Over-The-Air Evaluation of User Body Loss for Popular In-Ear Bluetooth Earbuds

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Over-The-Air Evaluation of User Body Loss for Popular In-Ear Bluetooth Earbuds

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Wireless earbuds have become the preferred electronic device for listening to music and for hands-free talking. The combined radio performance of the earbud and the handset determines the quality of the established communication link and hence the quality of the user experience. This paper presents an extensive comparative study of five common Bluetooth earbuds, where the transmit performance, in terms of total radiated power (TRP), is investigated. The measurements are conducted for the right-side earbud and for the low and high ends of the Bluetooth frequency spectrum. Moreover, two scenarios are considered; 1) the earbud is placed in free space; and 2) the earbud is placed in a person's ear. For the latter case, a total of 12 volunteers are involved in the measurement campaign. Measurements show that the mean performance deterioration, due to the placement of the earbud in the person's ear, ranges from 3 to 6 dB across the tested earbuds.

I. INTRODUCTION

Bluetooth in-the-ear headsets, also referred to as earbuds, have become hugely popular in recent years. This trend is only expected to continue, as technology moves towards smart headphones or "hearables" [1]. The popularity of earbuds is mainly due to features, such as comfortable in-the-ear fit, compact size, meaning that they are easy to carry even when not in use, and reasonable battery life. However, because of the small size of the earbuds, all internal components, such as Bluetooth chip, amplifiers, antenna, battery, power management system, microphone, speaker, etc., needed for the operation of the device, are tightly packed. One of the consequences of this compactness is that only a very limited volume is available for the deployment of the antenna. The restriction on the volume puts fundamental limits on the achievable performance of such an electrically small antenna [2], [3]. It has been shown that coupling between an electrically small antenna and loudspeaker coils can deteriorate the radiation efficiency of the antenna [4]. Also, the battery has an impact on the performance of antennas for wearable devices [5], [6].

Another inevitable performance issue arises from the fact that the antenna of the earbud is located in the direct vicinity of the human body and therefore interacts with the biological tissue. It is well known that the presence of lossy human tissue near the antenna can significantly degrade antenna performance [7]–[10]. Specifically, the presence of lossy human tissue in the near-field of the antenna leads to a shift in the resonant frequency and absorption of part of the transmitted power. Also, the proximity of the human body to the antenna distorts the radiation pattern. All these effects can be further compounded by the fact that the antenna is small, i.e. the antenna is more vulnerable [11]. It should be mentioned that the detrimental effect of the user presence depends on the actual design of the employed antenna [10]–[13].

Multiple studies of the user effect on mobile terminal antennas have been presented in the public literature, and some of them can be found in [7]–[10], [12], [14]. Investigations of the user impact on body-worn antennas have also been conducted [11], [15]–[17]. A few studies on headset performance as well as antenna design for applications, such as headsets and hearing-aids, have also been reported [5], [6], [13], [18]–[25].

To ensure a reliable connection between a mobile terminal and an earbud, link budgets for both up- and down-link must be satisfied. When designing an antenna intended for use in an earbud device it is important to consider the user impact, just as for mobile terminal antennas. A poorly designed antenna can result in intermittent signal loss, leading to loss of audio packets, and therefore reduced audio quality. In severe cases, the Bluetooth link may even disconnect, with complete music or conversation interruption as a result. To prevent the occurrence of such malfunctions, the RF performance of each type of earbud needs to be tested in the most critical scenario, namely, when the device is placed in a person's ear, that is in the vicinity of lossy biological tissue.

This paper provides a comprehensive comparative study of the impact that the human body has on the real-life radio performance of a set of commercially available earbuds. So far, to the authors' best knowledge no such work has previously been presented in the open literature. The systematic investigation of the user effect, presented in this paper, provides information about the expected decrease, overall and in specific directions, of the signal strength due to user presence. This knowledge is valuable to antenna designers as it reveals how the user affects different earbud radiator implementations, thereby enabling the designer to consider their structures. The presented work is also important to the industry as the presented comparative study allows companies to see how their earbud performs in relation to other competing products. The experimental setup and the designed measurement system for the study are of interest to other researchers needing to conduct similar investigations.

