Magnetic Human Body Communication based on double-inductor coupling

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***Abstract*— This paper proposes a new technique for Human Body Communication (HBC) that uses the magnetic coupling in transmitter and receiver. A discussion about the presence of parasitic paths, when magnetic coupling is used in the transmitter, and electrical coupling is used in the receiver is presented; showing that the technique presented here, reduces the influence of the surrounding environment at the same time that simplifies the conventional reception schemes. In addition, a physical-based model is presented, obtaining a good model-experiment correlation up to 20 MHz. This results suggest the possibility to use the double-inductor coupling technique for the HBC channel characterization, contributing in the design of portable applications for communications systems.**

***Index Terms*—Human body communication (HBC); magnetically-coupled HBC; double-inductor MHBC technique.**

I. INTRODUCTION

There is an increasing interest to connect wearable and mobile devices surrounding a person's body into a wireless body area network (WBAN) with efficiency and security. Traditionally, wireless communication based on radio frequency (RF) has been successfully used in most WBAN implementations. However, the major drawback of wireless RF propagation for portable devices is the high-power consumption, which limits their practical operation. Therefore, in the last few years, several papers have proposed to use the human body itself as propagation medium. It could be an efficient alternative to eliminate the power-hungry RF transceivers, for wireless communication in close proximity to the human body. This technology of wireless data communication is called Human Body Communication (HBC) and it provides high immunity to electromagnetic noise, higher privacy as well as it reduces the energy consumption in almost one order of magnitude when compared to popular RF technologies such as Bluetooth or Zigbee [1], [2].

Since the body-coupled communication technique was proposed by Zimermman [1], several methods to couple the signal into the body have been proposed. These techniques can be divided in two main groups: *i)* those that use the electrostatic field to generate an excitation signal into the body, which is subdivided in Galvanic (GHBC) and Capacitive (CHBC) coupling techniques; and *ii)* those techniques that uses the magneto-static field to induce the signal into the human body, also known as magnetically-coupled HBC (MHBC) [3], [4], [5].

Regarding the coupling technique, the optimization of electrode arrangement and the understanding of its associated parasitics are essential to help the design of transceivers that meet WBAN requirements of power consumption and signal integrity. Thus, this paper discusses the HBC channel integrity when a magnetic coupling is used in the transmitter and electrical coupling is used in the receiver, identifying the parasitic paths in the effective receiver-loop, when the ground electrode is detached from the body. In order to reduce that parasitics, a new coupling technique that uses magnetic coupling for both, transmitter and receiver is proposed. Also, the corresponding physically-based model is presented, which provides a good model-experiment correlation up to 20 MHz.

The rest of the paper is organized as follows, Section II reviews the basis for coupling techniques. Section III describes the general experimental setup used to perform the HBC channel measurements. Section IV shows that, when electrical coupling is used in the receiver, the HBC channel is preserved even though the effective receiving-loop is open. In section V, double-inductor coupling technique is proposed, the influence of the surrounding environment on its pathloss is evaluated and its corresponding model is presented. Finally, Section VI presents some concluding remarks.

II. HBC COUPLING TECHNIQUES

As shown in Fig. 1, in order to generate a differential excitation into the body, GHBC uses two electrodes attached to the skin as transmitter (TX). A similar pair of electrodes is used as receiver (RX) to sense the stimulated signal [3]. In GHBC coupling, the signal is completely confined into the body, for that reason it provides high independence to the surrounding environment, working acceptably in short distances (~15 cm) between TX and RX, at frequencies below 1 MHz [3], [5].

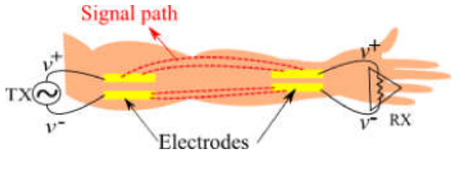

Fig. 1. Galvanic-coupled HBC.

In CHBC, TX and RX signal electrodes are touching the skin while ground electrodes are kept floating, as shown Fig. 2. In this technique, the forward signal path is into the body whereas the return path is created capacitively through the surrounding environment, for instance through the air. CHBC gets higher transmission distances between TX and RX (~150 cm), operating in a frequency range from 1 MHz to 100 MHz, which allows a higher data rate. However, this technique is more sensitive to external interferences [3], [5].

