Signal Loss in Body Coupled Communication: Guide for Accurate Measurements

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***Abstract*—Body Coupled Communication (BCC) is a growing research area that promises to deliver more secure and more energy-efficient body-area wireless sensor networks. Existing research articles on BCC show high variance in their experimental results, indicating potential methodological problems in the published work. We perform analysis of several potential methodological errors in the measurements, for instance, impedance mismatch, cable length issues, and not separating the ground planes. Our experimental results quantify the impact of these issues. Finally, we discuss the best practices for measurements, as well as their limitations.**

***Index Terms*—body-coupled communication, human body communication, body area networks, signal loss, measurements**

I. Introduction

Body-coupled communication (BCC) is a novel communication technology that uses the human body as a signal-transmission medium. BCC has the potential to deliver more secure and more energy-efficient communication for body-area networks, as the signal leakage and losses are smaller compared with conventional wireless technologies [1]. At the moment, the applications of BCC are at their infancy. Most of the existing research literature on the topic simply aims to characterize the human body channel. However, large number of publications on the topic suffer from a drawback that we propose to call the *measurement problem* of BCC: the results show high variance and virtually no repeatability between different research groups working on this topic (Fig. 1). Clearly, an improved measurement methodology is required to put the scientific study of BCC on a more solid footing.

In the recent years, this measurement problem is finally starting to get noticed and addressed by select research groups. Callejón *et al.* [2] discuss several measurement issues for galvanic-mode BCC, including grounding, connections and cables, impedance matching, potential confusion related to power gain *vs.* voltage gain measurements, and using spectrum analyzers or VNA as opposed to using oscilloscopes as the measurement devices. Maity *et al.* [3] categorize existing research articles in terms of their setups. For instance, they separately list articles that use common-ground setups (sometimes without explicitly saying so) and articles that use non-common-ground setups. Only the latter measure the full-bidirectional signal loss. In addition, they discuss and experimentally demonstrate the impact of the receiver's impedance on the measurement results. In a follow-up article Maity *et al.* [4] provide some further guidelines on how to accurately

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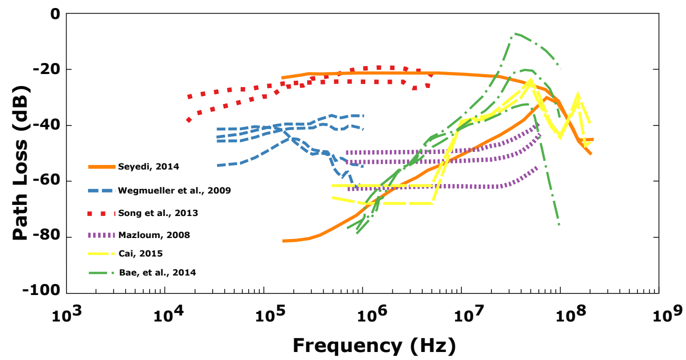

Fig. 1: BCC channel characteristic measurements show very large variance across research teams, indicating problems with measurement methodologies. Results from [6]– [11].

measure signal loss. Park *et al.* [5] discuss the importance of impedance matching, categorize existing works by whether they report voltage gain or power gain, and criticize some of the methods used to decouple the ground planes of the receiver and the transmitter.

With this paper, we aim to serve the practitioner in the field who is getting started with the common BCC measurement setup (Fig. 2). While the measurement problems described in the paper may seem obvious to a seasoned electrical engineer, the abundance of mutually contradictory, unclear and occasionally even wrong measurement results in the research literature [6]–[12], as well as our own initial mistakes, suggest that they are not at all obvious to researchers getting started in the area.

Hence, the main contribution of this paper is to categorize and experimentally investigate several potential problems with BCC measurements, specifically:

- failing to isolate ground planes;
- cable length issues;
- impedance mismatch;
- not accounting for measurement device characteristics.

