A Preliminary Study of On/Off-Body Propagation Channels for Brain Telemetry Using a Flexible Wearable Antenna

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***Abstract*—Flexible electronics are envisioned to play a major role in future wearable medical devices. An important component of this technology is flexible antennas. This paper presents a preliminary study of on-body and off-body propagation channels in Body Area Networks (BAN) using a small Ultra WideBand (UWB) flexible wearable antenna. The research is carried out with physical measurements in an anechoic chamber and a small laboratory room. The on-body measurements include propagation channels between two wearable devices placed on the head and various locations on the arm (i.e., shoulder to wrist). The off-body measurements cover propagation channels between a head-mounted device and an external device placed at various distances from the body. The wearable devices in these measurements use a small flexible antenna that can easily conform to the surface of the body. The measurements are conducted to better understand and characterize the wireless communication channels in applications such as brain monitoring or brain computer interface. The measurement results show that the UWB flexible antenna presented here performs well for both on-body and off-body communication channels.**

Keywords— Body Area Networks, Brain monitoring, Brain Computer Interface, RF propagation measurements, Ultra WideBand

I. Introduction

Interest in small personal wireless health monitoring devices has significantly increased in recent years. This is partially motivated by their potential to address challenges related to aging population and sufficient health services availability in rural areas [1]-[2]. Within this growing field, wearable wireless sensors provide the capability of 24/7 and location agnostic health monitoring. Being user-friendly, unobtrusive, and comfortable are essentially part of the requirements in the development of future's wearable devices [3]. As such, flexible electronics are envisioned to play a major role in this development process [6]. An important component of flexible electronics, specially when used for wearable senosrs, is the flexible antennas . Flexible antennas are an active area of research and developement with various applications in personal health monitoring, military, gaming, etc [7]-[11]. The main challenges in the development of flexible antennas are new materials for their design and fabrication with the ability to withstand mechanical strains and obtaining the desired radiation characteristics with surface adjustability for agiven application [7].

Brain monitoring and Brain Computer Interface (BCI) are a multidisciplinary research topic that has drawn considerable attention in recent years due to their many innovative and transformative applications. BCI could significantly improve the quality of life for injured or paralyzed people [3]-[5]. This application requires a high data rate wireless link from the paralyzed person's head to an external device or machine with computing capabilities. On/off/in-body propagation studies at UWB frequencies have been conducted by several researchers and the results are available in the literature [12]-[18]. However, to the best our knowledge, none of those studies involve using flexible wearable antennas for BCI applications.

The main objective of this paper is to provide preliminary measurement results for on and off-body propagation channels using a small flexible wearable antenna which was originally presented in [11]. Aside from flexibility, other advantages of this antenna are its small size (2 cm × 3 cm) and wide bandwidth covering the entire 3.1-10.6 GHz UWB spectrum as well as the 2.4 GHz ISM (Industrial, Scientific, and Medical) freuency band. These attributes makes this antenna suitable for different wearable sensor applications. For example, in [11], the antenna was studied for its in-body propagation chracteristics for wireless capsule endoscopy application. In this paper, we also investigate the feasibility of this antenna for on/off-body communication in brain telemetry usecases. The research is carried out with physical measurements in an anechoic chamber and a small laboratory room. The on-body measurements include propagation channels between two wearable devices placed on the head and various locations on the arm (i.e.,

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shoulder to wrist). The off-body measurements cover propagation channels between a head-mounted device and an external device placed at various distances from the body. The wearable devices in these measurements use a small flexible antenna that can easily conform to the surface of the body.

This paper is organized as follows: Section II describes the measurement scenarios and the antennas used during the experiments. The off-body and on-body channel measurements results for different scenarios are presented in Sections III and IV, respectively. Finally, conclusions and future works are discussed in Section V.

