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MOBILE TERMINAL ANTENNAS IMPLEMENTED BY USING DIRECT COUPLING

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ABSTRACT

The current trend in mobile terminals is an increasing number of systems. The volume occupied by the antennas of the radio systems is becoming more and more problematic and new low-volume antenna solutions are needed. Since the EMC shielding and the ground plane operate as the main radiating structure especially below 1 GHz, a very small antenna structure can be achieved by using a direct feed, i.e. galvanically inducing currents on the surface of the chassis. The feed can be placed over an impedance discontinuity, e.g. formed by a slot. Using this approach, an antenna structure for a small handheld digital television (DVB-H) receiver is presented. The antenna gain exceeds the specification by a 4-dB margin. The introduced antenna structure can also be used for multi-system terminals.

INTRODUCTION

As the number of radios increases in the mobile communications terminals, the reduction of the size of the mobile terminal antenna elements is very important. A compact coupling element antenna structure reduces the volume of the antenna element compared with a traditional PIFA structure [1] [1b]. The coupling element structure is based on the fact that the ground plane, or the chassis, of a mobile terminal operates as the main radiator especially at the lower RF frequencies (below 1 GHz). By optimising the coupling to the chassis, one can minimize the volume of the antenna structure. So, a further reduction in the volume of the antenna element can be expected by inducing directly, i.e. galvanically, currents on the surface of the chassis. In this paper, the feasibility of such a 'direct coupling' antenna is presented. The idea is applied to implement a handheld digital television (DVB-H) antenna.

Antenna structures for a DVB-H receiver are also presented in [2], [3] and [4]. The antenna structure in [2] is based on a compact coupling element and the volume occupied by the element is 1.5 cm^3. The antenna in [3] will be discussed later and the antenna in [4] is large and not internal.

REQUIREMENTS FOR A DVB-H ANTENNA

The DVB-H system operates at the UHF frequency band, 470 – 702 MHz, and the corresponding wavelength is 640 – 430 mm. Any antenna placed inside a handheld terminal will be electrically small and thus broadband operation is difficult to achieve. Therefore, covering the whole DVB-H band obviously leads to rather high losses and to low total efficiency of the antenna system. According to the current understanding of design capabilities, the realized gain including also the matching losses is specified to be -10 dBi at 474 MHz and it increases linearly to about -7 dBi at 698 MHz [5]. The specification is given for an antenna inside a real terminal and because of that, an extra margin to the specification is needed in the design because in the final product the plastic cover, other lossy parts of the terminal, and also the user typically cause significant additional losses.

IMPLEMENTATION OF A BROADBAND DVB-H ANTENNA

As the handheld terminal is electrically small, it is very difficult to realize an antenna that covers the DVB-H band 470-702 MHz (relative bandwidth about 40 %) with a typical matching criterion such as 6 or 10 dB return loss [6]. In this case, one has to use all means to maximize the radiation bandwidth of the antenna-chassis system. Basically, these consist of three aspects:

1) Minimizing the radiation quality factor of the system [1][1b]
2) Reducing the total efficiency to the lowest acceptable level [2]
3) Using optimal matching methods including dual-resonant matching [6]

When it comes to item 1), it was shown in [1] and [1b] that the effective radiation quality factor and thus also the bandwidth of the system depends largely on

Proc. 'EuCAP 2006', Nice, France
6–10 November 2006 (ESA SP-626, October 2006)

effective excitation of the chassis currents and the maxima of the bandwidth can be achieved at the resonant frequencies of the chassis. Therefore, in addition to maximizing the coupling to the chassis wave modes with minimum volume of the coupling element one should also try, if possible, to tune the chassis resonant frequency to match the centre frequency of the radio system.

Considering item 2) above, in a receive-only system like in this case, one may be able to accept a lower realized gain than typically in transceiver antennas. The design goal is to maximize the realized gain over the DVB-H band. For small antennas, the directivity is about 2 dBi and the realized gain is mainly controlled by the total efficiency. The antenna can be coupled so that the DVB-H band is covered but the price paid is lower total efficiency, see Fig. 1.