While some of the problems have been demonstrated previously, no existing research covers exactly the same ground that we do. Callejón *et al.* [2] demonstrate most of the same problems; however, they almost exclusively use a custom-made PCB with a phantom circuit instead of a real human in their experimental evaluation. The effect from the non-isolated ground problem has been demonstrated in several papers, *e.g.*, [1], [12]), however our results show a different frequency response than previous research. The impedance

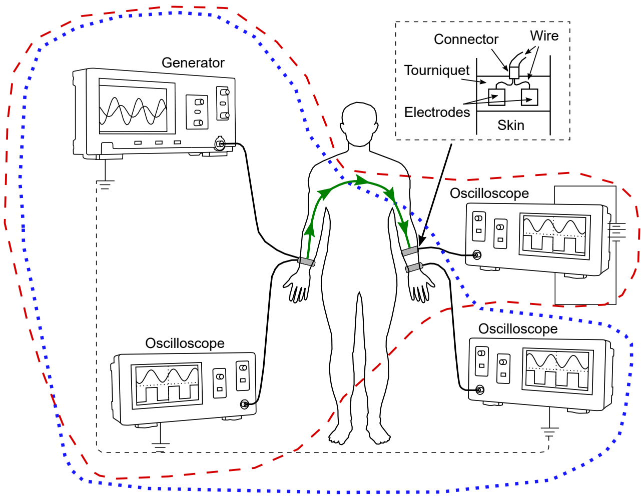

Fig. 2: Overview of the common measurement setup. In the red dashed area: measurement with a battery-power oscilloscope. In the blue dotted area: measurement with a mains-power oscilloscope.

mismatch problem has been discussed in [5]; however, they focus on the capacitive mode BCC and do not experimentally show the effects from a mismatch.

The paper is structured as follows: Section II describes the measurement goal and the setups; Section III analyzes four common measurement problems; Section IV summarizes good measurement practices and lists their limitations; Section V concludes the paper.

II. Measurement Setup

The aim of a BCC measurement setup is to characterize the human body channel in terms of signal loss. At its core, a basic setups consists of a signal generator (playing the role of a transmitter) that generates alternate current with V_{IN} voltage and an oscilloscope (playing the role of a receiver) that measures the voltage V_{RX} (Fig. 3) on the other side of the communication channel. Both the transmitter and the receiver are connected to a human test subject, via electrode-to-skin connections.

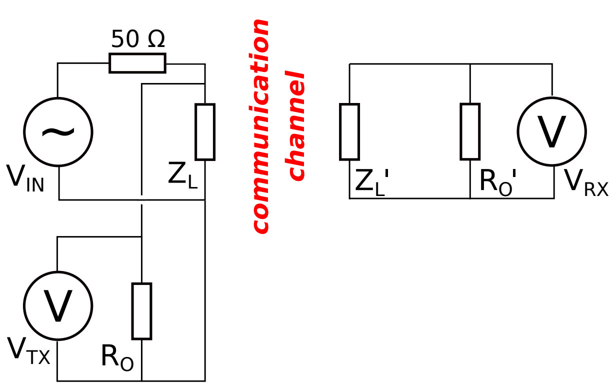

Fig. 3: High level schematic of the measurement system.

The two main modes of BCC are called *capacitive* and *galvanic* BCC. In capacitive BCC, only a single electrode is connected to the skin at the transmitter side, while the electrode for the return current is either not present, or is left floating. The same single-ended setup is used at the receiver side. In galvanic BCC, a two-electrode (differential) connection is made both at the receiver and transmitter sides. Further in this paper we focus on the galvanic BCC mode.

TABLE I: Symbols used in the manuscript.

Symbol	Explanation
V_{IN}	The generated input voltage
V_{TX}	Voltage on the TX-side skin-connected electrodes
V_{RX}	Voltage on the RX-side skin-connected electrodes
Z_L	Load impedance (*e.g.*, of the skin between electrodes)
R_O	Oscilloscope's impedance (resistance)
C_{GS}	Cable length between generator and splitter
C_{OS}	Cable length between oscilloscope and splitter
C_{SL}	Cable length between splitter and electrodes

