Wireless Communications for Medical In-Body Devices: Challenges for In-body Propagation

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Abstract

The use of wireless communications in medical devices is expected to improve the quality of life of patients as well as the early diagnosis of different kinds of diseases. Future wireless medical sensors will be deployed inside the human body collecting and monitoring different kind of parameters. To achieve these requirements, a proper wireless link is required as well as enough bandwidth and data rates. However, the transmission of wireless signals through the human body is challenging due to the high losses of the different body tissues. Thus, an accurate characterization of the transmission environment is mandatory to adequately design and test new medical devices.

The Mobile Communications Group of the ITEAM is currently involved in different research projects related to wireless body communications for medical in-body devices. These projects address different challenges of the wireless communications in this particular scenario: wireless in-body propagation in large frequency bands, body tissue electromagnetic characterization, and tissue emulation for wireless testing of medical devices. These tasks are currently undertaken with the support of the Hospital Universitario y Politécnico La Fe of Valencia, and the Centre for Biomaterials and Tissue Engineering of the UPV.

Keywords: in-body devices, phantoms, antennas, propagation, Ultra-Wideband, WIBEC.

1. Introduction

The use of wireless technologies in medical devices has increased dramatically in the last years. Significant advances in microelectronics have enabled the integration of biomedical sensors and radio transceivers into wearable and implantable wireless sensors [1]. Such devices collect and monitor key physiological data from the patient and send it to a remote node located inside or over the surface of the body. Pacemakers, cortical implants or wireless capsules endoscopy are examples of this type of wireless implanted medical devices.

The IEEE Standard 802.15.6-2012 for Wireless Body Area Networks (BANs) [2] allocates the different frequency bands and other parts of the electromagnetic spectrum to the operation of implantable or wearable sensors. The Medical Implant Communication Service (MICS) band was chosen to enable communication between in-body devices. MICS frequency band, which operates in 402-405 MHz, has good wave propagation conditions through biological tissues [3]. However, this band has a very low bandwidth to allow high data rate transmissions. In order to overcome this issue, the Industrial, Scientific and Medical (ISM) radio band (2400-2483.5 MHz) has been also widely considered as a candidate in order to enhance the in-body communications in next generation devices [4]. However, these multipurpose bands are commonly used for WLAN and WPAN networks so that they can be interfered by other commercial wireless devices. Thus, Ultra-Wideband (UWB) band, which can operate in the 3.1-10.6 GHz frequency band, is being considered as a potential candidate for wireless communications in medical applications due to its large bandwidth, low power consumption and miniaturization capabilities [2]. Nevertheless, the dielectric characteristics of human body tissues at UWB frequencies imply high path losses so that an accurate characterization of the in-body propagation is a key factor for a proper operation of future in-body medical devices.

The wireless operation of medical in-body devices can be tested in three main different ways [5]:

1) Electromagnetic software simulation [6], where no specific laboratory equipment is needed. However, software simulations cannot capture the effects of some physiological processes such as respiration, blood circulation, or temperature gradients. Furthermore, numerical simulations at UWB band requires accurate human body models as well as a high computational cost.

2) In-vivo experiments [7], [8], using animals that anatomically resemble some parts of the human body. However, such measurements are expensive and require the use of an operating room with all the necessary medical staff and governmental approval for the experimental implantation of the antennas.

3) Laboratory measurements [4], [9], using chemical compounds that replicate the dielectric properties (permittivity and conductivity) of human tissues, also known as phantoms, are widely known in wireless communications for other applications. However, not many phantoms can emulate the electromagnetic behaviour of the different body tissues in the whole UWB band. Therefore, laboratory measurements are not accurate enough due to the detuning of the phantoms in the frequency band under measurement [7].

In this framework, the Mobile Communications Group (MCG) of the ITEAM has being working towards: accurate characterization of the UWB in-body propagation channel which implies the design of novel in-body antennas taking into account the particular characteristics of the surrounding environment; development of tissue characterization tools that allow either measuring biological tissues in wideband as well as the characterization of chemical compounds for laboratory use; and the investigation of new phantom formulas for the emulation different body tissues in wideband that can be used for testing wireless communications signals and algorithms. In the following pages, the latest outcomes of the Mobile Communications Group in these areas are outlined.

2 Characterization of Body Tissues

Relative permittivity and conductivity are electromagnetic properties that determine some propagation effects such as path loss, reflection or velocity of propagation of a signal when travelling through materials or body tissues. Thus, gaining knowledge regarding these properties is crucial in order to understand the electromagnetic propagation inside the human body. On the one hand, the relative permittivity of a material is defined as the ratio between its absolute permittivity and that of the free space. It is a dimensionless, complex, frequency dependent value whose real part is known as dielectric constant and its imaginary part is known as loss factor. On the other hand, the conductivity (S/m) is a frequency dependent property that represents the losses related to the free charge conduction. Besides, conductivity values can be deduced from the loss factor ones.

