Towards Body Coupled Communication for eHealth: Experimental Study of Human Body Frequency Response

Juris Ormanis, Atis Elsts
Institute of Electronics and Computer Science, Latvia
Email: juris.ormanis,atis.elsts@edi.lv

***Abstract*—The Internet of Things promises to enable numerous future applications spanning many domains, including health care. Currently, most health care devices communicate either by using wires or by using a Radio Frequency technology such as Bluetooth or WiFi. In this paper, we describe an alternative communication method: Body Coupled Communication, where the signal is transmitted using an electrical field that propagates through the human body. We perform experimental measurements using a wrist-to-wrist setup to determine the human body frequency response in the 10 kHz to 30 MHz frequency range and find that the 3.25 MHz frequency has the lowest attenuation in this range. We also show that the frequency response patterns remain the same when a number of common chemical substances are applied between the electrode and the skin, and that electrically conductive substances such as sweat enhance the received signal strength.**

I. Introduction

In the past, healthcare sensors were mostly restricted to hospitals and labs. This is changing, as the advances in microelectronics have enabled proliferation of inexpensive, powerful, and energy-efficient embedded devices that can be interconnected in Body Area Networks (BAN). These new wearable sensors can achieve long-term health monitoring in natural environments without asking the residents to restrict their normal activities. In this way, the sensors enable applications such as ambient assisted living for people with chronic health conditions. Healthcare now can become more personalized, more evidence & data-based, more cost-effective and more convenient to the users and the medical personnel. However, many healthcare applications benefit from having multiple sensors located on different parts of the body:

- In quality-of-motion applications, multiple on-body inertial measurement (IMU) sensors are used to track the movement of different limbs and body parts, with the goal *e.g.*, of diagnosing and tracking the progress of neurodegenerative conditions (such as Parkinson's) and the recovery of post-operatic patients;
- In activity recognition applications, multiple on-body sensors (typically also IMU) increase the accuracy of and the range of activities recognized;
- In complex behavior analysis and diagnostic applications, multiple body sensors of different modalities benefit the tracking of behavior-related health conditions, such as diabetes, hypertension, depression and other mental health issues.

In so far, multi-sensor setups have been difficult to use outside of hospitals and labs, as the individual sensors often have to be interconnected with wires.

The goal of this paper is to investigate body-coupled communication (BCC) [1], [11], [14] methods to connect these multiple on-body sensors in a single wireless BAN. To this end, we measure the human body frequency response using BCC in the 10 kHz–30 MHz frequency range. We conduct two different experiments: first, we compare the BCC signal path loss on ten healthy volunteers in the given range; second, we study the impact of different substances covering the skin in the electrode contact points on a single reference volunteer. We find that the 3.25 MHz frequency has the lowest signal fading in the range, thus making it especially suitable for BCC data transmission systems. This result is robust under a variety of skin-covering substances.

The paper is structured as follows: Section II gives background on the BCC technology; Section III surveys related work in the area; Section IV describes the experimental study and the discussion of the results; finally Section V concludes the paper.

II. Background and Motivation

BCC is a technology that uses the human body as an electric field propagation medium [14], and provides an alternative both to wires and to radio frequency (RF) technology. There are two main BCC methods (Fig. 1): capacitive coupling and galvanic (wave-guided) coupling [11]. With *capacitive coupling* one of the transmission electrodes is connected to human body, while the other one is floating and directed away from skin. The receiver is configured in the same way. This means that the forward path of the signal propagates through human body, while the return path is through the air or ground. With *galvanic coupling*, all electrodes are connected

This work was supported in part by the ERDF Activity 1.1.1.2 "Post-doctoral Research Aid" (No. 1.1.1.2/VIAA/2/18/282).

This work has been supported by ERA-Net Flagship project CONVERGENCE (www.convergence-era.org/) - "Frictionless Energy Efficient Convergent Wearables for Healthcare and Lifestyle Applications".