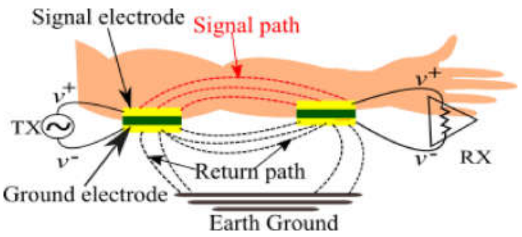

Fig. 2. Capacitive-coupled HBC.

In the Magnetically-coupled HBC, the magnetic quasi-static field carries the data signals from the TX to the RX, instead of the electrical quasi-static field used in the GHBC and CHBC approaches. MHBC uses a coil to induce a current in the human body, which can be sensed using two RX electrodes that closes the current loop through the body, as shown in Fig. 3. As the capacitive coupling, the magnetic coupling approach presents relative long distances of transmission, but in this case, the external interference is minimized [4], [6].

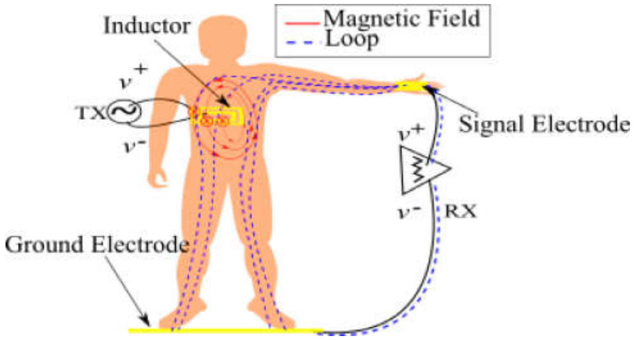

Fig. 3. Magnetically-coupled HBC.

For MHBC coupling method, when the foot or hand detaches from the corresponding electrode, the effective loop opens and the magnetic coupling disappear, interrupting the transmission [4]. However, it is important to consider that parasitic paths could appear, closing the effective loop and maintaining the transmission although the foot or hand are not touching the electrodes. To clarify this issue, experimental results showing that the ground electrode can be removed, maintaining a high transmission gain in the HBC channel, are analyzed hereafter.

III. EXPERIMENT

Two-port S-parameter measurements were performed up to 20 MHz using an Anritsu Vector Network Analyzer (VNA), which was previously calibrated using a SOLT (short-open-load-thru) calibration procedure, establishing by this way a reference impedance of 50 Ω. In order to get the HBC channel response by magnetically-coupled method, a person stands on a ground electrode, which is a 27.4 cm × 30 cm cooper plate, and closes the effective current loop touching the signal electrode, which is 9 cm × 10.5 cm cooper plate. These electrodes sense the current flowing through the body, as illustrated in Fig. 4. Then, to generate the magnetic field within the body a square inductor with a side of 6.73 cm, 0.15 cm of conductor spacing and 0.2 cm of conductor width was used.

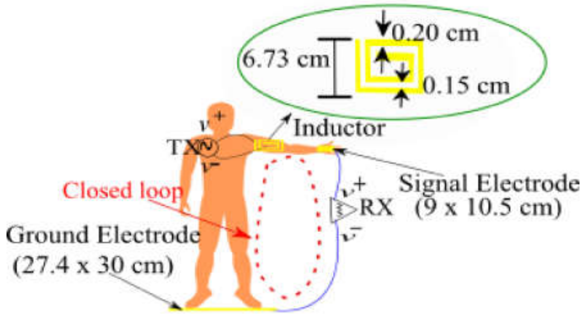

Fig. 4. Experimental setup used for measure the MHBC pathloss.

According to Fig. 4, the effective loop can be opened if the person is not touching the signal electrode but stands on the ground electrode or, if person touches the signal electrode but is not standing on ground electrode. These two possibilities are discussed in parallel with the experimental results in the following section.

IV. INFLUENCE OF THE GROUND ELECTRODE ON MHBC

The two possible cases to open the effective loop are illustrated in Figs. 5(a) and 5(b), respectively.

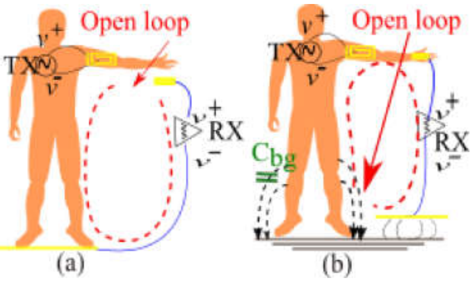

Fig. 5. Experimental setups for MHBC illustrating the opening of the effective loop when the person detaches: (a) signal electrode and (b) ground electrode.