From the public literature, it is clear that a lot of effort has gone into radio channel modeling for body-area-network (BAN) applications [26]–[29]. For the present study, the channel is static and body shadowing therefore does not vary over time. Evaluation of time-varying body-shadowing is only possible if the earbuds are operating in test mode, which unfortunately is not available for commercial products. Further, the radiation performance is measured in terms of

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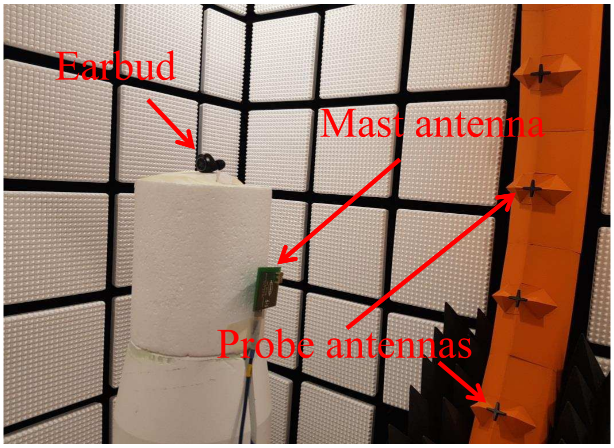


(a)

(b)

Fig. 1: Setup for testing the transmit performance of the right-side earbud placed in: (a) free space, and (b) right ear of a volunteer.

Total Radiated Power (TRP) and no specific path loss (S_{21}) performance is measured. No comparison to existing BAN path loss channel models is therefore possible. It should be mentioned that the earbuds are commercial devices and not prototypes and therefore the available information about their internal structure, such as e.g. antenna design is very limited. The variety of tests that can be conducted with such final products is limited in comparison to cases where a mock-up, which can be fully controlled, is used. Therefore, this paper solely focuses on the adverse effect that the body of a user has on the antenna performance of selected commercial earbuds.

This paper presents the results from a study of the radio performance of five popular and commercially available earbuds. The TRP of the earbuds is first measured in free space and subsequently in the presence of a person. A total of 12 volunteers were involved in the investigation. The change in the radiation pattern, when the earbud is placed in the user's ear, compared to the free space case, is discussed. Body loss is evaluated for each test case as this parameter combines and captures all effects of the user on the radio performance of the device. Therefore, body loss measurements can be used to compare the impact of the human body on the antennas of the different earbuds.

(a) (b) (c) (d) (e)

Fig. 2: Positions of the earbud antennas marked with red ellipse; (a) Beoplay E8 2.0, (b) Earin M2, (c) Bose soundsport free, (d) Apple Airpods 2, and (e) Beoplay E8 3rd Gen.

II. Performance Indicators

An earbud's ability to radiate power is, as mentioned, evaluated by the TRP metric. The TRP is a parameter adopted to evaluate the overall transmit performance of commercial wireless devices [12], [30]. The TRP is a gain-related parameter comprising the sum of all power radiated by a device, regardless of direction and polarization, averaged over the sphere, and it is calculated as [30]:

$$TRP = \frac{1}{4\pi} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \big(EIRP_{\theta}(\theta,\phi) + EIRP_{\phi}(\theta,\phi)\big) \sin(\theta) d\theta d\phi, \quad (1)$$

where EIRP is the Effective Isotropic Radiated Power. A higher TRP means that the earbud is capable of radiating more power.

In this paper, the TRP performance is evaluated for both free space and when the earbud is placed in the right ear of the volunteer. The two scenarios are illustrated in Figs. 1(a) and (b) respectively. The right-side earbud is used since it usually serves as a master for coupled-pair earbuds. Free space is here defined as the case where the earbud is mounted with no close-by objects around. In free space, the antenna's ability to radiate and collect a radio signal is generally better than when the antenna is in the vicinity of a user. Having results for both free space and in a user's presence, makes it possible to evaluate the impact of the user on the antenna operation. The difference between antenna performance in free space and when in presence of a user, is referred to as body loss [10].

To enable a comparison of radiation patterns for free space and user presence cases, the free space orientation of the earbud is kept similar to the orientation the earbud has when placed in a person's ear. However, perfect alignment between the two cases is not possible due to difference in pinna size and shape of the different volunteers, i.e. the in-ear orientation of the earbud for each volunteer is slightly different. This means that different free space orientations would be needed for each volunteer, which has not been ensured in this work. Volunteers also differ in body size, which leads to differences in the propagation distance (loss) to the different measurement probes in the anechoic chamber. However, these effects are inevitable in such a study and it is assessed that they have only a very limited impact on measurement results and that they, therefore, do not influence the conclusions of the study.