Most commonly, the BCC signal gain is measured as voltage gain, although power gain can also be used. It is defined as the proportion between the voltage difference registered on the receiver (V_{RX}) and the voltage difference generated on the transmitter (V_{TX}), and expressed in dB:

$$gain_{RX} = 20 \cdot log_{10}\left(\frac{V_{RX}}{V_{TX}}\right). \quad (1)$$

In our setups, an additional oscilloscope is present at the transmitter side, with the purpose to measure V_{TX}: the input voltage drop on the input electrodes. This is required because the impedance between the input electrodes is frequency-dependent. While the generator can be set to generate a constant voltage V_{IN}, this voltage is only constant if the impedance of the system under measurement is matched with the 50 Ω resistor in the generator itself. While this is typically the case with RF systems, it is clearly false if human is part of the circuit, meaning that the input voltage must be measured rather than assumed, because $V_{IN} \neq V_{TX}$. While the presence of this equipment may introduce its own impact on the measurement results, using a matched R_O=50 Ω minimizes this. It is important to stress that most of the published works in the area do not clarify whether they use V_{IN} or V_{TX} to calculate the signal loss; whether they measure V_{TX} at all, and what setup do they use to measure V_{TX}; as we are going to show in the next section, the latter is not trivial to build.

Measuring V_{TX} in comparison of the V_{IN} allows to quantify the TX-side gain of the system:

$$gain_{TX} = 20 \cdot log_{10}\left(\frac{V_{TX}}{V_{IN}}\right). \quad (2)$$

In our experiments we use a mains-powered Tektronix AFG3252C generator and two oscilloscopes: the mains-powered Tektronix MSO4032 and the battery-powered Fluke 190-502. The components are connected via BNC-BNC cables, BNC T-splitters, and BNC-to-open-wire cables (Fig. 4). The internal resistance of Tektronix AFG3252C is R_O=50 Ω, and it is set to generate alternate current with V_{IN} = 2 V (peak-to-peak amplitude before the R_O; equal to 1 V peak

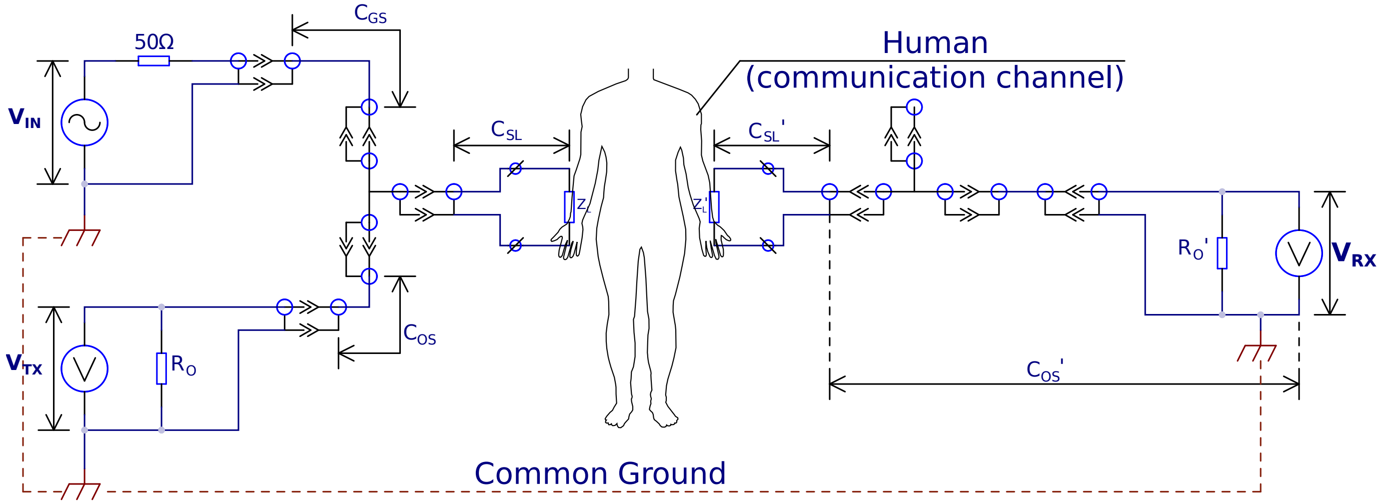

Fig. 4: The physical instantiation of the measurement system.

amplitude before the R_O). The measurements are made in the frequency range 50 kHz – 50 MHz, stepping a number of preset frequencies in this range. To make our work simpler and more repeatable, in the experiments where we are interested only in the TX-side performance, we use either a fixed 250 Ω resistor as Z_L instead of the human skin, or simply leave the electrodes unconnected ($Z_L = \infty$). The 250 Ω value approximately matches human skin impedance in these frequencies when our particular electrode setup is used. (We verified this with Zurich Instruments MFIA impedance analyzer.) For measurements with a human subject we recruited a male volunteer test subject (age: 29 years, weight: ≈ 90 kg, BMI: ≈ 27). The TX and RX electrodes were attached to the right hand and left hand wrists of the volunteer.

