INVITED PAPER

Antennas for Digital Television Receivers in Mobile Terminals

This paper reviews recent progress in antennas for digital television receivers in mobile terminals and presents a novel antenna designed for handheld digital video broadcast service.

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ABSTRACT | The incorporation of new services in handheld devices, such as the Digital Video Broadcast—Handheld (DVB-H) operating at the lower ultrahigh-frequency (UHF) band poses a challenge for antenna designers. Wideband small antennas or electrically tunable narrowband small antennas are needed to fulfil the performance requirement. It is well known that below 900 MHz the operation of embedded mobile terminal antennas is based on utilizing the whole structure of the terminal as a radiator. However, even this way reaching the whole required impedance bandwidth of about 46% at about 0.61-GHz center frequency is possible only either with clamshell-type terminals used as thick dipoles by feeding them from the hinge or with "large tablet"-sized terminals. With the popular smartphone-sized terminals with a monoblock structure the available bandwidth with good total efficiency is clearly smaller. We study the options to implement antennas for smartphone-type mobiles for receiving digital TV broadcasts at about 0.47–0.75-GHz frequencies. The mainly studied technology is the nonresonant capacitive coupling element (CCE)-type antennas having one of the smallest achieved volume-to-bandwidth ratios. We show that for a fixed-frequency antenna with a volume of less than a few cubic centimeters the total efficiency will become rather low due to moderate matching level, but the requirement of the DVB-H standard for the realized gain can easily be met. Additionally, we show that by having switching between two bands, one can implement a dual-antenna configuration with small total volume and significant multiple-input–multiple-output (MIMO) gain. Furthermore, we study the very important effect of the user's hands on the antenna performance and find that the effect can range from some increase of the total efficiency due to improved matching to significant losses caused by the hands. Finally, we propose some possible ways ahead in solving this very challenging antenna design problem.

KEYWORDS | Broadband antennas; broadband communication; broadcasting; digital TV (DTV); dual-antenna system; DVB-H; impedance matching; microstrip antennas; MIMO; mobile antennas

I. INTRODUCTION

Recently, there has been a significant increase in the number of different functionalities and radio systems included in handheld radio devices. In addition to the traditional cellular systems, many other radios have been introduced in mobile terminals, including FM radio, digital television (DTV), third-generation (3G), fourth-generation (4G; or LTE, LTE-A, etc.), global positioning system (GPS), Bluetooth, and wireless local area network (WLAN). The average size (length, width) of the terminals has increased only slightly since the time when the terminals were used mainly for voice calls and low-rate data services and the average thickness has decreased despite the increased number of supported radio systems. At the same time, embedded built-in antennas are in practice the only type used in the devices. The volume available for antennas is very limited inside a mobile terminal, and thus the size of the antennas is a very critical issue.

One proposed standard for handheld digital television is Digital Video Broadcast—Handheld (DVB-H) [1]. The start of the DVB-H has so far been slow mainly due to the lack of suitable services and terminals. In this paper, DVB-H is used as the reference system of a DTV standard since it is a typical broadband DTV standard for mobile terminals

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and used at least in Europe [2], [3]. However, there are also other broadcasting digital television standards for handheld devices, such as Advanced Television Systems Committee—Mobile/Handheld (ATSC-M/H) in North America, Integrated Services Digital Broadcasting (ISDB) "1seg" in Japan and South America, and Digital Terrestrial Multimedia Broadcast (DTMB) in China. All of them operate in the lower ultrahigh-frequency (UHF) band (typically around 0.47–0.80 GHz), and thus the antennas and design principles presented can be applied to other standards as well.

The ground planes of the printed circuit board (PCB), electromagnetic compatibility shieldings, and other conductive structures such as the display of a handheld device create a solid radio-frequency (RF) ground, here called a chassis. This electrically conductive chassis has a significant effect on the antenna operation because it acts as the main radiator at lower UHFs—i.e., below 1 GHz [4]–[6]. Therefore, the size of the chassis has a significant effect on the achievable bandwidth and also on the minimum size of the antenna element, especially at the DTV frequencies [7].

The purpose of this paper is to introduce DTV antennas in mobile terminals, their user interaction, and also propose some possible ways to solve the problem of implementing high-performance antennas at fairly low frequencies. The results can be useful also in implementing the future cellular systems that are obviously also aiming to utilize the frequencies below 0.8 GHz more and more in the future, for example, in the form of cognitive radios.

