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Over-the-Air Evaluation of the Antenna Performance of Popular Mobile Phones

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ABSTRACT Mobile terminals have become an integral part of people's everyday life. The ability of the handset to transmit and to receive power determines how good communication link it can establish. This paper presents results from a comprehensive study on the radio performance, in terms of total radiated power (TRP) and total isotropic sensitivity (TIS), of 16 mobile terminals, common in the Nordic countries, in different use scenarios - free space, talk mode using right and left hand phantom next to head phantom, and data mode with right hand phantom. The phones are tested following the standardized non-invasive procedure for 2G, 3G and 4G communication standards. It is found that there is a large spread in the performance among the tested phones even in free space (up to 9 dB for TRP and up to 5 dB for TIS) and the case is more severe when the user is located next to the handset. The results indicate that the vicinity of the user to the mobile terminal can lead to degradation up to 22 dB in the transmit performance and up to 8 dB in the receive performance.

INDEX TERMS Mobile phone, antenna, user effect, body loss, OTA, talk mode, data mode, TRP, TIS.

I. INTRODUCTION

The RF performance of a mobile phone is an important factor since it influences the network coverage area. Therefore, the ability of the handset to transmit and receive power, which affects the radio link budget, is crucial in the cell planning stage of any mobile communication system. Apart from the quality of connection, the communication performance of the mobile terminal also influences the lifetime of the battery.

An inherent problem for the handset antennas comes from the fact that they operate in vicinity of the human body and interact with the biological tissues. It is well known that the presence of a user lossy tissue in close proximity to the mobile phone antenna can significantly deteriorate its performance [1]–[3]. In general, the presence of a human tissue near the mobile phone changes the input impedance of the antenna which in turn changes the amount of power accepted by the antenna. Part of the power radiated by the antenna is absorbed in the tissue and therefore the radiation efficiency of the antenna is reduced. The change in the distribution of the electromagnetic field generated by the antenna due to the close proximity of human body leads to change in its radiation pattern. The detrimental effect of the human body depends on the design of the used antenna [3]–[9]. Furthermore, it has been shown that the degree of degradation strongly depends on factors such as position of the fingers of the hand with respect to the antenna (hand grip), hand size, distance palm - mobile terminal (study of mobile terminal grip styles over a sample population of 100 subjects has been presented in [10]) [4]–[7], [11]–[15]. In this work, however, we are not looking into this aspect, which has been covered by the literature, but rather into the difference in the performance between common models of handsets when using standardized phantoms of human head and hand.

The over-the-air (OTA) testing of mobile terminals equipped with single antenna system has been standardized by the Cellular Telecommunications & Internet Association (CTIA) [16]. The standard for testing mobile phones has been introduced in order to unify the procedure used by different researchers to conduct the study. The parameters under test, used to characterize the transceiver's performance and compare the handsets, are the total radiated power (TRP) relevant to the uplink (the phone is transmitting and the base station is receiving) and the total isotropic sensitivity (TIS) relevant to the downlink (the base station is transmitting and the mobile phone is receiving). In order to investigate the

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influence of the user, the latter is mimicked by a phantom of human head (specific anthropomorphic mannequin) and hand (with a certain grip depending on both form factor of the handset and its mode of operation) located next to the mobile terminal during the measurement. The position and orientation of the handset in the hand phantom and next to the head phantom have also been standardized for ensuring repeatable measurements and comparability of the transceiver's performance of different mobile phones.

The OTA testing of handsets is often referred to as an antenna test, even though the study includes more than the antenna itself. The transmitter and receiver electronics are also involved in the analysis but because they must fulfill the requirements for the technology standards, the variation in their performance among different phones is typically low. Due to that the main difference in the performance among the handsets comes from the antenna design [17], [18].