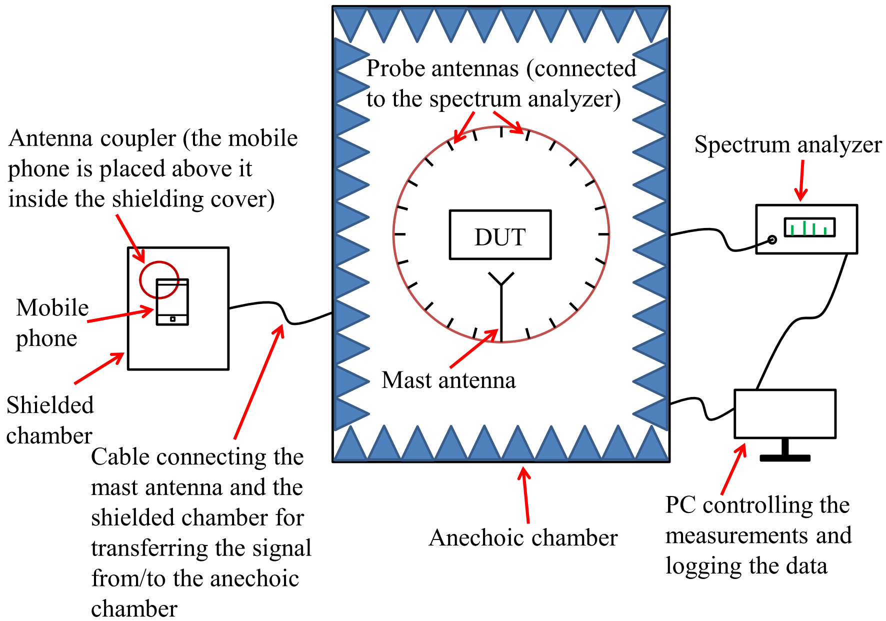
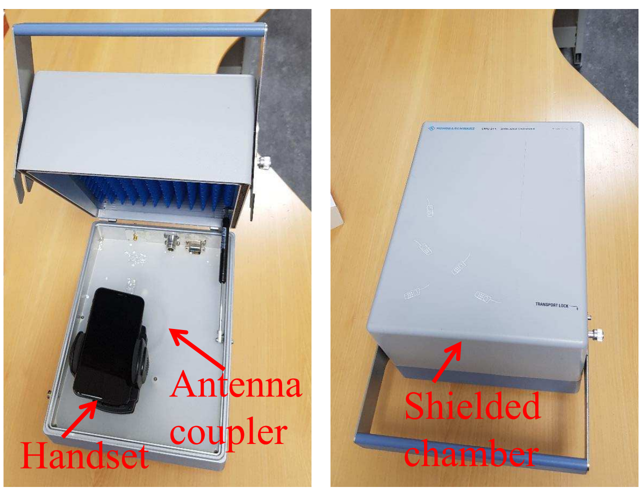


Fig. 3: Overview diagram of the measurement system. DUT is acronym for device under test.



(a) (b)

Fig. 4: Shielded chamber with; (a) open and (b) closed lid.

As shown in Fig. 1(b), the volunteers were sitting on a special chair during the test. In total, 12 volunteers were involved in the measurement campaign. The range of heights of the volunteers spans from 1.62 m to 1.91 m, while the weight of the volunteers ranges from 48 kg to 94 kg. Therefore, the group of volunteers introduces a large spread in terms of body sizes, which is beneficial for the investigation. The spread means that the findings of the presented study are representative in terms of user impact from a real customer population and therefore provides realistic estimations of earbud performance.

The earbuds used in the study are the Beoplay E8 2.0, Earin M2, Bose soundsport free, Apple Airpods 2, and Beoplay E8 3rd Gen as shown in Fig. 2. Since the earbuds are all commercial products, the available information, such as model of each earbud internal structure, antenna structure, and placement is very sparse. To qualify the reported measurement results, efforts were made to seek information about the different antennas and their location in the evaluated earbuds. All discussions below are based on information found in photos at the FCC website [31]. Looking at the photos of the internal structure of the earbuds, as provided at the FCC website, the following information about the used antennas was obtained; 1) Bose soundsport free uses an antenna resembling a planar Inverted-F Antenna (IFA), where the arm has a meander shape; 2) the antenna in the Earin M2 is a planar strip monopole but the precise structure cannot be determined from the photos; 3) both Beoplay E8 2.0 and Beoplay E8 3rd Gen have planar strip monopole antennas; and 4) for Apple Airpods 2, the photos do not show the type of antenna used. As already mentioned, no detailed performance information is available for the different antenna implementations. The approximate positions of the antennas inside the earbuds, as indicated in Fig. 2, are again based on photos provided at the FCC website. For the different earbuds, clear differences in antenna positioning can be seen.

