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# Effect of the Human Body on Total Radiated Power and the 3-D Radiation Pattern of Mobile Handsets

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**Abstract**—We investigate how the user's body affects the radiation characteristics, e.g., radiation pattern and total radiated power (TRP), of mobile phones. We carried out measurements for two Global System for Mobile Communications (GSM) 900/1800 phones with two measurement systems: a 3-D far-field pattern measurement system and the Rapid Antenna Measurement System (RAMS). Up to 13 mobile phone users participated in the measurements. The main objectives are to study how much the TRP varies between the users and how large an influence the user's hand, particularly its position on the mobile phone, has on the TRP. The contributions of the head and the hand to the total loss are separately studied as well. The standard deviation of the TRP results between the 13 users in the RAMS measurements was relatively low, i.e., less than 1 dB, when the users held the mobile phone in a predefined talk position on the left side of their heads. The standard deviation of the corresponding result was up to 3 dB when the users were allowed to freely select the way to hold the phone. The TRP results for two phantoms agreed well with the average TRP results for the test persons when only the loss contribution of the head was included. Hence, we conclude that the variable hand position and grip on the mobile phone are the main reasons for the large differences in the TRP between the users.

**Index Terms**—Antenna measurements, body loss (BL), efficiency, Global System for Mobile Communications (GSM), handset antennas, mobile communications, mobile phone, total radiated power (TRP).

## I. INTRODUCTION

**I**N MOBILE communication systems, the quality of the RF link between a base station and a mobile station strongly depends on the amount of power that is transmitted and received by the mobile station. The power depends, among other factors, on the mobile phone and antenna design. Moreover, the mobile phone is used in close proximity to a user's body, which reduces

the transmitted and received power. The ratio of the power (or efficiency) with and without the user's body is defined as body loss (BL). The BL may significantly vary, depending on the antenna or handset design [1], [2].

In [1] and [2], the mean effective gain and the BL have been evaluated for a large number of test users, up to 200, by means of radio channel field measurements at 1.89 GHz. The results show large differences, up to 10 dB, in the BL between the test users, even for the same mobile handset and radio wave propagation environment [1]. Depending on the antenna type, it was found that eight to 13 test persons are needed to obtain an estimate of the mean BL with a  $\pm 1$  dB confidence interval at a 90% level [2].

In [3], it was noticed using 3-D radiation pattern measurements for a group of test persons that the mean total efficiency converged to within  $\pm 1$  dB or better with 15 test persons in the Global System for Mobile Communications (GSM) 900 band.

However, in the measurements in [1]–[3], the way the users held the test phone was not predefined, but they held the phone in a way that each of them felt natural. In [1] and [2], the users could even select whether to hold the phone on the left or the right side of their head. Therefore, until now, it has not been obvious whether the large variation in the BL is due to anatomical differences between the users' heads or hands or due to the fact that users hold a mobile phone in various ways.

The main objective of this study is to determine the reason for the large variation in the BL between mobile phone users. For this, we investigate whether there are significant differences in the TRP and BL between a group of test persons when the way they hold the phone is accurately defined. In the first test setup, a particular way of holding the phone during the measurement is defined and implemented for the test persons. In the second predefined setup, the test person does not hold the phone in his/her hand, but the phone is positioned against the head with the help of a plastic fixture. Two measurement campaigns are carried out with two measurement systems: a 3-D far-field pattern measurement system and the novel Rapid Antenna Measurement System (RAMS) [4], [5], which is located at the Radio Laboratory of Helsinki University of Technology. In addition, with the RAMS, some additional setups are used, in particular, a user-selected talk position, which enables the determination of the variation between the measurement results that correspond to real usage. In both

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TABLE I  
SUMMARY OF MEASUREMENT CAMPAIGNS

<b>Measurement campaign 1:</b>	
Measurement system	3-D far-field measurement system
Number of test persons	3
Test setups	a) DUT 1 in free space
	b) DUT 1 on the user's left ear and in the hand, predefined talk position and handgrip
	c) DUT 1 on the user's left ear (no hand), predefined talk position
Test setup with phantom	d) DUT 1 on the left side of Phantom 1 (no hand)
Phantom	Head + shoulders phantom (Torso Phantom V2.0 by Schmid & Partner Engineering AG)
<b>Measurement campaign 2:</b>	
Measurement system	Rapid Antenna Measurement System (RAMS)
Number of test persons	13
Test setups	a) DUT 2 in free space
	b) DUT 2 on the user's left ear and in the hand, predefined talk position
	c) DUT 2 on the user's left ear (no hand), predefined talk position
	d) DUT 2 in the user's hand, the head tilted away from the DUT, predefined talk position
	e) DUT 2 on the user's left ear and in the hand, user-selected talk position
	f) DUT 2 in the user's hand, the head tilted away from the DUT, user-selected talk position
	g) DUT 2 in free space, the user sitting inside the RAMS but not touching the DUT
Test setup with phantom	h) DUT 2 on the left side of Phantom 2 (no hand)
Phantom	Head phantom (Generic Head Phantom by Schmid & Partner Engineering AG)

measurement campaigns, a comparison measurement is made with a human body phantom, simulating the head (and shoulders) of a man.

The results of this study will give new information for developing realistic phantoms for mobile phone performance testing procedures under standardization [6]–[8] and increase general understanding of the interaction between mobile phones and the user's body.

