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Effect of the User's Hands on the Operation of Lower UHF-Band Mobile Terminal Antennas: Focus on Digital Television Receiver

Jari Holopainen, Outi Kivekäs, Janne Ilvonen, Risto Valkonen, Clemens Icheln, and Pertti Vainikainen

***Abstract*—This paper deals with the effect of the user's hands on the performance of lower UHF-band antennas in handheld terminals. It is studied that how the input impedance, efficiency, and far-field directional pattern of the internal broadband digital television antenna are affected by the presence of the user's hands. The main part of the study has been carried out by applying finite-difference time-domain simulations. Measurements have been performed to support the results obtained by simulations. In the worst case, as much as 7–11 dB decrease of the antenna efficiency compared to free space case is shown. The results also indicate that the power absorption to the hand(s) is generally a more severe problem for the total efficiency than the change of the matching. On the other hand, it is also shown that in certain cases, the total efficiency of the antenna can even be improved due to the hands of the user. The results of this paper increase the understanding of the effect of the user's hands on the operation of the lower UHF-band antennas, whose operation is based on the radiation of a finite ground plane.**

***Index Terms*—Broadband antennas, digital television (DTV), digital video broadcast—handheld (DVB-H), electromagnetic compatibility, finite-difference time-domain (FDTD) simulations, microstrip antennas, mobile antennas, receiving antennas, small-antenna measurements, user effect.**

I. Introduction

It is very well known that the user of a mobile device affects the operation of the antennas by shifting the resonant frequencies and absorbing a part of the radiated/received power [1]–[7]. In addition, the directional pattern of the antenna is distorted compared to free space case. However, the user assumes that any system in portable devices is operating regardless of the position and place in the vicinity of the user, and thus, the user effect of the antennas should be taken into account in the design of the antennas, as well as the link budget of the whole system.

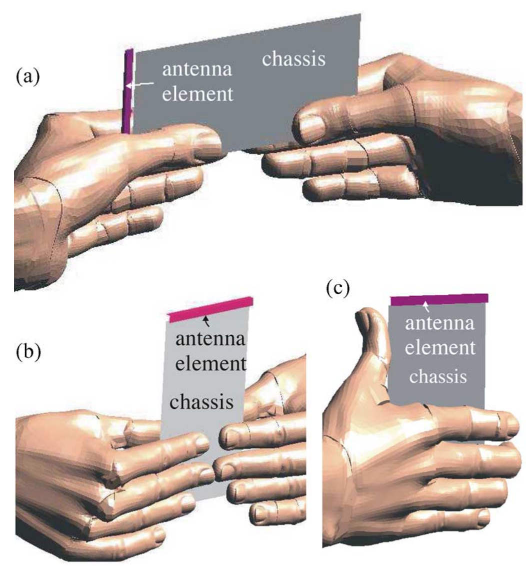

Fig. 1. Typical use positions of the DTV antenna handled in this paper. (a) Landscape browsing grip. (b) Portrait end grip. (c) Portrait palm grip.

Recently, there has been a significant increase in the number of different functions and radio systems built into handheld devices. One of such newcomers is the digital television receiver (DTV). One possible standard for handheld DTV is digital video broadcast—handheld (DVB-H) [8]. The start of the DVB-H has, so far, been slow mainly due to the lack of suitable services and terminals.

The implementation of broadband internal antennas for DTV receiver in mobile terminals has been studied in the previous publications of the antenna research team at Aalto University School of Electrical Engineering (prior to 2010 Helsinki University of Technology) [9], [10]. In this paper, the operation of the earlier published DTV prototype antenna in typical use positions is investigated. Since users are increasingly using mobile terminals for data services, the focus will shift from the talk mode to the data mode, and the effect of the user's hands on the operation of antennas will have even greater importance than earlier. Therefore, the main objective of the paper is to study the antenna performance in the presence of the user's hands (see Fig. 1). The studied parameters are matching, radiation and total efficiencies, and far-field directional pattern. They are studied with electromagnetic simulations and verified with measurements. According to the authors' knowledge this is the first systematic study for internal DTV antennas considering

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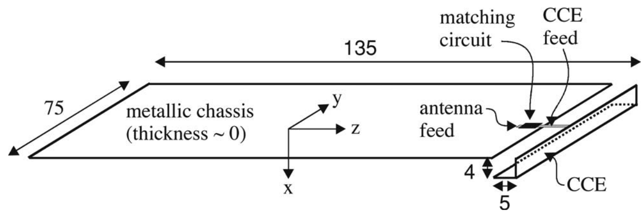

Fig. 2. Sketch of the DTV prototype. The dimensions are in millimeter.

the user's hand effect. The results of this paper are not restricted only to the examined antenna and DTV system, but they aim to gain general understanding on the user's hand effect at the lower UHF band.

II. Research Methods

The user effect is studied by comparing the results in free space with the results obtained when the terminal is held by the user. Because an exact prediction of all the different usage positions is impossible, only some typical use positions are considered in order to study the main trends of the user's hand effect phenomenon. In this paper, the selected representative examples are landscape browsing grip, and portrait end and palm grips (see Fig. 1). In the end and palm grips, the antenna element can be located either at the top or bottom part of the structure (in Fig. 1(b) and (c), the element is top-located).

A. DTV Antenna Prototype

In the DTV antenna prototype published in [9] and [10], the antenna element is a capacitive coupling element (CCE), whose principal function is only to couple currents to the metallic chassis, which supports a flat-dipole-type common-mode current distribution and operates as the main radiator of the mobile terminals at the DTV frequencies (0.47–0.75 GHz) [11], [12]. Since the used antenna concept is inherently nonresonant at the DTV frequencies, a dual-resonant lumped-element matching circuit is required to improve the matching over the DTV band. A dimensional sketch of the prototype is shown in Fig. 2. The prototype is a simplified model, which includes only metallic antenna structures, low-loss printed circuit board (PCB) substrate [13], and the matching circuit (Murata's chip coils and capacitors [14]). The other parts of the mobile terminal, such as the display and battery, would bring unnecessary complexity to the studied phenomena, and are thus left out of consideration. In the performance analysis, these parts are taken into account by an additional implementation margin.