III. Test Methodology

The measurement system contains multiple modules, as shown in the overview in Fig. 3. The Over-the-Air (OTA) measurement of the radiated power was conducted in a shielded anechoic chamber using a spectrum analyzer (Agilent E4440A) along with a multi-probe Satimo StarGate 24 system (SG24), produced by Microwave Vision Group (MVG). The SG24 system consists of 23 measurement probes distributed on a supporting ring. The power received by each of the probes was measured using the spectrum analyzer operating in zero-span mode with a bandwidth of 8 MHz; this is the maximum bandwidth of the used spectrum analyzer in this mode. Measurements over two 8 MHz wide frequency bands, centered at 2.406 GHz and 2.476 GHz, were performed, i.e. over the bands from 2.402 GHz to 2.410 GHz and from 2.472

GHz to 2.480 GHz. The lowest Bluetooth channel starts at 2.402 GHz, while the highest one stops at 2.480 GHz. The guard bands are positioned at 2.400 - 2.402 GHz and 2.480 - 2.4835 GHz. That is, measurements were conducted at the lowest and highest end of the Bluetooth spectrum. As the Bluetooth wireless technology standard supports 79 channels (1 MHz spacing), a total of eight channels (at each end of the spectrum) were measured simultaneously with this setup.

To counteract interference problems, the Bluetooth standard uses frequency-hopping spread spectrum technology based on a pseudo-random hopping pattern with 1600 hops per second. These 1600 hops per second are distributed across all 79 channels. As a direct consequence of this, it is to be expected that the signal occupies any given channel an average of approximately 20 times per second.

With the implemented measurement system, the spectrum analyzer records an 8 MHz band (eight channels) multiple times for a period of one second; one second is the time duration used to listen to one 8 MHz band per probe and polarization. From each recording, the peak value of the received signal is only kept. Due to the frequency hopping, an active Bluetooth signal is not always present within these 8 MHz during each recording. In such instances, only noise was recorded. However, the measurement setup guarantees that for the duration of the full one-second measurement period multiple signals were caught, i.e. no completely blank measurement instances would result. Among all detected signals for the one-second duration, the strongest signal was only kept and used for the TRP evaluation.

Before testing, the system was calibrated using a reference antenna. Both the SG24 and the spectrum analyzer were connected to a PC with software (Satimo Multi Measurement developed by MVG) for controlling the measurement and for logging data. The mobile phone (iPhone X), connected to the earbud, was placed in an RF shielded chamber (Rohde & Schwarz CMU-Z11), as shown in Fig. 4(a). More precisely, the handset was placed above an antenna coupler inside the RF shielding cover, which is located outside the anechoic chamber. The signal emitted by the handset is first received by the antenna coupler in the shielded chamber. Then, through a cable, this signal is passed to the mast antenna (see Fig. 3), placed inside the anechoic chamber. From here the signal is then finally wirelessly relayed to the earbud. In a reverse way, a signal is passed from the earbud to the mobile phone. During measurements, the shielding cover was closed (see Fig. 4(b)) in order to significantly attenuate any interference signals. The latter is crucial because the presence of any strong interference signal from other transmitters might force the handset to stop, through adaptive frequency hopping, using the channels of interest (within the measured 8 MHz bands). If the latter happens then - as mentioned - only noise would be measured. Further, all volunteers were asked to turn off the Bluetooth on their wireless devices, when sitting in the chamber, in order to remove any corruption of the measurement results. Uninterrupted communication between the earbud and handset was ensured by continuously playing music on the earbud. That is, the handset was sending sound data to the earbud and the earbud was sending acknowledgment packets to the handset.