Experimental results comparing the HBC channel response, when the measurement is perform using the electrode array illustrated in Figs. 4, 5(a) and 5(b) are shown in Fig. 6. Notice that, when the effective loop is open in the signal electrode, the HBC channel pathloss (shown in red line) is attenuated in approximately 20 dB, with reference to results when the effective loop is completely closed (green line). This result shows that when the signal electrode is not in contact with the person, transmission between the TX and the RX is not possible. On the other hand, when the effective loop is opened in the ground electrode, the signal electrode induces a current into the body, closing the effective loop through a parasitic path between the body and the earth-ground. In this case, according to the experimental results, the HBC channel pathloss is not affected by detach the ground electrode.

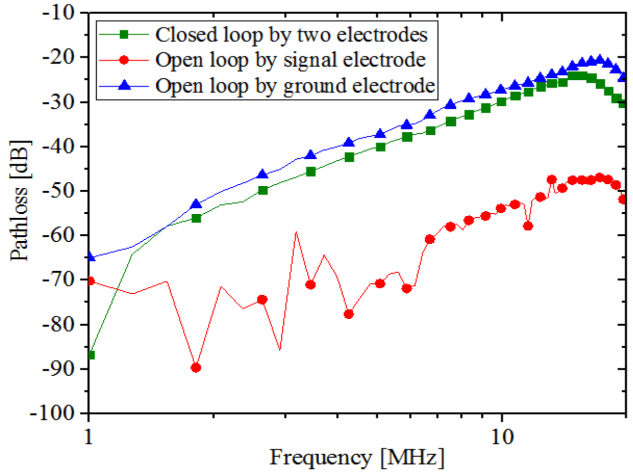

Fig. 6. Experimental pathloss when the effective loop is completely closed, and when it is opened in the signal or in the ground electrode.

Keeping in mind that, the impact on the HBC channel performance is not significant when the effective loop is opened in the ground electrode, measurements reducing the size of this electrode were performed in order to provide a better understanding of the results. In this regard, two additional cases were considered: *i)* when a small floating electrode is used, in this case a 15.3 cm × 12 cm cooper electrode (i.e. comparatively smaller than the used in the setup shown in Fig. 4.); and *ii)* no ground electrode is used. These two experimental arrays are illustrated in Figs. 7(a) and 7(b), respectively.

The experimental results in Fig. 8, shows that the influence of the ground electrode size is not significant up to 13 MHz, and have a small effect in the frequency range between 13 and 20 MHz. This experimental behavior evidences that the additional impedance, introduced by a parasitic path, does not affect the signal integrity for the HBC channel in the analyzed frequency range. This experimental result also shows that, when the frequency increases the impact of the capacitive path connecting the instrument ground could generate a significant parasitic impedance, affecting the coupling when MHBC technique is used.

As exposed above, in MHBC the contact with the signal electrode is always necessary. On the other hand, due to the floating ground, the HBC channel could turn susceptible to the environment fluctuations, and these could be a problem for develop practical applications using conventional MHBC technique. Nevertheless, this problem vanishes using the double-inductor MHBC technique, which is proposed hereafter.

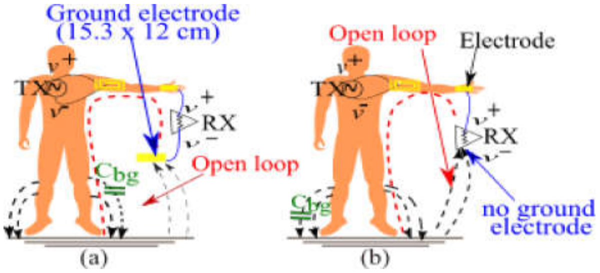

Fig. 7. Experimental setups for MHBC with signal electrode in contact and floating (a) small ground electrode and (b) no ground electrode.