Gabriel's database [10] is widely considered as a reference for getting the electromagnetic parameters of the different body tissues. It contains information of more than 50 different tissues in a very large frequency band (many of them, from 10 Hz to 20 GHz). This is the most widespread study for this purpose, in spite of the fact that tissue samples were mainly taken from animal specimens and measured on ex-vivo conditions. It is also possible to find works that contain dielectric properties of human tissues, although the available tissues are restricted to dermis and epidermis [11], liver [12], [13], breast [14] and tongue [15]. Most of these studies were performed measuring the different body tissues under different conditions using the open-ended coaxial system.

The Mobile Communications Group has implemented an open-ended coaxial measurement system for body

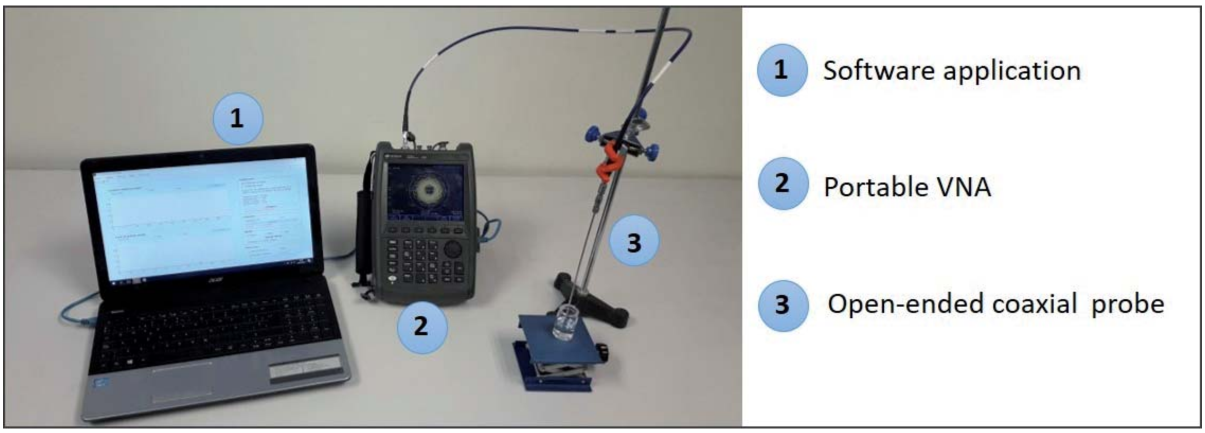


Figure 1. Open ended coaxial system setup.

tissue characterization as shown in Figure 1. It is composed of a vector network analyzer (VNA), an open ended coaxial probe, interconnection elements and a computer. This system is the most widespread one for measuring liquids, and semisolids since it covers a large bandwidth and is non-destructive, fast, and suitable for measuring liquid and semi-solid materials. The principle of operation is based on measuring the reflection of a material placed in the probe's end in a determined frequency bandwidth, and transforming it into electromagnetic properties after a previous calibration [16]. This calibration consists in measuring the reflection of reference materials with well-known electromagnetic properties (air, short circuit, deionized water and methanol) in order to relate a reflection measurement with its corresponding relative permittivity and conductivity. It is important to underline that with this system the contribution of the ionic conductivity is included in loss factor measurements, since these losses as well as those caused by the dielectric relaxation polarization are indistinguishable. This contribution can be observed mainly in frequencies below 2~3 GHz, where the ionic conductivity contribution is higher. A customized software application was also developed for controlling the whole measurement system as well as for data acquisition post-processing.

The measurement system has been used for characterizing ex-vivo healthy and cancerous samples of human colon tissue in the framework of CEI-2G project for the development of the new generation of Wireless Capsule Endoscopy (WCE). Such project is a jointly funded project between the UPV and the Hospital Universitario y Politécnico La Fe. Biological samples obtained from colonoscopy biopsies and surgery resections were analysed in the 0.5 to 18 GHz frequency band. The surgery samples of 20 patients were measured 20 minutes after their extraction at the facilities of the hospital. We observed that the dielectric constant was 8.8% higher in malignant tissues, whereas the conductivity was 10.6% larger [17], as can be observed in Figure 2. These results may have a potential application in colorectal cancer detection and diagnosis.

Measurements carried out between the ITEAM and the Hospital La Fe of Valencia shown that the complex permittivity of malignant tissues are higher (8.8% and 10.6% for the dielectric constant and the conductivity respectively) than that of the healthy ones.

As mentioned before, the use of chemical compounds that replicates the electromagnetic properties of human body tissues, i.e., permittivity and conductivity, can help in the development and testing of future wireless in-body medical devices. Such chemical compounds are commonly known as phantoms.