In both cases, free space and in the presence of a person, the mast antenna was located close to the earbud, as shown in Fig. 1, to establish and keep the communication link. This is needed since the received signal (depending on the direction of communication it is received by the earbud or handset) is quite weak due to loss in the antenna coupler as well as propagation loss in both wired and wireless signaling. Also, less than optimal efficiency of handset, mast, and earbud antennas introduces extra signal attenuation. That is, if the mast antenna is located further away from the earbud, no connection can be established.

It should be mentioned that the Bluetooth signal of the handset passed to the mast antenna and transmitted by the latter inside the anechoic chamber was measured and the TRP was approximately -25 dBm. This signal is very weak and therefore does not affect the measurement results, as the TRP of the earbud is significantly higher.

The power transmitted by the device under test was measured successively by each probe, distributed on the ring in the elevation plane (see Fig. 1), for each polarization (as already mentioned one measurement, per probe and polarization and for one 8 MHz band, takes one second). Then, the mast/chair was rotated along the azimuth and the power was measured again. This process continued until the full sphere was covered and then the resulting TRP value was finally evaluated using the measured EIRP values. Each measurement was done with 15° of resolution in elevation and with 30° of resolution in azimuth. These values were selected as a trade-off between measurement time and density of the measurement points, i.e. more points means that the persons have to stay longer in the chamber. A full spherical measurement for one 8 MHz wide frequency band takes several minutes. Therefore, to reduce measurement time, only the low and the high end of the Bluetooth spectrum was measured.

IV. Results and Discussion

The central frequencies, 2.406 GHz and 2.476 GHz, are used below for designating the results from the measurements conducted over the bands 2.402 - 2.410 GHz and 2.472 - 2.480 GHz, respectively.

A. Free space measurements

Free space results for TRP measurements for each of the tested earbuds are shown in Table I. Most of the earbuds show distinct differences in the transmit performance at the two ends of the spectrum.

Earbud	TRP (dBm)		Δ (dB)
	2.406 GHz	2.476 GHz	
Beoplay E8 2.0	-7.2	-6.5	0.7
Earin M2	-2.5	-5.6	2.9
Bose soundsport free	-1.2	2.3	1.1
Apple Airpods 2	-1.0	2.3	1.3
Beoplay E8 3rd Gen	-2.6	2.7	0.1

TABLE I: Measured TRP of the right-side earbuds in free space.

Generally, the devices perform better at higher frequencies except for Earin M2, which is the only device showing higher

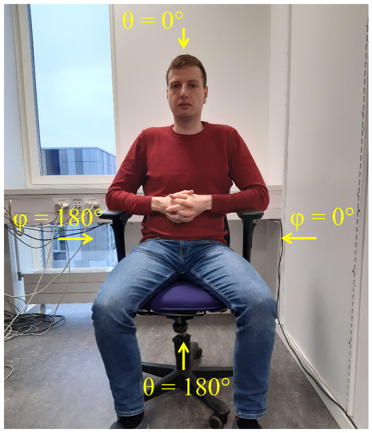


Fig. 5: Coordinate system used in the measurements.

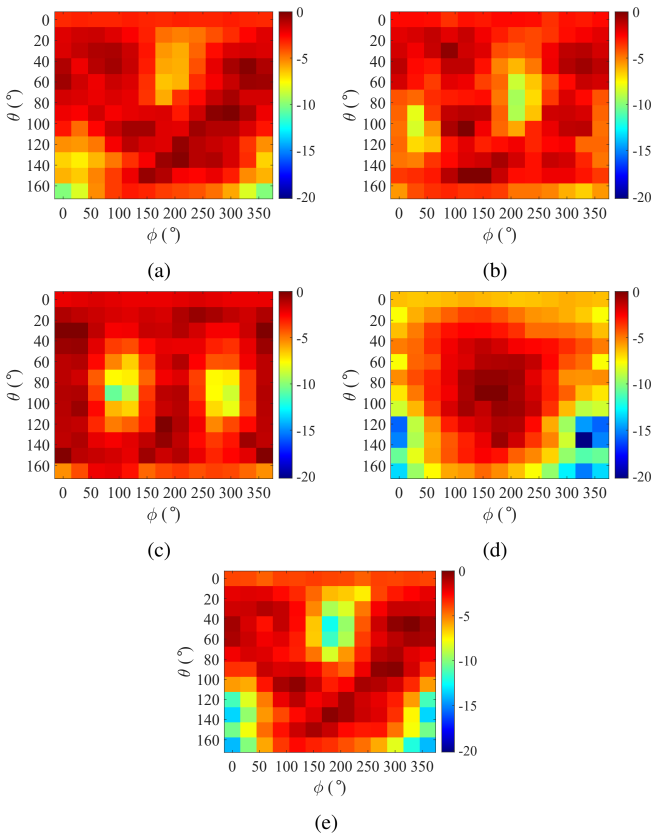


Fig. 6: Normalized measured EIRP (in dB) radiation pattern of the right-side earbud in free space at 2.406 GHz; (a) Beoplay E8 2.0, (b) Earin M2, (c) Bose soundsport free, (d) Apple Airpods 2, and (e) Beoplay E8 3rd Gen.