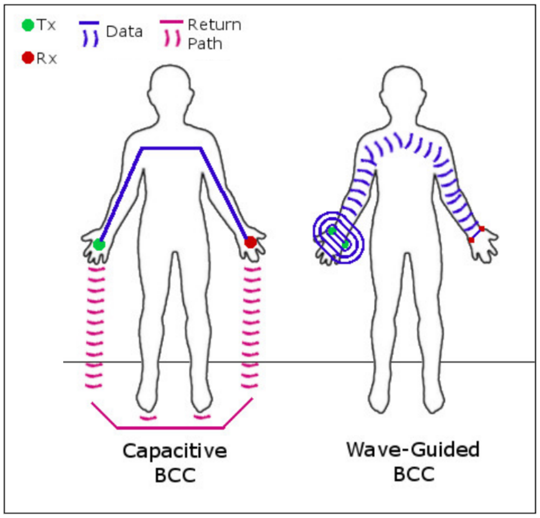

Fig. 1: Body Coupled Communication methods.

to the skin; this topology uses only the human body as the transmission medium.

A lot of technologies already exist for body area sensor networks. However, wired technologies are difficult to use in this application and are impractical for long-term, minimally obtrusive residential monitoring. Furthermore, wired connections may be impossible if the sensors are implanted within the body. On the other hand, wireless technologies that use RF (such as Bluetooth and WiFi) suffer from these problems:

- **Privacy and security issues** due to wireless transmissions vulnerable to sniffing, jamming, and side-channel attacks (*e.g.*, looking at the signal strength to detect the activity of the user [2]). These issues are especially pertinent to healthcare applications, and they are amplified by the levels of pervasiveness health sensors can have in the daily lives of the users.
- **Electromagnetic interference.** Stronger RF signals enable longer-range communication and higher-rate data transmission. However, using stronger signals also means that the amount of electromagnetic interference is increased.

The BCC has the potential to solve the aforementioned issues of wireless BAN:

- **Electromagnetic interference.** The undesired leakage from a BCC link is reduced compared to a RF link due to two reasons: firstly, most of the signal is restricted to the body itself (especially if galvanic coupling is used, as then the body acts as a wave-guide), secondly, due to the fact that the signal strength decreases more rapidly in the near field (*i.e.*, in the zone less than one wavelength away from the transmitter) than in the far field. The BCC signal is usually of much lower frequency (under 200 MHz) and does not need to propagate outside the near field for successful communication. This allows to reduce BCC signal strength without reducing the robustness or the data rate of a BCC system compared to RF based systems.
- **Privacy and security issues.** The physical properties of the BCC signal also mean that most of the signal does not leave the body of the user, or at least is much weaker with distance. This renders sniffing and side-channel attacks less possible; such attacks may require a physical connection to the user's body.

To explain the near-field argument in more detail for the interested reader: fundamental physics tells us that the near and far fields have different signal propagation models. In the far field, the amplitude of electromagnetic waves decreases linearly with the distance from the source; as a result, the line-of-sight signal strength decreases quadratically (known as the *inverse square law*). Meanwhile, in the near field, the amplitude of the electric field decreases super-linearly (quadratically or cubically) with distance. BCC typically takes place in the near field, with $\lambda \ll d$ (where λ is the wavelength and d is the distance between on-body transmitters, while most of RF communication does *not* take place in the near field.

III. Related work

A. Survey

The first study on BCC was performed in 1995 by Zimmerman as part of his master thesis at the MIT, later published in [14]. In his investigation, the capacitive coupling approach is utilized and the communication system consist of a TX and RX nodes which were battery powered. The TX and RX nodes are galvanically isolated one from another, so they do not share a common ground. Information is transmitted by varying electric field, that results in tiny current flow through human body. A carrier frequency of 333 kHz is used and data rate of 2400 bps can be achieved.

Partridge *et al.* subsequently use the original design of Zimmerman with added filters and amplifiers [7]. They perform quantitative measurements to analyze the impact of the electrodes and their placement on the system performance. The author conclude that size and shape of the electrodes have minor effects, while the distance between electrodes and their location on they body significantly change the signal strength. Their prototype uses frequency shift keying (FSK) and achieves 38.4 kbps throughput.

Fuji *et al.* [3] focus on experiments with higher carrier frequencies from 10 MHz to 100 MHz. They claim that the human body acts as a waveguide in this frequency range. Their prototype uses capacitive coupling, and their results include a signal attenuation model. They also investigate the relative positions of electrodes one to another on transmission parameters. Their experiments show that transverse dislocation of electrodes gives better results than longitudinal placement.

Yanagida has a patent on human body communication system with relatively high rate, low power consumption capacitive BCC [13]. One of the target applications is audio transmission. His experiments test multiple electrode sizes, material and carrier frequencies. The smallest signal loss is observed at frequency range from 500 kHz to 3 MHz, and 48 kbps throughput is reached.