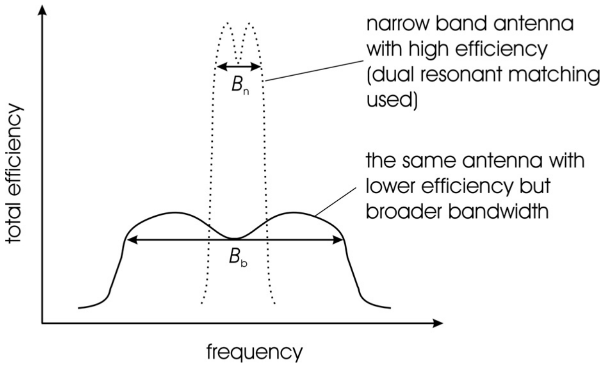

Figure 1. A narrow band antenna can be matched so that a larger bandwidth is covered with a lower total efficiency.

The total efficiency consists of the matching and radiation efficiency. There are basically three options. Firstly, one can use resistive loading of the antenna (lower radiation efficiency), secondly, use resistive matching (attenuators) or, thirdly, accept higher mismatch between the antenna and the receiver (lower matching efficiency). The third option can be shown to provide the maximum realized gain around the center frequency of a resonant antenna. As the antenna is used for reception only, some mismatch may be acceptable. Especially, if the LNA is designed together with the antenna so that the LNA adapts to the impedance of the antenna, some mismatch or rather non-50 ohm impedance is then acceptable [7]. In [2] it was presented that the return loss matching between 1 and 2 dB yields approximately the realized gain between -5 and -2.5 dBi, which is at least 2 dB more than required in the DVB-H specification.

As is well known, to optimize the matching (item 3 above) in the single-resonant case, one can instead of having perfect matching at the centre frequency (critical coupling) use optimal overcoupling to maximize the bandwidth [8]. However, more significant increase of the bandwidth can be obtained with dual-resonant matching as discussed in [6].

DIRECT FEED STRUCTURE AND CHASSIS SLOTS

In the 'direct coupling' antenna structure the currents to the chassis are fed galvanically. The best way would be to split the chassis in two parts and feed the antenna between the parts. In that case the terminal would operate as a thick dipole antenna. In a mobile terminal the chassis normally has to be a solid piece of metal due to the EMC issues. Then the chassis cannot be separated into two parts. However, in the chassis there can be an impedance discontinuity, e.g. formed by a slot. The feed can then be placed over the slot. The most optimal place for the feed (and the slot) would be in the middle of the chassis because the currents are strongest in the middle (as in a dipole antenna) and the coupling to the chassis wavemode would also be the strongest. Any conductive elements, such as the display, cannot be placed over the slot because it would cause galvanic contact or large capacitance over the slot and prevent the operation of the antenna. In this work one had to reserve some space in the middle of the terminal for the display and hence the slot with the feed is not placed in the middle. This will cause somewhat narrower bandwidth and worse matching at the resonant frequency compared to the most optimal feed location. Fig. 2 illustrates the antenna structure. The structure operates like a nonsymmetrically fed dipole antenna having a parallel inductance over the feed. The inductance is caused by the strip and the current path around the slot. The purpose of the other slot will be explained later.

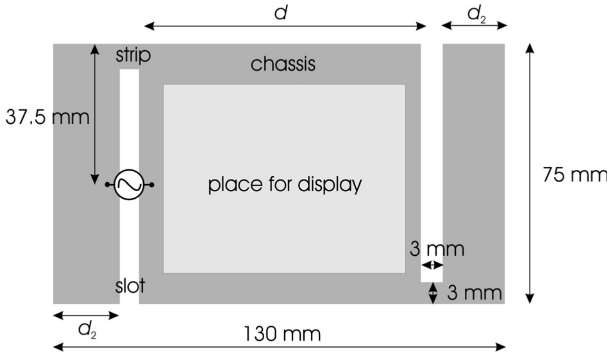

Figure 2. The idea of the direct coupling antenna and the structure used in the design.

Nokia 7700 was a prototype used for receiving DVB-H trial broadcasts. The dimensions of the terminal, 134 mm x 80 mm [length x width] [9], are somewhat larger than in present mobile terminals. They make it possible to have a display of moderate size for watching TV but also make it easier to implement a broadband antenna. Because of that, the dimensions of the chassis used in this work have been chosen to be 130 mm x 75 mm [length x width], see Fig 2. The size of the chassis should guarantee an adequate performance for the antenna. The lowest order (λ/2-length chassis) resonance of a 130 mm-long solid chassis is about 900 MHz [1]. The slot in the chassis lengthens the current path compared to the solid case and because of that, the first order resonant frequency decreases. This is especially important in the DVB-H application that operates at the frequency band 470 – 702 MHz. The current path can be lengthened further by adding another slot as in Fig. 2.