TRP at the lower frequency. The differences in measured TRP values and low versus high frequency performance among the tested devices are due to different feeding power and design of the earbuds antennas.

An example of the test setup in the anechoic chamber is shown in Fig. 1(a). As already mentioned efforts were made to have the orientation of the earbud in free space similar to the in-ear orientation. For better visualization, the coordinate system used in the measurements in the anechoic chamber is presented with respect to a sitting person as shown in Fig.

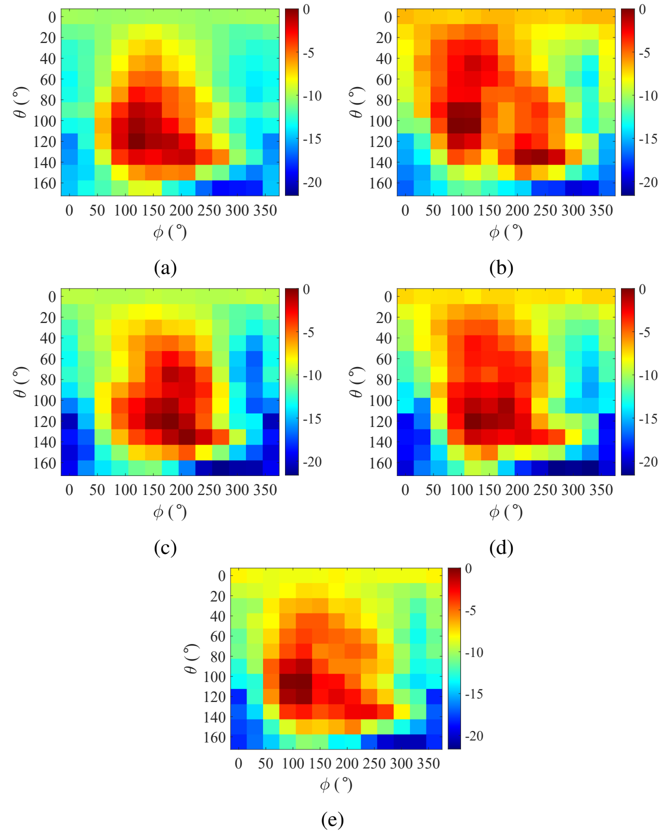


Fig. 7: Normalized mean measured EIRP (in dB) radiation pattern of the right-side earbud, when placed in the right ear of the volunteer, measured at 2.406 GHz; (a) Beoplay E8 2.0, (b) Earin M2, (c) Bose soundsport free, (d) Apple Airpods 2, and (e) Beoplay E8 3rd Gen.

5. The normalized measured EIRP radiation patterns of the earbuds in free space, measured at 2.406 GHz, are shown in Fig. 6. All presented results are obtained through measurement as follows; 1) the EIRP radiation patterns are measured in the anechoic chamber; and 2) for each of the earbuds the radiation patterns are normalized to the maximum value for that earbud. Presenting the measurement results in this way allows for an easy comparison of radiation patterns between the earbuds. The correlation between the earbud radiation patterns at 2.406 GHz and 2.476 GHz is quite high - the lowest value is found to be 0.93. Therefore, the shape of the radiation pattern changes insignificantly across the Bluetooth frequency band. However, a difference in the shape of the radiation patterns among the earbuds is observed. Here, out of all the tested devices, Apple Airpods 2 seems to have the most directional radiation pattern, pointing away from the direction where the user's head would be present.

B. *Measurements in the presence of a user*

TRP measurement results for when the earbud is placed in the volunteer's right ear are presented in Table II. It is observed that the spread is larger for the smaller-sized earbuds (Beoplay and Earin). An explanation for this could be that their antennas experience a stronger impact from differences in the shape and size of volunteer's pinna. This larger impact could result from the smaller distance between antenna and pinna in comparison to the same distance for the larger earbuds - Apple Airpods 2 and Bose soundsport free (see Fig. 2). The differences in TRP between the earbuds are a result of a combination of different antenna designs, different degrees of user impact, which depends on antenna design and placement, and different levels of input power.

