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Handheld Devices in Data Mode

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Abstract—The human body has an influence on the radiation from handheld devices like smartphones, tablets and laptops, part of the energy is absorbed and the spatial distribution of the radiated part is modified. Previous studies of whole body absorption have mainly been numerical or related to talk mode. In the present paper an experimental study involving four volunteers and three different devices is performed from 0.5 to 3 GHz. The devices are a laptop, a tablet, and a smartphone all held in the lap. The 3D distribution of radiation is measured. Comparing the integrated power in the case of a person present with the device alone allows the determination of the relative absorption in the whole body and the device. In general the absorption varies considerably between devices and as a function of frequency and person. The absorption varies from almost nothing to close to 100%. The shadowing of the body is apparent in all cases. The losses in the inbuilt antennas are often dominating and with a maximum total loss of 99% for the smartphone for one user. The absorption in the body is around 50%.

Index Terms—Mobile phone, whole body absorption, data mode

I. Introduction

The paper focuses on measurement of power absorption from modern wireless devices like a laptop, and a tablet, where the absorption may be in the device and in the human holding the device. For the latter the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] has given basic restrictions on the specific absorption rate (SAR), a local value inside the tissue and a global value, whole-body SAR (wbSAR); in the frequencies of interest the wbSAR limit is 0.08 W/kg. It will be apparent from the results presented later in the paper that in the practical situations considered the wbSAR is far below the basic restriction. Therefore, the focus is on measurement of absorption influenced by a person holding a device in the lap (data mode), since the total radiated power and its distribution is important for the wireless link.

For communication purposes, the power gain of the channel is important and may be evaluated in terms of the so-called mean effective gain (MEG), depending on both the antennas and the propagation environment, see *e.g.* [2]. For small mobile devices the influence of a user holding the device is important since large variations up to 10 dB have been measured previously for different users in the same radio environment (next to head, talk-mode) [3], [4]. Numerical evaluation of the user influence is possible using, e.g., finite-difference time-domain (FDTD) simulations, see [5]–[8], but

here the variations in the user influence are difficult to include. This problem is avoided if the antenna is measured in the anechoic room including different users as it was done in [9]–[11]. For the talk-mode case the location of the user's hand is the single most important issue for the variation in power obtained with different users [12]. Today's use of mobile devices include situations where the user holds the device in front of the body, e.g. for web browsing. As for the talk-mode case, it is expected that the user in this so-called data-mode may have a significant influence on the performance [13]. The performance of devices in data-mode including real persons has only been investigated in a few works, see [14] and references therein. In the current work the user influence is investigated for the data-mode usage of modern type devices. The incident power is coming from a device in a transmit mode, and the absorbed power is determined by measuring the radiated power in an anechoic chamber and compared with the available power. It is interesting to note that the opposite environment, a reverberation chamber, may also be used for finding the wbSAR [15], where the incident power is diffuse and coming from many directions, as will be the case in an indoor environment. Wide band measurements in an aircraft cabin with passengers have also been used as a lossy cavity [16] where the source is an access point in the cabin. The new aspects in this paper are the use of modern devices like tablets and laptops in an anechoic room using real persons, illustrating the impact on the absorption. Real persons have been used before, see above, but with mobile phones only, and at head positions, or with diffuse incidence. In addition the distribution of the energy in the far field is measured. The experiments are described in Section II and III, while the results are discussed in Section IV. Discussion and Conclusion in Section V and VI concludes the paper.

II. Measurements

The objective of the measurements is to obtain the radiation pattern in both the θ and ϕ polarization for different combinations of mobile devices and users (test persons) holding the devices. In addition, also S_{11} measurements are made. During the measurements the user sits in a wooden chair which is made for this kind of measurements and about 2.5 m high, so that the user is approximately in the middle of the anechoic room and the measurement coordinate system. The chair has armrests and pillows to ensure that the person is comfortable and can stay reasonably static for the about 20 minutes a measurement lasts. The full radiation pattern is obtained as a series of azimuthal (ϕ-angle) scans, obtained by rotating the

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Fig. 1: User in the measurement chair inside the anechoic room. The reference coordinate systems is also shown.

TABLE I: Users involved in the measurements.