## II. MEASUREMENTS

### A. Three-Dimensional Far-Field Pattern Measurements in an Anechoic Chamber

Table I presents the summary of the two measurement campaigns and the test setups used. The first measurement campaign was carried out with a 3-D far-field radiation pattern

measurement system located in an anechoic chamber. This spherical scan system is based on a rotating elevation arm, which provides the movement of a probe antenna along a semicircular trajectory. The test object is rotated in the azimuth direction. The measurement distance was about 2 m, and the far-field patterns were sampled at  $10^\circ$  steps both in the azimuth and elevation directions. Some more details on the system are presented in [9].

The device under test (DUT) used with the first measurement system is a dual-band monoblock GSM mobile phone (GSM900/GSM1800) that has an internal antenna. The chassis length is about 100 mm. This test phone is denoted as DUT 1. The measurements were carried out at the center channel (channel 698,  $f = 1747.4$  MHz) of the uplink band of the GSM1800 system. A radio communications tester was used as a base station simulator to establish and maintain calls

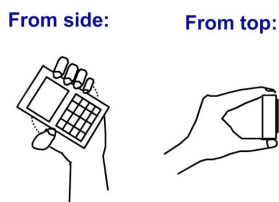


Fig. 1. Predefined grip on the DUT.



Fig. 2. One of the test persons in set-up c) during the first measurement campaign. In this setup, the test person did not hold the DUT with the hand, but the DUT was next to the head using a plastic fixture.

and to keep the transmitted power of the DUT at a maximum fixed level. A spectrum analyzer was used as the measurement receiver.

In the first experiment series [setup b) in Table I], the 3-D radiation pattern of the DUT was measured in the presence of three individual test persons. The phone was on the left side of the head in all the measurements, and each test person held the phone in his hand. The tilt angle, the way the user holds the DUT, and the handgrip were defined. A sketch of the user's handgrip on the DUT is shown in Fig. 1. This grip represents a typical way of holding a small mobile phone like DUT 1. In the measurement procedure, the DUT was first adjusted to the rotation center of the 3-D pattern measurement system and to a  $60^\circ$  tilt from the vertical axis by using an adjustable plastic fixture. Next, the test person sat down on a wooden bench on top of an expanded polystyrene pole installed on the azimuth turntable, set his head against the DUT, and gripped it in predefined way. It was ensured that the ear center of each test person coincided with the rotation center of the measurement system. DUT 1 was also measured in a free-space setup as a reference case for determining the BL. With the help of the plastic fixture, the DUT was in all the measurements, including the free-space measurement, in the same position. A calibration measurement was performed with a reference horn antenna whose gain and efficiency properties were known.

To distinguish the effects of the user's head and hand on the radiation characteristics, additional measurements were later performed on the same DUT with two of the test persons, but with a different setup, so that the DUT was not kept in the hand. The DUT was placed at the plastic fixture, and the test person held his head against the DUT in the predefined way (see Fig. 2). We assume that this setup corresponds quite

well to the measurement with a phantom model that does not include a hand. Again, a measurement of the DUT in the free-space setup served as a reference case. Due to the unavailability of valid calibration data for the second experiment series, the free-space total radiated power (TRP) result was normalized to the corresponding result from the first experiment series. The free-space TRP result then served as the calibration level for the other results from the second experiment series.

During the first measurement campaign, the DUT was also measured beside a phantom. The phantom is Torso Phantom V2.0 by Schmid & Partner Engineering AG, and it includes the head and shoulders but not a hand model. The phantom is denoted as Phantom 1, and it was filled with sugar- and water-based brain-tissue-simulating liquid prepared according to a recipe for the 1800-MHz frequency band [10]. The dielectric parameters of the liquid were measured previously, and at 1800 MHz, they were as follows: relative permittivity  $\epsilon'_r = 42$  and effective conductivity  $\sigma_{\text{eff}} = 1.7 \text{ S/m}$ . There was no spacer between the phantom and the phone, so it was placed against the plastic surface of the phantom. The thickness of the plastic shell of the phantom was 3–4 mm, according to the phantom's specifications. In the measurement with the phantom, the same plastic fixture and predefined position was used as in the measurements with the test persons.

The TRP, cross-polarization discrimination (XPD), and maximum effective isotropic radiated power (EIRP) were calculated from the measured 3-D patterns. The TRP can be calculated by integrating the sum of the  $\theta$ -polarized radiated power and the  $\phi$ -polarized radiated power over a closed surface that completely encloses the DUT. The XPD is the ratio of the total  $\theta$ -polarized radiated power to the total  $\phi$ -polarized radiated power. The EIRP is defined as the gain of a transmitting antenna in a given direction, multiplied by the net power accepted by the antenna from the connected transmitter [11]. The TRP corresponds to the total efficiency, and the maximum EIRP corresponds to the maximum realized gain, if the feed power of the antenna is known.

### B. Measurements With RAMS

As the first measurement system that we used is based on the mechanical movement of the DUT and the probe antenna, the measurement is not very fast; one full 3-D measurement takes more than 10 min. Thus, large measurement campaigns that involve several test persons, test positions, and frequencies are not very practical. Therefore, to acquire more statistics to our research, we carried out another measurement campaign with the recently developed RAMS. It consists of 32 dual-polarized probes that are arranged on a spherical surface, inside of which the DUT is placed [4]. An illustration of the RAMS in the test person measurements is shown in Fig. 3. The distance between the center of the sphere and each probe antenna is about 1.1 m. The probes are wideband Vivaldi-type antennas, and the system can be operated at 0.8–3 GHz. The probes are scanned by means of an RF switching network, which enables the measurement of a 3-D radiation pattern in approximately 3 s at a single frequency.