Although the antenna prototype is intended for a tablet-size terminal (length 135 mm × width 75 mm), the CCE-antenna concept is feasible also for smaller size terminals, e.g., 110 mm × 48 mm [10]. Since the operation principle of the CCE antennas in smaller size terminals is the same as in the tablet-size terminals, it can be expected that the trend of the results for the user's hand effect study will also be the same. The CCE-based antennas have also aroused interest among industrial antenna manufacturers, such as Pulse Engineering has implemented their planar internal DTV antenna [15] based on the similar CCE-antenna concept as used in this paper.

The performance of DVB-H antennas is typically specified using the realized gain [8]. The used DTV antenna prototype fulfills this realized gain specification with at least a 3.5-dB margin at 0.47–0.75 GHz in free space [10]. The matching across the DTV band is at least 2 dB in terms of return loss. The 2-dB return loss instead of the typical 6 dB or better is acceptable; first, due to the fact that the antenna is used in reception only, detailed reasons are stated in [10]. Second, the implementation losses introduced by other parts of mobile terminals, e.g., PCB (typically FR4), plastic covers, display, battery, earpiece, and microphone, will cause additional losses, and hence, improve the matching level. Thus, this aforementioned 3.5-dB margin is required to compensate for the additional implementation losses in real terminals [10]. The specific absorption rate (SAR) values are neglected, since DTV is a receiving-only system.

Since the chassis is the main radiator, the far-field directional pattern is similar to that of a dipole, "doughnut," and the directivity in the main lobe direction is 2 dBi. The directional pattern is shown later in Section V. The far field is practically linearly polarized: the long axis of the chassis oriented parallel to the z-axis (see Fig. 2) generates the far-field electric fields parallel to the elevation (theta) unit vector of the standard spherical coordinate system.

B. Simulation Tool, Settings, and Models

The simulations were performed with SEMCAD X, finite-difference time-domain (FDTD)-based electromagnetic simulator [16]. The antenna structure introduced in the previous section was used in the simulations without the matching circuit, since the user's hands are assumed not to affect the matching circuit. The simulated input impedance of the antenna was exported from SEMCAD X to MATLAB, where the matching circuit (consisting of ideal lumped elements) was modeled mathematically based on basic circuit analysis. In addition, all the antenna parts were modeled as perfect electric conductors (PEC). Thus, the user's hands cause all the losses, and the interpretation of the simulation results is straightforward. In addition, the hand has the largest influence with the lossless antenna structure (the criterion is the performance compared to the free space case). This can be stated in the following way: if the antenna structure included losses.

1) The matching level would be better—i.e., the magnitude of the reflection coefficient ρ would be smaller in the input of the DTV antenna—and thus, the decrease of the matching efficiency η_m due to the effect of the detuning by the user's hands would seem to be smaller on the better matching level. This can be shown with the help of the equation for the matching efficiency

$$\eta_m = 1 - |\rho|^2. \quad (1)$$

2) The decrease of the radiation efficiency $\eta_{\rm rad}$ due to the losses of the hands would also be smaller. This can be shown with the help of the definition of the radiation

efficiency

$$\eta_{\rm rad} = \frac{P_{\rm rad}}{P_{\rm rad} + P_{\rm ant} + P_{\rm hand}} \quad (2)$$

where $P_{\rm rad}$ is the radiated power, $P_{\rm ant}$ is the loss power in the antenna structure, and $P_{\rm hand}$ is the loss power in the hands. It can now be seen from (2) that increased $P_{\rm ant}$ makes the effect of $P_{\rm hand}$ on the radiation efficiency $\eta_{\rm rad}$ smaller. Thus, this means that the effect of the user could be made to seem smaller by designing additional resistive losses into the antenna structure. However, that would not be very reasonable.

The user's hands were modeled with the homogenous, fully posable human hand phantoms available in SEMCAD X. The phantom includes the thumb, four other fingers, palm, and wrist. In reality, the hand like this does not exist alone. Therefore, it was studied with electromagnetic (EM) simulations (the results are not shown in detail) that only the hand parts, which are in the reactive near-field region (thumb, fingers, and palm) can cause a significant effect on the operation of the antenna. Thus, it can be concluded that the other body parts cause only shadowing effect in the radiating near-field (Fresnel) and/or in the far-field (Fraunhofer) regions.

The electrical properties of the hand phantoms were modeled according to the target values for phantom hand material reported in [17]. Across the simulation band, the target value of the real part of the relative permittivity is 36.0–44.3, and the effective conductivity is 0.49–0.79 S/m. However, in this paper, we model the phantom with constant values interpolated at the center frequency of the DTV band (0.61 GHz); $\varepsilon'_r = 39$ and $\sigma_{\rm eff} = 0.65$ S/m. With these values, the maximum difference to the target values across the simulation band is 25%. This is assumed accurate enough as the uncertainty of the target values due to dry and moistened palm is up to 35% [17].

According to the authors' experience, a good compromise between the simulation accuracy and a reasonable simulation time is found when the adaptive nonuniform meshing was used with 2-mm maximum FDTD-mesh cell size inside the hand phantom ($\Delta x_{\rm max} = \Delta y_{\rm max} = \Delta z_{\rm max} = 2.0$ mm). The smallest wavelength in the hand phantom at the simulation band is 53.4 mm ($\lambda \approx c_0/f\sqrt{\varepsilon'_r}$) at 0.75 GHz. The maximum diagonal of the cell is $\Delta x_{\rm max}\sqrt{3} = 3.46$ mm, and thus, there are a minimum of 15 cells per wavelength. In the antenna structure and in the surrounding air, the maximum cell sizes were 1.0 and 10 mm, respectively. The perfectly matched layers (PML) were applied on the boundaries of the simulation domain.

The most critical dimension in the browsing and end grips is the distance between the thumb and the other fingers, i.e., the thickness of a terminal. The thickness of 10 mm was used, since it was estimated to be a realistic thickness of a DTV terminal. The distance from the chassis to the thumb and the other fingers is made equal (5 mm), and since the thickness of the CCE is 4 mm and the metallic chassis is very thin (see Fig. 2), the distance of the CCE from the fingers is only 1 mm. In all the cases, the CCE is on the same side as the fingers, since that is the typical location of the mobile terminal antenna elements. The other essential dimensions are illustrated in Figs. 3–5. For the browsing grip, the studies were performed with left and right hand alone and with both hands (see Fig. 3). For the end grip, the studies were performed using both hands and the CCE located either at top or bottom (see Fig. 4), and for the palm grip with one hand only and the CCE also either at top or bottom (see Fig. 5). The performance with the hand grips is compared with the results of a lossless free space case for which the (lossless and ideal) matching circuit was designed.