Distance *d* between the slots (see Fig. 2) has a significant effect on the resonant frequency, the matching at the resonant frequency and the available bandwidth. In Fig. 3 there are the impedance curves for the three different cases (*d* is 50, 70 and 90 mm) for the structure shown in Fig. 2 presented on the Smith chart. Case *d* = 70 mm, which leads to resonance at 689 MHz, has been found to be a good compromise between the performance of the antenna and the expected display size. In this design, the width of the display unit can be 70 mm. Broader slots (> 3 mm) and narrower strips (< 3 mm) would also yield higher performance for the antenna. The location of the feed in the slot does not significantly affect the performance of the antenna and thus, the feed is placed in the middle of the slot. As the matching is not very good at the lower DVB-H frequencies (around 500 MHz), a matching circuit is needed to improve matching (and the total efficiency) over the whole DVB-H band.

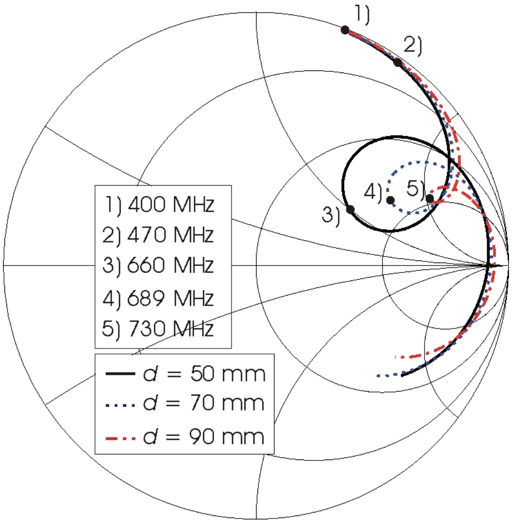

Figure 3. The impedance curves (0.4 – 1 GHz) of the direct coupling antenna structure having d = 50, 70 and 90 mm.

As shown in [1b], non-resonant coupling elements can be used to implement multi-system antennas by simply using multi-frequency matching structures. Thus also the presented direct coupling structure provides lots of potential to integrate other systems than just the DVB-H to the same terminal. In Fig. 4 the input impedance of the direct coupling with the chosen structure (*d* = 70 mm) is presented on the Smith chart at frequency range 0.4 – 3 GHz. Higher-order resonances of the chassis can be seen to at 1200 MHz, 1530 MHz and 2500 MHz. However, also between the resonances the achievable bandwidth is typically adequate for most radio systems. The antenna structures can be implemented using direct coupling or compact coupling elements. Also, if needed, the resonant frequencies of the chassis may be shifted to optimize the behavior at a certain frequency range.

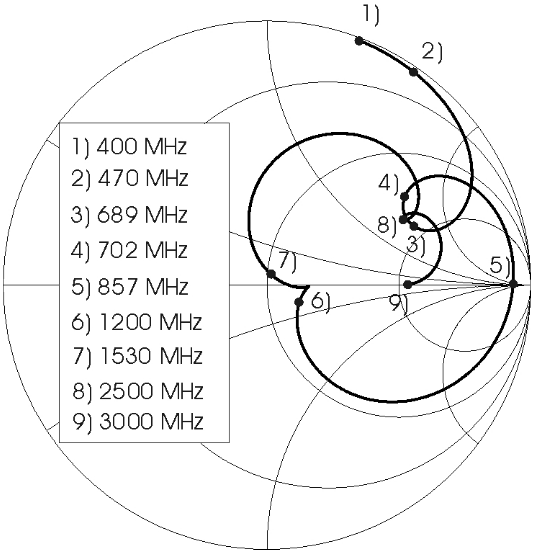

Figure 4. The input impedance curve at 0.4 – 3 GHz for the antenna structure having d = 70 mm.

PROTOTYPE ANTENNA

Using the structure presented in Fig. 2 with $d = 70$ mm, a prototype for DVB-H was designed, manufactured and evaluated. As it was already mentioned earlier, the matching (and the total efficiency) over the DVB-H band can be improved by using the matching circuit. As the chassis operates like a dipole antenna the equivalent circuit is a series RLC circuit [1] added with the parallel inductance caused by the strip. The equivalent circuit of the combination of the chassis and the matching circuit is presented in Fig. 5. The matching circuit topology was chosen according to the location of the impedance curve on the Smith chart (Fig. 4) [10]. The chassis and the matching circuit form a coupled resonator structure, which produces dual resonant operation.