II. Antennas and Measurement Scenarios

A. *Flexible wearable antenna*

The flexible antenna used in our experiments has been originally designed for both in-body and on-body communication [11]. The antenna is printed on the flexible Rogers XT8100 substrate with dimensions 20 mm by 30 mm, and a thickness of 50 µm. The antenna operates at the UWB frequency band (3.1-10.6) GHz as well as the 2.4 GHz ISM band. Fig. 1a shows the prototype of this linearly-polarized antenna. The radiation pattern of the antenna can be obtained using Dassault Simulia CST software [1] [19] and a homogenenous human voxel model as shown in Fig. 1b. The location of the antenna on the model's head is similar to its location during physical measurements. The 3D realized gains of the antenna in vicinity of the voxel head at 2.45 GHz, 4 GHz and 5 GHz are displayed in Fig. 2a-c. Further information about the flexible antenna and its radiation characteristics can be found in [11].

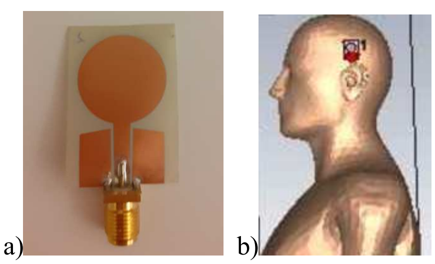

Fig.1 a) Prototype of flexible antenna, b) simulation model for measuring radiation patterns.

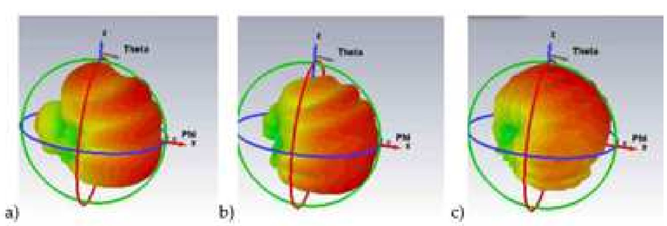

Fig. 2**:** 3D radiation patterns of the flexible antenna at: (a) 2.45 GHz, (b) 4 GHz, and (c) 5 GHz.

B. *Loop antenna*

A linearly polarized loop antenna has also been used for off-body channel measurements. The antenna (shown in Fig. 3) has dimensions of 39 mm × 53 mm and has a FR4 rigid substrate. This is slightly larger than the flexible antenna discussed earlier. The loop antenna operates at UWB frequency band (3.1-10.6) GHz and has been used in several on/off-body channel evaluation studies [15]-[16]-[20]. More information about this antenna and its radiation characteristics are available in [20].

Fig. 3. Loop antenna.

C. *Measurement Scenarios*

The measurements are carried out in an anechoic chamber as well as a small laboratory room. A volunteer[2] with the height of 160 cm participated in the experiments. The measurements are conducted using a Vector Network Analyzer with IF (Intermediate Frequency) bandwidth of 100 kHz and a sweeping time of 200 ms. The VNA is calibrated to eliminate the cable loss. For off-body channel measurements, the flexible on-body antenna is placed on the side of the volunteer's head (just above the left ear) and secured using a flexible band. At this position, the on-body antenna is about 155 cm from the ground. The external antenna is mounted on a pole at the height of 160 cm from the ground and distance d (10 cm < d < 130 cm) from the volunteer's head. This experiment set up is schematically shown in Fig. 4a. Both loop and flexible antennas are used as the external antenna for channel evaluations.

Aside from measurement scenarios with different distances between the on-body and the external antenna, additional scenarios are considered by rotating the volunteer in steps of 90 degrees (see Fig. 4b). This will allow us to conduct measurements with different antenna oreintations and also Non-Line-of-Sight (NLOS) scenarios when the volunteer's head is fully blocking the direct transmission path between the two antennas. As shown in Fig. 4b, both rotation angles of 0 and 90 degrees (i.e., Rot0, Rot90) lead to a Line-of-Sight (LOS) scenario; however, different antenna orientations in these two cases will impact the channel measurements. On the other hand, a rotation angle of 180 degrees (Rot180) will allow us to consider the shadow fading due to the volunteer's head blocking the transmitted signal. When the flexible antenna was used as both on-body and external antenna, the measurements were conducted at the 2.4 GHz ISM band as well as the 3.1-10.6 GHz UWB. However, for cases when the loop antenna is used as the external antenna, measurements were only done for the lower UWB frequency range of 3-5 GHz.