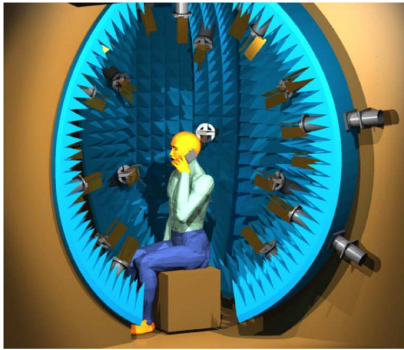


Fig. 3. Measurement setup with the RAMS.

A method based on the spherical wave expansion is used for the determination of the radiated field in the RAMS [12]. The radiated field of the DUT is characterized by a number of spherical vector waves, whose coefficients are solved based on the measured field samples. The 3-D far-field pattern and the TRP can be calculated from the vector wave functions.

The measurements with the RAMS were carried out with a diverse group of 13 test persons. The DUT used in this measurement campaign is denoted as DUT 2 and is also a monoblock GSM mobile phone. It has an internal antenna, and the length of the chassis is about 105 mm. Measurements on DUT 2 were performed both in the GSM900 and GSM1800 bands at the center channels of the uplink band: channel 62 (902.4 MHz) and channel 698 (1747.4 MHz). In the measurements, the DUT was in the transmitting mode, and a spectrum analyzer was used as the measurement receiver. The phone was set into the call mode by using a radio communications tester. The calibration of the measurement results into absolute TRP values in decibels relative to 1 mW (dBm) was carried out by performing comparison measurements for two monopole antennas (one for both frequency bands), whose total efficiency was known.

The same plastic fixture as in the first measurement campaign was also used in the measurements with the RAMS. The test persons sat on a wooden chair inside the RAMS system. To individually adjust the height position of each test person, expanded polystyrene blocks were added on the wooden chair, when needed. This way, it was ensured that the ear center of each test person coincided with the center of the RAMS. The test group consisted of ten male and three female mobile phone users. Several different test setups were used.

- a) The DUT is in a free-space setup in the plastic fixture.
- b) The DUT is with the user's head and hand in a predefined talk position.
- c) The DUT is with the user's head (predefined talk position)
- d) The DUT is in the user's hand (predefined talk position), and the user's head is tilted about 20 cm away from the DUT.
- e) The DUT is with the user's head and hand, in a user-selected talk position, with a freely selectable handgrip and positioning against the head.

- f) The DUT is in the user's hand the same way as in setup e), but the user's head is tilted similarly as in setup d).
- g) The DUT is in the plastic fixture, and the user's head is tilted away from the phone similarly as in setups d) and f), and he/she is not holding the phone in his/her hand.
- h) The DUT is next to a generic phantom head.

The measurements were carried out in a sequential order (not exactly the same as that in the list above). The measurements in setup h) were performed after all the measurements with the test persons. In setup e), the users were asked to hold the DUT on the left side of their heads in a way that they considered a natural talk position for the mobile phone in question. To ensure that the DUT was approximately in the center of the measurement sphere for each test person also in these freely selected talk positions, a string with alignment marks was used. One measurement operator observed the phone positioning and guided the test person's head and hand alignment so that the DUT was positioned as similarly as possible in each test case and in both frequency bands. A photograph was also taken before each measurement. The main RAMS test setups are shown in Fig. 4.

We were also interested in the TRP and the BL contribution of the isolated hand, and setups d) and f) were used to study them. However, the user's head and body cause some shadowing and attenuation, even when they are not in the immediate vicinity of the DUT but just inside the test system. Setup g) was needed in order to evaluate this effect. The result for the isolated hand was evaluated in the following way:

$$\text{TRP}_{\text{hand,isol}} \approx \text{TRP}_{\text{hand}} + (\text{TRP}_{\text{free space}} - \text{TRP}_{\text{user in RAMS}}) \quad (1)$$

where  $\text{TRP}_{\text{hand}}$  is the uncorrected result from setups d) or f),  $\text{TRP}_{\text{free space}}$  is the free-space measurement result (i.e., only the phone inside the measurement system), and  $\text{TRP}_{\text{user in RAMS}}$  is the value measured with setup g). All the terms are in dBm. The formula produces an estimate of the result that corresponds to the isolated hand by correcting the TRP that was measured with the hand plus the user's body with the attenuation from the user's body just being inside the measurement system.

The repeatability of the RAMS measurements was tested by carrying out 15 repeated TRP measurements for one of the users in the predefined talk position. After each repeat, the user released his grip on the DUT and stood up from the chair. Then, he again sat down on the chair and readjusted his head and hand positioning for the next repeat according to the measurement operator's guidance. Moreover, a free-space measurement was performed in the GSM900 band between each test person's measurement series. This way, the repeatability of the measurement system itself could also be monitored. The standard deviations for the TRP and BL results were calculated from decibel values.