User No.	Gender	Weight	Height
1	Male	80 kg	1.9 m
2	Male	92 kg	1.8 m
3	Male	85 kg	1.7 m
4	Female	44 kg	1.5 m

TABLE II: Overview of measured devices.

Label	Make	Type	Size [mm]
B	Fujitsu LifeBook P7010 + mockup antenna	Laptop	260×200
C	Samsung Galaxy Tab 8.9 LTE GT-P7320	Tablet	231×158
D	Samsung Galaxy S II LTE I9210	Smartphone	131×70

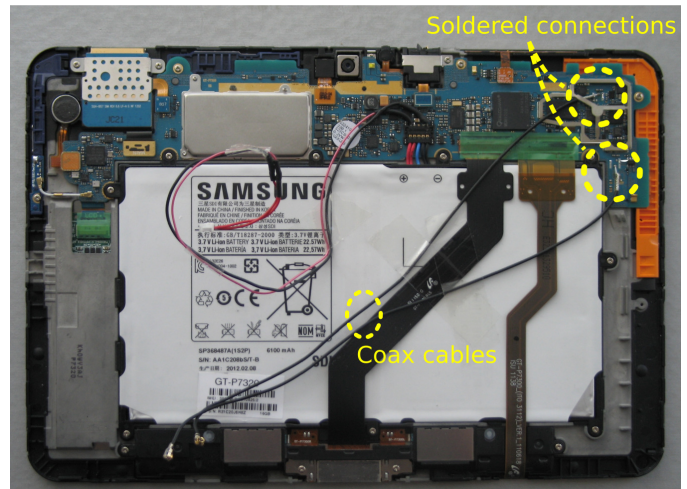Fig. 3: The tablet device with back cover removed, revealing the added coax cables connecting to the two antennas (only one used).

user and chair while the probe antenna is stationary. The dual-polarized probe is mounted on an arm that can rotate around the user, corresponding to different θ-angles in the radiation pattern.

The user holds the tablet or phone in a way that is natural for the device; the tablet or phone is held in one hand, supported by a piece of expanded polystyrene (EPS). Fig. 1 shows a user sitting in the wooden chair in the anechoic room. Using laser pointers the device/hand is placed so that the rotation center is approximately in the middle of the device. An overview of the users is given in Table I. In addition to the measurements with users, similar measurements were made for all the devices without a user, by placing the device in a fixture made of EPS. The fixture was placed on the measurement chair, so that the device was located approximately at the same height and location, as with the user present. Subsequently, these measurements are denoted as "free space (FS)."

The three devices measured are listed in Table II and Fig. 2 shows examples of how the devices are held by the users. Each device is modified by adding a small piece of coax cable, connecting the antenna inside the device to the measurement system. An example of this is given in Fig. 3, showing the connection for the tablet. Note that for practical reasons, the added extra cable is considered part of the device antenna. However, the extra loss is small, less than 0.3–0.9 dB, depending on frequency. Since the focus of the current work is power absorption, the changes caused by the added cables

were only investigated with respect to the losses and not the radiation patterns.

The radiation pattern measurements were made at 30 different frequencies in the three bands:

Low Band (LB): (760), 800, ..., 960, (1000, ..., 1120)
Mid Band (MB): 1850, 1890, ..., 2210
High Band (HB): 2510, 2565, ..., 2950, (3005)

all in MHz. For each of these bands, a measurement with a reference dipole was also made, specified for the frequencies 836 MHz, 1880 MHz, and 2450 MHz, respectively. Note that the results for the LB and HB are effectively limited in the following due to the frequency limits of the reference antennas, since the results are obtained via a combination of device and reference antenna measurements, as described in Section III. The unavailable frequency samples are shown within parentheses in the list above.

All spherical radiation patterns were made in a grid defined by all combinations of ϕ angles $0°, 15°, ..., 345°$ and θ angles $0°, 15°, ..., 165°$, i.e., using a $15°$ sampling density in both angles of a usual spherical coordinate system. Examples of the radiation patterns are shown in Fig. 4–6 for the three devices.

In addition to the radiation pattern measurements, also a S_{11} measurement was made for each user/device combination, i.e., including the influence of the user on the device.