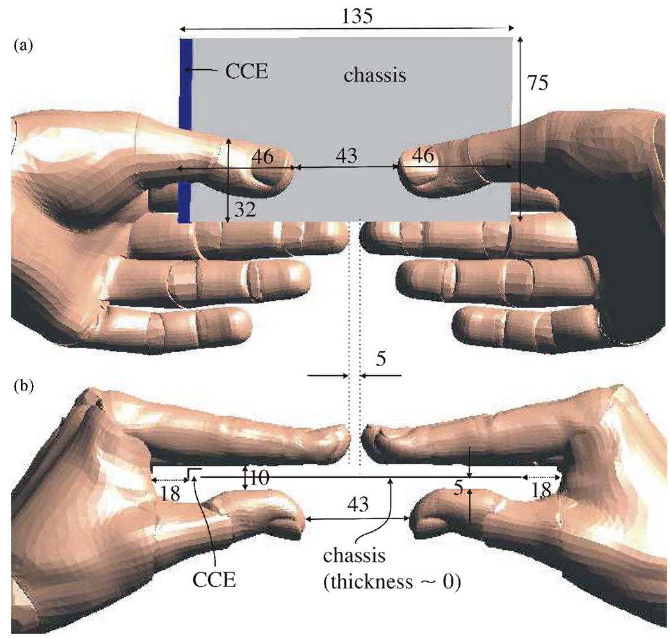

Fig. 3. Dimensions (in mm) of the browsing grip. (a) Front view. (b) Top view.

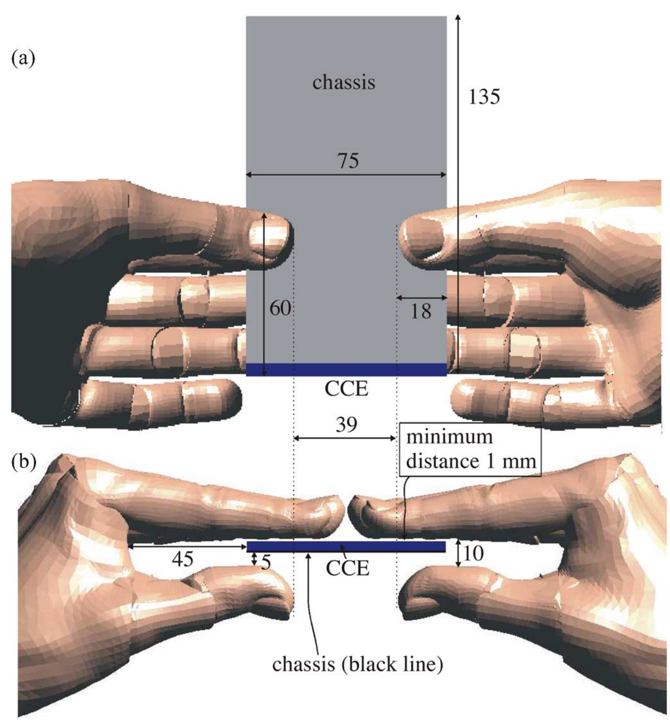

Fig. 4. Dimensions (in mm) of the end grip (here, CCE bottom-located). (a) Front view. (b) Top view.

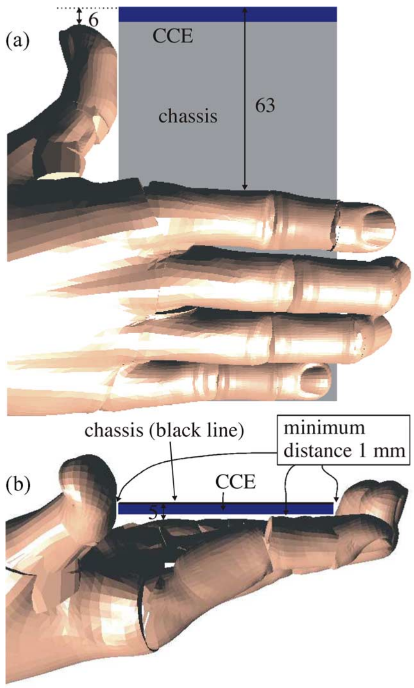

Fig. 5. Dimensions (in mm) of the palm grip (here, CCE top-located). (a) Front view. (b) Top view.

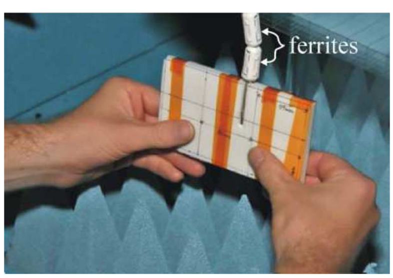

Fig. 6. Impedance measurements for the browsing grip in the impedance measurement box.

C. Measurements

The measurements are performed with the real hands of a test person instead of phantom hands. Thus, a direct and exact comparison between the simulated and measured results cannot be done, since the simulated and measured structures are different. Instead, one should observe the trends of the antenna behavior when the user-presence results are compared to the free space case. The measurements were performed with the prototype introduced in Section II-A. In order to have an identical measurement configuration with the simulations, the prototype was placed inside a 10-mm-thick Styrofoam case, for which the permittivity is close to that of air (see Fig. 6). The same grips are used as with the simulations (see Figs. 3–5).

The matching measurements were made in an impedance measurement box with a vector network analyzer (see Fig. 6). The efficiency measurements were performed in an anechoic chamber using a Satimo Stargate measurement system [18], which is fast and large enough to be used with a test person (see Fig. 7). The efficiency measurement accuracy is ± 1 dB given by the manufacturer. It can be assumed that the shadowing effect of the user's arms, head, and main body, which are not modeled in the simulations, has a certain effect on the measured efficiency results. In all the impedance and efficiency measurements, ferrites were used around the measurement cables in order to decrease the cable effect (see Fig. 6).

Fig. 7. Efficiency measurement for the browsing grip with the Satimo Stargate measurement system.

III. Matching

First, the effect of the user's hands on the reflection coefficient and input impedance was simulated for the browsing grip without the matching circuit in order to study the change of the impedance of the unmatched antenna structure (see Fig. 8). The following observations can be made.