In setup h), the DUT was measured in the RAMS with a generic head phantom as a reference case. The phantom head (denoted as Phantom 2) was filled with the same type of tissue-simulating liquid as the Phantom 1 in the first measurement campaign. The liquid has originally been developed for specific

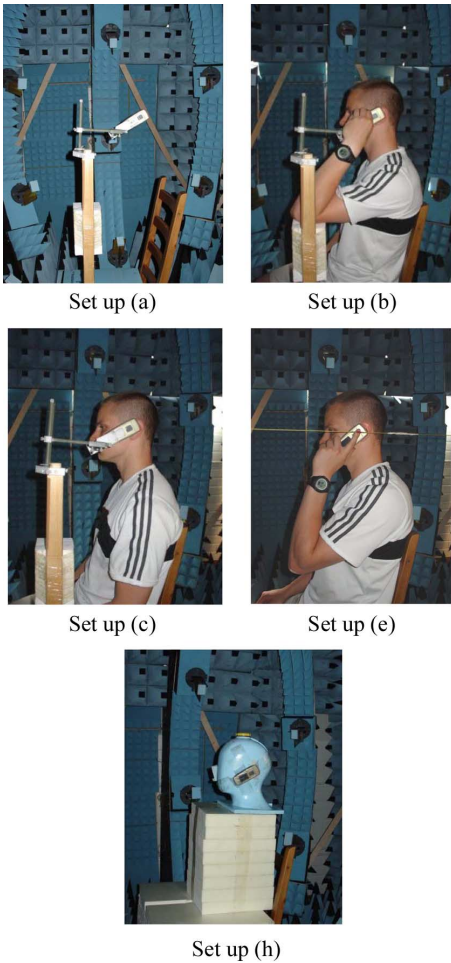


Fig. 4. Main measurement setups in the RAMS during the second measurement campaign. Setup a) DUT in free space. Setup b) Predefined talk position (head and hand). Setup c) Predefined position next to the head. Setup d) User-selected talk position (head and hand). Setup e) Talk position next to the phantom head.

absorption rate (SAR) measurements of mobile phones in the 1800-MHz band. However, the same liquid is also commonly used in radiation pattern measurements, both in the 900- and 1800-MHz bands. Using this liquid for the TRP measurement in the 900-MHz band typically introduces only a negligible error in the result if compared with the result that is obtained using a liquid that is specifically made for the 900-MHz band [13, pp. 231–232]. This is in contrast with SAR measurements, where the dielectric parameters of the liquid have a much more significant effect on the measurement result.

### III. RESULTS

#### A. Results With the 3-D Far-Field Measurement System

Figs. 5–7 show the measured radiation patterns of DUT 1. The figures present  $XY$ ,  $XZ$ , and  $YZ$  principal

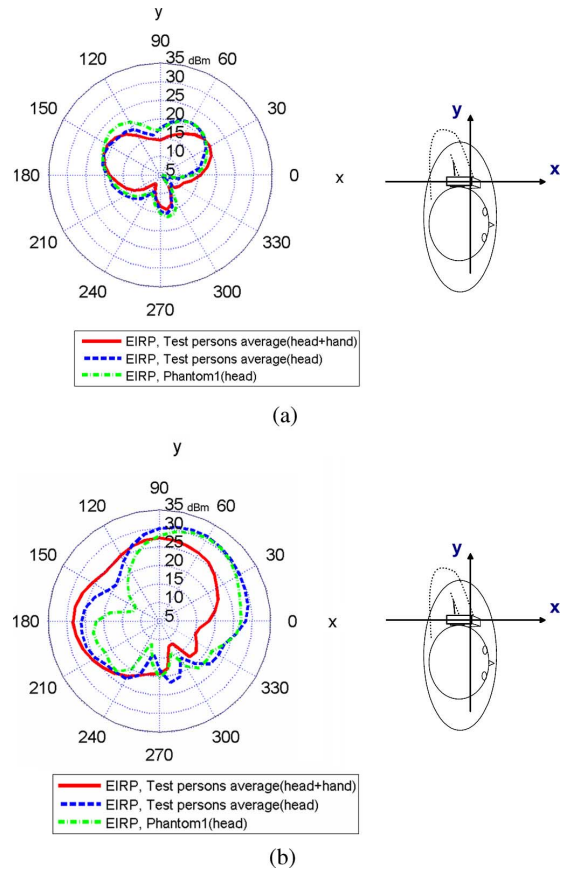
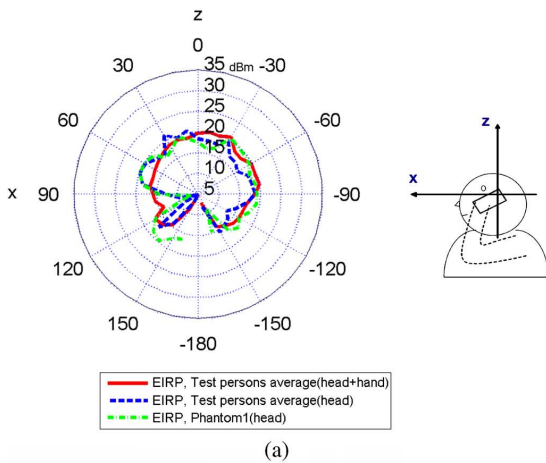


Fig. 5.  $XY$  plane EIRP pattern cut of DUT 1 at channel 698, measured with the first measurement system. Solid red line: Average of test persons (head + hand). Dashed blue line: Average of test persons (head). Dashdot green line: Phantom 1 (head). The amplitude unit is dBm. (a)  $\theta$ -polarization component. (b)  $\phi$ -polarization component.