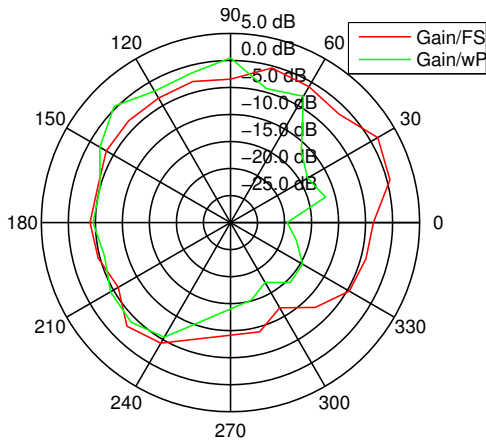Fig. 2: The three devices held by users; from left to right device B, C, D.

Fig. 4: XZ-cut of measured radiation pattern (both polarizations summed) for the laptop device with (Gain/wP) and without user (Gain/FS). The frequency is 1890 MHz.
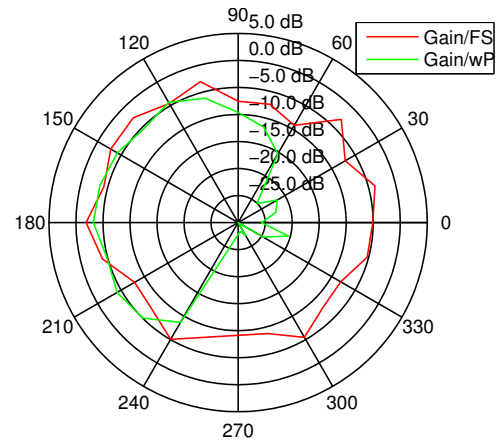

Fig. 6: XZ-cut of measured radiation pattern (both polarizations summed) for the smartphone device with (Gain/wP) and without user (Gain/FS). The frequency is 1890 MHz.
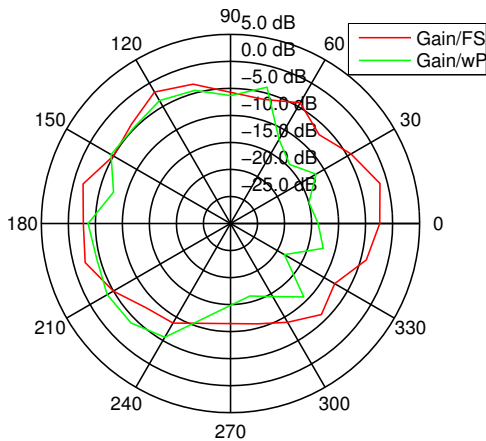

Fig. 5: XZ-cut of measured radiation pattern (both polarizations summed) for the tablet device with (Gain/wP) and without user (Gain/FS). The frequency is 1890 MHz.

III. DEFINITIONS AND THEORY FOR EXPERIMENTAL SETUP

The device antenna is fed with incident power P_{in}. The integrated radiated power is obtained as

$$P_{\text{rad}} = \Delta_\theta \Delta_\phi \sum_{k=1}^{K} \sum_{l=1}^{L} \left[Q_\theta(\theta_k, \phi_l) + Q_\phi(\theta_k, \phi_l) \right] \sin(\theta_k) \quad (1)$$

where K and L are the number of samples in the θ- and ϕ-angle, respectively, Δ_θ and Δ_ϕ are the associated angle sampling intervals. The power radiation patterns in the two polarizations are given by $Q_\theta(\cdot)$ and $Q_\phi(\cdot)$, respectively.

By comparing this with the input power it is possible to derive some results for the absorption of the device alone and for the combined device and person. Assuming a user is present, the power balance is modeled as

$$P_{\text{in}}^{\text{usr}} = P_{\text{rad}}^{\text{usr}} + P_{\text{L}}^{\text{usr}} + P_{\text{L}}^{\text{term}} \quad (2)$$

where $P_{\text{rad}}^{\text{usr}}$ is the total power radiated when a user is present, $P_{\text{L}}^{\text{usr}}$ is the loss in the user's body, and $P_{\text{L}}^{\text{term}}$ is the loss in the terminal, consisting of the actual antenna and other parts of the device. The power input to the antenna is given by $P_{\text{in}}^{\text{usr}}$. For the special case of FS, the user loss is absent and the terminal loss may be found as

$$P_{\text{L}}^{\text{term}} = P_{\text{in}}^{\text{free}} - P_{\text{rad}}^{\text{free}} \quad (3)$$

where $P_{\text{in}}^{\text{free}}$ is the input power and $P_{\text{rad}}^{\text{free}}$ is the measured radiated power.

