Measurement Results and Analysis on a HBC Channel

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***Abstract*—Human body communication (HBC) is a communication technology that uses the body of a person as a channel to propagate signals. Many characteristics of HBC present advantages over the most common radiation-based methods, which makes it an interesting alternative to implement the emergent body area networks. The characterization of the HBC channel presented in the literature still cannot provide a good and complete explanation for the channel behavior. In this work, we present our attempt to characterize the channel. A measurement setup was set up to properly preserve the HBC capacitive coupling and to investigate the impact of the test fixtures. The results show that the channel has a band-pass response, with dependence in channel length, and small variation for different electrode types, temporal variability or subjects. The results also indicate that the test apparatus has a non-negligible influence in the channel profile.**

Keywords — body area network; human body communication; HBC; IBC; BCC; capacitive coupling; test fixture influence.

I. INTRODUCTION

The technological and commercial emergence of wireless sensor networks (WSN), wearables and all sorts of smart devices is expected to facilitate the creation and the exchange of information with anyone or anything, anywhere and at any time: from civil consuming in entertainment or health-care applications to military activities [1]. In recent years, a new technology called Human Body Communication (HBC), has received increased attention due to some particular characteristics that make it a suitable alternative to overcome power consumption, interference and security issues, common in WSN, especially in body area network (BAN) applications. The HBC concept was first proposed in 1995 by Zimmerman [2], and it uses the human body as the main transmission medium for the communication signals.

Modeling of the body channel is essential to design transceivers. However, since the proposal of HBC, slow progress has been made in the understanding of the mechanisms involved in HBC propagation, and channel characterization is still a subject of discussion, mostly due to the dependence of the results on the measurement methodology and the challenges to preserve the correct channel path within the body. Channel measurements presented in [3] and [4] do not maintain the correct return path. In [5] the scope of measurements is limited. The high frequency behavior is not properly explained in [6], [7] and [8]. Most of these references do not mention how the test fixture influences the channel response. In this article, we will address these aspects to better explain the HBC channel. The next sections present the basic theory behind HBC, some of the last theoretical channel models, discuss published channel characterization results and present our channel measurements and results.

II. THE HBC CHANNEL

In HBC, electric signals are coupled to the body using electrodes instead of an antenna. The operating frequency is usually higher than 0.1 MHz, to avoid electromagnetic interference, and lower than 100 MHz, to minimize radiating the signal out of the body. These characteristics give some advantages to HBC, when compared to available wireless methods: it has lower interference, higher security and higher spectral efficiency due to the confinement of most of the signal into the body [9], [10]. Moreover, lower attenuation of the signal is achieved since it avoids the issue of body shadowing present in RF based techniques [9]. The operation in low frequency also has the potential of eliminating power-hungry RF front-end circuits, with the signal being generated by low-power digital and baseband analog circuits instead.

The HBC has two coupling methods: the capacitive coupling and the galvanic coupling. In the galvanic coupling technique (Fig. 1-a), a pair of electrodes is in contact with the skin at the transmitter and couples the signal to the body generating a differential signal that induces galvanic currents. The signals are captured by another pair of electrodes in contact with the skin at the receiver [11]. The absence of external ground makes this method independent of the environment and suitable for wearable and implantable devices. However, it has been shown that it only works acceptably at short distances (~15 cm) between transmitter and receiver, and with frequencies below 1 MHz, limiting its achievable data rate [6], [11].

The other method is the capacitive coupling (Fig. 1-b), also with two pairs of electrodes. In this method, one of the transmitter electrodes is attached to the skin, and the other is kept floating. In this way, the transmitter generates an electric potential, inducing an electric field in the body that is sensed by the receiver electrodes arranged in the same way. The floating electrodes are coupled to ground through the air, creating a return path, while the signal electrodes in contact with the skin create the signal forward path [7]. The need for an external ground makes the capacitive coupling only suitable for wearable devices and prone to environmental interference. Nonetheless, it has higher gain [10] and relatively higher frequency range of operation, between 1-100 MHz, which enables higher data rates than the galvanic coupling method [6] [12] [13]. The remaining of this article focuses on the capacitive coupling method.