Ruiz *et al.* work on multiple subtopics related to BCC [8], [9]. They claim that the most suitable frequency range for BCC is from 200 MHz to 600 MHz. Multiple signal modulation methods are tested in this range; throughput from 100 ksps to 5 Msps are achieved. Their experimental results show that MSK and BPSK are the most suitable modulation schemes for BCC.

Wegmueller *et al.* [12] use galvanic coupling. They construct a custom measurement board with optical interfaces to decouple it from any outside electro-magnetic signals, and use it for a clinical measurement study. They investigate the 1 kHz to 1 MHz frequency range. The authors argue that using higher frequencies would be possible, but increase the power consumption, as well as cause a larger part of the transmitted power to be radiated through the air. They claim galvanic coupling transmissions at RF frequencies will be purely wireless transmissions through air.

Our previous work on the topic [6] discusses BCC applications in the context of modern wearable electronics and presents. In contrast to this previous work which was a high-level architectural description, the present paper includes the discussion of a prototype measurement system and presents experimental measurement results.

Last but not least, the PHY and MAC layers of BCC communication have been codified in the IEEE 802.15.6 standard for Personal Area Networks [1]. This standard devotes its Section 10 to human body communication protocols. Its advised frequency for BCC is 21 MHz. In addition to the PHY layer, the standard describes a coding system and noise protection methods, as well as defines the minimum receiver sensitivity for different data rates. The standard assumes capacitive coupling. Its maximum defined throughput for for 21 MHz carrier frequency and bandwidth of 5.25 MHz is 1.3125 Mbits. 8-bit CRC is chosen for error detection, while the Gold sequence is selected for information encoding.

B. Discussion

The plethora of related work leaves open these questions for health-related BCC applications:

- Q1. Should we use capacitive or galvanic coupling?
- Q2. What frequency is the best for BCC?
- Q3. How do different substances that may cover the human skin affect the signal strength?

In terms of the coupling type (*Q1*), capacitive coupling causes part of the signal to be transferred over the air. This reduces the privacy and the interference-resilience properties of the BCC method. Hwang *et al.* [5], [4] show that when capacitive coupling is used, at high frequencies radiation from the transceiver node can interfere with the BCC device of another user at distance about 150 cm. Hence, for eHealth applications we prefer galvanic coupling, and investigate this method in the present paper.

In terms of frequency (*Q2*), multiple articles shows that lowest power loss appears in range from 1MHz to 100 MHz. However, all of them show a different central frequency. This could be the result of different electrode placement. In the present paper, we assuming wrist-worn devices and aim to find the optimal operational frequency for this specific placement.

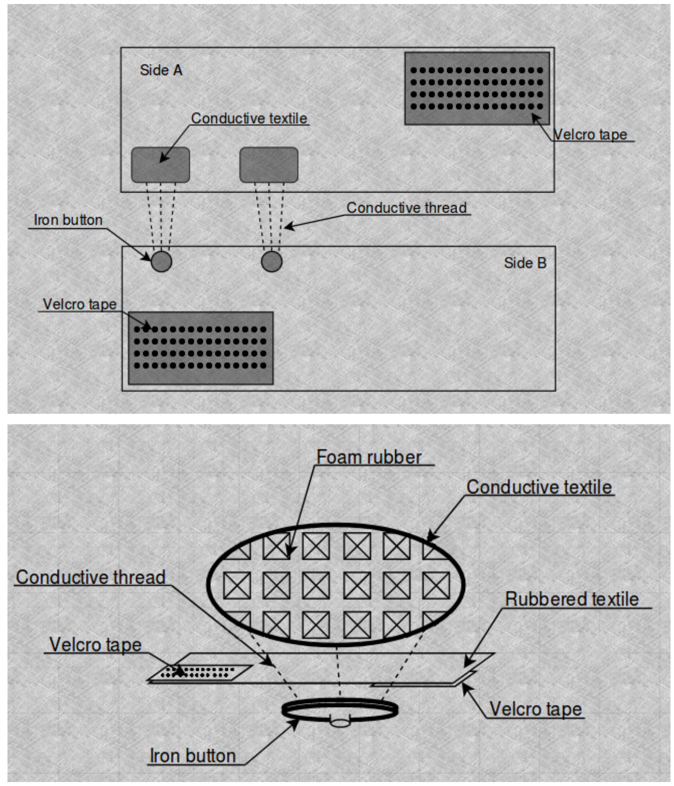

Fig. 2: Schematic of the prototype wristband. Top: inside and outside view, bottom: cross section view.