The consideration of the user effect, due to the natural use of the mobile phones next to the human body, is an important step in the designing process of any antenna intended to be used for handsets. The antenna performance is vital for the mobile terminal ability to ensure radio coverage in a low signal condition as a good antenna design can make the difference between having a network connection or not [18]. In order to ensure a connection between the handset and the base station, both uplink and downlink link budgets should be satisfied as the weaker between them determines the radio coverage [19]. According to information from the Danish Energy Agency, the weakest link for voice service is typically the uplink, while for data services it is typically the downlink [19]. Due to this, in the presented paper is investigated the transmit performance (TRP) for voice service and the receive performance (TIS) for data service since these are the crucial links in low signal conditions.

The aim of this paper is to provide data for the ability of 16 mobile phones (the list of models, used in the study, common in the Nordic countries over the last years was provided by the Danish Energy Agency) to transmit and receive power. It should be mentioned that the work presented in this paper is a follow-up on similar tests conducted for phones common in the market at the time of publishing the results, see [17]–[22].

II. PERFORMANCE INDICATORS

The mobile phone's ability to radiate power is determined by the TRP metric. This gain-related parameter is the sum of all power radiated by the mobile device, regardless of direction and polarization. The TRP is defined as [16]:

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

where EIRP is the effective isotropic radiated power. The higher TRP means that more power can be radiated to the base station (the signal is stronger at the base station) and therefore the phone has a better transmit performance (able to provide better connection). In this paper, the TRP is evaluated for voice service for talk mode in two scenarios: 1) phone next to the right-hand side of the head phantom placed in the right hand phantom (beside head hand right - BHHR) as shown in Fig. 1(a); and 2) phone next to the left-hand side of the head phantom placed in the left hand phantom (beside head hand left - BHHL) as shown in Fig. 1(b). The reason to study both BHHR and BHHL was to investigate the difference in the performance of the handsets for different use positions.

The mobile phone's ability to receive power is determined by the TIS metric. This gain-related parameter is a measure of the minimum power which has to be received by the mobile device in order to maintain a reliable communication [i.e. above some threshold for the bit error rate (BER)], assuming that the incident power is coming from all directions and for both polarizations. The TIS is defined as [16]:

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

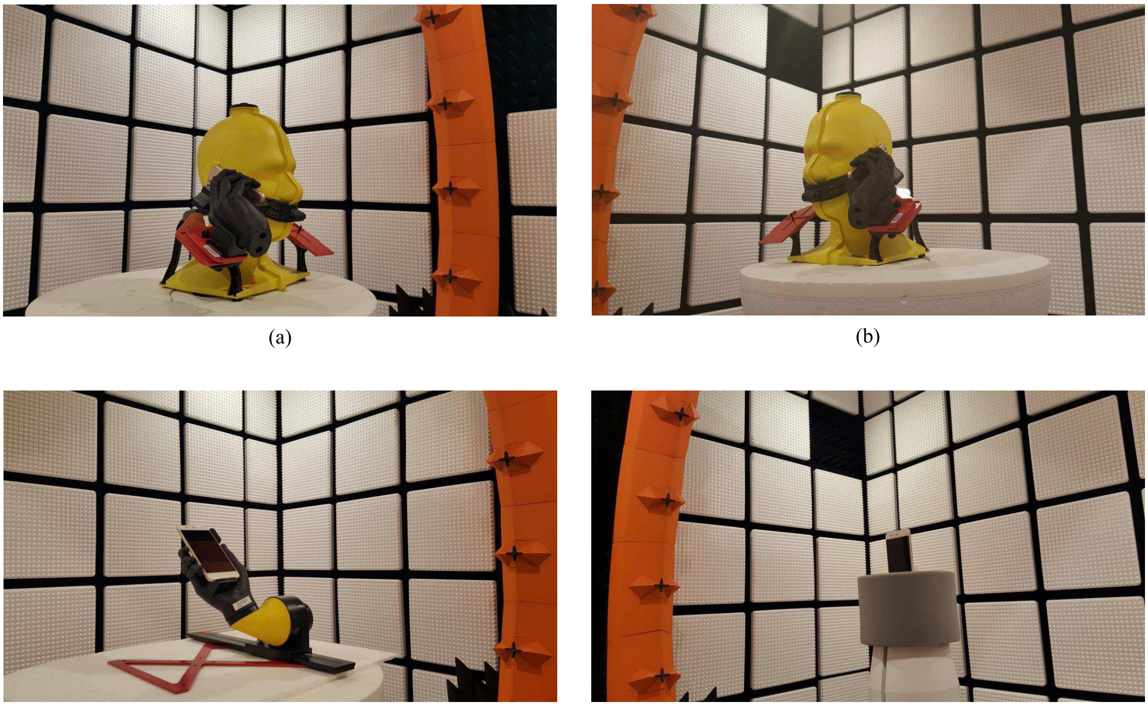
where EIS is the effective isotropic sensitivity. The lower TIS (more negative) means that less power is needed for maintaining a satisfactory downlink connection and the phone has better receive performance (it can operate in areas with a weaker signal). In this paper, TIS of the mobile terminals is assessed for data service in data mode as the device was placed in right hand (HR) phantom. This scenario is presented in Fig. 1(c).