II. DESIGN STRATEGIES AND AVAILABLE SOLUTIONS FOR UHF-BAND DTV RECEIVER ANTENNAS IN MOBILE TERMINALS

The frequency band of DVB-H is 0.47–0.75 GHz ($B_r =$ 46%) and the respective wavelength is 400–640 mm. As the typical length of a terminal is 100–130 mm, an internal DTV antenna is electrically rather small. Due to the inherent physical limitations described in [8]–[11], the implementation of small broadband DTV antennas is very challenging across the whole DTV band with the typical cellular antenna matching criterion (6-dB return loss). In theory, an object of the size of a typical smartphone could have the theoretical minimum radiation quality factor of about 1.5 [10] and, also in practice, a thick dipole, of which the mobile terminal chassis can be considered, can have the radiation quality factor of about twice the theoretical minimum. So, from that point of view, the required bandwidth should be possible. However, the practical limitations of the device like the large display and battery make it very difficult to use the device as a dipole, for instance, by feeding it from the center. Thus, the designer has to use all possible means to maximize the impedance bandwidth of the antenna. Basically, the design consists of three aspects:

1) minimizing the radiation quality factor of the antenna structure;
2) sacrificing the total efficiency to the lowest acceptable level;
3) using optimal matching methods including tunable matching circuits and/or multiresonant broadband matching.

In terms of 1), "traditional" terminal antennas, such as planar inverted-F antennas (PIFAs) and inverted-F antennas (IFAs), could be utilized as DTV antennas but the impedance bandwidth would be too narrow or the antenna size would become too large to be placed inside a handset. The new antenna solutions based on the exploitation of the radiation of the chassis will be handled in Section III.

Concerning 2), the design principle of the DTV antennas is to provide performance (efficiency) which is just enough for guaranteeing the operation with a certain reliability level [7], [12]. Hence, it is possible to sacrifice the efficiency since the DTV is a receive-only system and typically lower total efficiency can be accepted in receiving antennas compared to transmitter antennas. Based on the rough estimation performed in [7], the lowest acceptable total efficiency for a DTV antenna is in the order of −16 to −12 dB over the band. Similar calculations have been performed also in [12].

The expected DTV antenna performance in the DVB-H standard followed in this paper has been given in terms of the realized gain, which consists of the directivity and the total efficiency. In the DVB-H system specifications [1]–[3], the realized gain of the antenna placed inside a real mobile terminal is expected to be in the order of −10 dBi at 0.47 GHz and to increase linearly in decibels to about −6.5 dBi at 0.75 GHz. The basis of this realized gain was partly the achievable total efficiency at these frequencies for a handheld small terminal and partly the fact that the background level of man-made noise is anyway fairly high at the lower UHF band. When the directivity (2 dBi for electrically small antennas) is excluded from the aforementioned realized gain limit, the total efficiency across the band is expected to be in the order of −12 to −8.5 dB. Concluding the calculations above, the expected performance of a DTV antenna is at least 3.5 dB higher than the estimated lowest acceptable total efficiency in the previous paragraph.

In terms of 3), due to the inherently narrow impedance bandwidth of small antennas, tunable matching seems a reasonable choice for DTV antennas. However, one challenge is the nonlinearity caused by the semiconductor tuning component, which becomes a problem especially during the simultaneous use of, for example, the low-band cellular systems if a part of the strong transmitted signal is coupled to the DTV antenna. In addition, the tuning circuit is typically lossy, and it needs a control voltage and increases the overall complexity of the whole system. The microelectromechanical system (MEMS) capacitors may offer a solution to the nonlinearity problem in the future as their technology hopefully develops to be low cost and reliable. Another option might be to use active technologies to provide the required tunable reactance. Here one might also consider some already well-known linearization methods to reduce the possible nonlinearity of the tuning circuitry. According to [13], another challenge arises when the terminal is doing a handover from one transmitter to another. While receiving signal from the first transmitter, the receiver needs to simultaneously make a new channel scan, which might be complicated to perform with a single tunable antenna.

On the other hand, the high linearity and fixed matching network motivates the use of broadband multiresonant antennas whenever a suitable small antenna element can provide a sufficient performance. Finally, the matching strategy (tunable, broadband, or their suitable combination) is dictated by the volume available for the antenna element, available electrical components (including antenna technology), and the required performance of the system.

The available internal DTV antenna solutions are divided into two main categories according to the matching method [item 3)]. The first group is formed by the electrically tunable antennas which create an instantaneous resonance at a suitable frequency so that at least a single 8-MHz channel is covered. Examples of the electrically tunable antennas are introduced in [14]–[16]. The second main group is formed by the antennas with fixed broadband (typically multiresonant) matching. As stated above, the main challenge is to cover the whole DTV band with a sufficiently small antenna having the required realized gain performance [7], [17]–[23].