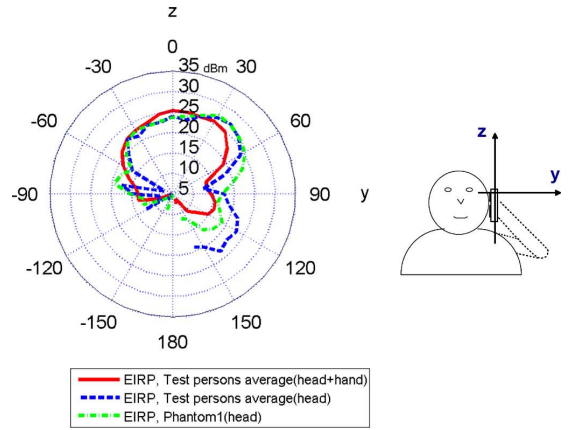
plane cuts of the measured 3-D EIRP patterns with  $\theta$ - and  $\phi$ -polarizations. The average of the radiation patterns measured for the three test persons and the radiation pattern measured for Phantom 1 can be compared. Next to each pattern plot, the orientation of the DUT and the test person or the phantom in the corresponding pattern cut is shown.

In Figs. 5–7, it can be seen that the pattern cuts for the phantom generally look very similar as the average pattern cuts for the heads of the test persons. When the hand was also included in the measurements, the average pattern cuts for the test persons have relatively large differences in certain planes, as compared to the two other setups. The largest differences occur in the  $XZ$  plane with  $\phi$ -polarization when  $\theta = 50^\circ - 150^\circ$  and in the  $XY$  plane with  $\phi$ -polarization. These differences seem to be due to the effect of the hand.

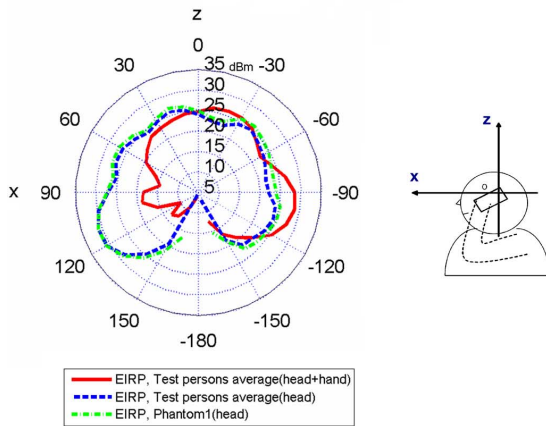
Some more radiation pattern plots and a comparison between the principal plane cuts between the three test persons are presented in [14]. It can be seen there that the overall shapes of the pattern cuts are fairly similar for all the test persons.



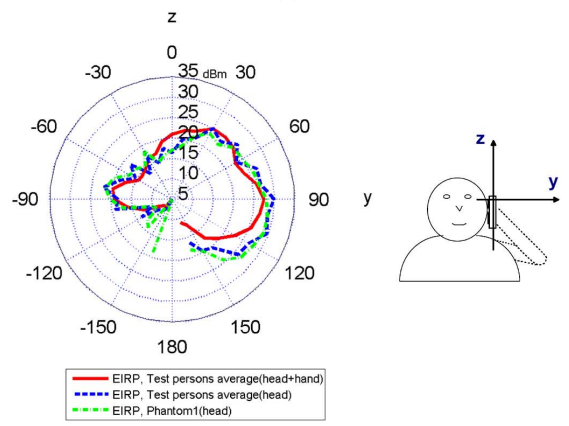
(a)



(a)



(b)



(b)

Fig. 6. XZ plane EIRP pattern cut of DUT 1 at channel 698. Solid red line: Average of test persons (head + hand). Dashed blue line: Average of test persons (head). Dashdot green line: Phantom 1 (head). The amplitude unit is dBm. (a)  $\theta$ -polarization component. (b)  $\phi$ -polarization component.

Fig. 7. YZ plane EIRP pattern cut of DUT 1 at channel 698. Solid red line: Average of test persons (head + hand). Dashed blue line: Average of test persons (head). Dashdot green line: Phantom 1 (head). The amplitude unit is dBm. (a)  $\theta$ -polarization component. (b)  $\phi$ -polarization component.

The largest differences occur in the XY and YZ planes with  $\theta$ -polarization.

Table II presents the numerical results from the first measurement campaign. The most interesting result from these measurements would be the total efficiency of the antenna and human body combination, but from active mobile phone measurements, it cannot be determined, since the actual net input power to the antenna is not known. However, since the nominal maximum output power is known, we can estimate the total efficiency. We call this estimated parameter realized total efficiency. The maximum output power level of GSM mobile stations specified in the GSM standard is +30 dBm for GSM1800 (power class 1) and +33 dBm for GSM900 (power class 4) at the antenna connector of the equipment, both with a tolerance of  $\pm 2$  dB [15]. The realized total efficiency values were thereby calculated by using the nominal maximum output power as the reference level. The results are given in Table II in the parentheses with the mean TRP values. Hence, the realized

total efficiency represents the sum of all the losses after the antenna connector, including mismatch and dissipative losses in the antenna (and the whole device), and the losses due to the effects of the user's body. The user has a twofold effect on the total efficiency. First, the presence of a human tissue near the mobile phone changes the input impedance of the antenna, which may either improve or degrade the antenna matching, thus changing the amount of radiated power. Second, part of the radiated power is absorbed in the tissue, leading to reduced radiation efficiency.