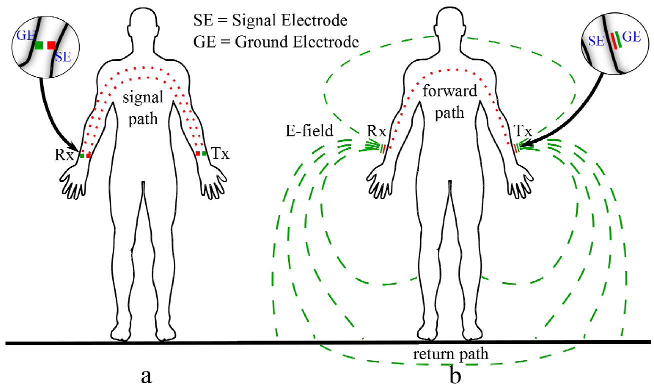

Fig. 1. HBC coupling methods: (a) galvanic and (b) capacitive.

III. CHANNEL MODELS

A more advanced understanding of the propagation mechanism behind the HBC has emerged with the efforts for channel modeling. Using the electrical properties of the body tissues as departure, the literature presents analytical equation-based models and distributed or lumped circuit-based models [12].

The analytical analysis presented in [5], based on an infinitesimal dipole approximation, shows that the physical mechanism of propagation in capacitive HBC is divided into three terms: surface wave far-field propagation, reactive induction field radiation and quasi-static near-field coupling. The channel response resembles a band-pass profile, with quasi-static near-field dominating in low frequency and surface wave far-field in high frequency, while the inductive field contribution is relatively low in both extremes. There is a channel dependence on frequency, distance of propagation and electrical properties of the human body. For the communication distance over the body, in low frequency the attenuation does not depend on channel length. However, in high frequency, the signal suffers higher attenuation as the ratio between transmitter and receiver electrodes separation and the wavelength increases. These results agree with most HBC experimental characterizations, as we will see ahead.

Circuit-based models present a more intuitive visualization of the channel response. In [13], the channel is modeled by a network of unit blocks as in Fig. 2, with component values estimated by FEM simulations of the body. The unit block model takes into account leakage coupling from the body to external ground and uses a compact parallel RC model for the body path (forward path). The model includes coupling capacitors from transmitter and receiver to the ground, as well. Analyzing this circuit, we can see that the series ground capacitance in the return path dominates the low frequency response, attenuating the signal. As the frequency increases, the body and the return impedances approach each other and their combined effect has to be taken into account. This gives a high-pass profile to the channel. So far, electrical models appear to be incomplete, since they cannot reproduce the high frequency behavior that leads to the band-pass profile identified previously [5]. This discrepancy at higher frequencies was also identified in the distributed circuit model presented in [6]. They point out that this divergence could be due to incorrect modeling of the return coupling and the leaking capacitances, assumed constant while a dependence on frequency could exist.

For a comprehensive review of the available HBC modeling approaches, we suggest the reference [12].

IV. CHANNEL MEASUREMENTS

Many aspects can be considered when evaluating the HBC channel: the material, arrangement and size of the electrodes, the location of the electrodes on the body, the channel loss with distance, frequency, body positions and movement, the response with different subjects, etc. However, it is a very challenging task to create in the laboratory the conditions, the measurement procedures, and the proper setup that replicates the correct HBC channel in real situations to evaluate these aspects. Mostly because of the dynamic nature of the body and the environment that have to be taken in account. Therefore, the measurement setup is the key to correct channel characterization and modeling.

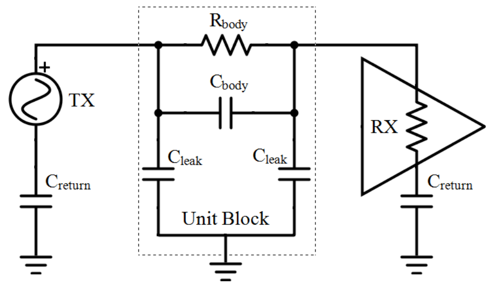

Fig. 2. Circuit model representing a 10 cm unit block for the arm *[13].*

Recent studies dedicated to the characterization of the HBC channel presented in [7], [8] and [9] have pointed out that the most crucial aspect to obtain the correct channel response is to preserve the capacitive coupling to external ground. Failure to recognize this need could lead to a channel response that resembles low-pass profiles or higher channel gain [3], [4], [7]. The most common ways to maintain the return path make use of custom transceivers powered by battery [5], [9] and balun isolated equipment [6], [7], [8]. However, even measurement results that observe this question have not been able to provide a good explanation for the HBC channel behavior, to contribute to model development or to establish design parameters for HBC transceivers.