1) The resonant frequency of the first-order wavemode of the chassis (length 130 mm) in free space is about 0.9 GHz [11]. The hand causes a decrease in the resonant frequency of the chassis to about 0.8 GHz in all the cases. This can be explained by the resonator theory. The dielectric material (hand) is placed "inside" the resonator, i.e., in the reactive near fields of the chassis. This will cause the resonant frequency to decrease in accordance with the perturbation theory [19]. The same thing can be understood also in such a way that the electrical length of the chassis becomes longer due to the dielectric material placed into the end of the chassis, and thus, the resonant frequency decreases.
2) In all the studied cases, the resistive part of the antenna impedance increases at the lower DTV frequencies compared to the free space case [see Fig. 8(b)]. There are two reasons causing this increase in the input resistance: First, the shift of the chassis resonant frequency will move the maximum of the input resistance toward lower frequencies. Second, the hand introduces resistive losses, which affect the input resistance.
3) When the hand is close to the CCE—i.e., in the left hand and both hands cases in Fig. 8—the negative (capacitive) reactance of the antenna changes fairly much to the less

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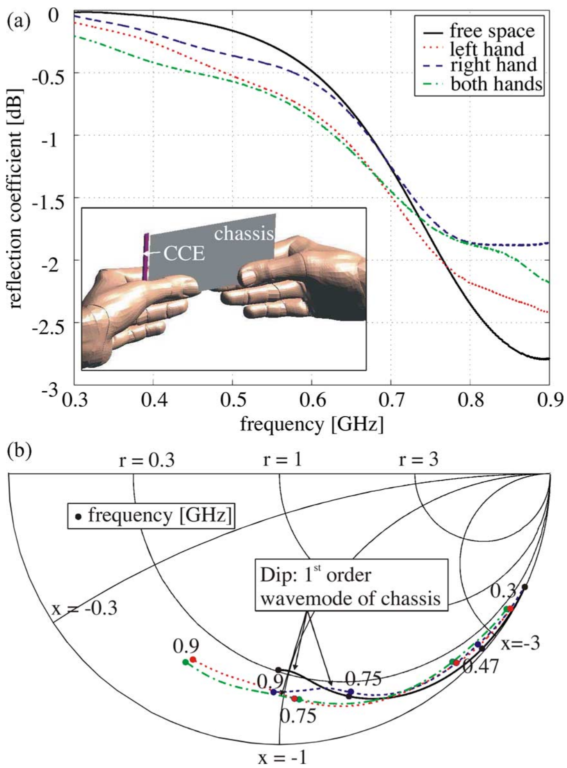

Fig. 8. Effect of the user's hands (browsing grip) on the (a) reflection coefficient and (b) input impedance of the antenna without the matching circuit.

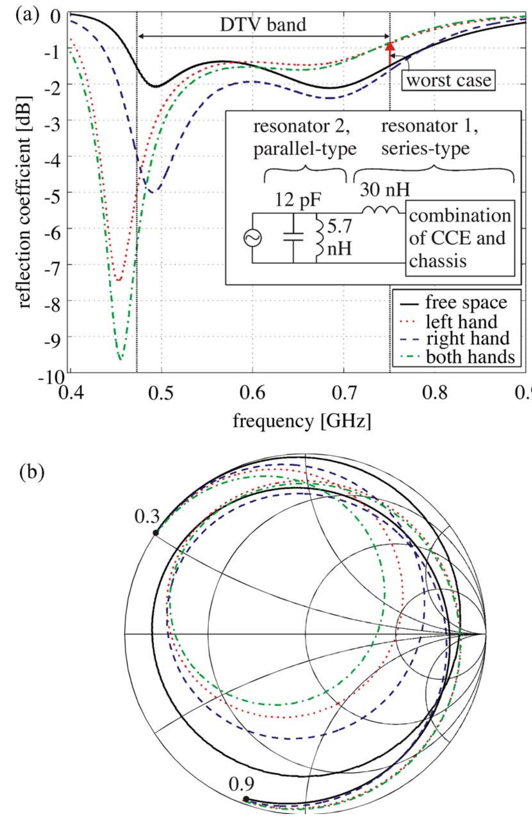

Fig. 9. Effect of the user's hands (browsing grip) on the (a) matching and (b) input impedance of the antenna with the matching circuit (simulated).

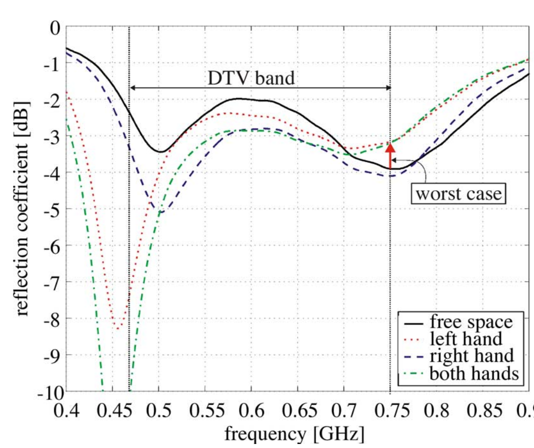

Fig. 10. Effect of the user's hands (browsing grip) on the matching of the prototype antenna (measured).

negative (inductive) direction at all frequencies. Since the matching circuit components are not affected, the change of the reactance can be expected to cause frequency shift of the usable impedance band of the matched antenna.

The same simulations were performed also with the end and palm grips, but the results are not presented here, since the same trends were found as with the browsing grip. A better insight on the phenomenon is obtained by modeling the wavemodes of the CCE and the chassis with a coupled-resonator equivalent circuit and by studying the user effect separately on the resonant frequency and the unloaded quality factor of each wavemode [20].

Next, the matching circuit, which was designed for the free space case, is inserted mathematically between the 3-D antenna structure and a 50-Ω feed. The simulated results for the browsing grip are shown in Fig. 9 and the corresponding measured ones in Fig. 10. Despite having measured 2 dB return loss in the prototype in free space, the simulated return loss is only 1.5 dB due to the lossless antenna model, as explained in Section II-B. As can be seen in Fig. 9, the worst case occurs when the hand is close to the CCE-–i.e., in the left hand and both hands case. In those cases, the impedance band is noticeably shifted downward in frequency, as expected due to the change of the reactance according to Fig. 8(b). The return loss is decreased in the worst case from 1.5 to 0.9 dB at 0.75 GHz [illustrated by the red arrow in Fig. 9(a)] causing 1.9 dB decrease in the matching efficiency (1). When the hand is not close to the CCE, i.e., in the right hand case, no frequency shift can be noticed, and in addition, the matching level is even improved over the whole DTV band. A similar phenomenon has been reported for a PILA in the 900-MHz cellular band in [21]. This happens because the reactance is essentially unchanged and the resistance of the antenna increases as discussed earlier [see also Fig. 8(b)]. On the Smith chart in Fig. 9(b), the impedance matching behavior can be understood in such a way that the antenna structure and the matching circuit form two coupled resonators. The first resonator, see Fig. 9(a), is formed by the combination of the CCE and chassis plus the 30-nH series inductor, and the second by the parallel *LC* resonator (5.7 nH inductor and 12 pF capacitor). These two resonators