The type of application as well as the nature of the device to be tested determines the physical requirements of the equivalent human model. Hence, a number of materials had been already reported in literature as an attempt to imitate the electromagnetic behavior of body tissues. Some of them were provided without a specific application, just for benefit of other researchers [18], [19], whereas others were custom made for the reported study [20], [21]. Phantoms can be found for several body tissues, being the breast the most pursued due to the medical imaging for cancer diagnosis [22], [23]. Other studies also include skin, fat, muscle or liver, but the list is not such larger. They are usually focused in modelling a certain part of the body such as torso or head. However, modelling the full body to take into account its full

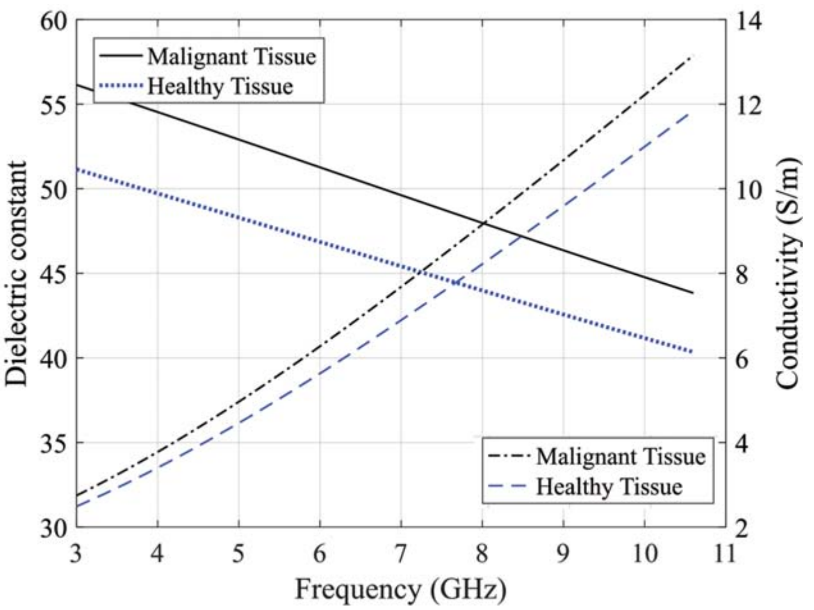


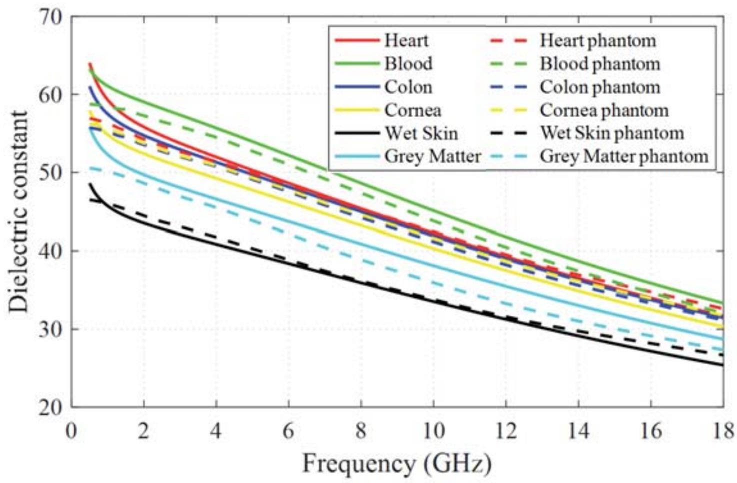
Figure 2. Dielectric constant (solid lines) and conductivity (dashed lines) for both healthy and malignant human colon tissues.

Phantom models patented by the MCG of the ITEAM provides a high accuracy for mimicking the permittivity and conductivity of different body tissues in a very large bandwidth (0.5–18 GHz).

interaction with the wireless technologies is not possible yet. Since permittivity is a frequency dependent parameter, phantoms are designed for working in a particular band. Thus, most of the phantoms only cover narrow bands, because since mimicking the trend of the dielectric properties with frequency in addition to those values is challenging. Consequently, the research community is currently focused on the investigation of new wideband phantom formulas. Moreover, the use of phantoms for exposure measurements and terminal testing in mobile communications is another wide application field of these phantoms, especially for future broadband mobile communications systems.

Regarding the chemical composition, liquids are more suitable for in-body propagation experiments or to fill containers as they can be shaped in any way. Solids and semisolids have the advantage of maintaining their shape without a container and keeping their properties in time because of the prevention of evaporation. The amount of proposed materials to fabricate them is quite large, even though there are some of them that are repeated, like oil [18], [20], [24] or gelatin [25], [26]. In fact, authors usually describe the effect of each additive in a way that future researchers can take advantage of their results to improve or create new phantoms with this knowledge. For example, salt is well-known for being the additive to increase the ionic conductivity or loss factor at low frequencies.