III. IMPLEMENTATION OF A BROADBAND DTV RECEIVER ANTENNA BASED ON A CAPACITIVE COUPLING ELEMENT

This paper focuses mainly on the implementation, design, and analysis of lower UHF-band broadband receiving antennas. The used antenna technology is a nonresonant capacitive coupling element (CCE) whose principle function is to couple the radiant common-mode electric currents on the surface of the chassis, while the CCE itself does not radiate significantly below 1 GHz [4]–[7]. See the antenna structure in Fig. 1. The impedance matching is done with an external matching circuitry.

A smaller radiation quality factor of the whole antenna can be achieved by strengthening the coupling between the CCE and the dominant wavemode of the chassis [item 1) in Section II]. The radiation quality factor of the dominant wavemode of a metal object with the size of current smartphones is about 3 at the frequencies, say, around 0.7 GHz. In order to maximize the coupling to the dominant chassis wavemode while minimizing the overall size of the CCE, the CCE needs to be placed at the short edge of the chassis (see Fig. 1), where the electric field maximum of the dominant wavemode (dipole-type radiator) is located. In addition, the element should be bent over the shorter edge of the chassis so that the surface of the CCE is perpendicular to the electric fields of the dominant wavemodes of the chassis. The vertical part of the CCE could be further lengthened on the upper side of the chassis (see Fig. 1), but that place is typically reserved for other components such as connectors, buttons, microphone/earpiece, and camera in real terminals.

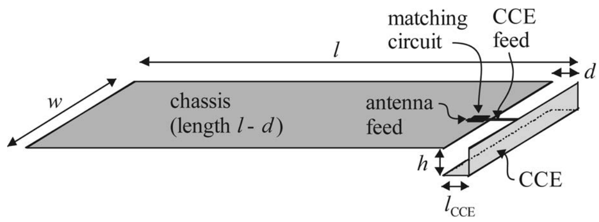

Fig. 1. ***CCE antenna structure used for digital television receiver.***

A DTV antenna prototype in a small-tablet-sized terminal was presented in [7]. The CCE structure was similar to Fig. 1 with the dimensions $l = 135$ mm, $w = 75$ mm, $h = 4$ mm, and $d = l_{CCE} = 5$ mm. The prototype easily fulfils the realized gain specification with at least a 3.5-dB margin at 0.47–0.75 GHz in free space (see Fig. 2). This 3.5-dB margin is justifiable in this simplified antenna prototype, which has losses only from the low-loss microwave PCB substrate, metal structures, and the matching circuit (high-performance RF chip coils and capacitors). Instead, in real terminals, the resistive losses (typically more than 1 dB)

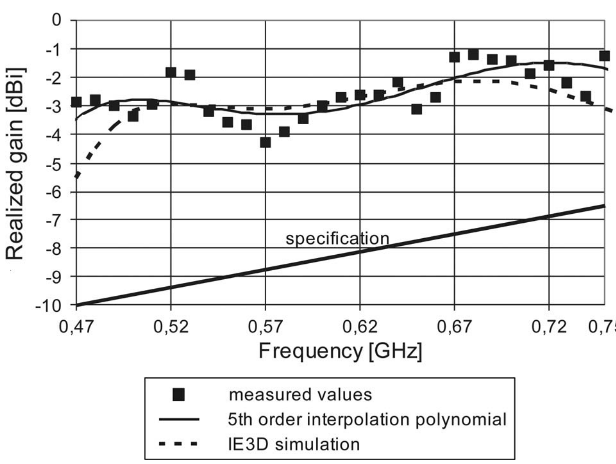

Fig. 2. ***Simulated and measured realized gain of the prototype.***

are introduced by the PCB, battery, display, covers, and other parts. These losses would decrease the unloaded quality factor and thus in practice the matching level would be better than 2-dB return loss reported in Fig. 3. On the other hand, this antenna is used in reception only, and a lower matching level than in the transceiver antennas of cellular systems is typically acceptable [7]. Finally, it can be concluded that it is relatively easy to implement a sufficiently small CCE having the required realized gain performance in small-tablet-sized terminals, which enable also relatively large touchscreen display and are thus fairly popular today.

The implementation of DTV antennas in smaller sized terminals is possible as well. However, decreased dimensions, especially the length l, of the chassis increase the radiation quality factor of the chassis at the DTV frequencies. Hence, the overall performance (efficiency/realized gain) of the antenna can be expected to decrease if the CCE is not changed. Thus, in order to maintain the performance of the antenna, the decrease of the total radiation resistance needs to be compensated by further increasing the coupling and/or by decreasing the radiation quality factor of the CCE. Hence, the size of the CCE has to be increased—i.e., d and/or h of the CCE have to be increased.