In general, many papers investigate the impact from electrode placement and shape. In contrast, we let the realities of non-functional requirements dictate these aspects. We note that wristbands have become the most popular wearable device type, hence, we focus on wrist-worn electrodes that are small enough to be unobtrusive to the user. In contrast, the effect from different substances (*Q3*) has not been clearly investigated. As a result, this is one of the focus points of the present research.

IV. Experimental evaluation

A. Experimental Wristband Prototype

As each experimental data point consists of measurements between two points on the body, two wearable bands were made for the experiments. The schematic view of these bands is shown in Fig. 2. On the inside (Side A) the band has two conductive spots made from conductive textile wrapped around a small piece of foam rubber; this is to ensure good and reliable contact with skin. On the outside, it has metal buttons useful for attaching measurement probes.

B. Measurement Setup

Fig. 3 shows the measurement setup and Fig. 4 shows the schematic for human body frequency response measurements. On the left of Fig. 4 there is the programmable signal generator

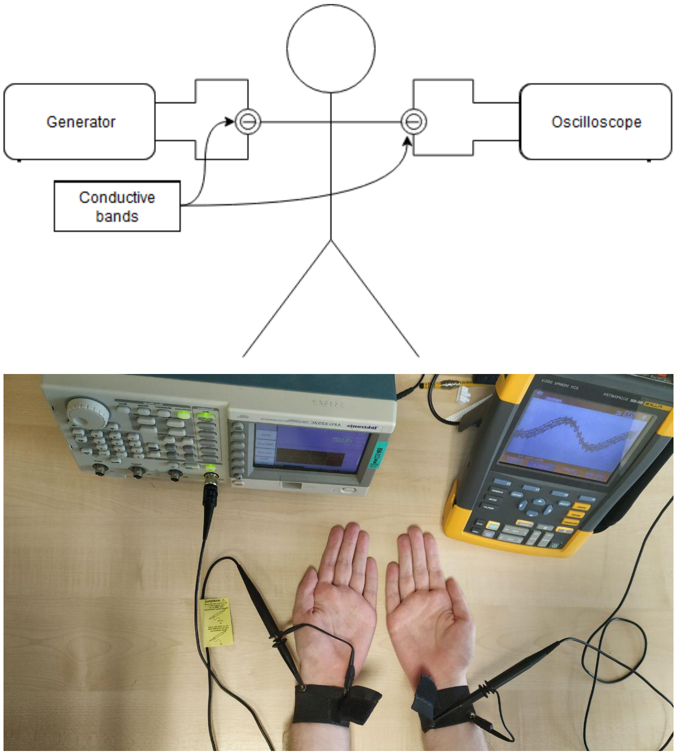

Fig. 3: Experimental setup. Top: outline, bottom: the prototype wristband in use.

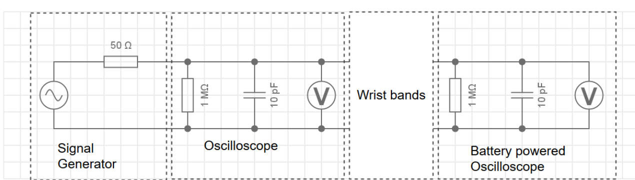

Fig. 4: Measurement schematic.

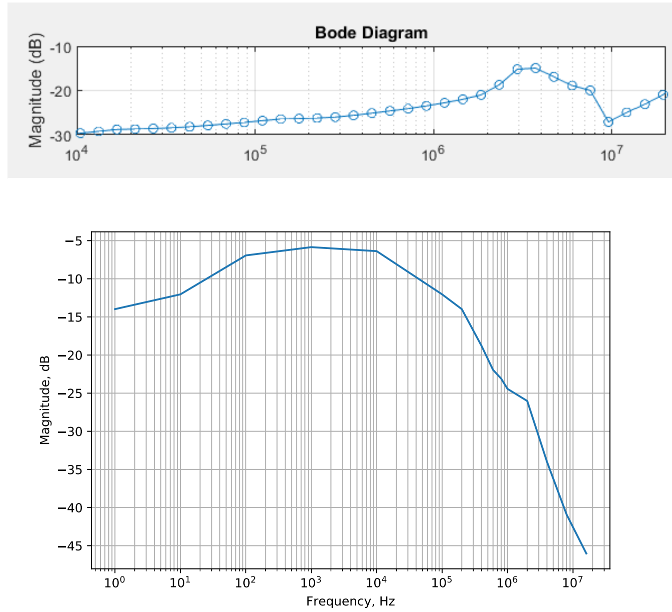

Fig. 5: Measured human body frequency response. Top: with battery powered oscilloscope, bottom: with mains powered oscilloscope.

