 297, pp. 150–160, 2019.
https://doi.org/10.1007/978-3-030-34833-5_13

GND electrodes. The second approach, which depends on the galvanic coupling principle, uses a pair of electrodes for both the transmitter and the receiver to propagate the electromagnetic wave. The signal is applied over two coupler electrodes and received by two detector electrodes. In both approaches, it has been shown that the attenuation of the body channel can be much lower than that of the air channel in frequencies up to 100 MHz [3]. An attractive feature of the galvanic coupling approach is that the signal is totally confined to the body, unlike capacitive coupling where the signal return path is established through the air, thus galvanic coupled signals experience minimal interference from other electronic devices, enabling robust and secure data exchanges. In this paper, we study the sensitivity of the galvanic IBC channel to the electrical, geometrical and biological parameters of the system, through observing the channel gain/attenuation profile over the frequency range of interest for IBC; 100 kHz to 100 MHz. In Sect. 1, we explain how we model the different parameters and features of the system using an accurate circuit model. In Sect. 3 we study the sensitivity of the system to the biological/electrical aspects of the communication channel; the body. Sections 4 and 5 then consider the impact of the system design parameters; properties of the electrodes as well as the transmitter (TX) and receiver (RX) nodes.

2 System Model

In [4], we present a simple circuit model for IBC using galvanic coupling, as shown in Fig. 1. In the proposed model, biological parameters are assumed to be variable, taking into consideration the impact of important factors; such as age and weight, on these parameters and thus on the overall attenuation profile. The impedances constituting the model are calculated according to the electrical properties - permittivity and conductivity - of the main five body tissues (fat, muscle, skin, cortical bone and bone marrow), the geometrical aspects of the body organs and finally the electrodes' material and dimensions.

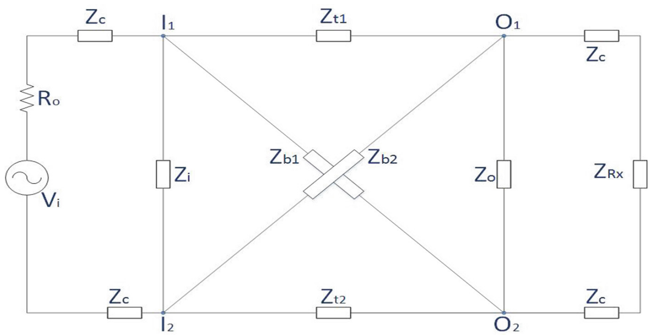


Fig. 1. Circuit model for galvanic coupling, is the signal source at the transmitter, Z_c: the coupling impedance between the electrode and the skin, Z_i: input impedance of the human body. Z_{t1} and Z_{t2} are the transverse impedances of the transmission path, while Z_{b1} and Z_{b2} are the cross impedances, the body output impedance is Z_0, output resistance of the transmitter is R_0 and Z_{RX} is the input impedance of the receiver [4, 5].

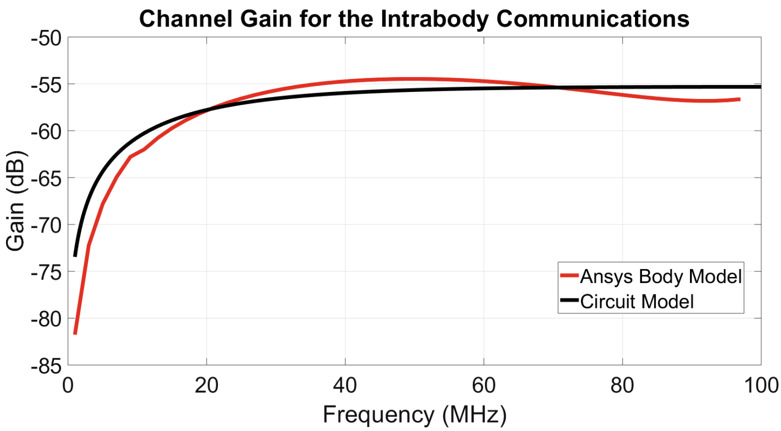
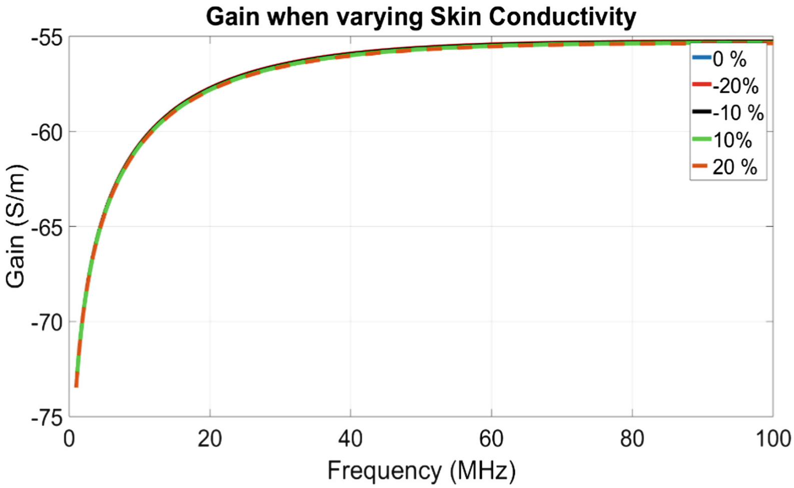