The limits for the size of the CCE for different-sized terminals were systematically studied in [7]. The electromagnetic-simulated results indicate that when exploiting optimal triple-resonant matching circuit with five lumped components, relatively thick ($h = 9$–14 mm) CCEs are required in today's typical-sized ($l = 110$ mm, $w = 48$ mm, and $d = l_{\mathrm{CCE}} = 5$–10 mm) terminals. Thus, it is very challenging to meet the required realized gain including the 3-dB margin in typical-sized terminals with thin and small enough CCEs. In order to make the CCE thinner (smaller h) without further increasing the distance d, the performance of the antenna has to be slightly sacrificed. For example, it was shown that in the above-discussed typical-sized terminal, a 3-mm thinner CCE (from 9 to 6 mm) is possible with only 0.3-dB decrease of the realized gain margin.

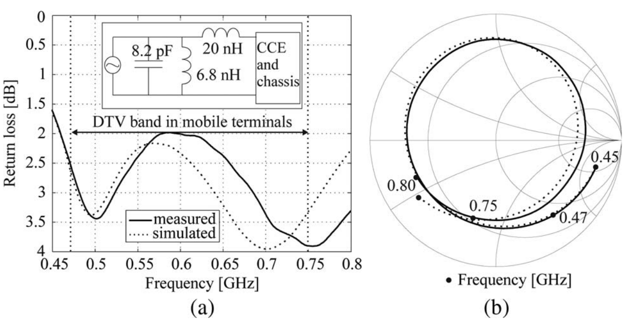

Fig. 3. ***Simulated and measured return loss of the small-tablet-sized DTV antenna structure prototype (a) in the Cartesian coordinate system and (b) on the Smith chart.***

In order to demonstrate the realistic operation of such DTV antennas, a simulated design including realistic (lossy) triple-resonant matching circuit components was also presented in [7]. The dimensions of the design are $l = 110$ mm, $w = 48$ mm, $h = 6$ mm, and $d = l_{\mathrm{CCE}} = 10$ mm. The DTV antenna design has at least 2.8-dB return loss, at least 2.5-dB margin to the realized gain specification, and a minimum of 22-dB isolation to the E-GSM antenna mounted on the opposite end of the same chassis. This design is considered to be a good compromise between the size of the CCE and the performance of the whole antenna.

The results of [7] also show that since the effective radiation resistance of CCE antennas is rather low at the DTV frequencies, the resistive losses (typically a few ohms of magnitude) in the matching circuit affect relatively much the radiation efficiency. Thus, it is very important that the losses of the matching circuit components are modeled realistically with the S-parameters of real components from the very beginning of the design process of CCE antennas.

Another issue that has to be taken into account is the interoperability between the DTV antenna and the E-GSM antenna which operates at 0.88–0.96-GHz frequency range. Especially, the antennas operating in the lower UHF band have inherently low isolation due to the strong coupling through the dominant wavemode (half-wave dipole mode) of the chassis. In the above-presented design, the total isolation between the DTV and E-GSM antennas is at least 22 dB but it is mainly obtained by the matching circuits which operate also as filters since the systems have certain frequency separation—i.e., the electromagnetic isolation, which is independent of matching, between the antennas is only a couple of decibels. However, this 22 dB is not enough according to the DVB-H specification, in which 61 dB of isolation is stated [2], [3]. Thus, one of the important research topics of the future is to study methods for how to provide high enough isolation between the antennas of different radio systems. This requires the development of the antenna technology (better electromagnetic isolation) and the circuit technology (better filtering with small enough insertion loss). This study would be beneficial also for multiantenna systems, such as low-band LTE.

IV. USER EFFECT FOR LOWER UHF-BAND DTV RECEIVER ANTENNAS

In this section and in paper [24], the operation of the earlier presented CCE-based lower UHF-band receiving antenna (see Fig. 1) in typical use positions is investigated. Since the mobile terminals are increasingly used for data services, the focus of the user-effect research is shifting from the talk mode to the data or browsing mode and thus the effect of the user's hands on the antenna operation has much greater importance than earlier. Therefore, the main objective is to study the antenna performance in the presence of the user's hands. The results are not restricted only to the examined antenna, but they aim to provide some general understanding on the effect of the user's hands within the lower UHF band.

Fig. 4(a) shows the studied CCE antenna structure in the landscape browsing grip, but also other use positions (portrait palm and end grips) are covered in [24]. The studied parameters are matching [Figs. 5, 6, and 7(a)], radiation efficiency [Fig. 8(a)], total efficiency [Figs. 7(b) and 8(b)], and far-field directional pattern. They are studied with electromagnetic simulations and verified with measurements. In order to make the interpretation of the simulation results more straightforward, the simulations are performed with a lossless antenna model. The user's hands are modeled with the lossy, homogenous, fully posable human hand phantoms available, for instance, in SEMCAD electromagnetic simulator tool by SPEAG [see Fig. 4(a)]. The measurements are performed with the real hands of a test person [see Fig. 4(b)]. One should note that not exactly identical structures are simulated and measured, and thus direct and precise comparison of the numeric values of the results is not possible to perform. Instead, one should observe the trends between the simulated and measured results.