The system is calibrated by using the measurements with reference antennas with low loss, assumed to be zero. In this case the radiated power equals the input power corrected for

reflections,

$$P_{\text{rad}}^{\text{ref}} = P_{\text{in}}^{\text{ref}} \left(1 - |S_{11}|^2 \right) = P_{\text{in}}^{\text{ref}} T^{\text{ref}} \qquad (4)$$

where T^{ref} is the transmission coefficient for the reference antenna, thus

$$P_{\text{in}}^{\text{ref}} = \frac{P_{\text{rad}}^{\text{ref}}}{T^{\text{ref}}} \qquad (5)$$

This input power is used as the reference for all experiments. There is a slight error due to unavoidable losses in the reference antennas, but as long as they are small relative to other losses, the error should be negligible.

For the general case the input power depends on the actual value of the transmission coefficient $T^{\text{dev}} = 1 - |S_{11}|^2$ for the device and the presence or not of the human body,

$$P_{\text{in}}^{\text{dev}} = P_{\text{in}}^{\text{ref}} T^{\text{dev}} \qquad (6)$$

Using (2) and (3), the loss in the user is

$$P_{\text{L}}^{\text{usr}} = P_{\text{rad}}^{\text{free}} - P_{\text{rad}}^{\text{usr}} + \left(T^{\text{usr}} - T^{\text{free}} \right) P_{\text{in}} \qquad (7)$$

Defining the total power input to the antenna as $P_{\text{tot}} = P_{\text{rad}}^{\text{usr}} + P_{\text{L}}^{\text{usr}} + P_{\text{L}}^{\text{term}}$, the relative losses given by

$$R_{\text{L}}^{\text{usr}} = \frac{P_{\text{L}}^{\text{usr}}}{P_{\text{tot}}} \qquad \text{and} \qquad R_{\text{L}}^{\text{term}} = \frac{P_{\text{L}}^{\text{term}}}{P_{\text{tot}}} \qquad (8)$$

shows where the power is dissipated. If we instead focus on the power actually leaving the antenna, the ratio

$$\eta_{\text{L}}^{\text{usr}} = \frac{P_{\text{L}}^{\text{usr}}}{P_{\text{L}}^{\text{usr}} + P_{\text{rad}}^{\text{usr}}} \qquad (9)$$

shows the loss in the user compared to the sum of losses in the user and terminal.

It should be noted that the subtraction of powers is an approximation, assuming that the absorption in the antenna is independent of the person. The error made is assumed to be negligible.

IV. RESULTS

A. User influence on radiation pattern

Fig. 4–6 show the horizontal radiation pattern of the three devices for one frequency and one example user. $\phi = 0$ is the forward scattering angle (away from the transmitter). The interpretation is clear: in the backscattering halfspace the influence of the body is minor, while the forward shadowing (green curve) may be as severe as 20 dB. In scattering environments the effects of shadowing may depend on reflections in the environment, as investigated in *e.g.*, [2] using the mean effective gain (MEG) measure.

B. Absorption by device without the human body

The relative absorption in the devices alone are shown in Fig. 7, computed using (8). This figure allows comparison among the devices, as commented in the paragraphs below.
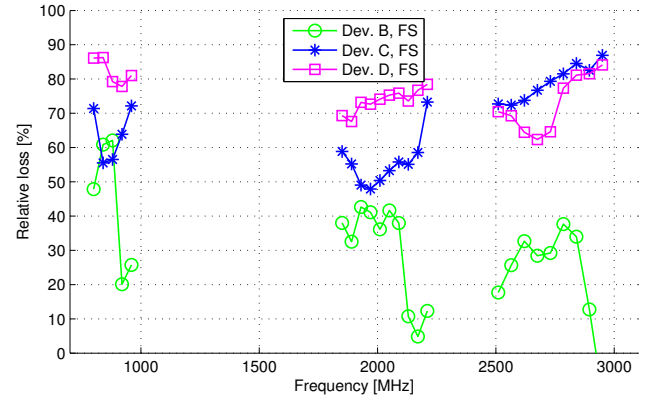