The MCG is also working towards the development of new phantom formulas for reproducing the electromagnetic behavior of human body tissues in wideband. To achieve this goal, the open-ended coaxial system previously described was used. This work has been undertaken together with the Centre for Biomaterials and Tissue Engineering (CBIT) of the UPV. First attempts led us to simple formulas to prepare easy handling phantoms [27] that can be reproduced in any laboratory. However, we observed that using basic compounds a low accuracy was achieved, so that further chemical materials were required. Afterwards, we found that using acetonitrile, salt or ethanol, we can model both parts of the relative and permittivity using a mathematical model. This model provides a high accuracy for mimicking the permittivity and conductivity of different body tissues in a large bandwidth (0.5–18 GHz). Thus, we are able to tune the composition in order to fit the dielectric properties towards those of the targeted tissues in wideband [28]. In this way, a large catalogue of mimicked tissues, which allow heterogeneous settings, was attained. These results were drawn on an issued patent [29]. Some of these phantoms are shown in Figure 3 in comparison with the literature data from real tissue measurements [10].



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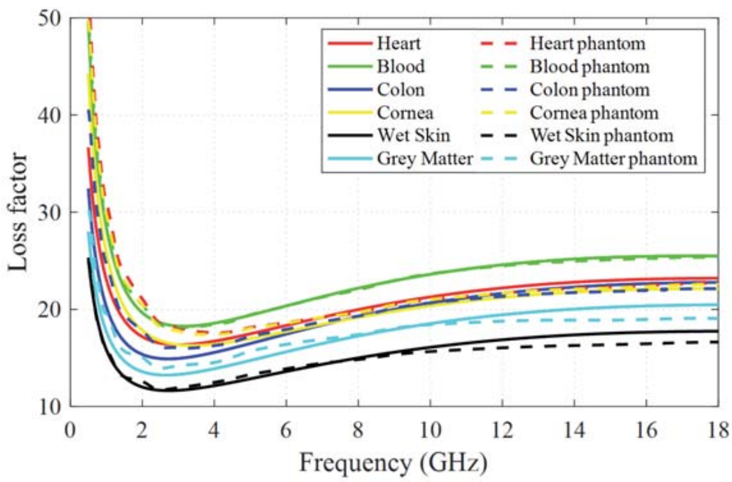


b)

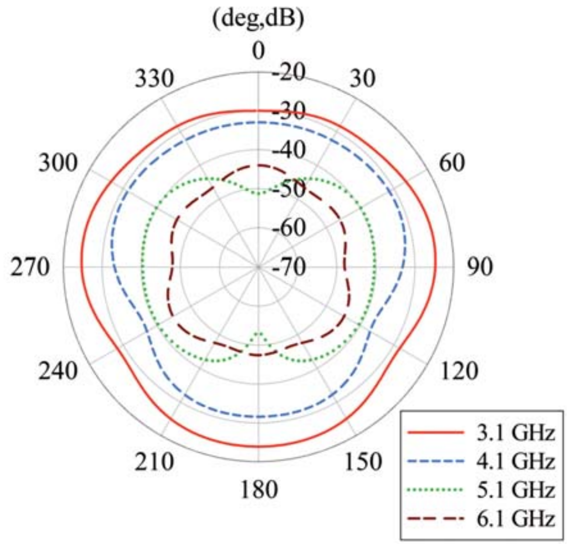
Figure 3. Relative permittivity of some phantoms in comparison with the literature values for their corresponding tissues according to [10]. a) Dielectric constant b) Loss factor.

3 Antennas for In-Body Communications

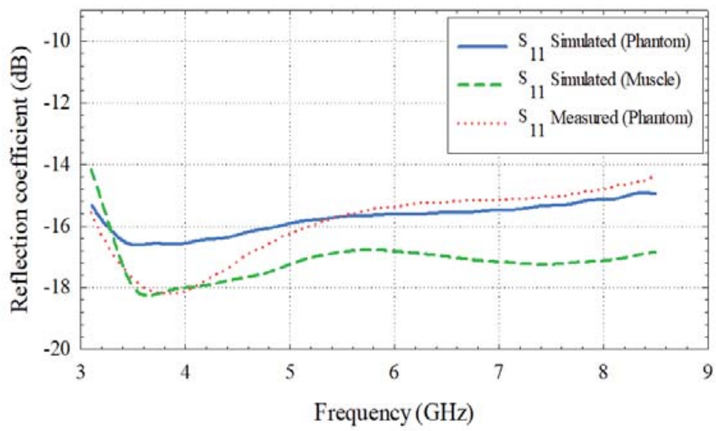
3.1 Implanted transmitters

Commonly, antennas are designed to work in free space. Therefore, the inclusion of the propagation medium in the designing stage is not quite relevant. However, this fact cannot be concluded in the case of antennas for in-body and on-body propagation scenarios. On the one hand, the wave propagation conditions are critically affected by the high absorption of human tissues. Besides, these losses dramatically increase as the working frequency increments [10]. On the other hand, complex permittivity of human tissues is frequency-dependent and higher that one in free space. Hence, the simulation setup plays a crucial role in order to reproduce this complex propagation scenario.