III. Typical Measurement Problems

The typical goal of the measurements in this field is to investigate the human body as a signal propagation medium. However, the signal strength is not independent from the components of measurement system itself, creating the same root cause for the following problems, which can be summarized as *measuring the setup itself, not the target*.

A. Failing to Isolate Ground Planes

For a successful communication between a BCC transmitter and receiver, electrical current must flow in both directions, in order to form a closed circuit (Fig. 2). By a convention, the flow from the transmitter to the receiver is called the *forward path*, and the flow from the receiver to the transmitter is called the *backwards path*. The forward propagation takes place across the human body, while the backwards propagation in capacitive BCC mainly happens through parasitic capacitance between the transmitter, the earth ground, and the receiver. In galvanic BCC, the backwards propagation also takes place across the human body; however, the alternative backward path through parasitic capacitance is still present, and may affect the measurement results. Studies show that the voltage loss in the

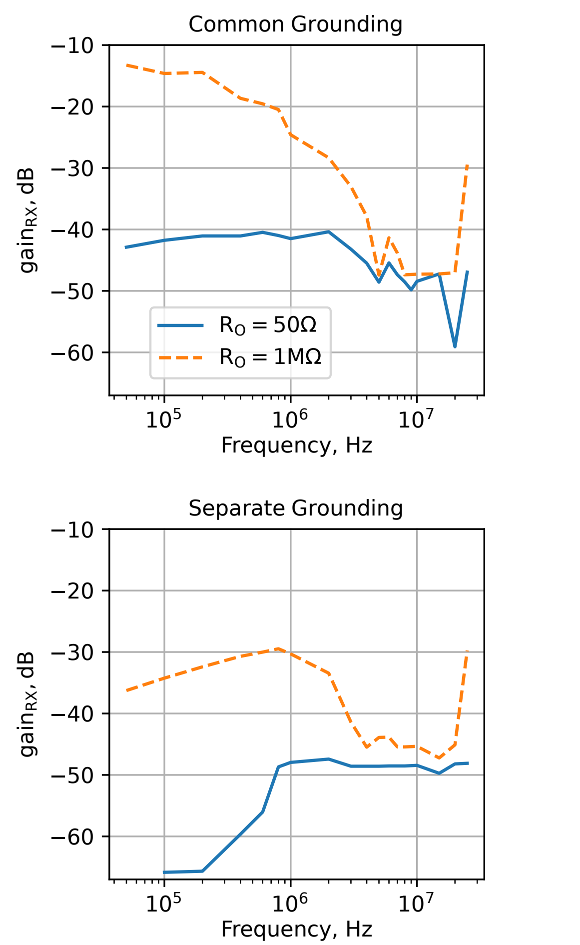

Fig. 5: Comparison between measurements with and without a common ground. The received signal is much stronger in the former case, especially at the lower frequencies.