Fig. 2. Comparison between the gain profile for the galvanic IBC channel calculated once through the circuit model then using the FEM model, showing how accurate the circuit model is.

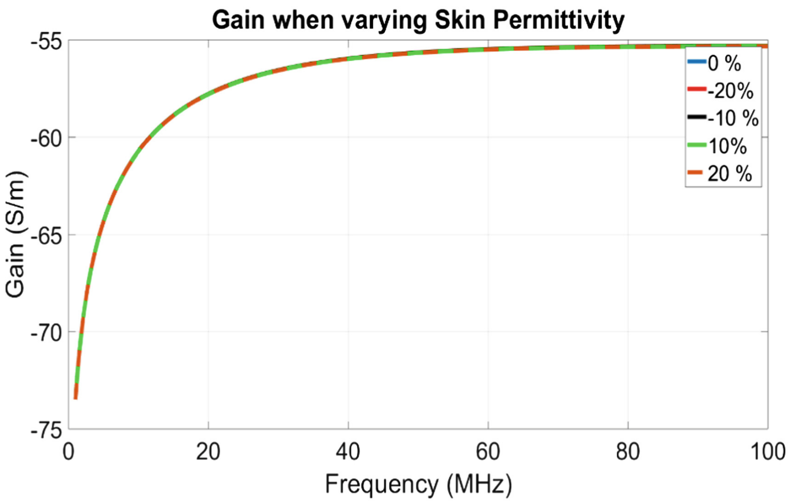
To validate our model, we compared the results we got with experimental measurements reported in the literature [4]. We also validated our model results, by comparing the gain profile calculated using our model with that generated using a full body FEM model developed by NEVA Electromagnetic group, using ANSYS HFSS environment [6]. Results are shown in Fig. 2, showing the accuracy of our proposed circuit model, for galvanic IBC.

3 Tissue's Electrical Properties

In [7], it was shown that electromagnetic waves possess better properties, that can support BAN requirements, versus ultrasonic waves as EM waves experience much less attenuation and delay when traveling through the body which is crucial for system designers. The basic human tissues' properties of concern are those of the complex dielectric properties; namely the permittivity and the conductivity. Thus the first sensitivity analysis test performed was on how the variation in these electrical properties would affect the IBC channel characteristics (gain). We studied the effect of varying the properties of each tissue solely in a range between −20% to 20% of the average nominal values [8], and results are plotted in for skin and muscles in Figs. 3 and 4. The error was also calculated (the deviation of the IBC channel gain from the nominal value, reported in Fig. 2) and summarized in Tables 1 and 2, where the maximum error percentage is reported for each case. As shown from the results, the IBC channel characteristics are much more sensitive to the conductivity of the tissues over the permittivity, since the conductivity mainly accounts for the signal transmission capability through a certain medium. This finding is crucial for applications like phantoms design, for manufacturing more accurate tissue mimicking materials [9]. From a tissue perspective, muscle, skin and fat layers tend to affect the characteristics of the IBC channel more than cortical bone and bone marrow, this is due to: (a) the better conductive properties of the first three tissues, (b) the fact that only a tiny portion of the signal will travel through the bones (since most of the signal is transmitted through the skin, then muscles, as shown in [10]).