Moreover, the free space performance (no head or hand present next to the handset; see Fig. 1(d)) of the mobile terminals was also studied. Free space (FS) is the case where the mobile phone is used in e.g. a hands-free installation. The main reason to carry out the FS study was to evaluate the body loss for each phone, i.e. to investigate the degradation in the transmit and receive performance due to the close proximity of the user to the handset [7].

III. TEST METHODOLOGY

The OTA test was conducted by using two radio communication testers from Rohde & Schwarz (CMU200 for GSM and UMTS bands, and CMW500 for LTE bands) along with Satimo StarGate 24 (SG 24) enclosed in a shielded anechoic chamber. The Satimo SG 24 consists of 23 dual-polarized probes distributed on a supporting ring. The probes can be used as both transmitters and receivers depending on the type of the study. Both Satimo SG 24 and radio communication testers were connected to a PC with software controlling the measurement and logging the data. The connection to the mobile terminal during the measurement was kept through a link (mast) antenna. It should be mentioned that before the tests, calibration by measuring a reference antenna was carried out.

The study was performed following the standard test procedure for mobile devices as defined in CTIA OTA test



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

FIGURE 1. Setup for: (a) voice service test with phone next to the right-hand side of the head phantom placed in the right hand phantom (beside head hand right - BHHR), (b) voice service test with phone next to the left-hand side of the head phantom placed in the left hand phantom (beside head hand left - BHHL), (c) data service test with phone placed in the right hand phantom (hand right - HR), and (d) voice and data service test with phone placed in free space (FS).

plan [16], 3rd Generation Partnership Project's TS 36.213 [23] and TS 36.521 [24]. However, there was an exception. If the mobile terminal had more than one antenna for a dedicated standard and frequency band the measurements were performed in the same way as for handsets with no antenna selection (i.e. with single antenna). In this way, the phone was allowed to select which antenna to use as it sees fit for the test situation. This deviation from the standard [16] (according to it each antenna must be measured individually by disabling the antenna switching system used in normal operation) was done since the phones are not commercially available with an option to disable the automatic antenna selection. Standardized phantoms, produced by SPEAG, for both TRP and TIS studies were used. It should be mentioned that the hand phantom used for testing each mobile terminal was selected, as defined by the standard, depending on the form factor of the handset and its mode of operation. For the tests, the handset was placed in the center of the ring. Also, in order to study the user effect, the mobile terminal was placed in the hand phantom and next to head phantom as defined in the standard [16].