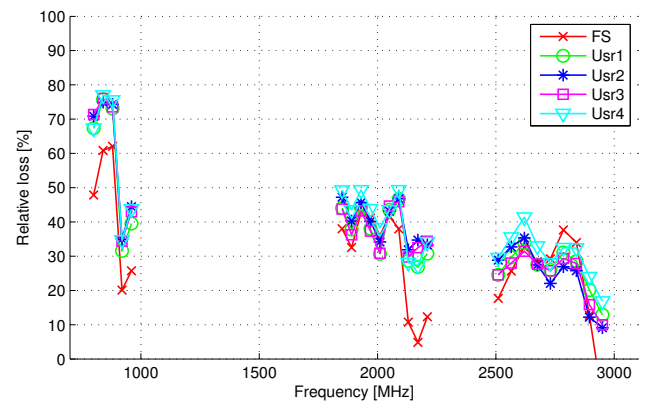Fig. 7: The relative terminal loss $R_{\text{L}}^{\text{term}}$ for all devices, see (8).

Fig. 8: Relative absorption by antenna alone, $R_{\text{L}}^{\text{term}}$ (red crosses and line) and combined device and different users, $R_{\text{L}}^{\text{term}} + R_{\text{L}}^{\text{usr}}$, see (8). For the laptop.

a) Laptop: In the laptop there is sufficient space for the antenna so the losses are not expected to be high. In the middle and high frequency band the absorption is around 30-40% in a non-resonant way. At the lower band around 900 MHz the absorption varies as from a resonant structure with the smallest absorption of 20% at 900 MHz which is also the frequency of best match. Recall that mismatch losses have been accounted for. It is noteworthy that near 2150 MHz the absorption is as low as 5%. One interpretation could be that the antenna current distribution is frequency dependent, and the most efficient distribution is at a resonance. However, this is a topic which deserves more studies.

b) Tablet: The tablet has an intermediate size between the laptop and the phone, which seems to be reflected in the range of absorptions from 49 to 87%.

c) Smartphone: The smartphone has less volume at its disposal for the antenna and less area to distribute the current over which leads to higher losses, in the present case between 62 and 86%, but the overall trends are similar with the highest losses at the low frequency band. The similar measurements in [17] for a planar inverted-F antenna (PIFA) antenna give an average loss of 62% in agreement with the highest frequencies.
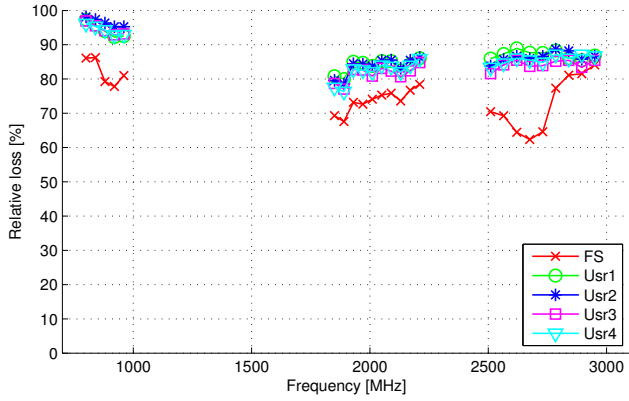
Fig. 9: Relative absorption by antenna alone, R_L^{term} (red crosses and line) and combined device and different users, $R_L^{\text{term}} + R_L^{\text{usr}}$, see (8). For the smartphone.
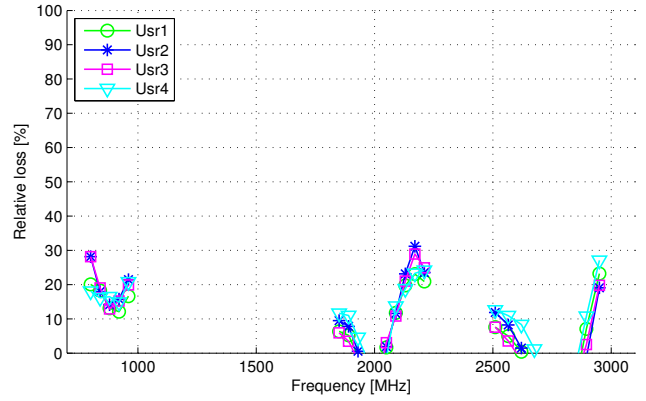