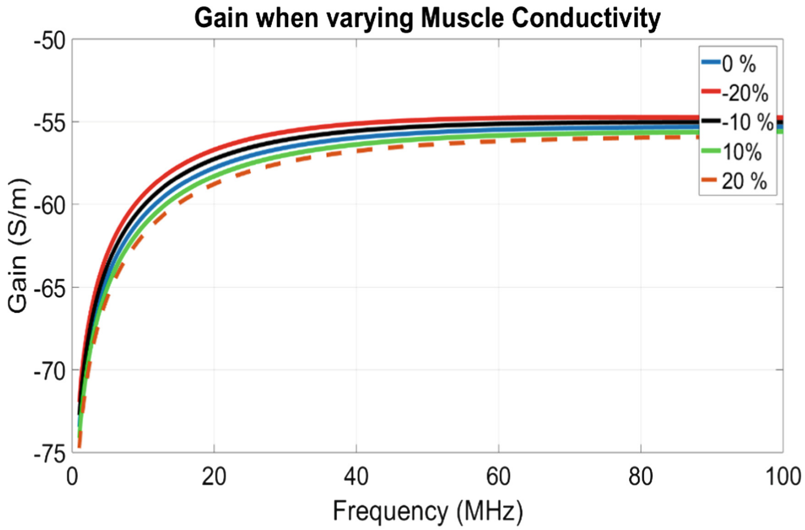


(a)

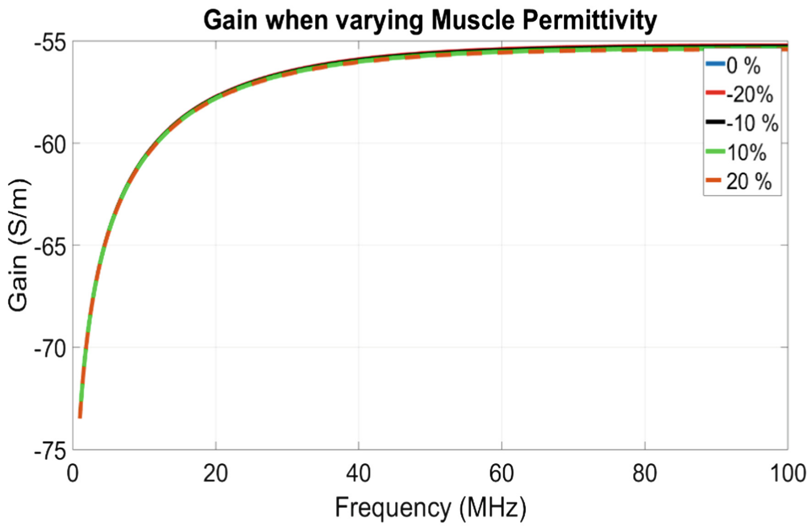


(b)

Fig. 3. The variation in the IBC channel gain profile, when varying the; (a) conductivity and (b) permittivity of the skin tissue, within the range −20% to 20% from the nominal measured values [8].



(a)



(b)

Fig. 4. The variation in the IBC channel gain profile, when varying the; (a) conductivity and (b) permittivity of the Muscle tissue, within the range −20% to 20% from the nominal measured values [8].

Table 1. Maximum error percentages for the deviation in the IBC channel gain when varying the electrical conductivity of the tissues.

Tissue	Conductivity			
	−20%	−10%	10%	20%
Skin	0.1013%	0.05008%	0.04923%	0.09785%
Fat	0.5278%	0.259%	0.2497%	0.4906%
Muscle	2.194%	1.053%	0.9776%	1.891%
Cortical bone	0.00461%	0.002302%	0.002302%	0.004617%
Bone marrow	0.0014%	0.000697%	0.000697%	0.0014%

Table 2. Maximum error percentages for the deviation in the IBC channel gain when varying the electrical permittivity of the tissues.

Tissue	Permittivity			
	−20%	−20%	−20%	−20%
Skin	0.04311%	0.04311%	0.04311%	0.04311%
Fat	0.03%	0.03%	0.03%	0.03%
Muscle	0.1624%	0.1624%	0.1624%	0.1624%
Cortical bone	0.00127%	0.001275%	0.001275%	0.001275%
Bone marrow	0.00052%	0.000524%	0.000524%	0.000524%