[1] Commercial products mentioned in this paper are merely intended to foster research and understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology.

[2] The experiments were conducted according to the University of Oulu Ethics Committee approval 10/2022 and ITL-2022-0350 at NIST.

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For the on-body channel measurements, two flexible antennas are used on the volunteer's body. The first flexible antenna is placed on the side of the head similar to the location described for the off-body scenaios. The second flexible antenna is initially placed on the edge of the left shoulder (i.e., same side of the body) and then moved down the arm at four other locations until reaching the wrist (see Fig. 4c). Assume that d_i^{LOS} , d_i^B , $i = 1,2, \ldots, 5$ denote the line-of-sight and the shortest body surface distances between the two antennas for scenario i respectively. Distances d_1^{LOS} and d_1^B are graphically illustrated in Fig. 4d. The LOS and body surface distances for all scenarios are listed in Table I.

The off-body measurement scenarios discussed earlier represent wireless communication for a non-invasive brain monitoring or brain computer interface where a head-mounted device collects data from several electrodes and transmits the information to a nearby device with processing capability. To allow further mobility of the user or increase the transmission range of the head-mounted device, another on-body device might be used as an intermediary processing element or a relay. This device may be placed on several locations of the body, e.g., arm or waist.

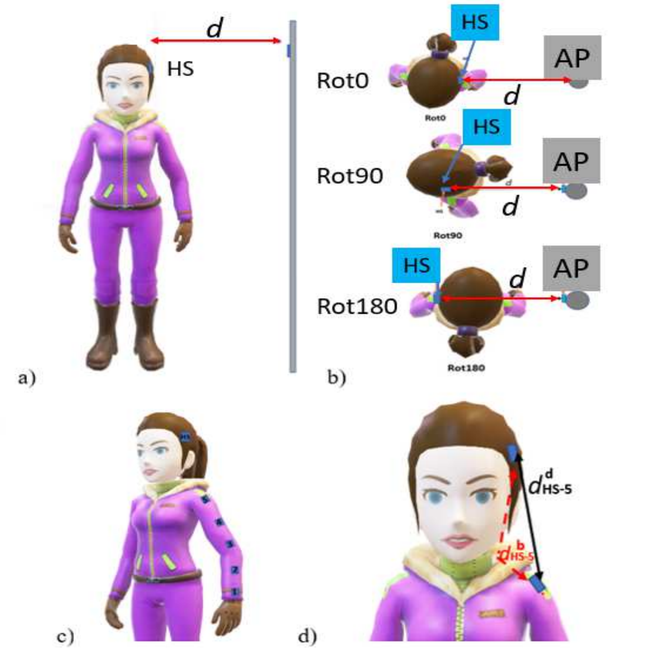


Fig. 4. a) Antenna location on the volunteer's head; b) Off-body measurement scenarios with rotations, c) Antenna locations 1 through 5 for on-body measurement scenarios; and d) LOS and surface distances in the on-body scenario.

TABLE I. Antenna distances in the on-body measurements

Distance	Scenarios				
	1	2	3	4	5
d_i^{LOS} (cm)	78	64	54	40	27
d_i^B (cm)	85	71	61	47	34

III. Off-body Propagation Channel Evaluation

A. *Using the flexible antenna at the external device*

If the flexible antenna is used on the head as well as the extrenal device, the measurement frequency range can be set to (2-10.6) GHz. Although, typically the flexible antenna is only used for on-body purposes, this combination will allow us to study the propagation channel at both 2.45 GHz ISM and (3.1-10.6) GHz UWB frequency bands. The forward transmission coefficient (S21) and Channel Impulse Response (CIR) without any rotation (i.e., Rot0) and distances of 0.5 m and 1 m are displayed in Figs. 5a-b, respectively. These measurements were conducted in a small laboratory environment.