Fig. 11: The absorption in the user relative to the total power, see (8). Meaningless results are not shown. Laptop measurements.
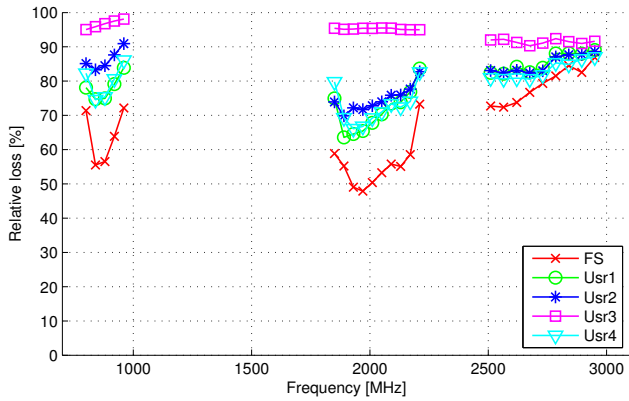

Fig. 10: Relative absorption by antenna alone, R_L^{term} (red crosses and line) and combined device and different users, $R_L^{\text{term}} + R_L^{\text{usr}}$, see (8). For the tablet.
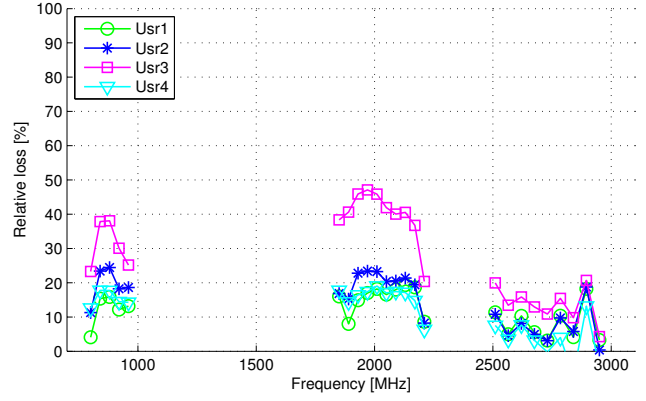

Fig. 12: The absorption in the user relative to the total power, see (8). Meaningless results are not shown. Tablet measurements.

C. Absorption including the human body

In addition to the FS results, Fig. 8–10 also shows the combined relative absorptions for the terminals and the user.

d) Laptop: It is not possible to measure the effect of the human in itself, only indirectly, since the absorption is measured twice, antenna alone and antenna and human together. In general the results from the four users cluster together with some variation. The problem is that for some frequencies it is not possible to distinguish the two measurements, with and without human presence. For the laptop this occurs near 2000 MHz and above 2500 MHz (Fig. 8) where the scattering from the human adds or subtracts from the antenna result. In such situations it is not possible to subtract powers with a meaningful result; in fact the absorption in the human may seem to be negative. If the total absorption is significantly larger than the absorption in the antenna we shall assume that error is small with the result shown in Fig. 11, where meaningless results have been removed.

The resulting user absorptions lie between 10 and 30% for

the laptop with some variation due to the different users.

e) Tablet: The results are shown in Fig. 12. Compared to the laptop there is now significant user influence reflecting the proximity of the hand to the antenna. The absorptions range from 0 to 50%.

f) Smartphone: The results are shown in Fig. 13. The user absorptions lie between 1 and about 25%, significantly lower than for the tablet. It should be noted that the subtractions of powers is an approximation.

D. Human absorption and total radiation

In the previous cases the losses in the device play a significant role. This is of course important from a communication point of view, but irrelevant from exposure to a human point of view. In this section we look at the absorption in the human versus the total power leaving the antenna, *i.e.* the sum of human absorption and radiated power, as given by (9).