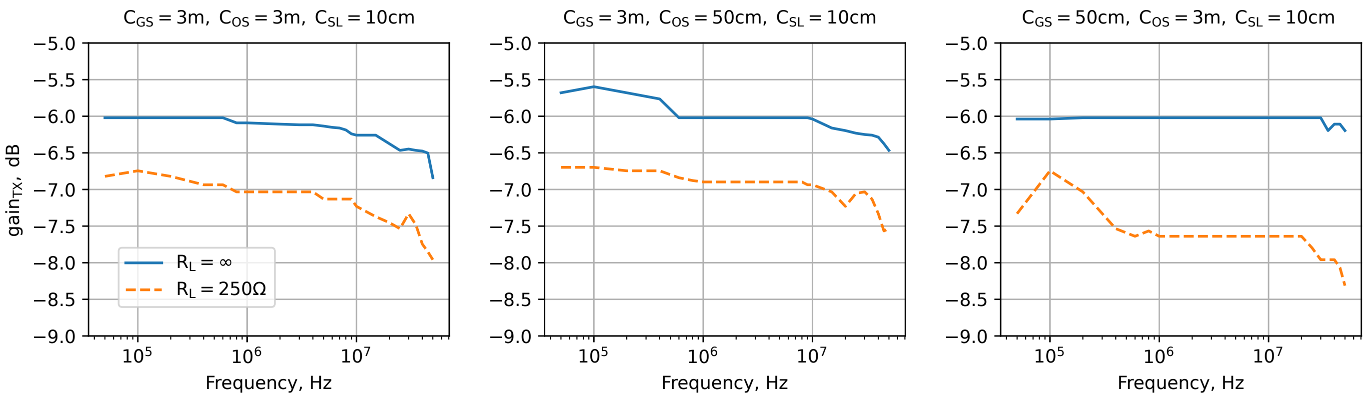

Fig. 6: Comparison between measurements with different cable lengths. R_O=50 Ω. Left: equal length cables; middle: shorter generator-splitter cable; right: shorter oscilloscope-splitter cable. There is up to 1 dB difference in the results between the subfigures.

forward path is relatively very low, on the order of 0.5 dB [3], as the human body is a good signal propagation medium at the BCC frequencies. In contrast, the parasitic capacitance path is characterized by a much higher impedance, resulting in a higher voltage drop (and thus a higher signal loss).

Due to these aspects, a proper isolation between the ground planes of the transmitter and the receiver is important. If the transmitter and the receiver are two battery powered wearable devices, as in the envisioned applications of BCC, there is no problem. However, signal-loss measurements often use stationary generators and oscilloscopes instead of such devices. If the measurement devices are powered from the same power source, they are going to share a ground plane, which has a much lower impedance than the "normal" backward path through parasitic capacitance.

To demonstrate this problem, we use the setup in Fig. 4, and optionally connect the devices to the same power source, introducing a common ground element. Fig. 5 shows the results. The graphs demonstrate that the common ground option leads to 5–20 dB increase in the signal strength depending on the frequency.

Existing literature suggest several approaches to solve this problem. Optical decoupling is a good but labor-intensive solution [6]. Powering the devices from decoupled power sources (batteries) is a simpler one. Decoupling through the use of balun is also possible [12], however, it introduces its own parameters in the measurement system and is not recommended [3], [5].

B. Cable Length Issues

When working with human test subjects, it is more convenient to use longer cables to facilitate the TX and RX electrode connection to different parts of the body (arms, legs, torso). However, this convenience comes at a cost. Depending on the frequency, the cables themselves may start to act as antennas: for instance, at 25 MHz the length of a quarter-wave monopole antenna is just 4 meters. Even at lower frequencies, the cable length has impact on their parasitic capacitance and resonance.

In order to test the impact experimentally, we first compare the signal loss depending on the length of the generator-splitter and oscillator-splitter cables (Fig. 6). This is a TX-side experiment: we report $gain_{TX}$ and either use a fixed Z_L=250 Ω for these experiments or leave the Z_L connection open. The results indicate that the setup with a smaller C_{GS} and longer C_{OS} shows the most linear behavior (Fig. 6 middle). The other two setups show a higher dependence on the signal's frequency.

A more severe problem appears if we increase the length of the splitter-electrode cable (C_{SL}). To be clear, we do not replace the short 10 cm BNC-to-open-wire cable, but rather extend it with another 3 m BNC-to-BNC cable, a change that introduces additional obstacles in the flow of the current. As a result, we measure the V_{TX} far from the actual Z_L. As Fig. 8 demonstrates, this is an unwise approach. Extremely high signal loss up to 25 dB is seen in some frequencies above 10 MHz.

While our experiments in this subsection are limited to the TX-side of the setup, symmetrical behavior is expected to take place in the RX-side of the setup.

C. Impedance Mismatch

The measurement of V_{TX} should be done with a load impedance R_O that matches the 50 Ω resistance of the generator (Section II). Oscilloscopes such as Tektronix MSO4032 come with a setting that allows to change R_O, typically between two values: 50 Ω and 1 MΩ. Existing research reports results both from 50 Ω and 1 MΩ setups; the RF-standard is 50 Ω. As long as the impedance is matched, the amount of resonance in the cables is minimized.