When the distance between the two antennas is 0.5 m, channel attenuation mostly varies between (45-57) dB. However, several deep fades are observed around, 2 GHz, 3GHz and 4 GHz. At 1 m distance, channel attenuation is mostly within 49 dB to 65 dB range with similar occurances of fadings. The fades are likely results of the multipath environment at the small laboratory room where the measurements were conducted, as well as nulls in the antenna radiation pattern. The severe fadings didn't occur when the same measurements were conducted in the anechoic chamber.

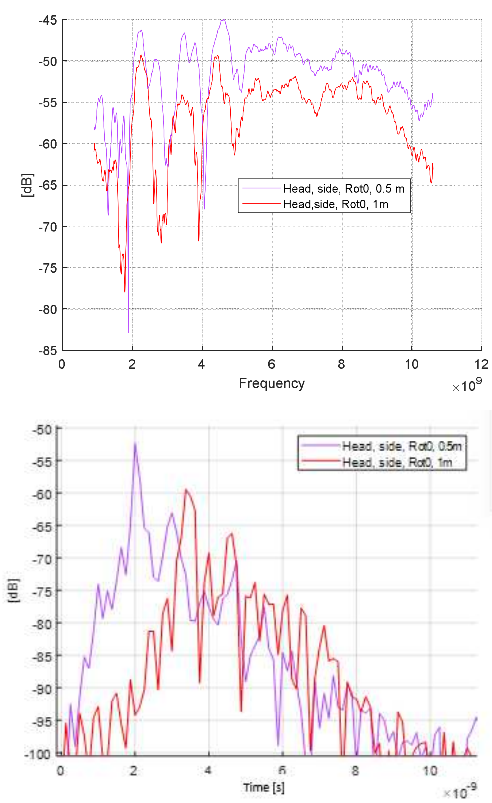


Fig. 5: Off-body channel measurements with the flexible antenna a) Forward transmission coefficient (S21) b) Channel impulse response

B. *Impact of Body Rotation*

The impact of body rotation on the channel attenuation has also been studied according to the scenarios described in Fig.4b at the distance of 1 m. The corresponding S21 parameters and impulse responses are shown in Fig. 6a-b, respectively. As observed, body rotation has a strong impact on the channel attenuation in all frequencies below 10 GHz. Although, line-of-sight (LOS) component exits for both 0 and 90 degrees rotations, and the change in the distance between the two antennas is small; the difference in the resulting S21 is noticeable. This is mostly due to the impact of the antenna radiation pattern on the pathloss between the two antennas and variation in the multipath profile at the receiver antenna. At 180 degrees rotation, the head will be blocking the LOS path and the resulting shadow fading is quite visible in both the S21 and impulse response plots compare to no rotation (i.e., Rot0). An additional delay of around 0.5 ns is also observed for the first arrival path in the CIR corresponding to the Rot180 scenario. This is due to the non-negligible increase in the distance between the two antennas, and NLOS condition. Also, compared to the Rot0, multipath fadings for Rot90 and Rot180 occur at different frequencies.