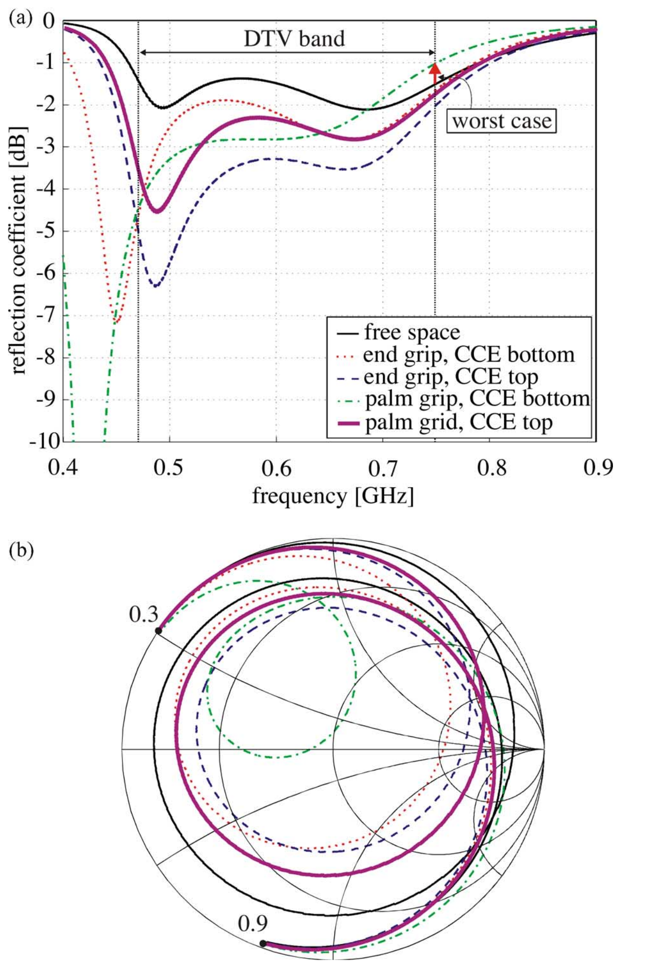

Fig. 11. Effect of the user's hands (end and palm grips) on the (a) matching and (b) input impedance of the antenna with the matching circuit (simulated).

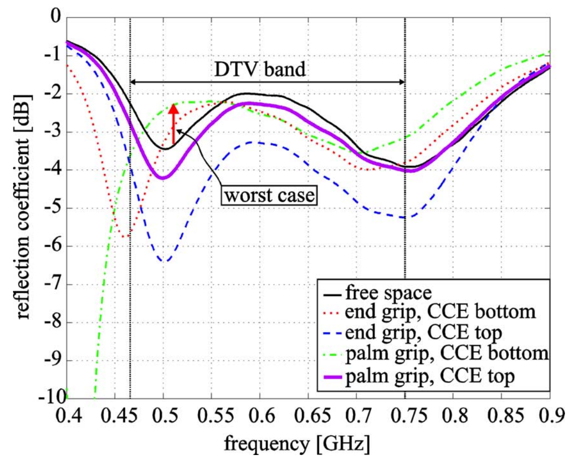

Fig. 12. Effect of the user's hands (end and palm grips) on the matching of the prototype antenna (measured).

create dual-resonant operation, as explained in [22]. The operation of the antenna from the matching point of view can be seen to become slightly nonoptimal in all the cases (except for the free space case for which the matching circuit was designed to be optimal), since the inner loop becomes asymmetrical with respect to the center of the Smith chart [23]. This happens since the resonant frequency of the first resonator changes significantly due to the hand.

Generally, the same trends can also be noticed both in the measured results and the simulated ones. However, in the measured results, the change of the matching does not seem as severe as in the simulations due to the losses of the prototype (and thereupon improved matching level, as explained in Section II-B) and since the impedance bandwidth of the antenna is somewhat larger on the upper edge of the band. The maximum degradation of the return loss at the DTV band occurs at 0.75 GHz, the change being from 3.9 to 3.2 dB, illustrated by the red arrow in Fig. 10. The matching efficiency is decreased only by 0.6 dB due to this change (1).

The same simulations and measurements have been made with the end and the palm grips; the results are shown in Figs. 11 and 12. As expected, the worst case happens when the hand is close to the CCE, i.e., in both CCE bottom-located cases. It can be seen from Fig. 11(b) that the input impedance behavior becomes highly nonoptimal in the case of a bottom-located CCE with the palm grip, i.e., the impedance loop is highly asymmetrical with respect to the center of the Smith chart. However, the maximum decrease of the matching efficiency is only 1.5 dB (1), both in the simulated case (at 0.75 GHz) and the measured case (at 0.51 GHz).

General representativeness of the three selected grips was tested by measuring the reflection coefficient of several other grips as well. According to these measurements, it could be concluded that the results obtained with the grips shown in Figs. 3–5 represent well a typical user's hand effect on the operation of the tested antenna.