The MCG along with the Electromagnetic Radiation Group (GRE), both from iTEAM, are collaborating for designing, miniaturizing and optimizing new antenna candidates for future medical systems. With regard to implantable antennas, they have specific requirements such as having a suitable overall size to be implanted, an omnidirectional radiation pattern to communicate with a body sensor array and an antenna matching within the whole frequency range of interest. Considering all these premises, both groups work towards developing implantable antennas in order to characterize the propagation channel in a feasible way. From this collaboration, a UWB CPW-Fed (Coplanar Waveguide) antenna has been miniaturized, optimized and manufactured for this purpose [30]. From the initial simulation stage, this antenna is designed taking into account the dielectric properties of the human muscle tissue to achieve an efficient in-body transmitter. For that, the in-body antenna is wrapped with layers which have the properties aforementioned. Consequently, a thorough miniaturization and optimization procedure is performed to achieve the demanded design requirements [31].



■ **Figure 5.** Simulated radiation pattern of in-body transmitter at 3.1 GHz, 4.1 GHz, 5.1 GHz and 6.1 GHz.

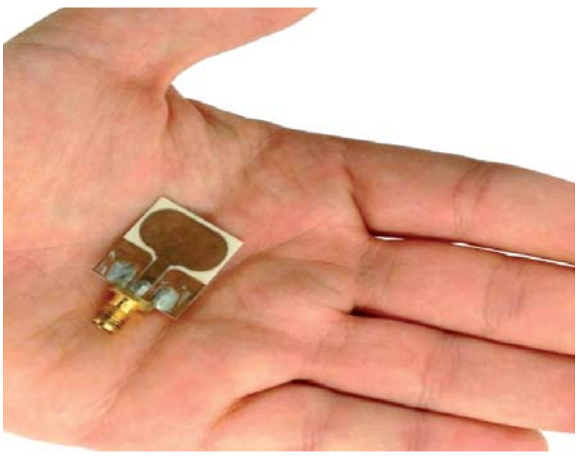


■ **Figure 6.** Measured and simulated reflection coefficient.

Once the radiation parameters of the in-body antenna matched to the design requirements, it is highly relevant to test the reliability of the experimental setup as well as the antenna efficiency in real experiments. Therefore, the UWB in-body antenna was manufactured at the iTEAM facilities (see Figure 4). The availability constraints of performing experimental in-vivo measurements as well as the impossibility to carry out measurements with human subjects are real issues. Thus, alternative compounds with electromagnetic behavior close to that of the body tissues can be prepared. As a first approach, a sucrose solution ($C_{12}H_{22}O_{11}$/1.0M) [32] that emulates the human muscle electromagnetic behavior within UWB frequency range 3.1-10.6 GHz is used to test the manufactured antenna. The measured and simulated results concluded from Figure 5 and Figure 6 enable to keep researching in this kind of antennas in order to achieve more efficient antenna models as well as smaller ones to be embedded in real implantable devices such as a wireless capsule endoscope, pacemaker, etc. [33], [34].

3.2 On-Body Receivers

In a typical in-body to on-body (IB2OB) propagation scenario, the implanted transmitter sends data from inside to outside the body. Concretely, on-body receivers are placed in contact with the human body skin surface. Therefore, on-body antennas have to get an antenna matching when they are located between layers of human tissues in front and air at the rear. Also, a good



■ **Figure 4.** Manufactured antenna at iTEAM facilities.

The MCG along with the GRE of the iTEAM have designed, miniaturized and optimized new antenna candidates for implanted and wearable devices that will operate in future wireless medical systems.

radio penetration depth through body tissues should be achieved. Moreover, the use of a beam antenna rather than an omnidirectional one is preferable for this purpose. This is due to the fact that it can mitigate the reception of unwanted interfering signals as well as focusing usefully the power towards the human body.

From the collaboration between GRE and MCG, new on-body receivers within UWB frequency band have been assessed. The gained experience in this field by both groups is allowing the considerations of new complex paradigms. According to UWB on-body receivers, the use of heterogeneous scenarios in the simulation setup seems to be quite essential since the radio waves go through several tissues which have different dielectric properties. Currently, we design multilayer antenna models where all human tissues involved in the propagation scenario are considered from the initial designing stage (see Figure 7). In particular, a kind of antennas has been proposed as UWB on-body receiver due to its good radiation parameters and broadband characteristics in free space. As a first UWB receiver candidates, UWB slotted patch antennas have been designed and optimized to work in this harsh propagation scenario efficiently. Once the antenna is properly miniaturized, the use of different optimization techniques is totally necessary to achieve the established design requirements. In the first slotted patch antennas assessed, different structures have been considered such as including a reflecting plane to focus the power to body tissues, a specific feeding structure in order to achieve a more compact structure and circles at both sides of the patch to enhance the antenna performance [35].