The result for the Laptop is shown in Fig. 14. The maximum human absorption is 50%, in general below 20%. There is only
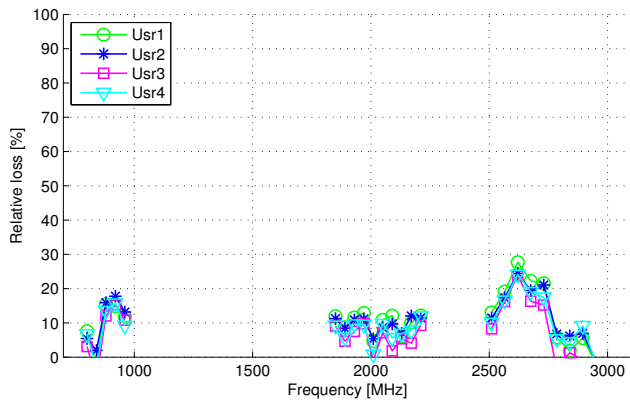
Fig. 13: The absorption in the user relative to the total power, see (8). Meaningless results are not shown. Smartphone measurements.
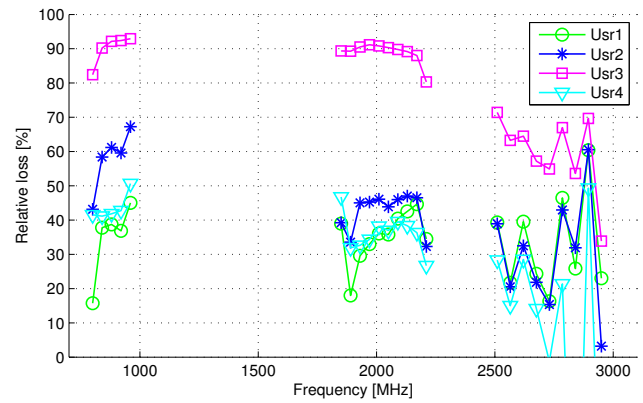

Fig. 15: Absorption in user relative to the power absorbed in user and radiated, see (9). For different users and with the tablet.
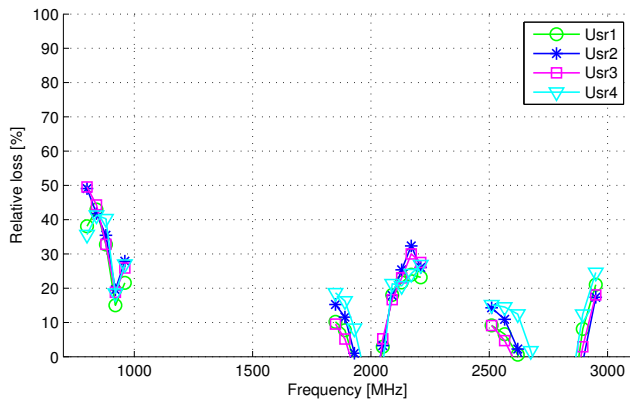

Fig. 14: Absorption in user relative to the power absorbed in user and radiated, see (9). For different users and with the laptop.
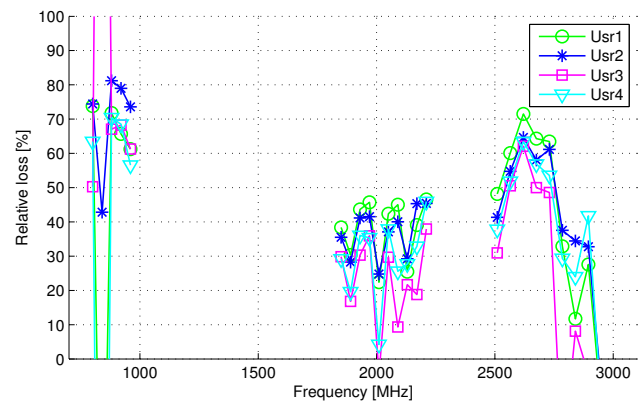

Fig. 16: Absorption in user relative to the power absorbed in user and radiated, see (9). For different users and with the smartphone.

little variation between the users. In the case of the Tablet (Fig. 15) the situation is markedly different, since the user is closer to the antenna. The absorption may range from 20% to 90% in the middle frequency range. The situation is not too different for the Smartphone (Fig. 16) with an approximate overall absorption for all users of around 50%.

Note that in case the absorption in the user is erroneously estimated to be negative, as discussed above, the relative absorption defined in (9) may also become either negative or larger than 100%. The plots in Fig. 14–16 are limited to the meaning full 0–100% range.