The maximum difference in the TRP between the three test persons is only 0.2 dB. The mean BL<sup>1</sup> due to the user's head is 1.6 dB. The increase in the BL due to the user's hand is 2.6 dB. The variation in the maximum EIRP is larger than that in the TRP, which is easy to understand, as the maximum EIRP is a

<sup>1</sup>For convenience, absolute values of BL are used in the discussion throughout the text.

TABLE II  
TRP, MAXIMUM EIRP, XPD, AND BL RESULTS FOR DUT 1 AT CHANNEL 698 FROM MEASUREMENT CAMPAIGN 1. IN THE PARENTHESES (SECOND COLUMN) IS THE REALIZED TOTAL EFFICIENCY (IN DECIBELS), REFERRED TO THE NOMINAL MAXIMUM TRANSMISSION POWER OF GSM1800 MOBILE PHONES (+30 dBm)

Setup	TRP [dBm] (dB)	EIRP <sub>max</sub> [dBm]	XPD [dB]	BL = TRP (head/head+hand) – TRP (free space) [dB]
a) Free Space	28.0 (-2.0)	34.2	-2.1	0
b) User 1 (head+hand)	23.8 (-6.3)	29.8	-3.9	-4.2
b) User 2 (head+hand)	23.9 (-6.1)	30.1	-4.7	-4.1
b) User 3 (head+hand)	23.7 (-6.3)	29.3	-4.4	-4.3
c) User 1 (head)	26.5 (-3.5)	34.3	-5.7	-1.5
c) User 2 (head)	26.3 (-3.7)	34.3	-7	-1.7
d) Phantom 1 (head)	26.3 (-3.7)	34.4	-5.8	-1.7

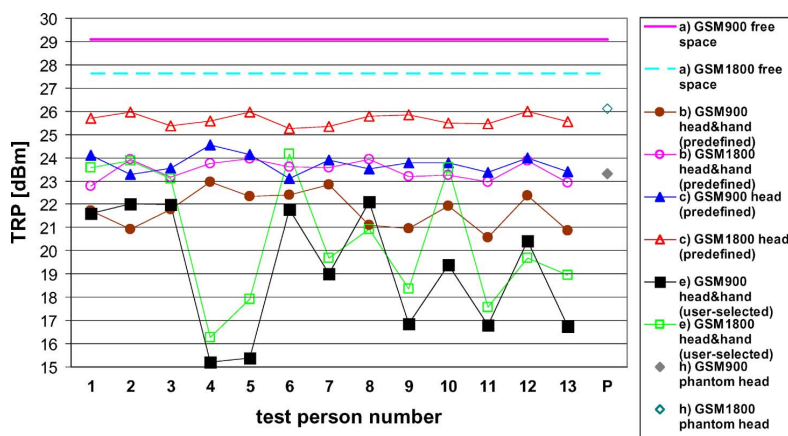


Fig. 8. TRP results obtained with the RAMS for DUT 2, with the 13 test persons and Phantom 2 in the main setups and two frequency bands.

peak quantity, and the TRP is an average quantity. Furthermore, the variation in the XPD is larger than that in the TRP, which suggests that the radiation pattern shapes are altered more than the average radiated power.

The short-term repeatability (i.e., when repeating the measurement without changing anything in the setup) of the TRP measurements with the 3-D far-field measurement system has been tested earlier to be on the order of 0.1–0.2 dB for measurements with a phantom [9].

### B. Results With the RAMS

Fig. 8 presents a graph of the TRP results that were obtained with the RAMS. Tables III–V present the main numerical results.

It can be seen that the variation in the TRP results is large when the users held the test phone in a freely selected way [setup e)]. The standard deviation of the TRP between the 13 test persons is up to about 3 dB, and the maximum difference is as much as about 8 dB. In the case of some users, the effect of the head and hand is especially large, and the TRP is relatively low. In particular, for two of the users, the TRP is about 15 dBm at GSM900, which is 18 dB below the nominal maximum output power of +33 dBm. The realized total efficiency values are given in Tables III and IV in the parentheses with the mean TRP results. For the GSM900 band, the mean

value of the realized total efficiency for setup e) is –13 dB (Table III). This agrees well with the measured total efficiency results given in [3], which range from –15 dB to –11 dB for five GSM phones in the GSM900 band for a group of test users. In [3], a coaxial RF feed cable was used in the measurements, and due to this, the total efficiency could be determined. In Fig. 8, it can be seen that the trends look quite similar in both the GSM900 and the GSM1800 bands; a test person who has a low TRP value at 900 also has a generally low TRP at 1800 MHz, with one exception.

In the predefined talk position [setup b)], the standard deviations of the TRP and BL results are low: 0.8 dB at 900 MHz and 0.4 dB at 1800 MHz. The low deviation in the predefined talk position is in accordance with the results that were obtained in the first measurement campaign, where the difference in the TRP results between the three test persons was very small. The differences in the results of the predefined talk position test setup can be explained by small remaining positioning differences and anatomical differences between the test persons. The repeatability of the test person measurements is relatively good in the predefined talk position; the standard deviation of the TRP is about 0.4 dB at 900 MHz and 0.1 dB at 1800 MHz for 15 repeats for one of the test persons. The standard deviation of the free-space measurements is 0.1 dB at 900 MHz for 13 repeats.