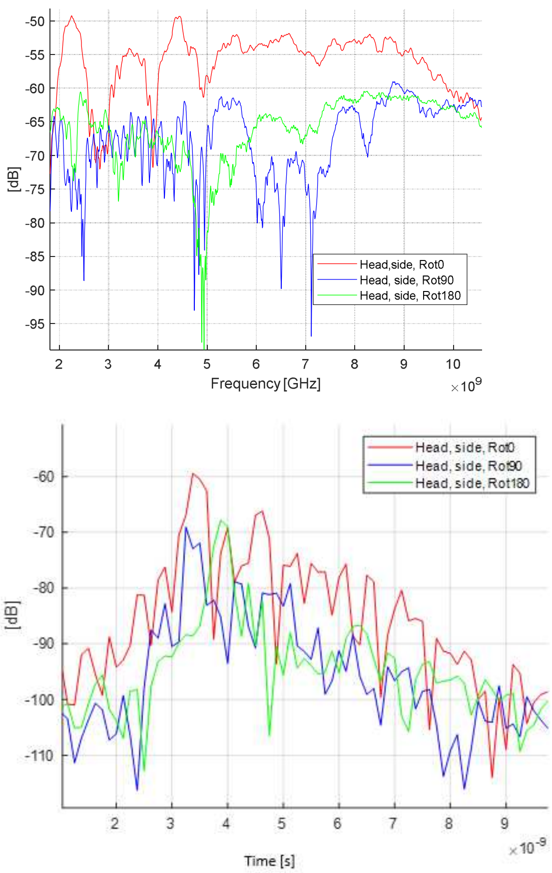


Fig. 6: Impact of body rotation on the channel with flexible antenna a) Forward transmission coefficient (S21) b) Channel impulse response

C. Using the loop antenna at the external device

In this section, the off-body channel characteristics are studied when the loop antenna is used as the external device antenna. The loop antenna has been designed and optimized for on/off-body communication at frequencies between 3 to 5 GHz; therefore, improvements in the channel parameters can be expected with this antenna. The frequency and time domain channel characteristics results are shown in Figs. 7a,b when the distance between the two antennas are changed from 10 cm to 130 cm in steps of 20 cm, respectively. As observed, channel attenuation is relatively flat at short distances within the mesaured frequency band. As the distance between the two antennas increases beyond 70 cm, multipath fading will lead to occurance of several deep fades in the forward transmission coefficient of the channel. As expected, channel attenuation increases with distance. In adition, the timing of the first arrival path in the CIR (corresponding to the LOS component) also increases with the distance between the two antennas. The authors note the slight degredation in the amplitude of the LOS component when the distance is 70 cm. This could be due to the slight and unintentional turning movement by the volunteer during the measurements.

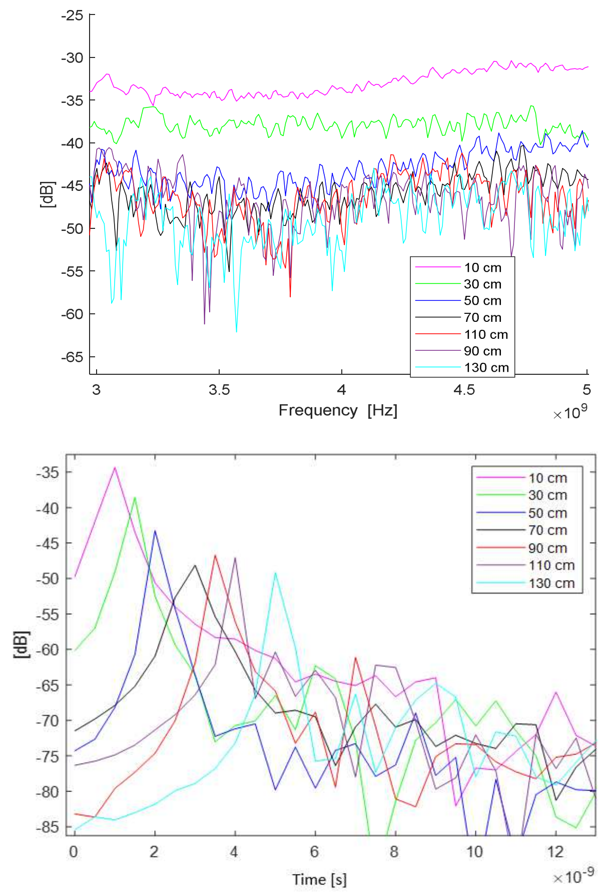


Fig. 7: Off-body channel measurements with the loop antenna a) Forward transmission coefficient (S21) b) Channel impulse response

D. Impact of Body Rotation

The impact of body rotation on the channel attenuation is described in this section. Considering the scenarios described in Fig.4b and the distance of 30 cm, the S21 channel parameters and impulse responses are presented in Fig. 8a-b, respectively. Similar to the results described in section 3.1.1, antenna orientation has a strong impact on the channel response. S21 variations of nearly 18 dB in case of Rot180 and up to 55 dB for Rot90 scenarios are observed across the measured frequency range. This is again due to the antenna radiation pattern and changes in the multipath profile of the channel.