As discussed in [10], instead of broadband matching, an alternative way to cover the whole DTV band is to use narrowband matching with a tuning method, as presented in [24]. To understand the main differences from the user's hand effect point of view, a brief simplified comparison between the broadband and narrowband matching cases is performed. The lossless CCE-based antenna structure was matched with a single-resonant ideal L-section matching circuit at 0.475 GHz with the typical cellular antenna matching criterion, 6 dB return loss. In the same way as earlier, the effect of the user's hands on the matching is studied (see Fig. 13). The resonance of the antenna is shifted very significantly downward in frequency in the left hand and both hands cases. The return loss is decreased in the worst case from 6 to 0.8 dB (shown with the red vertical arrow), decreasing the matching efficiency by 7.0 dB (1), which is 5 dB more than in the worst broadband case shown in Fig. 9. Although the matching level is worse than in the worst broadband case, not too strong conclusions should be drawn from this brief comparison. Anyway, it seems that in the worst case for the selected antenna structure and the hand grips, the effect of the user seems to be somewhat more significant for the narrowband matching with 6 dB matching level than for the broadband matching with moderate matching level (see Fig. 9). However, at the higher frequencies (not shown here), the effect of the hand

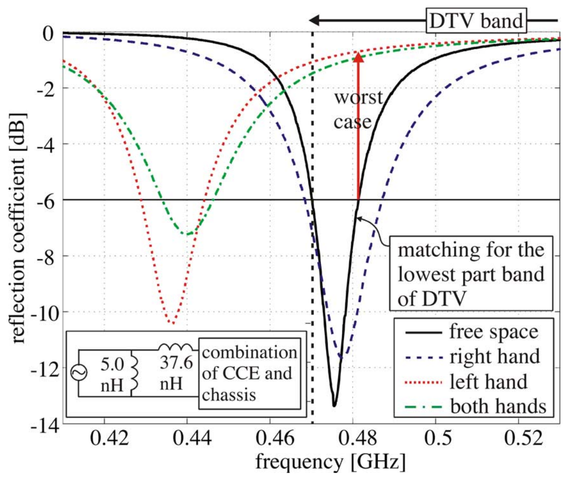

Fig. 13. Effect of the user's hands (browsing grip) on the matching of the same antenna structure with narrowband matching.

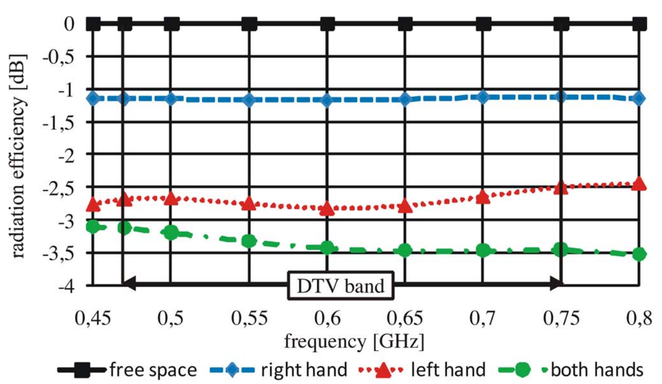

Fig. 14. Simulated radiation efficiency of the antenna for the browsing grip. The dots show the simulated frequencies.

on the narrowband matching is not as significant. Finally, it can be concluded that the studied broadband antenna configuration is potentially less vulnerable to impedance detuning effect than the narrowband configuration.

IV. Efficiency

The radiation efficiencies with the different hand grips were simulated with SEMCAD X, as described in Section II-B. The results are shown in Figs. 14 and 15. The results indicate that the hands decrease the radiation efficiency at least by 1.2 dB, and up to 8.7 dB in the worst case within the DTV band. The worst case occurs when the hand covers the antenna element almost completely, i.e., the CCE is bottom-located in the palm grip. Large tissue region in the close proximity to the antenna element is problematic for cellular antennas as well [25]. Instead, when the hand is far from the CCE, the absorption by the hand is shown to be moderate (the maximum losses about 2 dB). Therefore, the losses are significantly higher when the lossy hand is close to the CCE. This is due to the fact that the radiation quality factor of the CCE is much higher than that of the chassis. It is well known that a high radiation quality factor will usually lead to relatively high resistive losses compared to structures with a lower radiation quality factor. This can be studied as well with the equivalent circuit model based on coupled resonators, as discussed in [20]. An alternative view on the loss mechanisms can be gained by observing the electric field distributions inside dielectric material as done in [26] and [27].

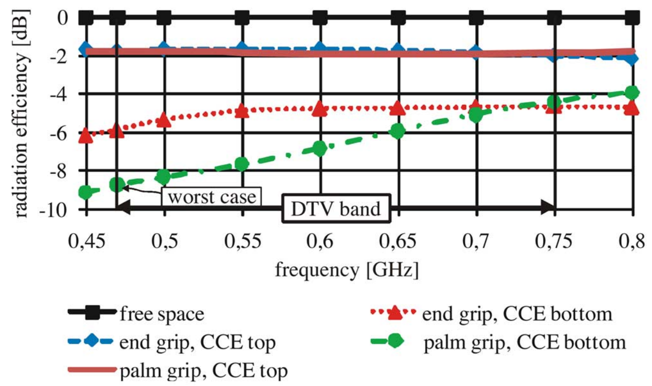

Fig. 15. Simulated radiation efficiency of the antenna for the end and palm grips. The dots show the simulated frequencies.

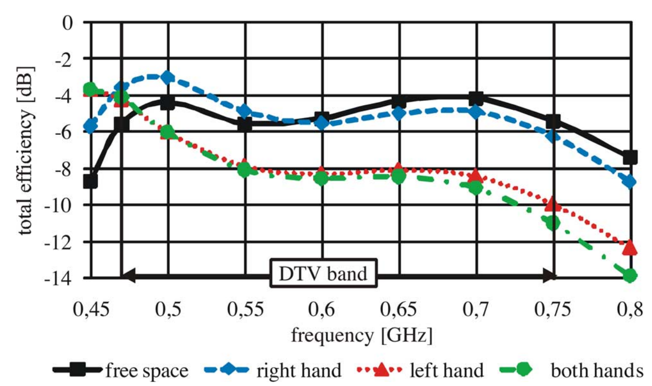

Fig. 16. Simulated total efficiency of the antenna for the browsing grip. The dots show the simulated frequencies.

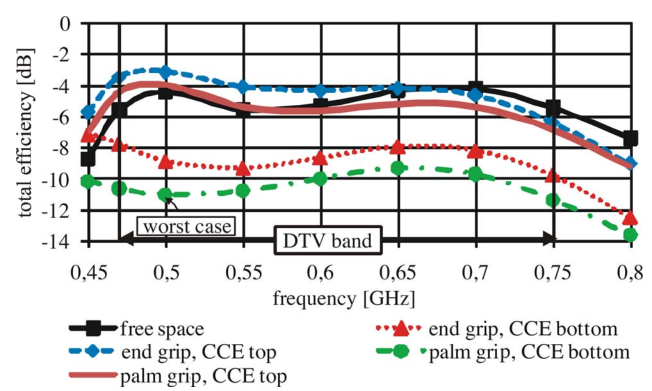

Fig. 17. Simulated total efficiency of the antenna for the end and palm grips. The dots show the simulated frequencies.