4 Electrodes

Electrodes are responsible for connecting the electronic systems to the human body through transducing ionic currents from the human body into electric currents and vice versa, thus modeling the electrode and electrode-body compact impedance has a significant impact on the overall channel model. Parameters as the electrode size, material, shape, width, thickness …etc. should all be taken into account. Other factors that further determine the value of the electrode-contact impedance include the operating frequency, spacing between each of the electrode pairs (ex: separation between the two electrodes of the transmitter) and the location of the electrodes on the human body. In [11], the authors investigated various techniques to reach an accurate electrical circuit representation of the electrode-body contact. A double order model, shown in Fig. 5, was adopted, since it accurately models the interaction at the interface between the metal electrode and the electrolyte gel solution, as well as that between the electrolyte and the skin. In the model, C_d represents the double layer capacitance between the electrode and the electrolyte solution in the body tissue, R_a is the activation polarization resistance, R_w and C_w represent the diffusion polarization impedance (Warburg impedance), Z is the reaction impedance and Z_t is the impedance of the tissue under the electrode (skin). We first study the effect of using different electrode materials; copper, brass and stainless steel.

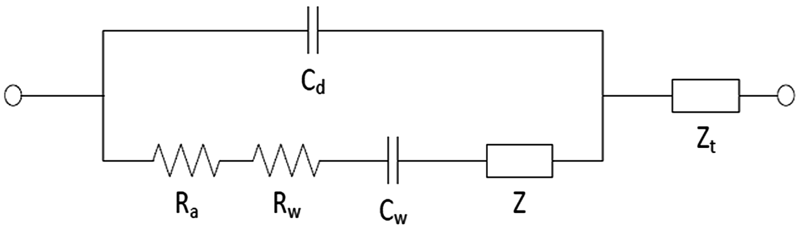


Fig. 5. Contact impedance circuit model proposed in [12], taking into consideration the activation polarization, diffusion polarization, reaction impedance and the body tissue impedance.

Material dependent parameters reported in [12] are used, and results are shown in Fig. 6, showing how sensitive the channel is to the material used (thus the electrode impedance). In Fig. 7, we study the impact of the separation between electrodes of each node, where the separation is varied; 1 cm, 6 cm and 10 cm, while the electrode area and distance between the TX and RX are kept fixed at 20 cm^2 and 10 cm respectively. In Fig. 8, the electrode area is varied; 1 cm^2, 10 cm^2 and 100 cm^2 while the distance between the TX and RX nodes and separation between pair of each node are kept constant at 10 cm and 6 cm respectively. As the electrode area increases, its impedance drops till the body input impedance becomes dominant over it, thus the body input impedance will have the higher impact on the channel profile [11], and matching improves between the body input impedance and the electrode impedance specially at lower frequencies.

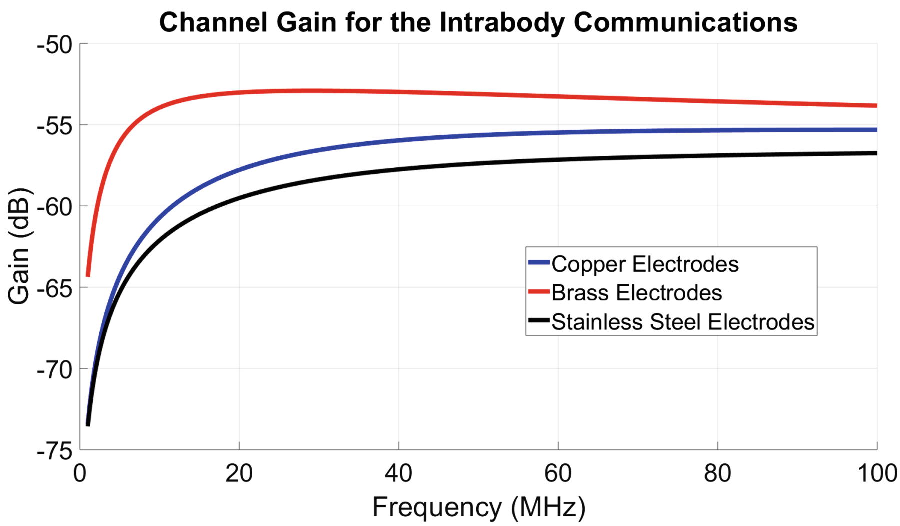


Fig. 6. Channel model for galvanic intra-body communications for three different electrode materials; copper, brass and stainless steel.