Fig. 7 shows the normalized mean measured EIRP radiation pattern, as averaged across all volunteers, for each earbud at 2.406 GHz. As in free space, the correlation between the radiation patterns at 2.406 GHz and 2.476 GHz is quite high - the mean correlation is here 0.96 when averaged across volunteers and earbuds. It can be seen that the mean radiation patterns of the earbuds have similarities. More specifically; 1) the lowest correlation is 0.82 at 2.406 GHz and 0.84 at 2.476 GHz; 2) the mean correlation across all earbuds is 0.92 at both 2.406 GHz and 2.476 GHz; and 3) the highest correlation is 0.96 at 2.406 GHz and 0.95 at 2.476 GHz. These results show that user presence tends to uniform the shape of the radiation pattern of the earbud antennas even though they have different designs and placements. This uniforming is a result of the signal blockage from the user's body.

C. Body loss

It is of great interest to study how much the antenna performance is affected by the presence of the user. To this end, the body loss parameter shows the performance deterioration of the system, when it is placed in the vicinity of the human body. The body loss is independent of the direction of communication, meaning that it has the same value no matter if the device is tested in the transmit or receive mode. Since this parameter, in our case, is defined as the difference between the power transmitted by the antenna in free space and that in the presence of a user, the actual power level at the port antenna is not important, since it is the same in both cases and therefore is subtracted. Hence, body loss is a very useful tool for comparing earbuds based on their susceptibility to user presence.

The distribution of the mean, averaged across all volunteers, body loss at 2.406 GHz over the measured angles is shown in Fig. 8. A higher body loss value means that the user has a stronger impact on the antenna performance. A negative body loss means that in a certain direction the radiation is higher in the presence of a user than for free space. As one can see, large variations in the body loss among the earbuds is observed.

Table III shows the measured body loss for each earbud. The standard deviation is the same as for the TRP measurements in presence of a volunteer (see Table II). In terms of mean value, Apple Airpods 2 shows the lowest body loss at both frequencies, while Earin M2 has the highest one at 2.406 GHz and Beoplay E8 3rd Gen at 2.476 GHz. The largest difference in the mean body loss across devices is 3 dB. At 2.406 GHz: 1) Bose soundsport free has 3 dB minimum body loss while Apple Airpods 2 and Beoplay E8 3rd Gen have 1 dB, and 2) Earin M2 has 12 dB maximum body loss compared to 5 dB for the Bose soundsport free and Apple Airpods 2. At 2.476 GHz: 1) Beoplay E8 2.0 has 2 dB minimum body loss while Bose soundsport free has 4 dB, and 2) Beoplay E8 2.0 has 10 dB maximum body loss compared to 6 dB for Apple Airpods 2. Differences between max and min values of up to 9 dB at 2.406 GHz and up to 8 dB at 2.476 GHz are observed.