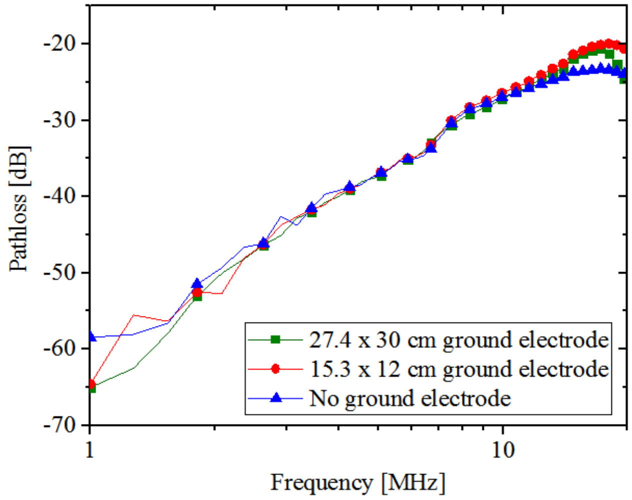

Fig. 8. Experimental pathloss obtained when the ground electrode size changes.

V. DOUBLE-INDUCTOR MHBC TECHNIQUE

Double-inductor MHBC takes advantage of the magneto-static field in both TX and RX. As shown in Fig. 9, this coupling technique uses a coil in the TX to induce a current within the human body, and a similar inductor is used as RX to sense the stimulated signal. In order to implement the double-inductor MHBC, two planar square inductors were designed on FR4, having a side of 6.73 cm, a conductor spacing of 0.15 cm and a conductor width of 0.2 cm, as shown in the inset in Fig. 9.

Here it is important to remark that, a magnetic field is considered quasi-static, if the distance (d) between the inductors (or antennas) of the TX and the RX satisfies the relationship [7]:

$$d \ll \frac{c}{2\pi f} \tag{1}$$

where c is the speed of light and f is the frequency. Since double-inductor MHBC works in the megahertz range and a magneto quasi-static field decreases as the cube of the distance, this coupling method is limited to the proximity of a human body. Then, as proof of concept, the signal transmission was evaluated for two distances, in close proximity of ~1 mm from the skin, and with a separation of ~5 cm. As shown in Fig. 10, increasing the separation between the inductors from the skin, signal transmission through the body decreases, in this case, experimental results shows that for 5 cm of separation, HBC pathloss decreases ~25 dB at 20 MHz. This results evidences that, the spatial region involved in the data transmission, using the double-inductor MHBC technique, is limited to the vicinity of the body, making of this technique a very effective way to establish short-range communications with high security.

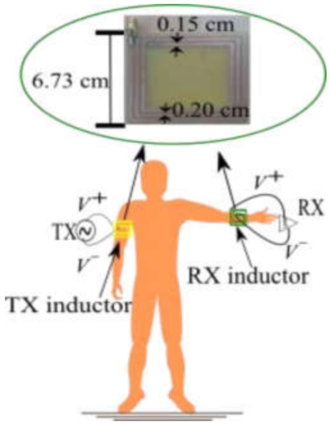

Fig. 9. Double-Inductor MHBC.

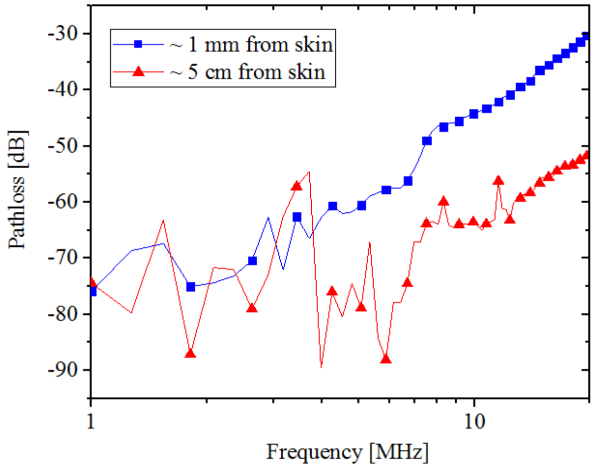

Fig. 10. Experimental measurements with separation of 1 mm and 5 cm from skin.

Fig. 11 shows a comparative evaluation of conventional MHBC (illustrated in Fig. 3) versus double-inductor MHBC (illustrated in Fig. 9). Notice in Fig. 11 that, double-inductor MHBC provides less attenuation for transmitted signals, in comparison to conventional MHBC. This is associated to the fact that, double-inductor MHBC eliminates the capacitive transitions (i.e. signal and ground electrodes), required to close the receiver loop in conventional MHBC, reducing at the same time the parasitic paths, discussed in section IV. Therefore, the double-inductor MHBC technique simplifies the reception scheme, improving the signal transmission through the human body.