The whole body SAR in W/kg is proportional to the relative absorption shown in Fig. 14–16

V. DISCUSSION

The paper discusses absorption when commercial wireless devices are used by real persons. The absorptions are measured as the difference between radiated and input power, and thus there is an inbuilt inaccuracy. In cases where the results are meaningless, such as negative absorptions, the results are not

shown. The number of persons is only four, but the time spent on users is large, since it takes about 20 minutes for one device and one person. The persons are instructed to hold the devices in the lap, as they would normally. In several situations it was noted that there is only little spread of the results among the users, indicating good accuracy. Occasionally, a user will have a hand close to an antenna affecting the absorption drastically. It should be noted that the presence of the hand also influenced the matching, but this is an effect which is compensated for. There are two sets of measurements, one without the person and one with. In most situations with the persons included, the absorption increases sufficiently to make it possible to subtract the two absorptions (with and without a person) to give an estimate of the absorption in the human body. In one case (the laptop at 2000 MHz) the total absorption is so close to the device absorption that it is meaningless to subtract the two, the apparent absorption may be negative in such situations. But the total absorption is also of interest from a communication point of view. Absorption of 95% corresponds to a loss of 13 dB, which is not negligible. The losses from a human reach high

values mainly due to the inefficient antenna; a better antenna would reduce the total losses to less than 50%. The different devices show rather similar qualitative behavior. The radiation patterns as modified by the body show no surprises, a common feature is a deep null behind the body, and only small changes in other directions. Note that this is in an anechoic chamber, in real environments the null will be filled with scattering from other objects.

VI. Conclusion

By integrating the radiated power over all angles in an anechoic room and compare with the input power, it is possible to estimate the human absorption and the antenna efficiency of a radiating device such as a mobile phone or a tablet, including the influence of the user, who holds the devices in the lap. It is an interesting result that the influence of the antenna itself is in most cases the dominant factor for the losses. If the antenna losses were zero the total losses would be less than 50%.

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He has been a Visiting Professor in Tucson, Arizona, Christchurch, New Zealand, Vienna, Austria, and Lund, Sweden. From 1993-2003, he was Head of the Center for Personkommunikation (CPK), dealing with modern wireless communications. He has published widely on antennas, radio wave propagation, and communications, and has also worked on biological effects of electromagnetic systems. He was on the management committee for COST 231 and 259, a collaborative European program on mobile communications. Professor Andersen is a Life Fellow of IEEE and a former Vice President of the International Union of Radio Science (URSI) from which he was awarded the John Howard Dellinger Gold Medal in 2005.

Jesper Ødum Nielsen received his master's degree in electronics engineering in 1994 and a PhD degree in 1997, both from Aalborg University, Denmark. He is currently employed at Department of Electronic Systems at Aalborg University where main areas of interests are experimental investigation of the mobile radio channel and the influence mobile device users have on the channel. He has been involved in MIMO channel sounding and modeling, as well as measurements using live GSM and LTE networks. In addition he has been working with radio performance evaluation, including over the air testing of active wireless devices.

Gert Frølund Pedersen was born in 1965 and married to Henriette and have 7 children. He received the B.Sc. E. E. degree, with honour, in electrical engineering from College of Technology in Dublin, Ireland in 1991, and the M.Sc. E. E. degree and Ph. D. from Aalborg University in 1993 and 2003. He has been with Aalborg University since 1993 where he is a full Professor heading the Antenna, Propagation and Networking LAB with 36 researcher. Further he is also the head of the doctoral school on wireless communication with some 100 phd students enrolled. His research has focused on radio communication for mobile terminals especially small Antennas, Diversity systems, Propagation and Biological effects and he has published more than 175 peer reviewed papers and holds 28 patents. He has also worked as consultant for developments of more than 100 antennas for mobile terminals including the first internal antenna for mobile phones in 1994 with lowest SAR, first internal triple-band antenna in 1998 with low SAR and high TRP and TIS, and lately various multi antenna systems rated as the most efficient on the market. He has worked most of the time with joint university and industry projects and have received more than 12 M$ in direct research funding. Latest he is the project leader of the SAFE project with a total budget of 8 M$ investigating tunable front end including tunable antennas for the future multiband mobile phones. He has been one of the pioneers in establishing Over-The-Air (OTA) measurement systems. The measurement technique is now well established for mobile terminals with single antennas and he was chairing the various COST groups (swg2.2 of COST 259, 273, 2100 and now ICT1004) with liaison to 3GPP for over-the-air test of MIMO terminals. Presently he is deeply involved in MIMO OTA measurement.