First, in the matched case [Figs. 5 and 7(a)] the impedance band is tuned downwards in frequency when the hand is close to the CCE (left hand case). The tuning happens since the total reactance increases due to the fact that the resonant frequency of the CCE decreases [25]. On the Smith chart in Fig. 6, the impedance operation becomes also nonoptimal (asymmetrical inner loop with respect to the center of the Smith chart) since the resonant frequency of resonator 1 (see Fig. 5) changes significantly due to the hand. The matching efficiency in the simulated case in Fig. 5 decreases 1.9 dB in the worst case at 0.75 GHz. In the corresponding measured case, the degradation of the matching efficiency is smaller since the impedance band is somewhat larger on the upper edge of the band. When the hand is at the opposite end to the element (right hand case) and loads only the chassis wavemode, the impedance band stays essentially unchanged [25]. Actually, the

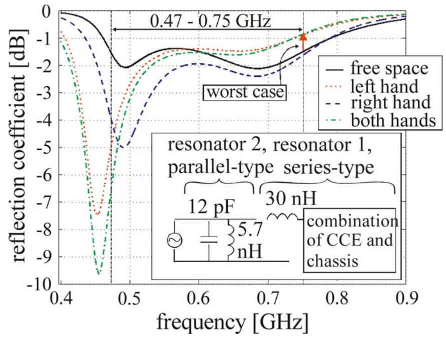

Fig. 5. ***Effect of the user's hands on the matching of the antenna with the matching circuit (simulated).***

matching level is even improved at the whole band since the total resistance of the antenna increases. The same effect is reported also in [26]. The same trends of the matching behavior can be noticed with other hand grips, such as portrait palm and end grips in [24].

The radiation efficiency [Fig. 8(a)] shows the following trend: when the hand loads only the chassis half-wave wavemode (right hand case), the resistive losses are clearly lower than the losses caused by the loading of the CCE mode (left hand and both hands case) [25]. The total efficiency behavior [Figs. 7(b) and 8(b)] is interesting: it can actually increase in some cases (right hand case). This happens since the improvement of the matching efficiency is larger than the degradation of the radiation efficiency. This "positive hand effect" is also reported at the 0.9-GHz band in [26]. In general, the hand close to the CCE has the most significant effect on the antenna operation at 0.47–0.75 GHz and losses of several decibels compared to the free-space case can be expected. In addition to these results, the simulated realized gain directional patterns are shown in [24]. Generally, it can be concluded that the distortion of the directional patterns due to the user's hands seems not very problematic since the pattern remains rather omnidirectional.

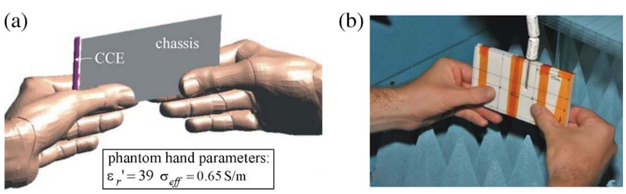

Fig. 4. ***Studied antenna in the landscape browsing grip: (a) in the SEMCAD simulator and (b) in the impedance measurements.***

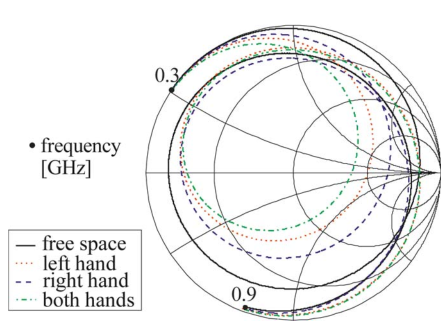

Fig. 6. ***Effect of the user's hands on the input impedance of the antenna with the matching circuit (simulated).***

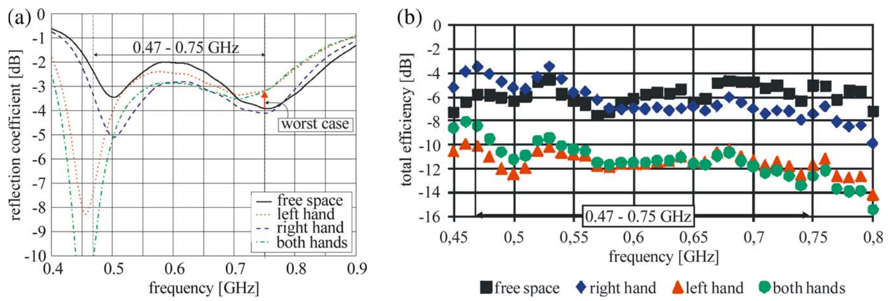

Fig. 7. ***Effect of the user's hands on the (a) matching and (b) total efficiency of the prototype antenna (measured).***