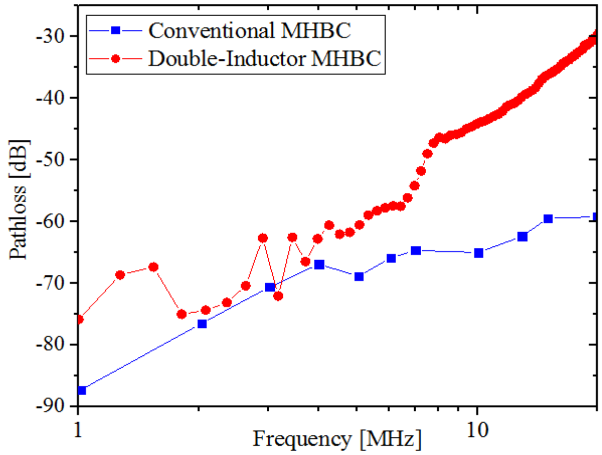

Fig. 11. Comparison of the experimental data reported in [4] for conventional MHBC with Double-Inductor MHBC.

A. Influence of the surrounding environment

In order to determine the influence of the surrounding environment on the HBC channel, when the double-inductor MHBC technique is used, measurements were performed in two different sceneries; in a research laboratory (i.e. with tables, chairs and measuring instruments around); and in a conventional office (i.e. with metallic desks and cabinets, computers, etc.). In both cases, the distance between inductors was 1 m and the separation between the inductor and the skin was ~1 mm. The experimental results, presented in Fig. 12, shows that the HBC pathloss is preserved in the evaluated frequency range, for both cases. This evidences that, data transmission via magneto quasi-static field is not affected by conductors or dielectrics in the surrounding environment, and shows the potential of the double-inductor MHBC technique for its integration in applications for WBAN.

For completeness, measurements were performed in different days on the same person. As shown in Fig. 13, no significant degradation of the pathloss is observed, showing the robustness of this technique to environmental changes, such as temperature or humidity, and proving that the data transmission, using double-inductor MHBC, have a good repeatability under different ambient conditions.

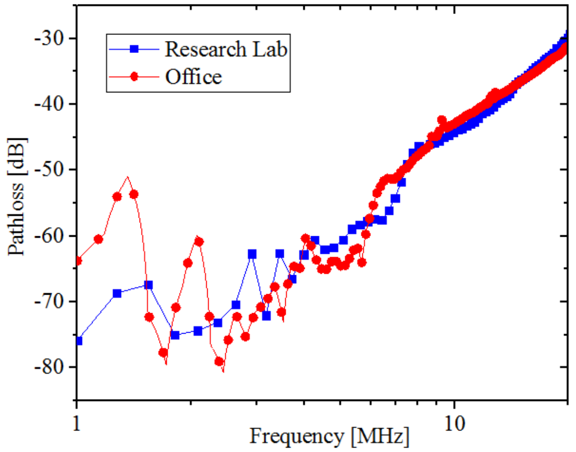

Fig. 12. HBC pathloss for double-inductor MHBC technique in two different environments.

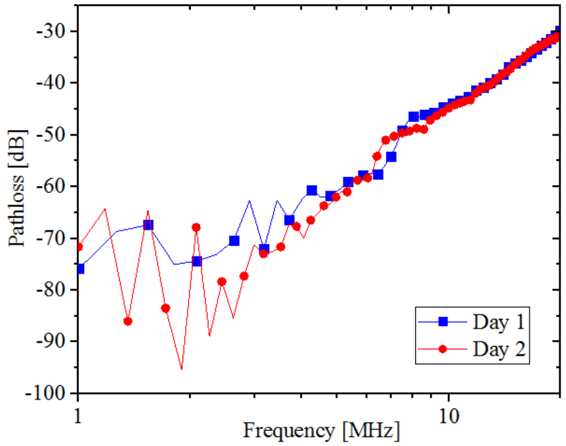

Fig. 13. Experimental measurements obtained for double-inductor MHBC technique in different days.

Experimental results presented above strongly suggests that, when the double-inductor MHBC technique is used, the influence of the surroundings can be neglected without loss of reliability in the modeling of the HBC channel. Thus, a physically-based model, that provides a better understanding of the double-inductor MHBC technique, is presented in the following section.