From an experimental point of view, the performance of the antenna in a real propagation scenario is highly relevant. Therefore, an optimized UWB on-body slot patch antenna has been manufactured (see Figure 8) in the antennas laboratory of iTEAM in order to evaluate the reliability of the simulation setup as well as the real radiation parameters of this kind of antennas considering human subjects.

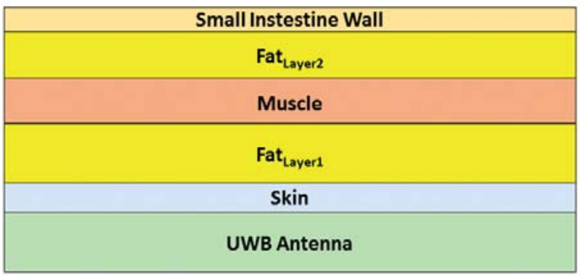


Figure 7. Multilayer antenna model.

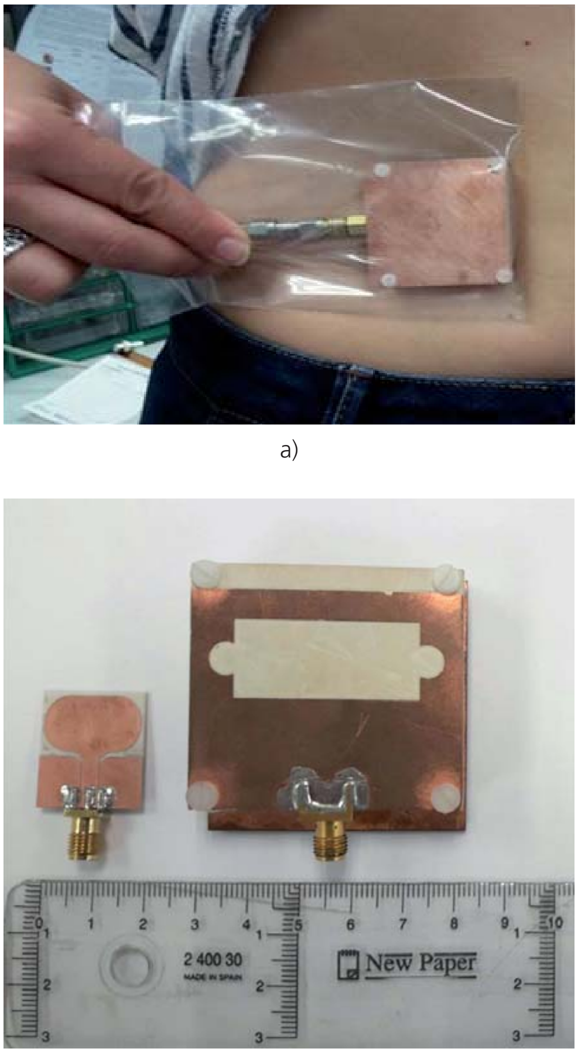
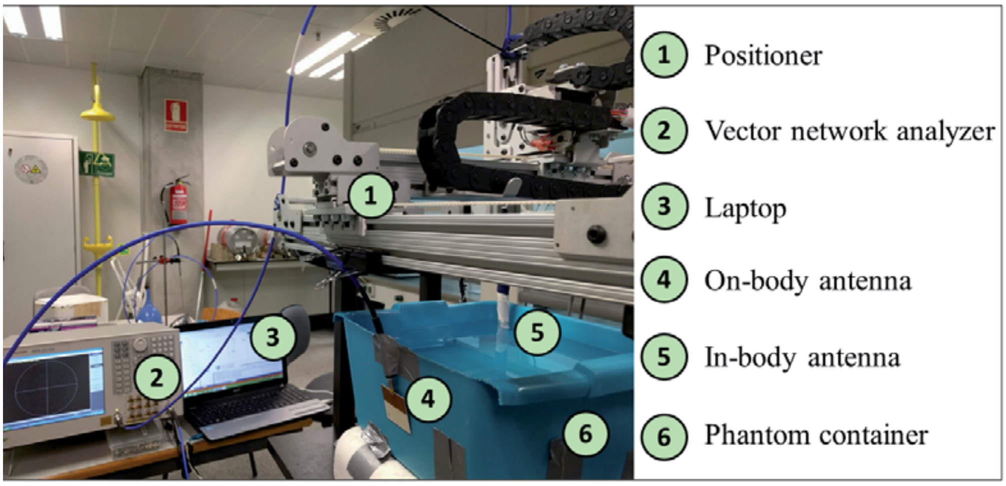


Figure 8. On body slot patch antenna designed: a) over the human body; b) compared with the in-body transmitter.