On the receiver side, using a higher impedance for R'_O allows to register a higher voltage and so in a way minimize the signal loss [3]. However, this only applies to voltage gain, because higher impedance leads to lower current, so the power gain of the receiver is not maximized. For maximizing the power gain, which some argue is a more relevant parameter for BCC systems [5], matching, rather than maximizing, the impedance on the receiver side is expected to give the best results. On another note, in order to better approximate the characteristics of real-life wearable devices, the load impedance should be resistive, not capacitive [4].

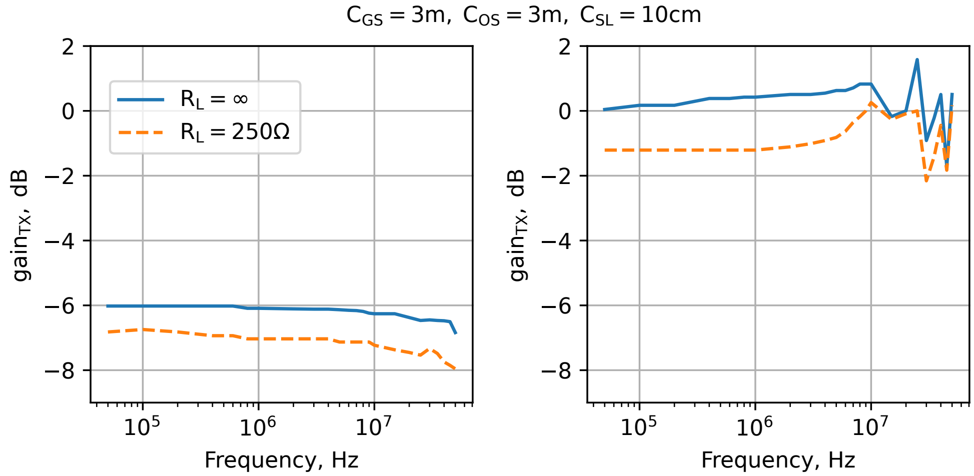

Fig. 7: The effect from changing oscilloscope resistance (impedance). Left: R_O=50 Ω; right: R_O=1 MΩ. The right graph shows a much higher gain and chaotic frequency response caused by the high impedance of R_O. Another anomaly is that with $Z_L = \infty$ the results indicate signal gain, rather than loss.

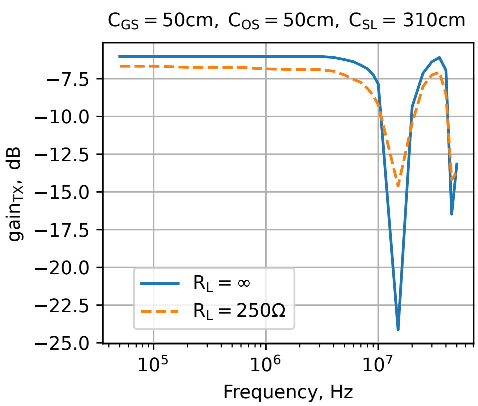

Fig. 8: The effect from connecting the TX-side oscilloscope far from the Z_L. R_O=50 Ω. The length of the splitter-to-electrode cable (C_{SL}) is 310 cm, and it consists two physical cables connected via BNC connectors. As a result, anomalous loss is seen in some frequencies.

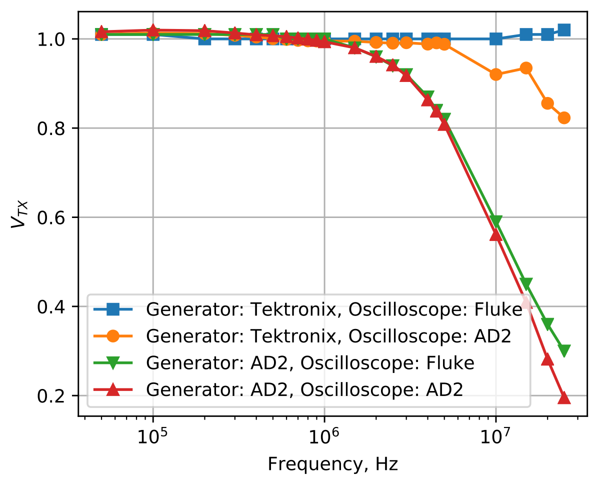

Fig. 9: Frequency response curves of different generator and measurement devices. The exxpected peak-to-peak V_{Tx} is 1 V in this setup.