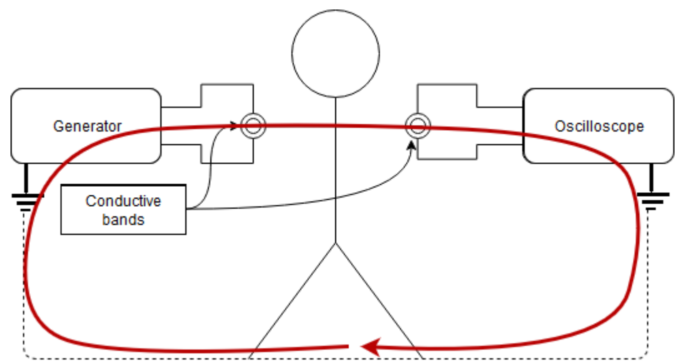

Fig. 6: Explanation of the mains-powered oscilloscope results: undesirable signal propagation through grounds skews the frequency response measurement.

Tektronix AFG3252C with output impedance of 50 Ω and accuracy of output signal of $\pm 1\,mV$ [10]. The signal generator connects to the input wrist band. On the right, there is an oscilloscope. The oscilloscope channels have input resistance 1 MΩ and series capacitance of 10 pF.

C. Mistake in the Measurement Setup

Initially, a single stationary (mains-powered) oscilloscope was used for both Tx an Rx signal measurements. When this setup was validated with a mobile, battery-powered oscilloscope on the Rx side, a large mismatch in the results was discovered (Fig. 5). The peaks and troughs in the signal loss graphs are in different places. In the stationary oscilloscope experiment the best signal propagation was observed on frequencies between 50 and 200 kHz, while the mobile oscilloscope experiment showed that the best results in the 2 – 4 MHz frequency range.

We explain the discrepancy in the following way: when the generator or oscilloscope is powered by battery, there is no connection between generator and oscilloscope except through the human body. Hence, coupling through ground does not take place. In contrast, when both generator and oscilloscope are powered from the same power source, capacitive coupling through grounding wires takes place (Fig. 6). (If the coupling would involve power lines in addition to the grounding wire, the 50 Hz AC wave would be also seen on the oscilloscope.) We note that in the related work literature, some papers do not discuss this aspect and appear to use common ground for both Rx and Tx side, *e.g.*, [8]. This may skew and render invalid their published measurement results.

D. Experimental Study

For the study we recruited 10 volunteer participants: 7 males and 3 females with age varying from 22 to 50 years, body

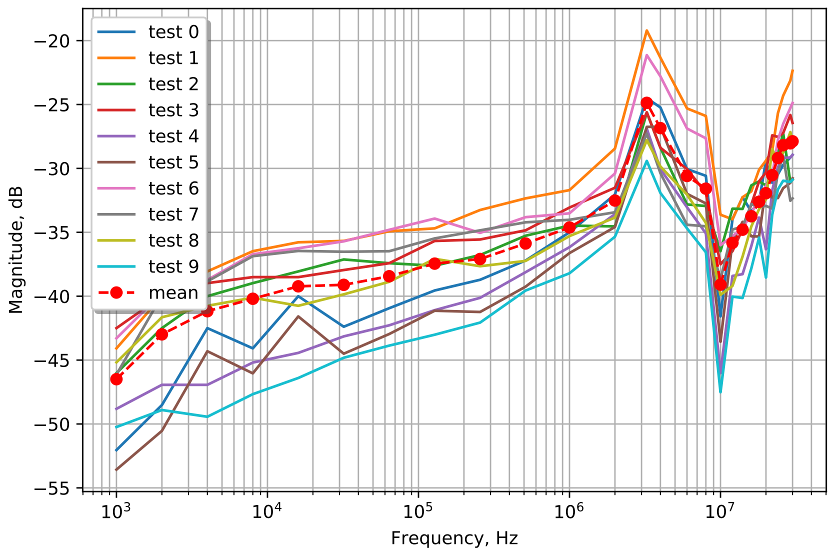

Fig. 7: Frequency response of the human body.

mass between 50 and 130 kg, and body mass index between 19.5 and 34. Each participant was asked to carefully wash their wrists and then dry them, so that no body oil, cosmetics, dirt or water would remain between their wristbands and skin. Following that, the participant was asked to wear the bands on both wrists as shown in Fig. 3.