4 Propagation through Human Tissues

In-body channel characterization within any frequency range is challenging. On the one hand, the use of living subjects implies a high cost in medical equipment and is highly constrained due to moral reasons. On the other hand, channel characterization by means of simulation software with anatomical computer models can lead to acquire an expensive high-performance computer hardware. Other cost-effective solution to emulate the dielectric properties of human tissues can be the use of chemical dissolutions known as phantoms [36]–[38].

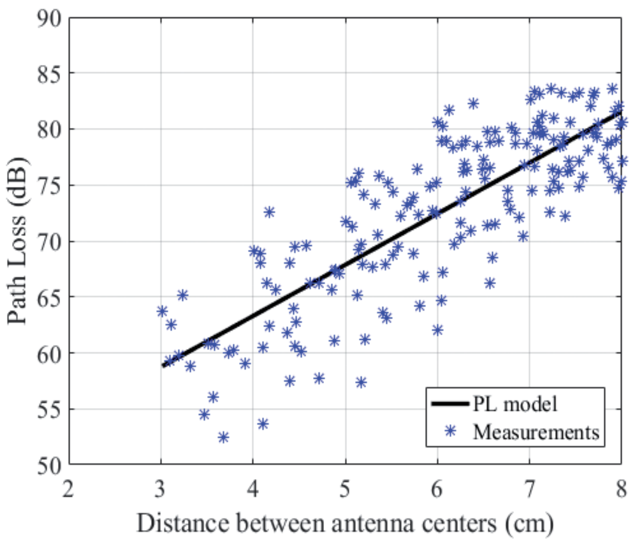
During this last year, several types of phantoms have been used in our facilities to test the in-body channel performance within UWB. Since the size of tiny antennas can affect the radiation efficiency among other features, it is highly relevant to assess the impact of miniaturization



■ **Figure 9.** Novel experimental setup.

in the in-body channel performance. Hence, a measurement campaign within UWB was carried out at iTEAM facilities [30]. For this campaign, two experimental scenarios were considered. An IB2OB scenario and an in-body to off-body (IB2OFF) scenario where the in-body transmitter is located inside the body whereas the off-body receiver is moved away from the body surface [2]. In both scenarios, a well-known sugar phantom was used to reproduce the complex permittivity of the human muscle tissue within UWB [32]. From the results showed in [30], we could observe the similar behavior by using a miniaturized antenna compared with those obtained by using a larger one. On the other hand, with aim to performing a channel characterization with a large amount of measurement points, we have built a novel experimental setup by using a high accurate phantom. To the best of our knowledge, the phantom used in this setup achieves the most accurate imitation of the dielectric features of the human muscle tissue from 0.5 to 18 GHz. Besides, an automatic 3-axis positioner and a vector network analyzer were used to perform an automated measurement campaign in 20×20×3 locations. Figure 9 depicts this new experimental setup.

The obtained measurements with this experimental setup have enabled a thorough study of the UWB in-body channel performance in a realistic way. For instance, we are able to perform a spatial channel characterization in different experimental in-body scenarios. This spatial measurement setup allows imitating different positions and movements of future in-body devices. Concretely, the path loss model as well as the channel diversity in transmission and reception have been studied considering an in-body to in-body (IB2IB) and in-body to on-body (IB2OB) scenarios [39]. For the IB2IB scenario, the path loss was well-fitted by a linear approximation model from 3 to 8 cm, while



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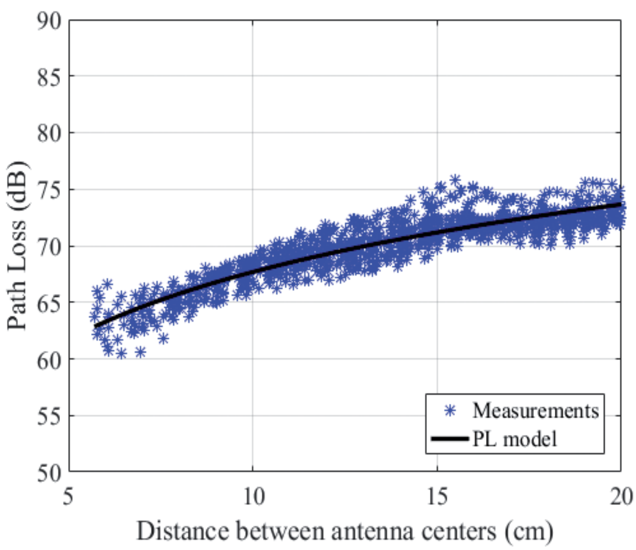

b)

■ **Figure 10.** Measured and fitted path loss: a) IB2IB, b) IB2OB.

the model which best fitted the measured path loss for distances between antennas ranging from 5.5 to 20 cm was a log-distance model for the IB2OB scenario, as depicted in Figure 10.