During TRP measurement, the device under test was set to transmit with the maximum allowed power for the studied mobile standard and frequency band. The power was measured successively by each probe (the probes are distributed on the ring along elevation; see Fig. 1) for each polarization. Then the mobile phone was rotated along azimuth and the power was again measured by the probes along elevation. The process continued until a sphere was covered and then the TRP value was evaluated. Each TRP measurement was done with 15° stepping for both elevation and azimuth (as by standard) and it took less than 5 min in total.

During TIS measurement, one probe at a time was set to transmit with certain power (for one polarization) a data signal to the phone and the BER was evaluated. Then the power was lowered with step of 0.5 dB and the BER was again evaluated. The process continued until BER reached a certain threshold. Thus, the minimum power needed to satisfy the specified BER was known for one direction and polarization. The procedure was repeated until all directions and both polarizations were tested, and then the TIS value was evaluated. Each TIS measurement was done with 30° stepping for both azimuth and elevation (as by standard) and it was quite time consuming due to this iterative process - can take more than 2 hours. As defined in the standard [16], for UMTS bands the sensitivity is equivalent to the minimum power that results in a BER of 1.2% or less at 12.2 kbps data rate with 95% confidence, while for LTE bands the sensitivity corresponds to the minimum power required to provide a data throughput rate greater than or equal to 95% of the maximum throughput of the reference measurement channel.

The study was limited only to the frequency bands commonly used in Denmark (and in general in Europe). Also, in order to limit the number of tests for each device, only

TABLE 1. Results for the measured TRP of the phones for FS, BHHR and BHHL scenarios for the studied GSM and UMTS bands (in green - best phone, in red - worst phone). The phones are sorted from the best to the worst performing according to GSM900 in BHHR setup.

Mobile Phone	TRP (dBm)											
	GSM900			UMTS900			GSM1800			UMTS2100		
	FS	BHHR	BHHL	FS	BHHR	BHHL	FS	BHHR	BHHL	FS	BHHR	BHHL
Doro 7070	28.7	23.5	23.6	20.7	14.5	14.8	27.6	25.2	26.0	18.9	17.4	17.2
Samsung Galaxy S9	27.2	20.7	20.7	17.0	10.5	10.9	26.1	21.6	23.5	18.4	13.4	16.2
Samsung Galaxy S9+	27.6	20.5	20.3	18.1	11.5	10.0	26.0	18.8	21.7	18.6	11.8	15.8
Samsung Galaxy S8	27.4	19.9	20.9	16.9	10.4	10.9	25.8	21.3	22.7	19.7	13.8	17.1
Huawei P20 Pro	26.7	18.5	19.7	17.5	7.2	9.5	23.6	19.0	17.8	18.8	11.0	9.7
Nokia 7 Plus	24.7	17.8	15.0	15.6	9.8	6.0	24.6	20.7	19.9	19.5	14.7	15.3
iPhone 7	27.4	17.5	14.0	18.2	9.2	3.3	25.3	11.0	20.4	18.5	7.3	14.5
iPhone 8	26.8	17.4	10.5	17.9	9.1	-0.7	23.7	18.1	18.8	18.1	7.5	12.3
iPhone X	25.4	17.4	16.2	16.3	9.0	6.4	22.7	16.9	18.1	17.0	11.7	14.1
iPhone 8 Plus	26.2	17.3	7.7	17.7	8.3	-1.4	24.6	17.5	18.8	18.8	10.6	13.7
Sony Xperia XA2	27.8	17.3	18.0	18.9	8.1	9.6	22.5	19.9	16.8	18.0	14.9	9.8
OnePlus 6	25.6	16.3	12.8	16.1	6.8	2.9	24.1	20.6	16.6	16.5	12.9	9.4
Huawei P10 lite	29.7	15.8	15.1	20.2	7.9	6.7	25.9	19.0	19.3	19.6	11.9	12.9
Huawei P9 lite mini	27.0	14.6	16.2	18.8	5.1	7.3	26.3	23.1	20.5	16.4	13.2	14.0
iPhone Xs Max	20.5	14.4	15.2	15.9	-1.3	6.2	22.6	14.2	18.3	16.9	9.9	14.0
Huawei P10	28.0	12.0	18.2	18.7	3.5	9.3	25.9	11.5	19.6	18.8	13.6	10.8

TABLE 2. Results for the measured TRP of the phones for FS, BHHR and BHHL scenarios for the studied LTE bands (in green - best phone, in red - worst phone). The phones are sorted from the best to the worst performing according to LTE800 in BHHR setup.