Also, similar to the results with the flexible antenna, there is an additional 0.5 ns delay for the first arrival path in the NLOS channel impulse response corresponding to the Rot180 scenario. However, the timings of the first arrivals in the Rot0 and Rot90 scenarios are almost identical due to minimal change in the distance between the transmitting and receiving antennas.

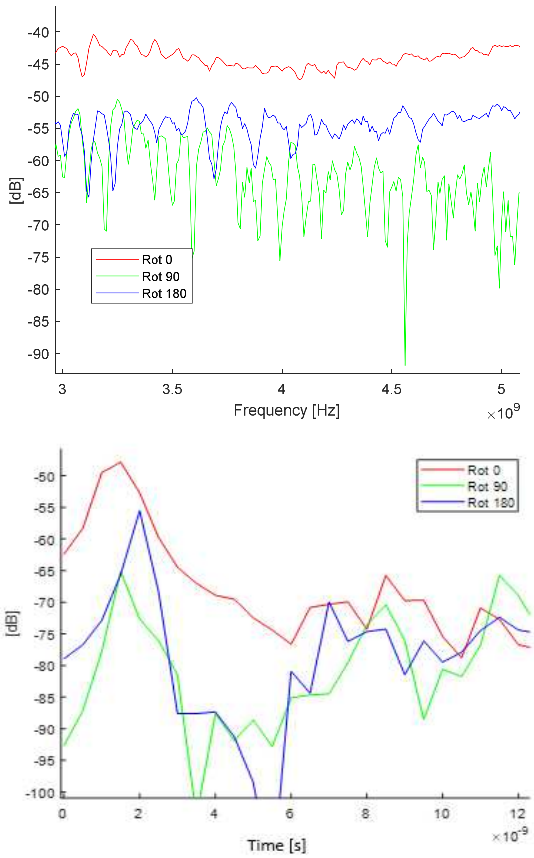


Fig. 8**:** Impact of body rotation on the channel response with the loop antenna a) Forward transmission coefficient (S21) b) Channel impulse response

E. Comparison of the results obtained in the anechoic chamber and small laboratory

In this section, we briefly compare the off-body channel results in the anechoic chamber and the small laboratory. The comparison is for the case when we use the loop antenna at the external device. Fig. 9 shows the channel impulse response for various distances measured in the two environments. As observed, the differences between the impulse responses measured in anechoic chamber and small laboratory are relatively minor for short distances. The minor discrepancies are likely due to the slight unintentional movements of the volunteer during the measurement process. As the distance between the two antennas increases, delayed arrivals due to multipath becomes more visible in the CIR obtained from the small laboratory environment. The equipment and objects in the small laboratory cause reflections and scattering of the transmitted radio waves, leading to a rich multipath environment during the channel measurement. The impact of these multiple paths becomes more evident for higher distances.

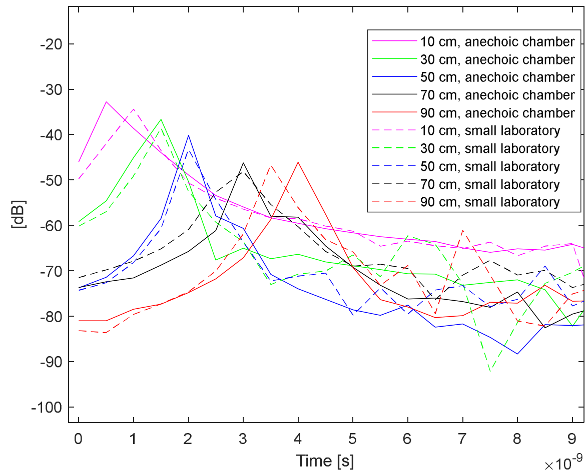
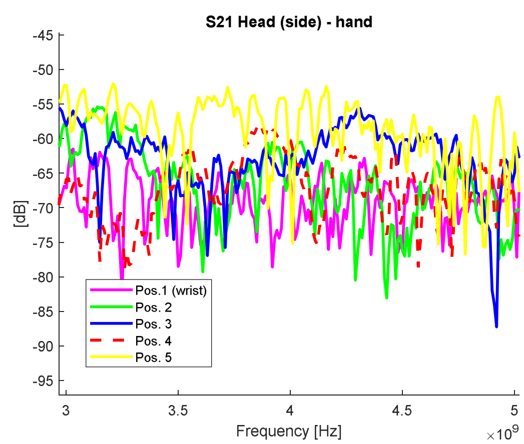