In the remaining of this text, we will describe our HBC measurements attempts and findings. To start, we opted for a vector network analyzer, with one port as the transmitter and the other port as the receiver. In this way, baluns were necessary to decouple the HBC ground from the VNA port grounds, which are internally connected and otherwise would bypass the HBC ground. The operating range of the baluns and VNA cover the desired characterization band between 1-100 MHz. The signal is fed to the body through coaxial cables with electrodes adapted in its ends. The power of the injected signal was 0 dBm, in agreement with safety requirements [14]. The forward path signal electrode and the return path ground electrode were positioned in a vertical structure. A diagram of the measurement setup can be seen in Fig. 3.

The influence on the channel response on the following aspects was verified: material of the electrodes, differences between subjects and distance of propagation over the body. We performed the tests with the subjects sitting and with the signal being injected only in the wrist. The arms were extended to the front, at 75 cm from the floor, and resting over a table.

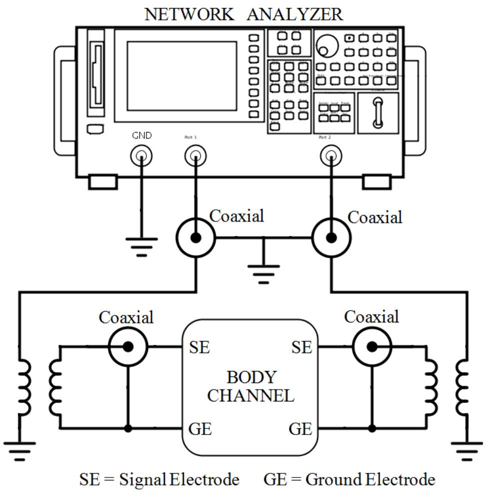

Fig. 3. HBC Measurement setup.

A. Propagation distance

The channel variation with distance was verified through measurements taken using copper electrodes separated by 15 cm, 30 cm and 140 cm. For the propagation distances of 15 cm and 30 cm, the signal was injected in the right wrist and measured in the same arm. For the 140 cm distance, the signal was injected in the right wrist and measured in the left wrist. At this distance, both arms were extended to the front and separated from each other by a horizontal distance of 30 cm. The results can be seen in Fig. 4 and shows that the channel presents a band-pass profile. For low frequencies, below 5 MHz, there are little differences in signal level for the distances tested. As discussed before, this is mostly related to the return path impedance that dominates the channel response in this range. At medium frequencies, between 5-40 MHz, the channel response is dependent on the distance of communication over the body, with longer distances inflicting more attenuation of the signal. The peak gain occurs around 30-40 MHz depending on the channel length. For frequencies above 40 MHz, the attenuation is initially independent of distance, and then a valley appears around 70-80 MHz in the results. This behavior was also identified in [7] and [13], and is related to the discontinuous interface of the cable connections [13].

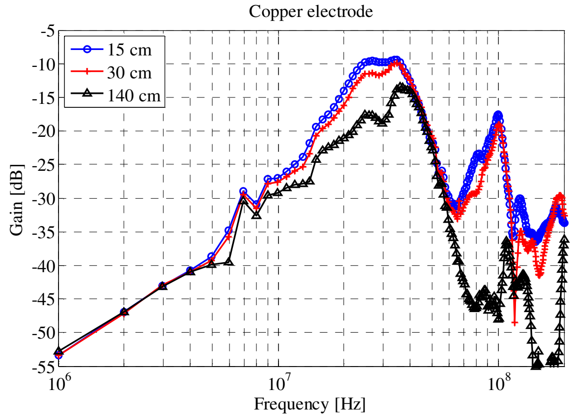

Fig. 4. Measurement results for different channel propagation distances:15 cm (blue), 30 cm (red) and 140 cm (black) with copper electrodes.