Mobile Phone	TRP (dBm)								
	LTE800			LTE1800			LTE2600		
	FS	BHHR	BHHL	FS	BHHR	BHHL	FS	BHHR	BHHL
Doro 7070	18.5	12.9	13.1	18.9	16.3	17.4	17.5	15.0	15.6
Samsung Galaxy S9	16.4	10.7	9.3	18.1	14.2	16.3	16.9	14.4	14.8
Samsung Galaxy S8	17.8	10.1	10.0	18.7	14.2	15.6	17.8	15.3	14.9
Samsung Galaxy S9+	17.3	9.5	8.8	18.5	11.7	14.5	17.8	13.4	9.9
iPhone 8	16.3	8.7	0.1	16.5	4.7	11.4	15.7	13.7	5.6
iPhone X	16.5	8.7	6.6	16.0	10.3	11.6	16.5	13.5	8.3
iPhone 7	16.2	8.3	3.0	18.0	4.1	13.4	18.1	14.7	13.0
Huawei P10 lite	17.6	7.7	5.0	17.4	10.4	10.7	16.9	12.0	9.6
Nokia 7 Plus	14.5	7.4	4.5	17.3	13.5	12.4	15.0	10.7	10.9
iPhone 8 Plus	17.0	7.3	-4.9	17.5	10.5	11.9	17.1	12.4	6.6
Huawei P20 Pro	16.0	6.5	7.9	16.1	10.8	9.5	15.1	10.3	6.2
Sony Xperia XA2	16.5	6.4	7.4	16.2	14.0	9.4	14.6	10.1	12.6
Huawei P9 lite mini	17.6	6.0	6.2	16.4	13.5	10.4	16.8	11.0	13.3
Huawei P10	18.3	5.8	6.9	19.5	6.8	13.2	16.3	8.7	6.0
OnePlus 6	15.9	5.4	1.9	16.3	12.9	6.7	17.0	14.1	13.9
iPhone Xs Max	16.1	0.3	5.8	16.7	7.6	12.4	16.3	5.8	12.9

the middle channel (instead of all three) was measured as representative for each band since it is considered that the in-band performance of the antenna is relatively stable. The TRP measurements for both free space and talk mode were conducted for: GSM900, GSM1800, UMTS900 (UMTS VIII), UMTS2100 (UMTS I), LTE800 (LTE20), LTE1800 (LTE3), and LTE2600 (LTE7). The TIS measurements for both free space and data mode were conducted for: UMTS900, UMTS2100, LTE700 (LTE28), LTE800, LTE1800, and LTE2600. The used bandwidth was of 10 MHz for the tests of LTE700, LTE800, and LTE1800 band, while of 20 MHz for the tests of LTE2600 band, as defined by the standard.

IV. RESULTS AND DISCUSSION

The list of mobile phones employed for the study, as already mentioned, was provided from the Danish Energy Agency and these are some of the most common handsets in the Nordic countries in the last years. Among all tested handsets, only Doro 7070 is a smart feature phone with clam shell shape (for talk mode test was used fold hand phantom, while for data mode - narrow hand phantom) while the rest are smartphones (depending of the width of the phone for testing both talk and data mode was used either PDA or wide grip hand phantom).