During the experiments multiple measurements are performed on each participant, and the data processed, resulting in a realistic average frequency response of the human body. The input and the output voltages are measured for the frequency range 1 kHz to 30 MHz, as shown in Fig. 4 (The red dots of mean graph on the Fig. 7 are representing selected frequencies for measurements of previously mentioned frequency range). These values can then be converted to attenuation using the standard equation:

$$Attenuation[dB] = 20 \cdot log_{10}(\frac{V_{out}}{V_{in}}) \tag{1}$$

where V_{in} is the input voltage and V_{out} is the output voltage.

E. Human Body Frequency Response

The experimental results are shown in the Fig. 7. It can be seen that in the 1 kHz to 1 MHz range the received signal level increases slightly. At 3.25 MHz there is peak where the signal level reaches -25 dB on the average. In the best experiment, the maximal signal level is -18 dB. The measurements differ in their attenuation level, but all other settings are stable between the experiments. The biggest difference in the attenuation level between two experiments is 10 dB. The minimal attenuation level is consistent between the participants: it takes place at approximately the same frequency in all experiments.

F. Impact of Different Substances

In the real world, the wrists of the users are not always clean and dry. There can be multiple types of substances between the wristband and skin. This substance can be of biological origin, such as sweat and body oils; they can be applied on purpose, such as cosmetics and gels, or get between the wristband and skin accidentally, such as cooking or machine oil and dirt. All of these substances can impact the path loss function and add unexpected irregularities in the frequency response curve.

For this additional experiment nine common substances are chosen: 1) Distilled water; 2) Salted water (equivalent to sweat); 3) Brackish water; 4) Salty water; 5) Machine oil; 6) Medical electrodes; 7) Skin care cream (oily); 8) Skin care lotion; 9) Concealer.

The measurement setup and method is the same as described previously. The only difference is that the participant should carefully wash their wrists and then dry them, so that no body oil, cosmetics, dirt or water remains on the skin, and then apply one of the experimental substances to their wrists.

The signal loss data in channel for each substance is presented in Fig. 8. The data clear show that the overall shape of the frequency response function remains unchanged. The only difference is in the gain level. A slightly unexpected result is that salty water improved gain; the signal attenuation in the 3.2 MHz frequency with salty water is just 22.4 dB.

Sorting the substances by their attenuation levels (in descending order) creates the following list:

1) Salty water
2) Salted water (similar to sweat)
3) Brackish water
4) Distilled water
5) Medical electrodes

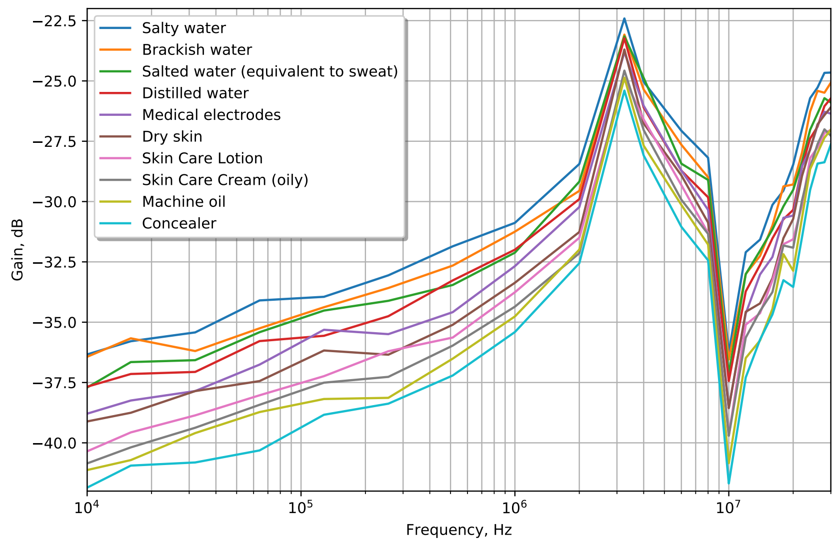

Fig. 8: The impact of different substances on the human body frequency response.