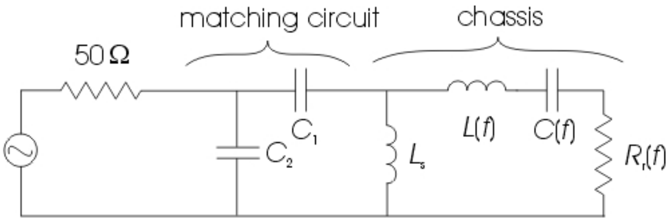

Figure 5. The equivalent circuit of the chassis and the matching circuit. L_s is caused by the strip.

The capacitors of the matching circuit are from Murata GRM18 series, and the component values are C_1 = 3.9 pF and C_2 = 5.6 pF. The printed circuit board used is RT Duroid 5870 ($\varepsilon_r = 2.33$, $\sigma = 4.9 * 10^{12}$ S/m, h = 0.79 mm and the loss tangent $\tan\delta = 0.0012$). A photo of the antenna structure is presented in Fig. 6.

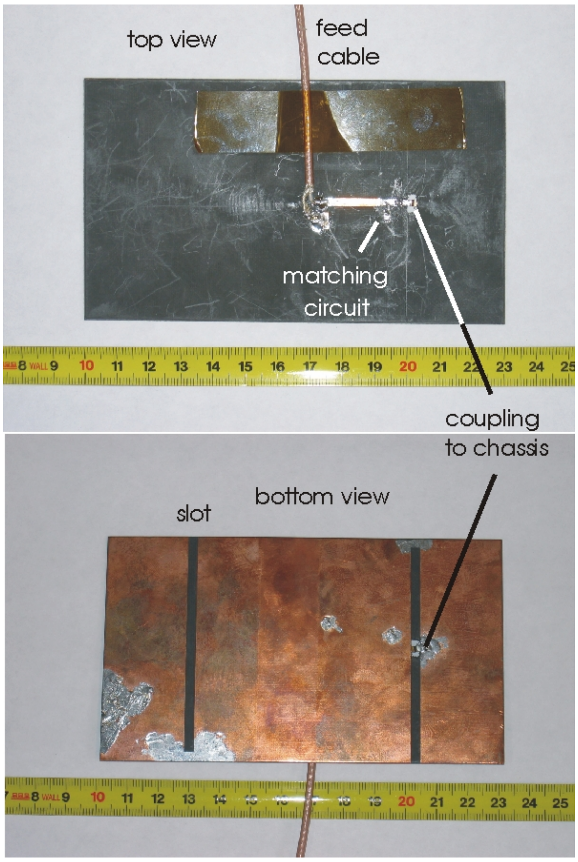

Figure 6. A photo of the prototype.

The simulated and measured frequency responses of the reflection coefficient of the prototype are shown in Figs. 7 and 8. The results agree very well. The difference between the simulated and measured results is caused mainly by the relatively large tolerances in the capacitance values ($\Delta C = \pm 0.5$ pF) of the capacitor used in the matching circuit. As can be seen, the return loss is at least about 1.6 dB across the DVB-H band. Based on the results of [6], one can see from the Smith chart presentation in Fig. 8 that the dual resonant operation is not optimal. The main problem is that instead of having the optimal double-loop response around the Smith chart centre there is only a small dip at 0.675 GHz indicating clearly too weak coupling to the chassis resonance. The reason for that is the location of the coupling structure far away from the middle of the chassis. The second problem is that the resonant frequency of the chassis (about 690 MHz) is not equal to the centre frequency of the DVB-H system (586 MHz). As shown in [1] and [6] such a difference of almost 20 % reduces clearly the achievable bandwidth with dual-resonant matching. The reason for this is that with the required mechanical structure it is not possible to add more slots to the chassis and that way decrease its resonant frequency even more.

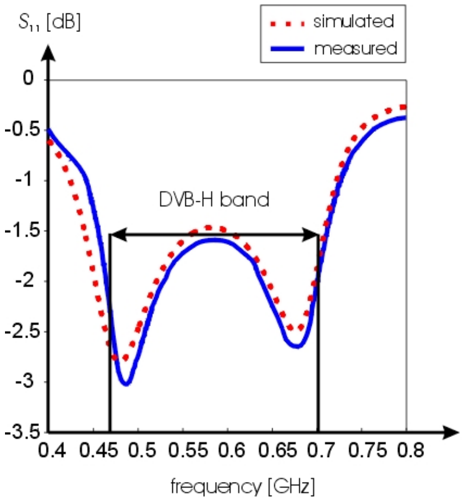

Figure 7. Simulated and measured reflection coefficients of the prototype.