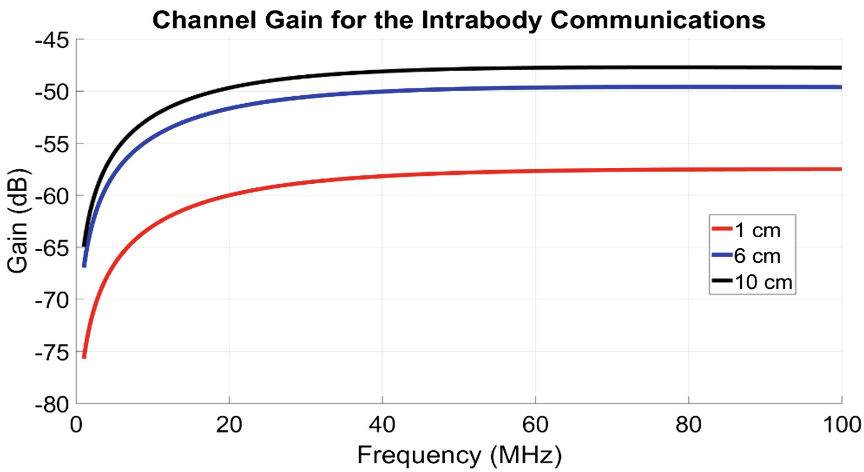


Fig. 7. Varying the separation between electrodes of each node; 1 cm, 6 cm and 10 cm, while both the electrode area and distance between TX and RX are kept constant.

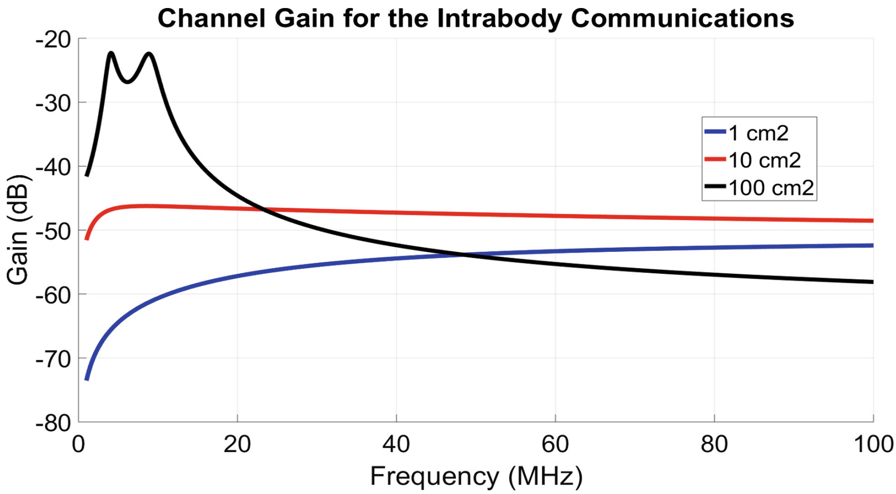


Fig. 8. Varying the electrode area; 1 cm^2, 10 cm^2 and 100 cm^2, while the distance between the TX and RX nodes and separation between pair of each node are kept constant.

Moreover, changing the separation between the electrode pairs at each node, changes the input impedance seen between these two electrodes according to the model proposed in [4], thus the final channel gain will be determined according to the relation between the various impedances (input impedance, electrode impedance, transmission path impedance …etc.).

5 Transmitter and Receiver Nodes

The final blocks in the IBC system are the transmitter and the receiver nodes. Since the channel characteristics are mostly affected by the relation between the impedances of the basic blocks of the system; an impedance matching issue for maximum power transfer between the electronics system and the body and vice versa, we will investigate the impact of the TX output impedance and the RX input impedance on the IBC channel. In Fig. 9, we vary the magnitude of the RX input impedance between 100, 1K, 10K, 100K and 1M Ω, and observe the channel gain. As expected, the gain of the channel improves as the RX input impedance value increases, as more signal power is delivered to the receiver node. However, after reaching a certain value ($\sim$10K in this case) the gain saturates, since the RX input resistance becomes much larger than the system impedance, thus most of the power is transferred from the system (body and electrodes) to the RX anyway. On the TX side, the TX output impedance is our concern, since it partially determines the portion of the power that will be delivered from the source to the system. While 50 Ω would be the nominal value that most devices/circuits try to design according to, for matching purposes, we included other values; 10, 100, 500, 1K, 2K, 5K and 10K Ω to study its impact on the gain of the channel, as shown in Fig. 10. Clearly the gain improves as the value of the resistance drops, as less power is lost in the TX node; more transmitted to the system.