TABLE III  
TRP RESULTS FOR DUT 2 AT CHANNEL 62 FROM MEASUREMENT CAMPAIGN 2 WITH 13 TEST PERSONS AND PHANTOM 2. REALIZED TOTAL EFFICIENCY VALUES (IN DECIBELS), REFERRED TO THE NOMINAL MAXIMUM TRANSMISSION POWER OF GSM900 MOBILE PHONES (+33 dBm), ARE SHOWN INSIDE PARENTHESES

GSM 900:	Mean TPR [dBm]	Std. dev. of TRP [dB]	TRP <sub>max</sub> [dBm]	TRP <sub>min</sub> [dBm]	TRP <sub>max</sub> - TRP <sub>min</sub> [dBm]
a) Free Space	29.1 (-3.9)	0.1	29.3 (-3.7)	29.0 (-4.0)	0.3
b) Head+Hand (predefined)	21.8 (-11.2)	0.8	23.0 (-10.0)	20.6 (-12.4)	2.4
c) Head Only (predefined)	23.7 (-9.3)	0.4	24.5 (-8.5)	23.1 (-9.9)	1.4
d) Hand Only (predefined)	26.6 (-6.4)	0.6	27.7 (-5.3)	25.9 (-7.1)	1.8
e) Head+Hand (user-select.)	19.9 (-13.1)	2.7	22.1 (-10.9)	15.2 (-17.8)	6.9
f) Hand Only (user-select.)	24.5 (-8.5)	3.3	27.7 (-5.3)	18.4 (-14.6)	9.4
h) Phantom 2 (head)	23.3 (-9.7)	N/A	N/A	N/A	N/A

TABLE IV  
TRP RESULTS FOR DUT 2 AT CHANNEL 698 FROM MEASUREMENT CAMPAIGN 2 WITH 13 TEST PERSONS AND PHANTOM 2. REALIZED TOTAL EFFICIENCY VALUES (IN DECIBELS), REFERRED TO THE NOMINAL MAXIMUM TRANSMISSION POWER OF GSM1800 MOBILE PHONES (+30 dBm), ARE SHOWN INSIDE PARENTHESES

GSM 1800:	Mean TPR [dBm]	Std. dev. of TRP [dB]	TRP <sub>max</sub> [dBm]	TRP <sub>min</sub> [dBm]	TRP <sub>max</sub> - TRP <sub>min</sub> [dBm]
a) Free Space	27.6 (-2.4)	N/A	N/A	N/A	N/A
b) Head+Hand (predefined)	23.5 (-6.5)	0.4	24.0 (-6.0)	22.8 (-7.2)	1.2
c) Head Only (predefined)	25.6 (-4.4)	0.2	26.0 (-4.0)	25.3 (-4.7)	0.7
d) Hand Only (predefined)	25.2 (-4.8)	0.4	25.7 (-4.3)	24.3 (-5.7)	1.4
e) Head+Hand (user-select.)	21.4 (-8.6)	2.8	24.2 (-5.8)	16.3 (-13.7)	7.9
f) Hand Only (user-select.)	23.7 (-6.3)	2.8	26.4 (-3.6)	19.1 (-10.9)	7.3
h) Phantom 2 (head)	26.1 (-3.9)	N/A	N/A	N/A	N/A

The total BL is high in the user-selected talk position [setup e)], in particular in the GSM900 band, where the mean BL of the head and hand is about 9 dB. In the GSM1800 band, the mean BL is 3 dB lower, i.e., about 6 dB. The mean BL (head and hand) values are approximately 2 dB smaller in the predefined talk position than in the user-selected talk position in both frequency bands. The mean BL due to the head in the predefined position is 5.4 dB at 900 MHz and 2 dB at 1800 MHz. The corresponding BL results for the phantom head are 5.8 dB at GSM900 and 1.5 dB at GSM1800, which shows that, at least in this case, the measurement with a phantom gives a good approximation of the loss from real users' heads. The mean isolated BL due to the hand in the predefined position is about 2 dB in both the GSM900 and GSM1800 bands. In the user-selected position, the corresponding result is about 4 dB at 900 MHz and about 3 dB at 1800 MHz.

Sliding averages were also calculated for the TRP results in order to see how fast the variation in the mean value converges as a function of the number of test persons. The sliding averages were calculated so that the mean TRP was first calculated for the first two users, then for the first three users, etc.,

and, finally, for all the 13 users. The difference between the mean TRP result between  $n$  and  $(n + 1)$  users was calculated, and for the user-selected talk position, the mean TRP converged within  $\pm 0.3$  dB for about eight test persons, both at GSM900 and GSM1800. From this, we conclude that the group of 13 users is statistically sufficient, which is in accordance with [2] and [3].

The results indicate that the variable handgrip is the main reason for the large differences that occur between individuals when the handgrip is not predefined and that the anatomical differences between the users' heads play only a smaller role in the differences.

### C. Comparison of the Results From Both Measurement Campaigns

The main results from the two measurement campaigns are compared in Table VI. Even though DUT 1 and DUT 2 are different GSM phone models, the results obtained for them from the two measurement campaigns are quite comparable in the GSM1800 band, where the comparison can be made.