From measurements, correlation at the transmitting side was also computed and is depicted in Figure 11. On the one hand, for the IB2OB scenario, correlation was found to be higher if transmitters were located at the same height and the same horizontal plane. However, such correlation decreases when the relative height between transmitters increases. On the other hand, for the IB2IB scenario, a correlation value below 0.5 was found whatever the distance between transmitters. The correlation at the receiving side was also calculated (see Figure 11), obtaining that the use of two receiving antennas separated more than one wavelength is necessary to obtain uncorrelated channel impulse responses in reception [39].

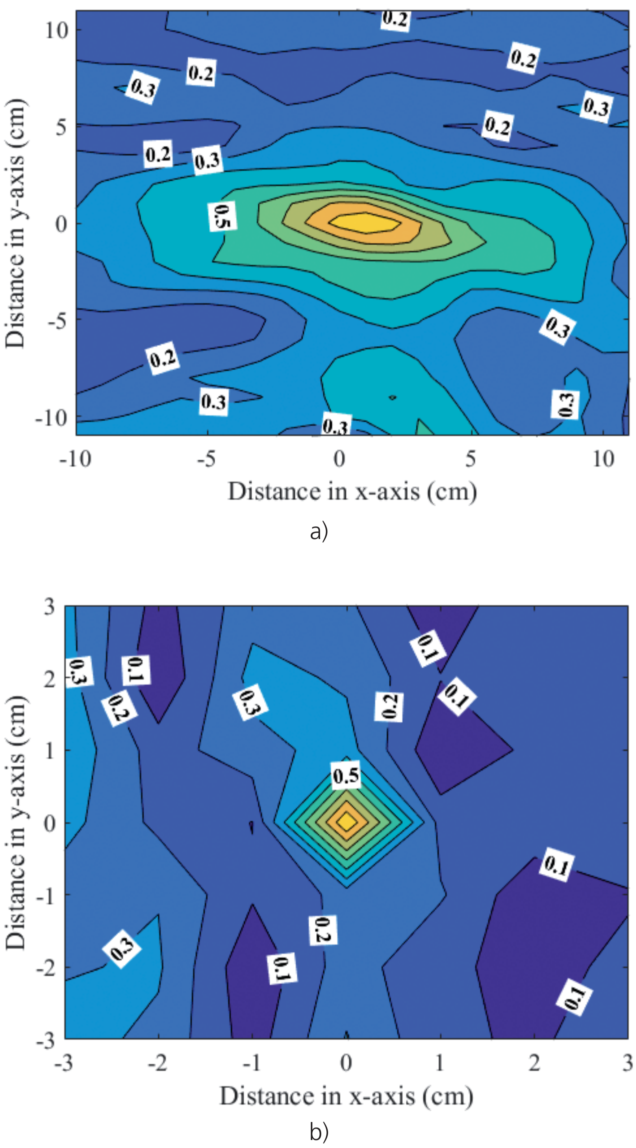

Figure 11. Correlation in transmission where transmitters are located in the same Z plane: a) IB2OB and b) IB2IB.

5 Conclusions

Wireless communications for in-body medical devices implies the propagation of signals through human body tissues. However, the human body as propagation medium imposes several constrains that restricts the development and testing of new in-body devices. Firstly, the electromagnetic properties of body tissues are not real and constant, but complex and frequency-dependent, so that they should be properly characterized. Secondly, the performance of the antennas used at body communications are highly influenced by the surrounding tissues, this is, for the specific part of the body where they will be used. Finally, the use of humans at the development stages of in-body devices is not possible. Moreover, ¬in-vivo animal experimentation is very restricted due to ethical reasons. As a solution, chemical phantoms for mimicking the electromagnetic behavior of human body tissues are widely employed for the development and testing of this kind of medical devices. However, these phantoms should be accurate enough for a faithful reproduction of the different body tissues. All these issues get more complex considering wireless wideband communications.

In this framework, the MCG of the iTEAM have managed to: 1) characterize different human body tissues up to 18 GHz, also considering not only healthy but also malignant tissues; 2) develop accurate phantom formulates to replicate a wide variety of body tissues in wideband up to 18 GHz; 3) develop either in-body and on-body antenna models for improving the radio link between in-body and on-body nodes; 4) analyze the radio link from an experimental point of view using the phantoms previously described.

The research lines of the MCG in this area are currently driven towards: the miniaturization of wideband antenna designs but maintaining efficiency and operation frequency band; the development of multilayer phantoms that allow a complete replication of the radio link in experimental analysis; the deduction of a complete radio channel model considering not only path loss models but also a tap-delay model taking into account the frequency-dependent nature of the different body tissues involved in the radio link.

Acknowledgments

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