The performed studies give also insight into how to compensate the effect of the user. Possible ways would be to:

1) try to place the antenna element in such a location that the user's hand does not cause very high losses;
2) match the antenna over a wide enough impedance bandwidth so that the detuning does not result in significant degradation of matching efficiency [see Fig. 7(a)]; or
3) use an adaptive matching circuitry with a matching detector (adaptive matching is related also to frequency-tunable antennas); or
4) use multiple antenna elements (antenna diversity) and select the element in use based on the location of the hand(s).

V. DUAL-ELEMENT ANTENNAS FOR DTV TERMINALS

The use of multielement antenna systems such as multiple-input–multiple-output (MIMO) or antenna diversity can enhance the mutual information or reliability of the wireless communications systems compared to single-element antenna systems [27]. Multielement antennas can also be used to compensate the user effect [28]. In [29], the feasibility of implementing multielement antenna configurations in DVB-H receivers has been studied. Due to low frequency and small size of the terminal it is difficult to implement uncorrelated internal antenna elements. However, by choosing the locations of the antennas wisely and utilizing polarization diversity, relatively low pattern correlation can be achieved. In [29], the pattern correlation of less than 0.6 has been achieved over the whole DVB-H bandwidth by using two CCE antennas which are located in the corners of the ground plane at the same short edge of the chassis (see Fig. 9). The MIMO performance of the dual-element antenna structure was evaluated in realistic propagation environments with an antenna analysis tool called measurement-based antenna testbed [30]. It has been shown in [29] that at high reliability levels the use of a 2×2 MIMO system can provide up to four times higher mutual information compared to a single-input–single-output (SISO) configuration with the same total antenna volume. At lower reliability levels the difference is smaller. If the total antenna volume of a dual-element multi-antenna system is the same as the antenna volume of a single antenna and the typical-sized terminal is used, switchable matching circuits need to be used to cover the whole DVB-H frequency band. In a tablet-sized terminal it might be possible to match the whole frequency range without switches.

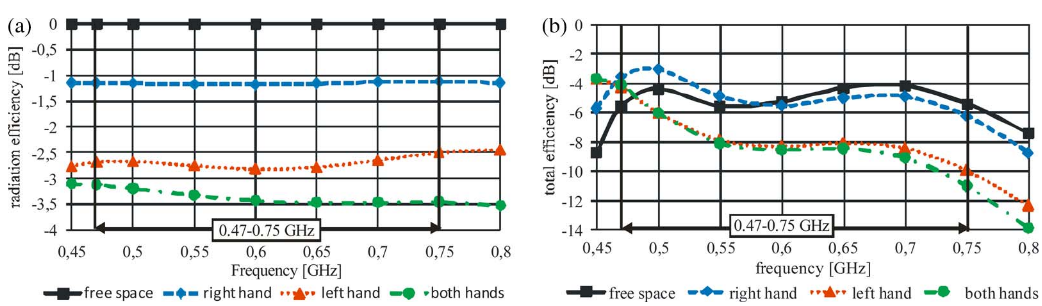

Fig. 8. ***Simulated (a) radiation and (b) total efficiency of the antenna. The dots show the simulated frequencies.***

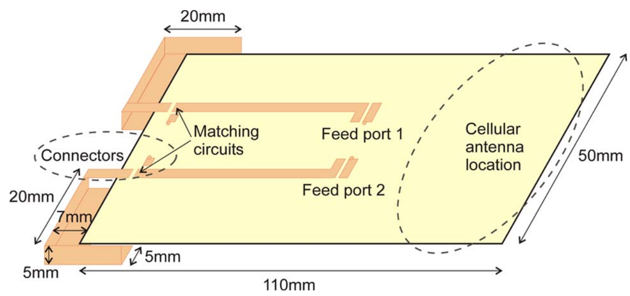

Fig. 9. ***Dual-element antenna prototype for a handheld digital television terminal [29].***