B. Electrode material

To verify the influence of the electrode material we used two types of electrodes. An Ag/AgCl standard ECG electrode with effective electrode area of 1.5 x 1.8 cm² and a copper PCB electrode with an area of 2 x 2 cm². Bigger copper electrodes would be hard to keep in contact with the skin, affecting the channel response. In both cases, a 2 x 2 cm² copper PCB was used as the ground electrode. It was fixed 4.5 mm above the Ag/AgCl electrode, due to geometry of the electrode, and 1.5 mm above the copper electrode. We did three measurements, with time intervals of 5 minutes, for each electrode type. The results are presented in Fig. 5, 6 and 7 for the three propagation distances.

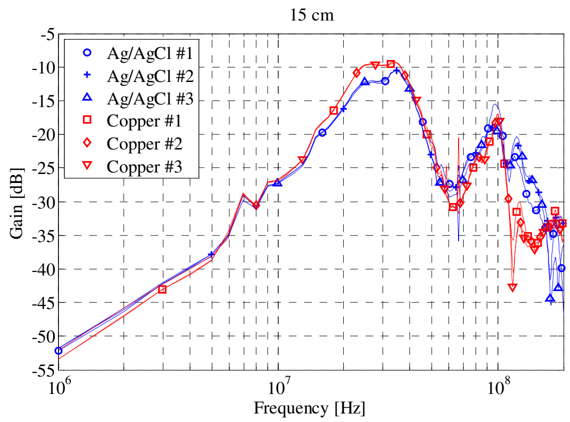

Fig. 5. Measurement results for copper (red) and Ag/AgCl (blue) electrodes material with a propagation distance of 15 cm.

As can be seen, variability between measurements with the same electrode type is negligible, pointing to a stable channel response in regard to time variation and external interference. For different electrode type the band-pass profile and peak frequency did not change significantly. The copper electrodes performed slightly better in general than Ag/AgCl electrodes. However, the difference is always lower than 3dB, being concentrated in the region between 20-40MHz for 15 cm and 30 cm propagation distances. For 140 cm channel length, attenuation is almost identical for the two types of electrodes.

An explanation for this arises from the measurement setup: in this particular case the distance between transmitter and receiver electrodes over the body (140 cm) was higher than the distance between them over the air (30 cm). With this configuration, the coupling through signal radiation could be dominating the channel response in high frequency. In reference [7], they did not find significant differences between electrode types for a body channel distance of 36 cm.

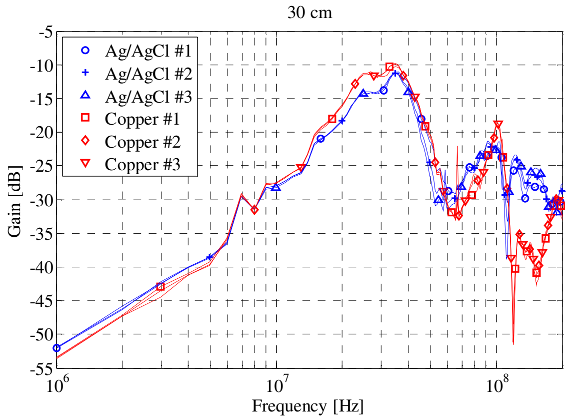

Fig. 6. Measurement results for copper (red) and Ag/AgCl (blue) electrode material with a propagation distance of 30 cm.

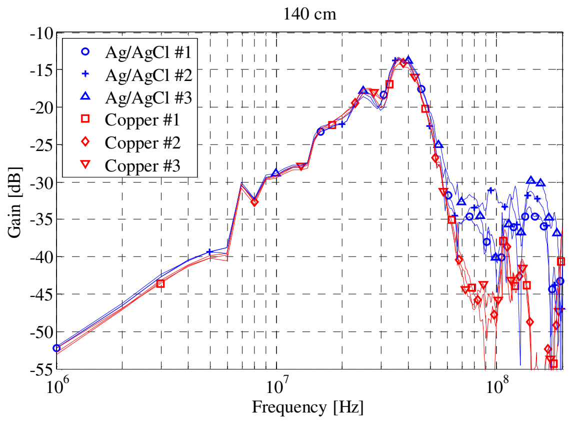

Fig. 7. Measurement results for copper (red) and Ag/AgCl (blue) electrode material with a propagation distance of 140 cm.