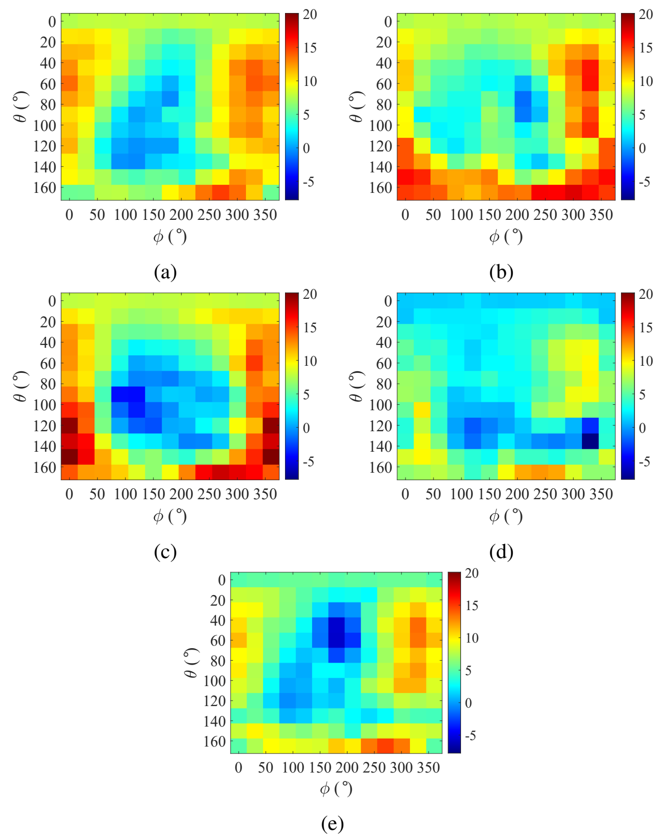


Fig. 8: Mean body loss pattern (in dB) at 2.406 GHz; (a) Beoplay E8 2.0, (b) Earin M2, (c) Bose soundsport free, (d) Apple Airpods 2, and (e) Beoplay E8 3rd Gen.

From Fig. 6 it can be seen that the antenna design for the Apple Airpods 2 is more directional, when measured in free space, than the other devices tested. The direction of maximum radiation for the Apple Airpods 2 is away from the intended user, as Fig. 6(d) shows. Looking at Fig. 7 it is found that all tested devices show similar in shape radiation patterns when measured in the presence a volunteer. The directionality of the radiation can here be attributed to the body shadowing of the volunteers. Comparing Figs. 6 and 7 it is evidently seen that the Apple Airpods 2 device is least affected by the user body when radiation characteristics are considered. This is also supported by the results listed in Table II, where the Apple Airpods 2 shows the lowest mean body loss value.

Taken all together, most of the earbuds show higher body loss at higher frequencies, i.e. the antenna performance is more affected at the high end of the Bluetooth spectrum.

V. Conclusion

In this paper, an extensive comparative study of the performance of five popular earbuds is presented. The measurements are based on the participation of 12 volunteers, which provides for a reasonably large data set, and therefore it is possible to present a representative finding of user body impact on the earbud's performance.

Earbud	TRP (dBm)					
	2.406 GHz			2.476 GHz		
	min	mean ± std	max	min	mean ± std	max
Beoplay E8 2.0	-16.7	-12.1 ± 2.5	-8.9	-16.5	-11.4 ± 2.4	-8.2
Earin M2	-14.2	-8.3 ± 2.2	-5.3	-14.7	-11.2 ± 1.6	-8.6
Bose soundsport free	-5.7	-5.0 ± 0.5	-4.3	-5.6	-2.8 ± 1.1	-1.3
Apple Airpods 2	-5.6	-3.5 ± 1.2	-2.2	-3.9	-1.5 ± 1.1	-0.3
Beoplay E8 3rd Gen	-9.0	-6.4 ± 1.7	-3.9	-6.0	-3.4 ± 1.9	0.0

TABLE II: Measured TRP when each earbud is placed in the right ear of the volunteer.

Earbud	Body loss (dB)					
	2.406 GHz			2.476 GHz		
	min	mean	max	min	mean	max
Beoplay E8 2.0	1.7	4.9	9.5	1.7	5.0	10.0
Earin M2	2.8	5.8	11.7	3.0	5.6	9.1
Bose soundsport free	3.1	3.8	4.5	3.6	5.1	7.9
Apple Airpods 2	1.2	2.5	4.6	2.6	3.8	6.2
Beoplay E8 3rd Gen	1.3	3.9	6.4	2.7	6.2	8.7

TABLE III: Results for the evaluated body loss for the earbuds.

Measurements of the transmit capabilities of the earbuds in free space, and when placed in a person's right ear, have been conducted over two 8 MHz bands centered at 2.406 GHz and 2.476 GHz. Most of the earbuds have a higher radiated power at the lower frequency. The biggest observed difference in the TRP between the low and high frequency band is 5 dB in free space and 3 dB (using the mean values) in the presence of a person. The larger-sized earbuds demonstrate a lower variation in TRP in the presence of a person. The user presence alters the radiation patterns and thereby significantly reduces the differences between the earbuds in that regard. In free space and in the presence of a user, each earbud demonstrates similar radiation patterns at the low and high ends of the Bluetooth spectrum.

In order to asses the user impact on antenna performance, the body loss parameter has been evaluated. The difference in the body loss among the earbuds is due to the different antenna designs and placements. The largest difference in mean body loss found between the two frequencies is less than 2.5 dB. The lowest body loss measured is 1 dB while the highest one is 12 dB.

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