The simulated total efficiency (see Figs. 16 and 17) was calculated by combining the radiation efficiency and the matching efficiency. In the worst case (at 0.5 GHz, CCE bottom-located in the palm grip in Fig. 17), the total efficiency decreases by 6.6 dB compared to the free space case. On the other hand, the total

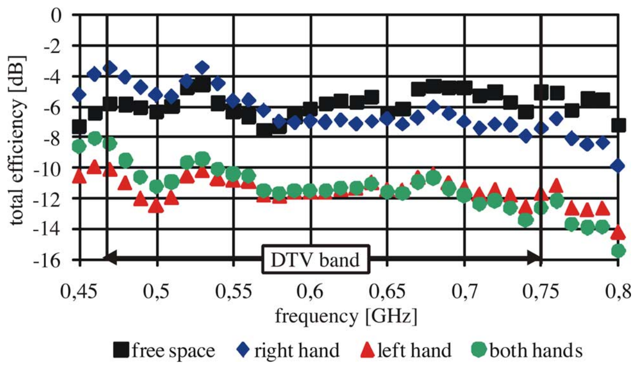

Fig. 18. Measured total efficiency for the browsing grips.

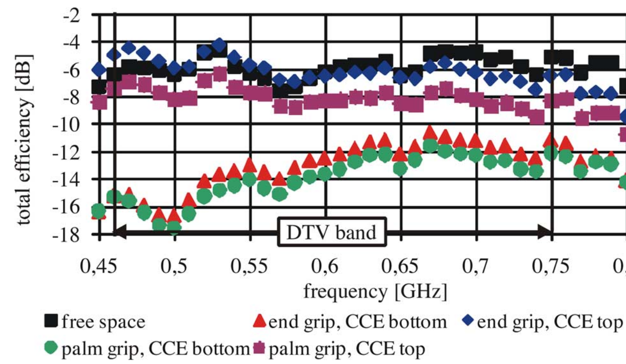

Fig. 19. Measured total efficiency for the end and palm grips.

efficiency can even increase in some cases (right hand in Fig. 16, end and palm grips when the element top-located in Fig. 17) compared to the free space case. This is possible because the improvement in the return loss on the moderate matching level (1–2 dB, see Figs. 9 and 11) causes relatively large improvement in the matching efficiency (1). The total efficiency is thus increased, since the improvement in the matching efficiency more than compensates the decrease of the radiation efficiency. Thus, the hand located far from the CCE seems to be actually useful in certain cases from the DTV operation point of view, as reported also for the 900-MHz band cellular systems in [21].

The total efficiency measurements were performed, as described in Section II-B. The results for the browsing grip are presented in Fig. 18 and for the end and palm grips in Fig. 19. Even though there is some ripple (maximum about 2 dB peak to peak) in the results caused by the measurement system, the same trends can be seen in the measured results as in the corresponding simulated ones. Consequently, the measured total efficiency is shown to increase compared to the free space with the same specific hand grips (right hand: end grip, CCE top) as in the simulated results. The total efficiency decreases in the maximum about 11 dB (at 0.5 GHz palm grip CCE bottom-located) at the DTV band compared to the free space case. Larger losses in the measured results compared to the simulated ones are not surprising because the shadowing effect of the head and main body of the user was not taken into account in the simulations. The measurement inaccuracy may also affect, as well as the different electrical parameters of real human hands from those of the parameters used in the simulations.

Finally, the worst case efficiencies of the different hand grips compared to the free space are summarized in Table I. One should note that the matching efficiency added to the radiation efficiency is not equal to the total efficiency, since the worst cases of the matching and radiation efficiencies do not occur at the same frequency. Thus, the simulated matching and radiation efficiencies should only be compared together as well as the simulated and measured total efficiencies. Generally, it can be concluded that according to the simulations, the absorption of the power to the hands is clearly a larger problem than the decrease of the matching efficiency. Equal trend has been shown also for resonant-type cellular antennas in [25]. However, the absorption losses can also be kept reasonable if the hand is not too close to the antenna element. Even though the measured total efficiencies are systematically smaller than the corresponding simulated ones, a very good correlation (calculated correlation coefficient 0.94) between the simulated and measured worst case results can be seen in Table I.

TABLE I
SUMMARY OF THE SIMULATED AND MEASURED EFFICIENCIES IN THE WORST CASE COMPARED TO THE FREE SPACE RESULTS

grip	Match eff. Sim. [dB]	Rad eff. Sim. [dB]	Tot eff. Sim. [dB]	Tot eff. Meas. [dB]
Right hand	+0.32	**-1.2**	**-0.8**	**-2**
Left hand	**-1.9**	-2.8	-4.5	-6
Both hands	**-1.9**	-3.5	-5.6	-7
End, CCE bottom	+0.31	-5.9	-4.5	-9
End, CCE top	**+1.0**	-1.9	-0.97	-2
Palm, CCE bottom	-1.5	**-8.7**	**-6.6**	**-11**
Palm, CCE top	+0.51	-2.0	-1.4	-3

V. Far-Field Directional Patterns

The far-field directional patterns are studied, since they can provide the best overall view on the effect of the user's hands on the operation of the antenna. The directional patterns are shown for the three main cuts at 0.47, 0.60, and 0.75 GHz in accordance with the lower and upper edges, and the center of the DTV band. The patterns are given as the simulated realized gain, which includes the radiation and matching efficiencies and the directivity of the antenna. Instead of dividing the realized gain into the elevation (theta) and azimuth (phi) polarization components, only the magnitude is shown because of the clarity of the figures. However, the polarizations are verbally described later. The patterns are shown for the browsing grip in Figs. 20–22. The patterns for the end and palm grips are not shown, since the trends are the same as with the browsing grip.

A few observations can be made from the total realized gain patterns as follows.

1) The maximum total realized gain has a clear correlation with the total efficiencies shown in the previous section. This is, of course, very apparent.
2) The hand can be noticed not to direct the pattern very significantly to any specific direction, i.e., the directivity of the antenna increases only a couple of decibels. This is confirmed by studying the maximum directivity.