VI. CONCLUSION

The implementation, design, and user effect of the lower UHF-band (below 1 GHz) broadband antennas for DTV in mobile terminals is presented. The design principle of such broadband receiving antennas is to sacrifice the performance (efficiency) of the antenna to the lowest acceptable level in order to implement the required impedance bandwidth with a sufficiently small and low-profile CCE antenna structures. The shape and location of the CCE was designed to optimally excite the dominant wavemode of the chassis. In addition, optimal multiresonant matching circuits, consisting of high-Q lumped elements, were applied. In particular, the lower limit for the size of the selected CCE-based antenna structures embedded within terminals of different sizes was studied. The results indicate that in today's small- and typical-sized smartphones relatively thick and large CCEs are required to provide the required performance for the DTV system in the lower UHF band. On the other hand, in small-tablet-sized terminals the CCE can be made significantly thinner and smaller. Generally, the size of the chassis has a significant effect on the required size of the antenna element. The user's hand very close to the CCE was shown to cause a large influence on the antenna operation among the studied hand grips. In that case, the total efficiency decreases significantly, which is mainly due to the absorption of the hand (not the mismatching). When the hand is located far from the CCE, it is not difficult to keep the performance up and actually, in certain cases, it was shown that the hand can even improve the total efficiency of mobile terminal antennas.

Another way to improve the performance of the DTV terminals is to utilize multielement antenna techniques. Unfortunately, it is not trivial to implement uncorrelated internal antenna elements because the size of the terminal is relatively small compared to the wavelength in the lower UHF band. However, by choosing the locations of the antennas wisely and utilizing polarization diversity, the pattern correlation of less than 0.6 can be achieved. In this case, the multielement antenna can increase the mutual information compared to the single-antenna configuration with the same total antenna volume. In addition, multielement antennas might be used to compensate the user's hand effect.

In the future, it is proposed to examine new ways how to couple more efficiently to the dominant wavemodes of the chassis than with the capacitive coupling elements applied in this paper. The ultimate goal could be the "zero-volume antenna" (see some initial work toward that in, e.g., [31]) that excites the wavemodes without setting significant restrictions to the other functionalities of the terminal but provides higher total efficiency and broader bandwidth at 500–800 MHz than is possible currently. Furthermore, such an antenna is also tolerant to the effect of the user and can be utilized also by other radio systems of the terminal than DTV. This is very challenging, but in our opinion, still a realistic way forward. ■

REFERENCES

[1] DVB Project, Digital video broadcasting (DVB); DVB-H implementation guidelines, V1.4.1, Standards & Technology (cited 9.1.2012), Apr. 2009. [Online]. Available: http://www.dvb.org

[2] EICTA, "Mobile and portable DVB-T/H radio access—Interface specification," Tech. Rep., ver. 2.0, 2007.

[3] DVB Project, "DVB-H implementation guidelines," DVB Document A092, Tech. Rep., Rev. 2, May 2007.

[4] P. Vainikainen, J. Ollikainen, O. Kivekäs, and I. Kelander, "Resonator-based analysis of the combination of mobile handset antenna and chassis," *IEEE Trans. Antennas Propag.*, vol. 50, no. 10, pp. 1433–1444, Oct. 2002.

[5] J. Villanen, J. Ollikainen, O. Kivekäs, and P. Vainikainen, "Coupling element based mobile terminal antenna structures," *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2142–2153, Jul. 2007.

[6] J. Holopainen, R. Valkonen, O. Kivekäs, J. Ilvonen, and P. Vainikainen, "Broadband equivalent circuit model for capacitive coupling element—Based mobile terminal antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 716–719, 2010.

[7] J. Holopainen, O. Kivekäs, C. Icheln, and P. Vainikainen, "Internal broadband antennas for digital television receiver mobile terminals," *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3363–3374, Oct. 2010.

[8] L. J. Chu, "Physical limitations on omni-directional antennas," *J. Appl. Phys.*, vol. 19, pp. 1163–1175, 1948.

[9] R. C. Hansen, "Fundamental limitations antennas," *Proc. IEEE*, vol. 69, no. 2, pp. 170–182, Feb. 1981.

[10] J. S. McLean, "A re-examination of the fundamental limits on the radiation Q of electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 44, no. 5, pp. 672–676, May 1996.

[11] H. F. Pues and A. R. van de Capelle, "An impedance-matching techniques for increasing the bandwidth of microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 37, no. 11, pp. 1345–1354, Nov. 1989.

[12] D. Manteuffel and M. Arnold, "Considerations for reconfigurable multi-standard antennas for mobile terminals," in *Proc. IEEE Int. Workshop Antenna Technol., Small Antennas Novel Metamater.*, Chiba, Japan, 2008, pp. 231–234.

[13] B. S. Collins, "Small antennas for the reception of future mobile television services," in *Proc. IEEE Int. Workshop Antenna Technol.*, Santa Monica, CA, Mar. 2009, DOI: 10.1109/IWAT.2009.4906969.