C. Different subjects

To verify the influence on channel response of different test subjects we performed three sets of measurements in two subjects. The setup was the same as tests for the propagation distance in Section IV-A. The subjects had about the same height, but different weight and body composition. Fig. 8, 9 and 10 present the results for the three channel distances. Until about 5 MHz the attenuation is independent of the subject. This is consistent with the fact that, at low frequencies, the return path dominates the channel response. As frequency and distance of propagation increases, also does the difference in attenuation between the subjects. This indicates that the body composition alters the channel response. However, the differences are small, and the band-pass profile and peak frequency did not change. These results qualitatively agree with the results found in [7].

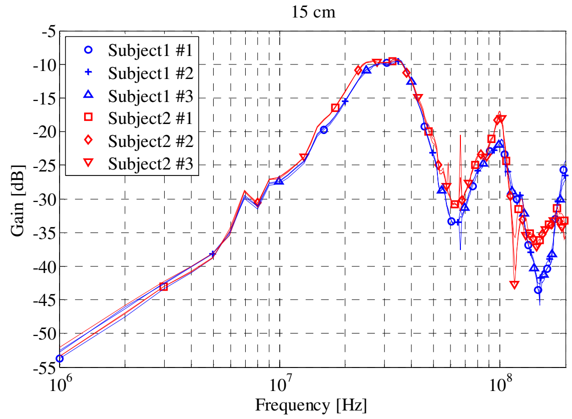

Fig. 8. Measurement results for different subjects: Subject 1 (blue) and Subject 2 (red), with a propagation distance of 15 cm and copper electrodes.

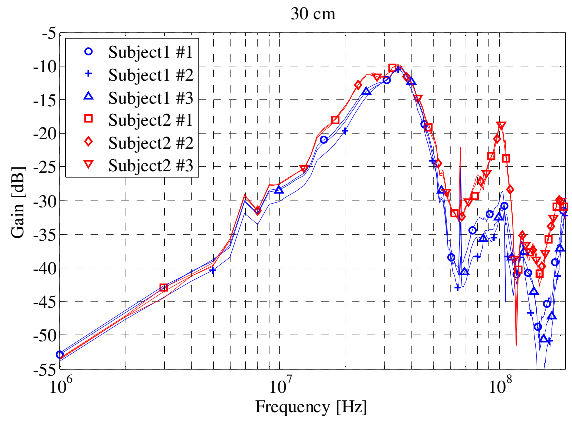

Fig. 9. Measurement results for different subjects: Subject 1 (blue) and Subject 2 (red), with a propagation distance of 30 cm and copper electrodes.

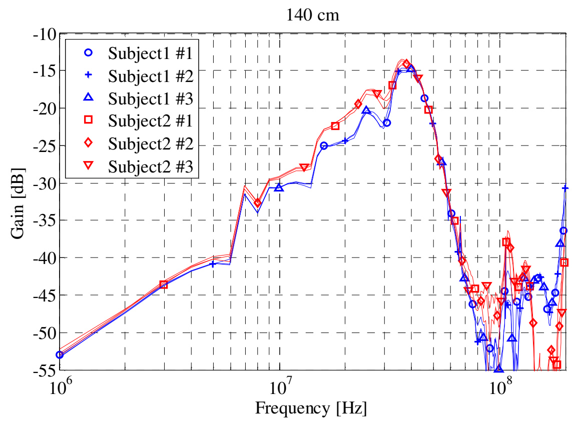

Fig. 10. Measurement results for different subjects: Subject 1 (blue) and Subject 2 (red), with a propagation distance of 140 cm and copper electrodes.

D. *Cable length and de-embedding*

During measurements, it was verified that the length of the coaxial cables has influence over the channel response in high frequency. To investigate this relationship, an additional set of measurements was done by varying the cable length. First, through a SOLT calibration, the measurement reference plane was moved to the baluns input. Then the S-parameters of the body channel and fixtures were obtained to apply the procedure of test fixture de-embedding [15]. To de-embed the cables connecting the electrodes to the body, a model was simulated using the manufacturer information, and the S matrix was obtained. This was necessary because our cables did not have preassembled terminations for the connection to the electrodes, preventing an experimental characterization. Measurements were taken with the subject standing and with three cable length combinations: two long cables of approximately 70 cm each (LL), two short cables of approximately 20 cm each (SS), and a combination of one short cable and one long cable (SL). The results, after de-embedding, are presented in Fig. 11, 12 and 13 for all cable combinations and propagation distances.