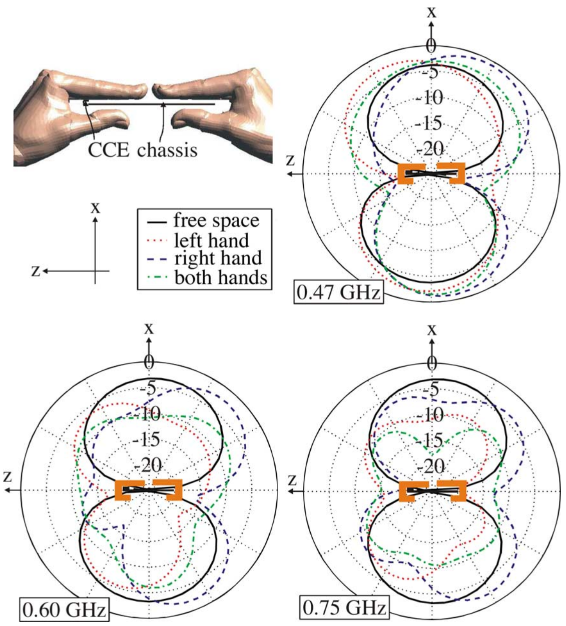

Fig. 20. Magnitude of the realized gains (in dBi) in the elevation plane (azimuth angle 0°) for the top view of the browsing grip.

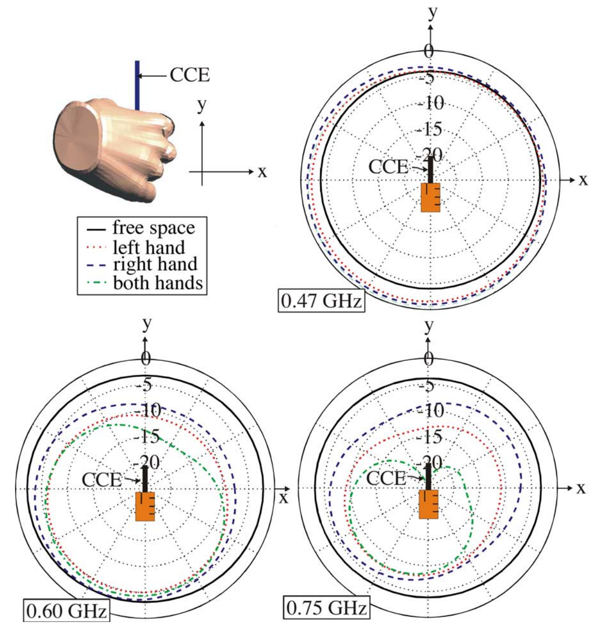

Fig. 22. Magnitude of the realized gains (in dBi) in the azimuth plane (elevation angle 90°) for the side view of the browsing grip.

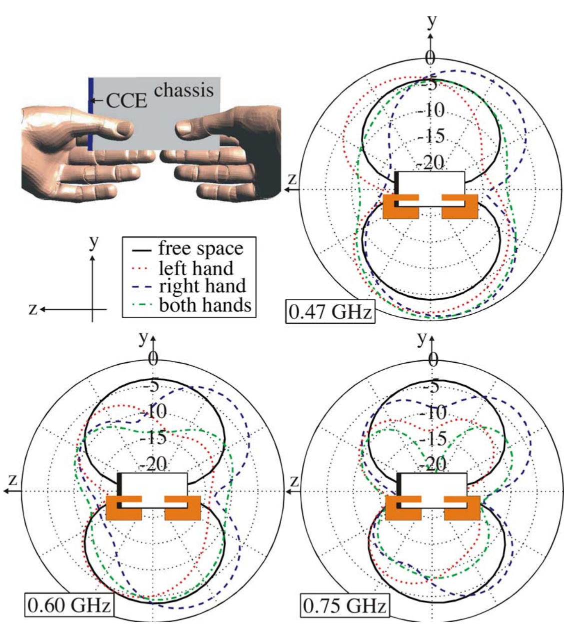

Fig. 21. Magnitude of the realized gains (in dBi) in the elevation plane (azimuth angle 90°) for the front view of the browsing grip.

3) At the lowest frequency (0.47 GHz), the "doughnut" shape of the directional pattern stays roughly the same. Generally, the lower the frequency is, the smaller is the change/distortion of the directional pattern compared to the pattern in free space.

As told in Section II-A, the far field is practically linearly polarized in free space, the elevation (theta) component being the main polarization. The cross polarization, the azimuth (phi) component of the realized gain is less than −25 dBi. It can be shown that due to the user's hands the cross-polarization level increases, especially to the directions, where the main polarization has a minimum, i.e., to the direction of z-axis in Figs. 20 and 21. For the right hand, left hand and both hands cases, the realized gain cross-polarization levels are in the maximum −13, −15, and −13 dBi, respectively.

Generally, it can be concluded that the distortion of the directional patterns does not seem very problematic. Thus, the main problem caused by the user's hands seems to be the decrease of the total efficiency, which decreases noticeably the magnitude of the realized gain.

VI. Conclusion

The user's hand effect on the operation of the broadband handheld DTV antenna was studied. The change of matching, radiation and total efficiencies, and the far-field directional patterns of an antenna structure based on a CCE were investigated with simulations and measurements.

The main effect on the matching is the detuning of the impedance band downward in frequency. This problem can be relieved by having somewhat extended impedance bandwidth at the upper edge of the DTV band in the free space. On the other hand, the decrease of the radiation efficiency was shown to be a more severe problem than the decrease of the matching efficiency. The radiation patterns were shown not to be distorted to any specific direction due to user's hands.

A hand very close to the antenna element has the biggest influence on the antenna operation. The hand located far from the antenna element is not at all difficult to deal with and actually, in the certain cases, it was shown that the hand can even improve the performance of the DTV antenna. The obvious solution to decrease the user's hand effect is to choose the place of antenna element so that the user does not put the hand too close to the antenna element. That might, however, be very challenging. Other possible option to decrease the user effect might be to use multielement technology, as in [28], and the use of the diversity techniques based on antenna selection, or other combining techniques. However, finding an optimal way to compensate the effect of the user requires lots of further work.

The study could also be continued by performing measurements with hand phantom, see [29], or by performing a measurement campaign with a large number of users in order to obtain real-life statistical results as introduced in [30]. One alternative way to study the overall performance of the antenna and propagation environment might be to use the mean effective gain (MEG), which takes into account the directional pattern (including the polarization) of the antenna, and the incident waves [31].

The results of this paper increase the common understanding on the effect of the user's hands of the lower UHF-band antennas in mobile terminals because the results and main trends are analyzed and explained comprehensively. The results of this paper are also supported by the other studies in [1]–[7], [20], [21], and [25] performed for antennas, whose operation is also based on the exploitation of a finite ground plane.

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