A. TRP

The measurement results for TRP of all tested mobile phones in all scenarios for GSM and UMTS bands are presented in Table 1 (sorted from the best to worst performing phone according to the GSM900 in the BHHR setup), while for LTE bands in Table 2 (sorted from the best to worst performing phone according to the LTE800 in the BHHR setup). Significant differences among the handsets depending on the frequency band and tested scenario can be seen. In the cases where the mobile terminal is placed in the hand phantom and next to the head phantom, one can see that: 1) UMTS900 and

TABLE 3. Minimum and maximum difference between TRP values for: 1) BHHR and BHHL (negative values correspond to the case where TRP for BHHL is higher than that for BHHR); 2) FS and BHHR; and 3) FS and BHHL for each studied frequency band.

Standard	BHHR-BHHL (dB)		FS-BHHR (dB)		FS-BHHL (dB)	
	min	max	min	max	min	max
GSM900	0.0	9.6	5.2	16.0	5.1	18.5
UMTS900	-0.4	9.7	5.8	17.2	5.9	19.1
GSM1800	-0.3	-9.4	2.5	14.4	1.6	7.5
UMTS2100	0.2	-7.2	1.5	11.2	1.7	9.1
LTE800	0.1	12.1	5.6	15.9	5.4	21.9
LTE1800	-0.3	-9.4	2.3	13.9	1.5	9.6
LTE2600	0.2 (-0.2)	8.1	2.0	10.5	1.9	10.5

TABLE 4. Results for the measured TIS of the phones for FS and HR scenarios for the studied LTE and UMTS bands (in green - best phone, in red - worst phone). The phones are sorted from the best to the worst performing according to LTE700 in HR setup. N/A means that the phone does not support the corresponding frequency band.

Mobile Phone	TIS (dBm)											
	LTE700		LTE800		LTE1800		LTE2600		UMTS900		UMTS2100	
	FS	HR	FS	HR	FS	HR	FS	HR	FS	HR	FS	HR
Samsung Galaxy S9+	-94.8	-93.3	-94.8	-93.3	-98.6	-96.6	-91.9	-90.6	-108.4	-107.9	-110.5	-107.7
Samsung Galaxy S9	-95.5	-92.6	-94.5	-92.6	-98.9	-96.6	-91.7	-90.0	-106.5	-105.9	-110.2	-108.2
iPhone 8 Plus	-95.6	-91.7	-94.6	-91.5	-96.8	-94.5	-91.3	-88.3	-109.2	-108.4	-111.7	-108.7
iPhone 8	-96.2	-91.4	-95.6	-91.5	-97.0	-94.6	-90.8	-88.8	-109.5	-106.7	-110.0	-108.0
iPhone 7	-95.7	-91.2	-95.3	-91.3	-96.0	-91.9	-92.7	-90.5	-109.8	-106.3	-110.5	-106.9
Huawei P20 Pro	-93.6	-91.1	-92.9	-91.0	-98.1	-95.2	-89.5	-88.3	-107.7	-105.5	-110.4	-107.9
Samsung Galaxy S8	-94.0	-90.8	-95.0	-92.8	-97.5	-94.9	-93.0	-92.1	-107.2	-105.0	-108.1	-107.8
OnePlus 6	-93.3	-90.2	-93.3	-89.0	-96.6	-94.3	-93.3	-89.5	-107.1	-104.5	-109.7	-107.5
iPhone X	-94.2	-90.0	-94.6	-91.1	-94.2	-92.0	-89.7	-86.5	-107.3	-103.4	-109.1	-106.4
Huawei P10	-94.4	-89.7	-94.0	-90.8	-96.1	-92.2	-90.8	-89.4	-108.9	-106.4	-110.3	-108.5
Nokia 7 Plus	-93.6	-89.6	-93.0	-91.0	-95.1	-93.3	-88.3	-87.8	-106.4	-105.6	-107.4	-104.7
iPhone Xs Max	-94.4	-88.8	-93.5	-88.2	-96.2	-93.5	-93.0	-90.7	-106.8	-105.1	-107.4	-104.8
Doro 7070	N/A	N/A	-94.2	-91.2	-96.5	-95.3	-92.4	-89.8	-109.3	-105.2	-111.3	-108.7
Huawei P9 lite mini	N/A	N/A	-93.7	-88.8	-94.2	-93.1	-92.3	-91.1	-106.8	-98.4	-111.3	-109.9
Huawei P10 lite	N/A	N/A	-95.4	-92.6	-97.6	-94.1	-92.8	-89.6	-107.9	-104.8	-109.9	-106.5
Sony Xperia XA2	N/A	N/A	-94.7	-90.0	-95.3	-93.6	-90.1	-88.2	-108.1	-104.8	-107.9	-104.9