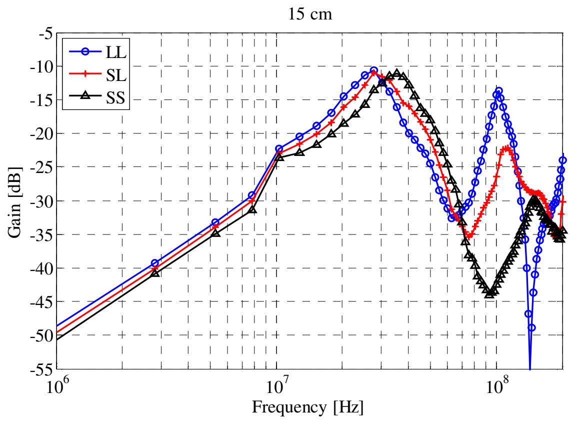

Fig. 11. Measurement results for different cable size: LL (blue), SL (red) and SS (black), with a propagation distance of 15 cm and copper electrodes.

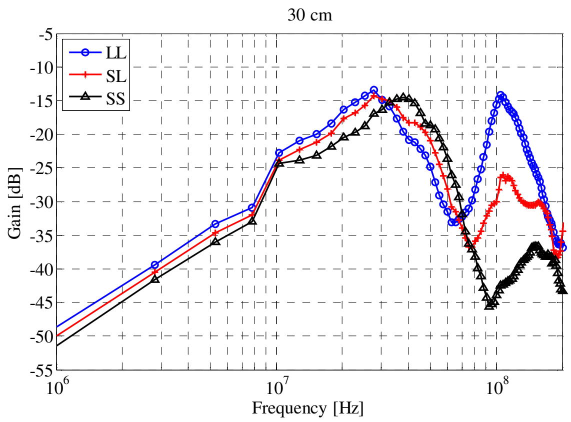

Fig. 12. Measurement results for different cable size: LL (blue), SL (red) and SS (black), with a propagation distance of 30 cm and copper electrodes.

The general channel band-pass profile previously identified was mostly preserved. This is more evident in the results with short cables (SS), where the frequency shift moved the second peak beyond our balun range. Moreover, these results point to an apparent influence of the cable length in the frequency response even after de-embedding. With shorter cables, the first peak in channel response is shifted to higher frequencies. The difference between the frequencies where this peak occurs is in the worst case 15 MHz, with a gain difference of 2 dB, for the 140 cm channel distance in Fig 13. The valley and the secondary peak were also shifted as the results show. This could indicate a resonance phenomenon involving the cables, the ground coupling electrode, the capacitance between signal and ground electrodes or other parts of the body channel.

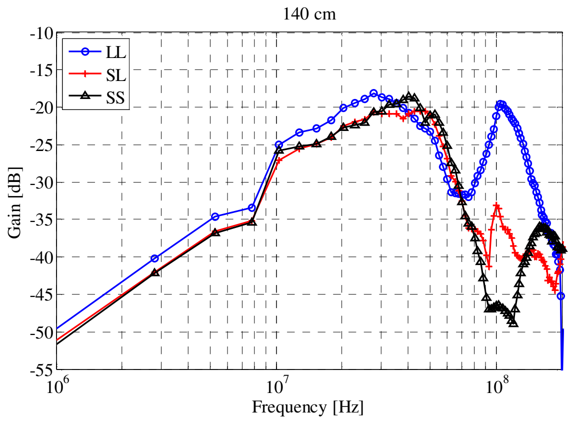

Fig. 13. Measurement results for different cable: LL (blue), SL (red) and SS (black), size with a propagation distance of 140 cm and copper electrodes.

E. *Resistive channel approach*

To further investigate, the body path was replaced by a resistor of 330 Ω. This value is near the value of the electrode-body contact impedance in an intermediary frequency [7]. The resistor was directly connected to the signal electrodes to emulate the body channel. With this, we expected to minimize the issue of body leakage or radiating signal. At first a test was performed with the return path preserved, in other words, the ground electrode was kept floating in the air. Fig. 14 (top) presents the measurement results after de-embedding.