[14] M. Komulainen, M. Berg, H. Jantunen, and E. Salonen, "Compact varactor-tuned meander line monopole antenna for DVB-H signal reception," *Electron. Lett.*, vol. 43, no. 24, pp. 1324–1326, Nov. 2007.

[15] L. Huang and P. Russer, "Electrically tunable antenna design procedure for mobile applications," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 12, pp. 2789–2797, Dec. 2008.

[16] Z. D. Milosavljevic, "A varactor-tuned DVB-H antenna," in *Proc. IEEE Int. Workshop Antenna Technol., Small Antennas Metamater. Appl.*, Cambridge, U.K., Mar. 2007, pp. 124–127.

[17] J. Holopainen, J. Villanen, M. Kyrö, C. Icheln, and P. Vainikainen, "Antenna for handheld DVB terminal," in *Proc. IEEE Int. Workshop Antenna Technol., Small Antennas Novel Metamater.*, White Plains, NY, Mar. 6–9, 2006, pp. 305–308.

[18] R. Li, B. Pan, J. Papapolymerou, J. Laskar, and M. Tentzeris, "Low-profile broadband planar antennas for DVB-H, DCS-1800, IMT-2000 applications," in *Proc. IEEE AP-S Int. Symp. Antennas Propag.*, Honolulu, HI, Jun. 10–15, 2007, pp. 4729–4732.

[19] J.-K. Wee, J. W. Park, I. S. Yeom, B.-G. Kim, and C. W. Jung, "Compact DVB-H antenna with broad dual-band operation for PMP applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 580–583, 2010.

[20] K.-L. Wong, Y.-W. Chi, B. Chen, and S. Yang, "Internal DTV antenna for folder-type mobile phone," *Microw. Opt. Technol. Lett.*, vol. 48, no. 6, pp. 1015–1019, Jun. 2006.

[21] H. Rhyu, C. Jung, J. Byun, M. Park, Y. Chung, T. Kim, and B. Lee, "DVB-H antenna design using folder-type chassis and coupling element on a ferrite," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 453–456, 2009.

[22] J.-N. Lee, J.-K. Park, and J.-S. Kim, "Design of the DVB-H antenna using the coupling concept," in *Proc. 39th Eur. Microw. Conf.*, Rome, Italy, Sep. 29–Oct. 1, 2009, pp. 532–535.

[23] DVB-H EU 470–750 MHz planar PWB antenna, Pulse Part No. W3510. [Online]. Available: http://www.pulseeng.com

[24] J. Holopainen, O. Kivekäs, J. Ilvonen, R. Valkonen, C. Icheln, and P. Vainikainen, "Effect of the user on the operation of lower UHF-band mobile terminal antennas: Focus on digital television receiver," *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 3, pp. 831–841, Sep. 2011.

[25] J. Holopainen, O. Kivekäs, J. Ilvonen, R. Valkonen, L. Martinez, P. Vainikainen, J. R. Kelly, and P. S. Hall, "Equivalent circuit model-based approach on the user body effect of a mobile terminal antenna," in *Proc. IEEE Antennas Propag. Conf.*, Loughborough, U.K., Nov. 8–9, 2010, pp. 217–220.

[26] P. Hui, "Positive hand effects on mobile handset antennas," in *Proc. Asia-Pacific Microw. Conf.*, Macau, Dec. 16–20, 2008, DOI: 10.1109/APMC.2008.4958011.

[27] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bölcskei, "An overview of MIMO communications—A key to gigabit wireless," *Proc. IEEE*, vol. 92, no. 2, pp. 198–218, Feb. 2004.

[28] R. Valkonen, S. Myllymäki, A. Huttunen, J. Holopainen, J. Ilvonen, P. Vainikainen, and H. Jantunen, "Compensation of finger effect on a mobile terminal antenna by antenna selection," in *Proc. Int. Conf. Electromagn. Adv. Appl.*, Sydney, Australia, Sep. 20–24, 2010, pp. 364–367.

[29] M. Kyrö, M. Mustonen, C. Icheln, and P. Vainikainen, "Dual-element antenna for DVB-H terminal," in *Proc. Antennas Propag. Conf.*, Loughborough, U.K., Mar. 17–18, 2008, pp. 265–268.

[30] P. Suvikunnas, J. Villanen, K. Sulonen, C. Icheln, J. Ollikainen, and P. Vainikainen, "Evaluation of the performance of multiantenna terminals using a new approach," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 5, pp. 1804–1813, Oct. 2006.

[31] J. Holopainen, J. Villanen, C. Icheln, and P. Vainikainen, "Mobile terminal antennas implemented by using direct coupling," in *Proc. 1st Eur. Conf. Antennas Propag.*, Nice, France, Nov. 6–10, 2006, DOI: 10.1109/EUCAP.2006.4584489.

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