LTE800 where the worst performing phone in BHHR scenario has some 5 dB lower TRP than the second worst performing phone; and 2) LTE800 where the worst phone in BHHL case has some 5 dB lower TRP than the second worst performing phone. That is, the worst performing phone transmits significantly lower power compared even with the second worst performing phone. For all frequency bands and for both BHHR and BHHL scenarios (except BHHR for LTE2600), one of the mobile phones shows always the best performance. Moreover, in some of the cases this handset outperforms the second best one with some 3 dB, i.e. it can transmit twice higher power than the second best phone. For some of the bands the best performing phones in BHHR/BHHL setup have similar or higher TRP than the worst performing phones in FS which shows the difference in the optimization of the deployed antennas.

In FS scenario, variation in the performance among the phones in the range 3-5 dB depending on the frequency band is observed. Exception is the case GSM900 where a very big difference is observed - the worst performing phone has TRP some 9 dB lower than the best performing phone and some 4 dB lower than the second worst performing phone. The spreads between the phones for the cases BHHR and BHHL expectable are higher than those in FS. The variation in the transmit performance among the studied phones at low frequencies (12-16 dB for BHHR and 16-18 dB for BHHL) is higher than that at high frequencies (10-14 dB for BHHR and 8-11 for BHHL).

In order to obtain general information about the sensitivity of the phones to the way of holding them, Table 3 presents the maximum and minimum difference between TRP in BHHR and BHHL scenario (it is denoted as BHHR-BHHL). It should be mentioned that the negative values correspond to the case where the performance in BHHL case is better than that in BHHR. For some of the handsets large difference in the TRP between BHHR and BHHL cases is observed - up to 12 dB at low frequencies and up to 9 dB at high frequencies. This clearly shows that the antennas have not been well optimized (design and/or location) for operating in both use scenarios.

Based on the results presented in Table 1 and 2 it can be seen that the transmit performance is significantly better if the phone is in a hands-free installation rather than in contact with the head and hand. In order to see the range of additional losses due to the vicinity of a lossy human tissue to the handset (i.e. the body loss), Table 3 shows the maximum and minimum difference between TRP in FS and BHHR (denoted as FS-BHHR), and between TRP in FS and BHHL (denoted as FS-BHHL). The minimum difference for both FS-BHHR and FS-BHHL can reach up to 6 dB. The maximum body loss

TABLE 5. Minimum and maximum difference between TIS values for FS and HR for each studied frequency band.

Standard	FS-HR (dB)	
	min	max
LTE700	-1.5	-5.6
LTE800	-1.5	-5.3
LTE1800	-1.2	-4.1
LTE2600	-0.5	-3.8
UMTS900	-0.4	-8.4
UMTS2100	-0.3	-3.5

in TRP for BHHR is up to 17 dB, while for BHHL is up to 22 dB. The handset showing quite high reduction in TRP in case of BHHL for LTE800 (around 22 dB) actually has some 3 dB better performance in FS than the worst one in FS. The results in Table 1 and 2 indicate that the mobile terminals having the worst performance in BHHR/BHHL scenario are not the worst ones in FS. It should be mentioned that the handsets often have very poor performance only in one of the cases, i.e. either in BHHR or in BHHL. The significant decrease in TRP, when the head and hand are next to the mobile terminal, means much less power received at the base station which, in turn, can cause a significant decrease in the radio coverage and thus need for more base stations. This clearly points out the need of studying the user effect and improving the antenna design.