To demonstrate the impact of mismatched impedance when measuring V_{TX}, we set R_O=1 MΩ and show the results in Fig. 7. Similarly to the previous subsection, this is a TX-side experiment and we report $gain_{TX}$. The reader invited to compare these results with the left subfigure of Fig. 6, which uses the same cable lengths but has R_O=50 Ω. The higher impedance setup leads to a more nonlinear frequency response, as well as tends to inaccurately report signal gain rather than loss.

Achieving good impedance match may not be possible in realistic conditions, especially if the goal is to test multiple human subjects and to test multiple locations on each subject. A potential workaround is to build a calibration table using a number of reference input impedances, and then subsequently apply these calibration coefficients in a post-processing stage to correct the frequency response of the system.

D. Not Accounting for Measurement Device Characteristics

Even when the impedance and the cable lengths of the devices in the setup are matched, other factors may affect the measurement results. Rather than trying to enumerate all possible factors, a different strategy is to measure the frequency response of the generator and oscilloscope themselves, and compensate for that when calculating the signal loss, for example, using a calibration table in the post-processing code.

In order to show this problem, we introduce a new pair of devices in our experiments: Digilent Analog Discovery 2 boards (AD2). The board can serve both as USB oscilloscopes and variable power supplies, essentially being a low-cost portable replacements for both the transmitter and the receiver side of the measurement setup. Unfortunately, their frequency response curve is not nearly as linear as that of the more expensive higher-accuracy dedicated devices.

In this experiment we simply measure and report the V_{TX} using the TX-side of the setup with a fixed Z_L=250 Ω. Fig. 9 shows that while the frequency response is approximately linear with $f \leq 1$ MHz, it starts to drop sharply for the AD2 devices in higher frequencies, especially after 5 MHz. The Tektronix oscilloscope also shows some nonlinearities in frequencies ≥10 MHz.

IV. Best Measurement Practices

To summarize the results:

- V_{TX} must be measured, rather than assumed.
- Shorter cables are better. Equal-length cables are better. V_{TX} should be measured close to the Z_L (*i.e.*, the skin-electrode contact).
- Impedances in the system should be matched in order to maximize the power gain on the receiver. If this is not possible, an impedance-specific calibration table can be built and used instead.
- The characteristics of the measurement device impact the results, especially in the higher BCC frequencies (above 5 MHz). A frequency-specific calibration table should be built and in a post-processing step the measurement results are adjusted with frequency-depend coefficients.
- The TX-side of the setup should be isolated from the RX-side of the setup, for example, by using battery-powered devices or optical decoupling.

Ultimately, we need to also take into account that:

- The parasitic capacitance characteristics are heavily affected by the sizes of the device ground planes. Large form-factor oscilloscopes and generators are likely to have different capacitance compared with small form-factor wearable devices [3].
- All connections and cables introduce new parameters in the system and affect the measurement results.
- The voltage gain and power gain on the receiver depend on the load impedance of the receiver, which in turn depends on the characteristics of the receiver device.

These points suggest that obtaining ground-truth measurements in BCC is best done with battery-powered wearable prototypes, whose size, connections, and load impedance closely matching the ultimate BCC-enabled end-user wearable devices of the future. Nevertheless, preliminary investigations with generators and oscilloscopes can help to determine the desirable parameters of these wearable devices, in terms of their minimum ground plane size, electrode connections to the device, and their desirable load impedance.

V. Conclusion

In this paper we demonstrated a number of potential mistakes in measuring the human body as a signal propagation medium. Experimental results show that each of these mistakes can significantly change the measurement results, in some cases up to 20 dB. However, this article barely scratches the surface of the possible factors impacting the BCC signal-to-noise ratio on wearable devices. Our future work includes investigating ways to design and connect electrodes in order to maximize the gain, as well as building real battery-powered wearable prototypes capable of data exchange via BCC.

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