B. Equivalent Circuit Model for Double-Inductor MHBC technique:

The simplest model capable to represent the electrical characteristics of the tissues over frequency uses only two components, forming a single parallel *RC* circuit [8]. It captures the cell membrane capacitive behavior and the extra/intra cellular liquid, as is illustrated in Fig. 14. In this case, the effects of the self-inductance, due to the induced current within the human body are captured by C_T, R_T and L_2; while C_L and R_L includes longitudinally paths to couple the TX with the RX into the body.

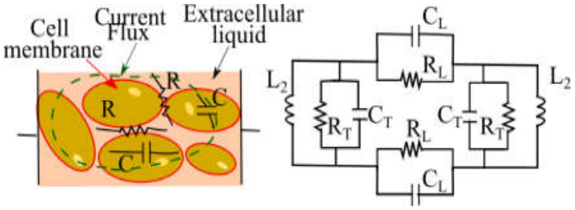

Fig. 14. Electrical model of human body tissue.

Fig. 15 shows the complete equivalent circuit model for double-inductor MHBC technique. For simulation purposes, the values for C_L (330 pF), C_T (470 pF), R_L (20 kΩ) and R_T (2 kΩ) are taken from the model proposed in [8]. L_1, that represents the self-inductance of the TX and RX inductors, have values of 1.1 µH; R_{in} and R_{out} are the resistances of the instrument ports. In addition, the self-inductance of the human body (L_2) is 32.476 nH, and the mutual inductance (M) between L_1 and L_2 is 136.53 nH. L_2 and M values were obtained by an iteration procedure.

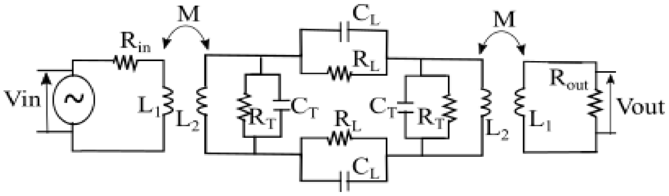

Fig. 15. Circuit model for double-inductor MHBC technique.

The pathloss of the equivalent circuit model for MHBC, using the double-inductor coupling technique, was calculated as $20log(Vout/Vin)$ and the simulation result was evaluated against the corresponding channel measurement. As shown in Fig. 16, a good model-experiment correlation above 2 MHz (up to 20 MHz) is obtained. Notice also in Fig. 16 that, due to limitations to induce currents into the body by small variations of the magnetic field, discrepancies among model and the experimental data occurs at very low frequencies. This is an inherent limitation of the magnetically-coupled methods.

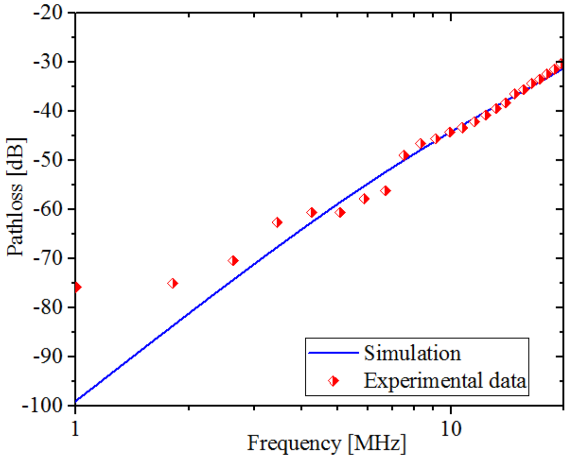

Fig. 16. Experimental results and model simulation of double-inductor MHBC technique.

VI. CONCLUSION

Measurements were performed to evaluate if MHBC requires both signal and ground electrodes in contact with the human body. The obtained results show that when the signal electrode is not in contact with the person, the HBC channel pathloss is affected, nevertheless when the effective loop is open by ground electrode, the HBC pathloss is not affected. Also, the ground electrode was reduced, evidencing that it does not affect the HBC pathloss for frequencies between 1 MHz and 20 MHz, and showing that the ground electrode could generate a significant parasitic impedance as the frequency increases.

Since HBC channel could turn susceptible to the environment fluctuations due to the floating ground, an alternative technique that takes advantage of the magneto-static field in both TX and RX was proposed, it was called double-inductor MBHC. This technique shows a great potential for application in fully portable devices, avoiding the necessity to contact the human body using electrodes. Finally, the proposed equivalent circuit model for double-inductor MHBC technique provides a very good model-experiment correlation from 2 to 20 MHz, providing a useful tool for design purposes.

VII. ACKNOWLEDGMENTS

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