B. TIS

The measurement results for TIS of all tested phones for FS and HR are shown in Table 4 (sorted from the best to worst performing phone according to the LTE700 in the HR setup). The phones which do not support LTE700 are marked with N/A. According to the data the best performing handsets have lower (better) TIS in HR case than the worst performing ones in FS for the corresponding frequency band. Also, the worst operating phones in FS do not show the worst performance in case of HR (the only exception is for UMTS2100).

It is observed that in FS the spread at low frequencies (below 3 dB) is smaller than that at high frequencies (below 5 dB). For most of the bands the introduction of a human hand increases the spread among the phones and it is around 5 dB. Exception is UMTS900 where the spread is of 10 dB. In this band, the worst performing phone has TIS some 5 dB higher (worse) than the second worst performing one. That is, the worst performing phone has significantly lower sensitivity than the second worst performing one.

For easier investigation of the deterioration of the antenna performance due to the holding of the mobile terminal in hand (i.e. the body loss), Table 5 shows the minimum and maximum difference in TIS between the cases FS and HR (denoted as FS-HR). It should be kept in mind that the results are negative due to the fact that in FS the handset antenna is more efficient and can receive weaker signals, i.e. the mobile terminals have lower TIS value in FS case than in HR case. Over all studied bands, reduction in TIS in the range between some −0.3 dB and −5.6 dB is observed. Only for UMTS900, the maximum body loss in TIS is around 8 dB. In comparison, the second highest reduction in TIS for this band is of 4.1 dB which is significantly smaller. The change in the data rate for TIS difference is a function of the signal level, receiver, antenna system, radio channel condition and network settings, but in case of a low signal strength, a couple of dB reduction in TIS results in a significant decrease in the data rate [19], [25].

V. CONCLUSION

In this paper results from a study for the communication performance of 16 contemporary mobile phones have been presented. The transmit performance has been studied for voice service in talk mode (both BHHR and BHHL) while the receive performance for data service in data mode (HR). Moreover, all studies have also been conducted in FS. Across the studied GSM, UMTS and LTE bands spread in TRP for FS up to 9 dB has been observed. A large variation in the transmit performance among the phones in the BHHR/BHHL setup has been seen. The spread is: 1) at low frequencies up to 16 dB for BHHR and up to 18 dB for BHHL; and 2) at high frequencies up to 14 dB for BHHR and up to 10 dB for BHHL. It should be mentioned that at low frequencies the maximum variation is larger than what has been seen before [18], [19], [21], [22]. At high frequencies the maximum spread is larger compared to what has been found in [18], but smaller than the one presented in [19], [21], [22]. For some of the phones quite significant dependence of TRP on the side of the head where the phone is positioned has been observed. A maximum difference in TRP of some 12 dB between BHHR and BHHL has been found. In comparison, up to some 14 dB has been seen in [19] and up to some 11 dB in [22]. The comparison between the performance in FS setup and that in BHHR/BHHL setup has shown that the ability to transmit power is far better if the phone is in a hands-free installation. The degradation is higher at low frequencies and it has a maximum value of some 17 dB for BHHR scenario and of some 22 dB for BHHL scenario.

A variation in TIS up to 5 dB and up to 10 dB has been observed among the phones in FS and HR, respectively. The spread found in this study for HR is lower than what has been seen in [19], [22]. It has been observed that the maximum body loss in TIS can reach up to 8 dB. However, for many phones the reduction in TIS caused by the hand holding the phone is 2-3 dB.

It can be concluded that a large variation in the communication performance among the studied handsets has been observed. The study has shown once again that the user effect should be taken into account when designing a mobile phone antenna.

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