6) Machine oil
7) Dry skin (baseline with no substances applied)
8) Skin care lotion
9) Skin care cream (oily)
10) Concealer

The results show that the more electrically conductive is material between wristband and hand, the higher the resulting gain.

V. Conclusion

In this paper we study BCC communication for potential eHealth applications involving wearable electronics. We construct an experimental study with 10 volunteer participants and test the human body frequency response in a wrist-to-wrist BCC communication scenario in the 10 kHz to 30 MHz frequency range. The results show a consistent pattern in the received signal strength that shared among all participants. The peak frequency is 3.25 MHz. Additionally, we study the impact from various substances covering the skin in the contact points. We find that some substances such as salted water (with salt content similar to human sweat) increase the received signal strength, while cosmetics tend to have a small attenuating effect. The peak frequency remains unchanged. Our future plans include the development of a BCC-based data transmission system prototype and experiments with different modulation methods and MAC protocols on top of it.

References

[1] "IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," *IEEE Std 802.15.6-2012*, pp. 235–249, Feb 2012.

[2] X. Fafoutis, L. Marchegiani, G. Z. Papadopoulos, R. Piechocki, T. Tryfonas, and G. Oikonomou, "Privacy leakage of physical activity levels in wireless embedded wearable systems," *IEEE Signal Processing Letters*, vol. 24, no. 2, pp. 136–140, 2016.

[3] K. Fuji, K. Ito, and S. Tajima, "A study on the receiving signal level in relation with thelocation of electrodes for wearable devices using human body as a transmission channel," *IEEE Antennas and Propagation Society International Symposium 2003*, vol. 3, pp. 1071–1074, June 2003.

[4] J. Hwang, J. Sung, C. Hyoung, J. Kim, D. Park, and S. Kang, "Analysis of signal interference in human body communication using human body as transmission medium," *IEEE Antennas and Propagation Society International Symposium 2006*, pp. 495–498, July 2006.

[5] J. Hwang., J. Sung, C. Hyoung, J. Kim, D. Park, and S. Kang, "EM simulation and analysis on the ground electrode of human body communication," *36th European Microwave Conference 2006*, pp. 1122–1123, September 2006.

[6] J. Ormanis and K. Nesenbergs, "Human skin as data transmission medium for improved privacy and usability in wearable electronics," in *2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*. IEEE, 2018, pp. 1–6.

[7] K. Partridge, B. Dahlquist, A. Veiseh, A. Cain, A. Foreman, J. Goldberg, and G. Borriello, "Empirical measurements of intrabody communication performance under varied physicalconfigurations," *Proc. User Interface Softw. Technol. Symp*, p. 183–190, November 2001.

[8] J. Ruiz and S. Shimamoto, "Experimental evaluation of body channel response and digital modulation schemes for intra-body communications," *IEEE International Conference on Communications 2006*, vol. 1, pp. 349–354, June 2006.

[9] J. Ruiz. and S. Shimamoto, "Statistical modeling of intra-body propagation channel," *Proceedings IEEE Wireless Communications and Networking Conference*, pp. 2063–2068, March 2007.

[10] Tektronix. AFG3000C Series Datasheet. [Online]. Available: https://www.tek.com/datasheet/afg3000c-arbitrary-function-generator-datasheet

[11] W. J. Tomlinson, S. Banou, C. Yu, M. Stojanovic, and K. R. Chowdhury, "Comprehensive survey of galvanic coupling and alternative intra-body communication technologies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 2, pp. 1145–1164, 2018.

[12] M. Wegmueller, A. Kuhn, J. Froehlich, M. Oberle, N. Felber, N. Kuster, and W. Fichtner, "An attempt to model the human body as a communication channel," *ETH Zurich, Tech*, 2006.

[13] T. Yanagida, “Human body communication system and communication device,” Patent, March, 2006.
[14] T. Zimmerman, “Personal area networks (PAN): Near-field intra-body communication,” *IBM Systems Journal*, vol. 35, no. 3-4, pp. 609–617, 1996.