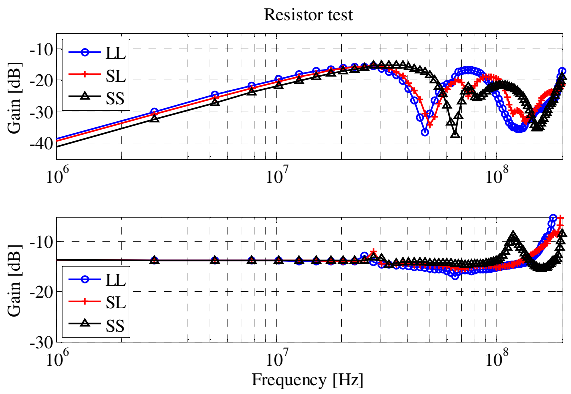

Fig. 14. Measurement results for the resistive channel and different cable size: LL (blue), SL (red) and SS (black), with ground electrodes floating (top) and shorted (bottom).

The low frequency attenuation was preserved for the floating ground. This was expected since the capacitive coupling of the return path was also preserved. The valley followed by a second peak is present and has a similar behavior as the one described in the previous sections, indicating that its origin could indeed be related to the interaction between electrodes and cables. Above 100 MHz the behavior cannot be confirmed due to the limited frequency of operation of the balun. For the same setup a second test was executed with the ground electrodes directly shorted, Fig. 14 (bottom). Keeping the resistor and shorting the return path leaves us only with the resistor attenuation on the signal, as expected. No resonance effect seems to appear now that the ground coupling capacitance was excluded from the resistive channel.

The last test compared the system response when the ground electrodes were kept floating and measurements were made with and without baluns. As mentioned before, the baluns isolate the HBC return path from the network analyzer ground in each port, without it the channel response would be flat, or low-pass in the case of HBC [7]. For the 'resistive channel' we expected a flat response across the frequency range, but the results in Fig. 15 (top) show that a valley still appears, shifted to 90 MHz. The persistent resonance effect and its shift in frequency indicate that the floating ground electrode still has influence over the frequency response. Both responses are flat with the ground electrodes shorted Fig. 15 (bottom).

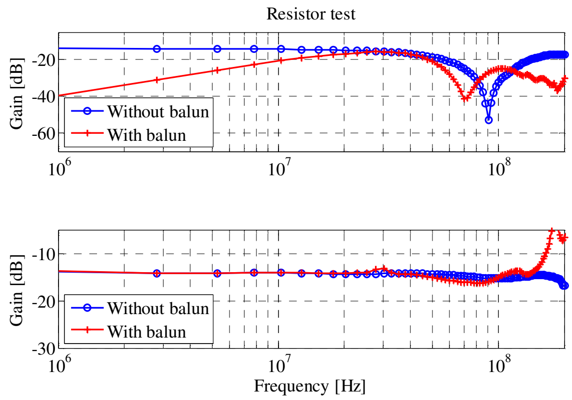

Fig. 15. Measurement results for the resistive channel with baluns (blue) and without baluns (red), with ground electrodes floating (top) and shorted (bottom).

These results are an indication that the capacitive return path, as well as other components in the measurement setup and in the channel (cables, baluns, and electrodes), should be better modeled and included in HBC models to improve the understanding of the channel and create more accurate models.

V. CONCLUSION

In our measurements, we identified that the channel attenuation has a high dependence on frequency, with a band-pass profile, and a moderate dependence on distance. Different electrode types and subjects also affected attenuation, but with limited outcomes. The results overall agree with other channel measurements published in the literature. However, measurements with coaxial cables of different length showed the influence of the test fixture in the frequency response. Also, tests in a resistive channel, to verify the influence of the baluns and of the capacitive coupling, showed that the return path not only dominates the channel response in low frequency, being actually responsible by important characteristics of the channel profile. Most results published by other authors do not identify these characteristics, specially the influences of test fixture. Thus, based on our results, modifications to HBC models seem to be necessary, and could help to better understand and replicate the correct channel response.

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