Fig. 9: Comparison of the CIRs obtained from the off-body measurements in the anechoic chamber and the small laboratory.

IV. ON-BODY PROPAGATION CHANNEL EVALUATIONS

In this section, on-body propagation channels are evaluated between the flexible antennas located on the side of the head and the arm as shown in Fig. 4c. The pathloss versus frequency and channel impulse response for each scenario are presented in Figs. 10a-b. As observed, channel attenuation varies significantly along the measured frequency range. In addition to the LOS component, reflections (from nearby objects in the small laboratory room), refractions and creeping waves could lead to a multipath propagation environment which would cause the increase in fading density versus frequency. The impact of the multipath is more visible for larger distances between the two antennas. As seen in Fig. 10b, the LOS component is more noticable for the shortest distance (i.e., when the second flexible antenna is located on the shoulder). On average, channel attenuation across the measured frequency range and scenarios varies mostly between 51 and 62 dB.



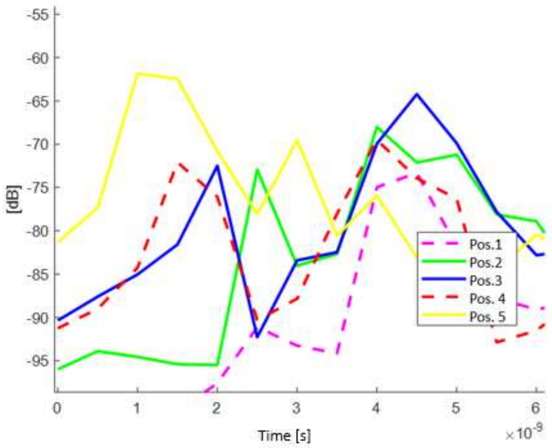


Fig. 10: On-body measurement scenarios with the flexible antenna: a) S21 parameters and b) Channel impulse responses.

V. Conclusions and Future Works

This paper presented a preliminary study of on/off-body propagation channels with a small UWB flexible antenna. The selected scenarios could represent wireless communication for a noninvasive brain monitoring or BCI application where a head-mounted device collects data from several electrodes and transmits the information to a nearby device with processing capability. To allow further mobility of the user or to increase the transmission range of the head-mounted device, another on-body device might be used as an intermediary processing element or a relay. This device may be placed on several locations, however, in this study we have chosen several locations on the arm for on-body measurement evaluations.

The preliminary on-body measurements show promising results with the flexible antenna, even for the channel with the longest distance between the two antennas (i.e., the head-wrist channel). However, it is necessary to conduct more in-depth evaluations with more number of volunteers having different body shapes and sizes. In addition, since the flexible antenna used in this study is linearly polarized, the impact of the hand movements and rotations should also be studied. These evaluations will be part of our future research in this area.

More detailed comparisons between channel measurements conducted in anechoic chamber and small laboratory are needed to better identify the impact of the environment on the channel response. This is especially important for the off-body channel where other objects in the environment causes reflections and scattering of the transmitted signal. We also plan to conduct more extensive measurements in different environments and antenna types and body locations. Those measurements will provide the necessary information to obtain a statistical channel model for a wireless BCI use case.

Acknowledgment

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