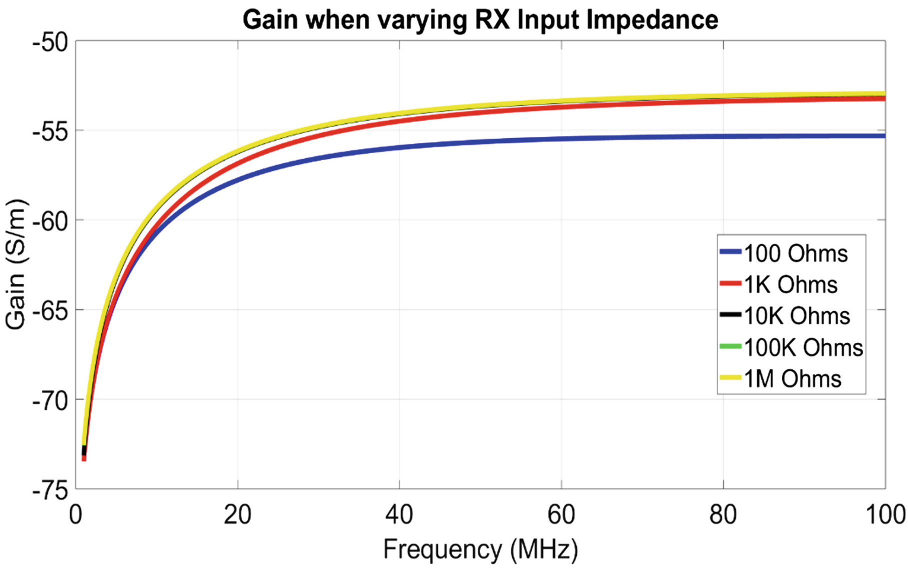


Fig. 9. Gain when varying the value of the RX input impedance; 100, 1K, 10K, 100K and 1M Ω.

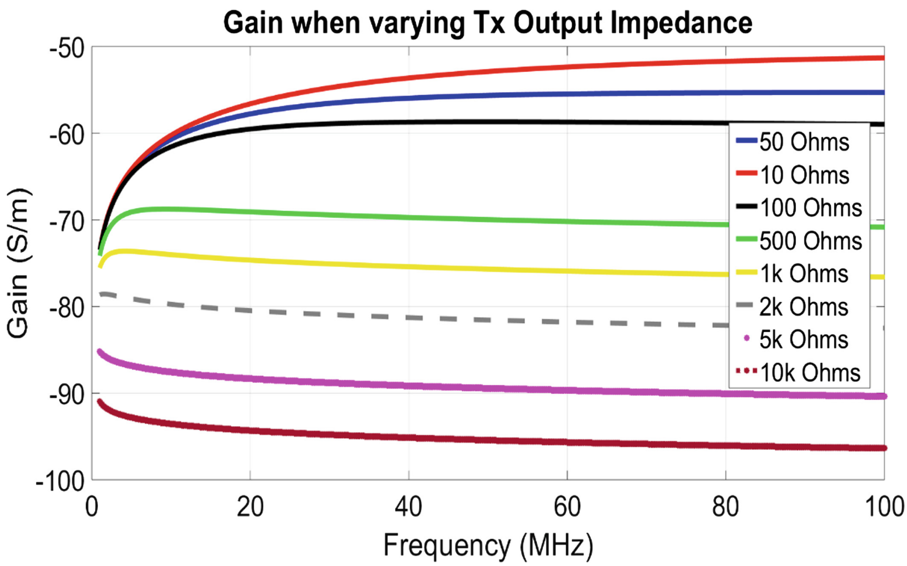


Fig. 10. Gain when varying the value of the TX output resistance; 10, 100, 500, 1K, 2K, 5K and 10K Ω.

6 Conclusion

In this paper, we investigated the relationship between the system's electrical, geometrical, biological parameters and the IBC galvanic coupling channel profile. It was shown how the channel is more sensitive to the tissue's conductivity over their permittivity. Also as expected, the properties of the electrodes impact the channel gain profile significantly. Contribution of the RX input impedance and the TX output resistance was also discussed. The paper provides a basic guideline for the relationships between the basic IBC system blocks, showing how sensitive the channel is to the parameters of each of these blocks, which is crucial for the system architect, to improve the system's efficiency and performance.

Acknowledgments. The authors gratefully acknowledge that this work was supported in part by the National Institute of Justice (NIJ) grant number 2016-R2-CX-0014.

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