TABLE V  
MEAN BL RESULTS FROM MEASUREMENT CAMPAIGN 2 FOR DUT 2

Predefined talk position:	GSM900, Mean BL [dB]	GSM900, st.dev. of BL [dB]	GSM1800, Mean BL [dB]	GSM1800, st.dev. of BL [dB]
b) 13 users (head+hand)	-7.3	0.8	-4.1	0.4
c) 13 users (head)	-5.4	0.4	-2.0	0.2
d) 13 users (hand)	-2.5	0.6	-2.4	0.4
g) 13 users (no hand, no head, user away from the DUT)	-0.5	0.3	-0.7	0.2
13 users (hand, isolated loss )	-2.0	0.6	-1.7	0.3
h) Phantom 2 (head)	-5.8	N/A	-1.5	N/A
User-selected talk position:	GSM900, Mean BL [dB]	GSM900, st.dev. of BL [dB]	GSM1800, Mean BL [dB]	GSM1800, st.dev. of BL [dB]
e) 13 users (head+hand)	-9.2	2.7	-6.2	2.8
f) 13 users (hand)	-4.6	3.3	-3.9	2.8
13 users (hand, isolated loss )	-4.1	3.3	-3.2	2.8

Although the fact that the results are so alike is more like a coincidence, it is noted that both DUTs are quite similar: Both are monoblock phones that have nearly equal sizes, and both phones may also have the same type of internal antenna.

#### IV. CONCLUSION

We have investigated the effects of the user's head and hand on the TRP, BL, and radiation pattern of GSM phones. The 3-D far-field radiation characteristics of GSM 900/1800 MHz mobile phones in the talk position with real users and a phantom were investigated in two measurement campaigns. A specific position and grip was defined for the test person's hand, and the phone remained in the same position due to a plastic fixture in all the corresponding test setups. Moreover, the measurements were repeated so that the test users did not hold the phone, but it was in the plastic fixture, and the test person held his or her head against the phone. This way, we could independently study the effect of the head. In the second measurement campaign, a few additional setups were used, because the variation in the TRP results between the test persons, when they are allowed to hold the phone in a way that they desire, was also of particular interest.

In the first measurement campaign, the variation in the BL between the three different test persons was only about 0.2 dB at GSM1800 in the predefined talk position. In the second measurement campaign, with the other measurement system, the standard deviation was a little higher: about 0.8 dB at GSM900 and 0.4 dB at GSM1800 in the predefined talk position. However, the number of the test persons was also higher, i.e., 13; therefore, the measurements using the second

measurement system are statistically more significant. In the RAMS measurements, it was found that the variation in the TRP and the BL between the test persons is high when they can freely select the talk position. The standard deviation was up to about 3 dB, and the minimum TRP value was about 8 dB lower than the maximum TRP recorded. These large variations are in line with related previous studies [1]–[3], where the talk position has been freely selectable by the test users.

We conclude that the main contribution to the large variation between the BL of a number of users is the individual hand position and grip on the mobile phone. The anatomical differences between the users' heads are clearly less significant. Moreover, the differences between the mean BL of the test persons' heads and a phantom were small, i.e., about 0.5 dB or less, for the measurement setups, where the mobile phone was mounted with a fixture against the user's head or the phantom. This was observed with both measurement systems. This effectively shows that phantom heads can well be used to simulate the real user's head in an average sense. Still, it was seen that the effect of the hand is also important. However, it is difficult to develop a phantom hand that would be suitable and realistic for various mobile device form factors and models on the market. Moreover, a phantom hand could considerably increase the total measurement uncertainty and make the measurements poorly reproducible. This is why phantom hands have commonly been omitted from mobile antenna performance measurement setups. Nonetheless, there is increasing interest and activity in related international working groups in developing a practical phantom hand that could be standardized.

Based on the experiences that we acquired during the measurements, we found the RAMS, due to its near-real-time

TABLE VI  
SUMMARY OF THE MAIN RESULTS THAT WERE OBTAINED FROM THE TWO MEASUREMENT CAMPAIGNS

	Measurement campaign 1	Measurement campaign 2
Measurement system	3-D far-field measurement system	RAMS
Device under test denotation	DUT 1	DUT 2
Device under test systems	EGSM 900/1800	EGSM 900/1800
Antenna type	internal	internal
Number of test persons	3 (head+hand), 2 (hand)	13
Measurement channels	698	62 / 698
Mean TRP in free space [dBm]	28	29.1 / 27.6
Mean TRP (head+hand) [dBm] in predefined talk position	23.8	21.8 / 23.5
Mean TRP (head) [dBm] in predefined talk position	26.4	23.7 / 25.6
Mean TRP (hand) [dBm] in predefined talk position	N/A	26.6 / 25.2
Mean TRP (head+hand) [dBm] in user-selected talk positions	N/A	19.9 / 21.4
Mean TRP (hand) [dBm] in user-selected talk positions	N/A	24.5 / 23.7
Mean BL (head+hand) [dB] in predefined talk position	-4.2	-7.3 / -4.1
Mean BL (head) [dB] in predefined talk position	-1.6	-5.4 / -1.9
Mean BL (hand) [dB] in predefined talk position	N/A	-2.5 / -2.4
Mean BL (head+hand) [dB] in user-selected talk positions	N/A	-9.2 / -6.2
Mean TRP (phantom) [dB]	26.3	23.3 / 26.1
Mean BL (phantom) [dB]	-1.7	-5.8 / -1.5

nature and lack of mechanical rotation of the test object, to be very practical for these kinds of measurement campaigns that involve a number of human test persons.

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