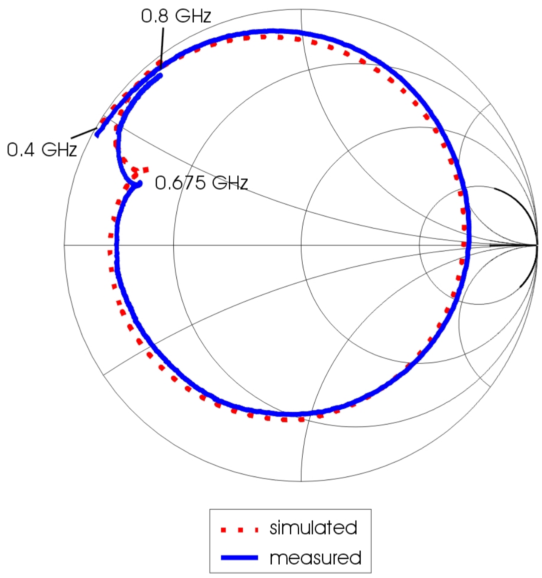

Figure 8. Simulated and measured reflection coefficients of the prototype on the Smith chart.

The 3D patterns were measured with a Satimo Stargate system and the total efficiency and the realized gain were computed from the results. The simulated and measured total efficiencies and realized gains are shown in Figs. 9 and 10. The simulated and measured results agree well. The difference is obviously caused by the uncertainty in the measurements. The realized gain specification is fulfilled with a 4-dB margin, which is needed for the extra losses caused by the lossy parts of the phone and the user. The radiation pattern is similar to that of a dipole antenna and the maximum directivity is about 2 dBi.

If the matching level of 1.6 dB return loss is not acceptable, a 2.2 dB attenuator can be added between the antenna and the receiver. Then the matching is at least 6 dB but the margin to the realized gain specification would only be about 2 dB.

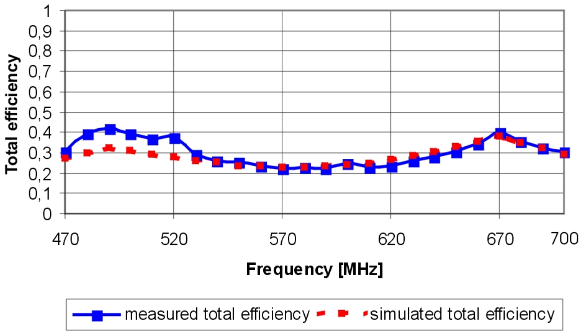

Figure 9. The simulated and measured total efficiencies of the prototype.

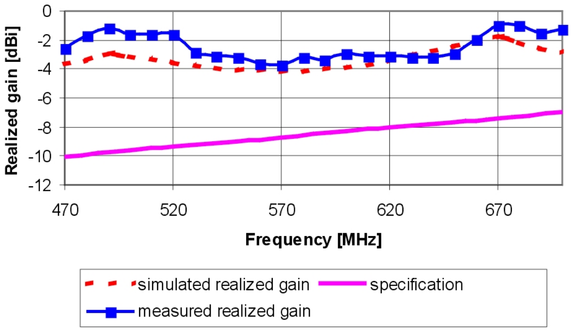

Figure 10. The simulated and measured realized gains of the prototype.

CONCLUSIONS

A new approach of implementing an antenna was introduced. A traditional antenna element such as PIFA or coupling element was replaced by a direct coupling feed over an impedance discontinuity, which was implemented by a slot in the chassis of the terminal. Another slot was added to further decrease the resonant frequency of the chassis. By using this new approach, a prototype antenna for the DVB-H system was studied, designed and manufactured. The dimensions of the terminal structure are 130 mm x 75 mm [length x width]. One important design parameter is a rather loose matching criterion, which is possible because the antenna is used for receiving only. The return loss over the DVB-H band is at least 1.6 dB. The simulation and measurement results showed that the performance exceeds the realized gain specifications with a 4 dB margin across the DVB-H band.

Although the volume of the feed structure is almost zero, the effective volume of the antenna is not zero because no conductive elements can be placed over the slots. The matching circuit also uses some printed circuit board area. It is very difficult to compare the occupied volumes of the different DVB-H antennas in [2], [3] and [4].

The antenna structure could also be used in a clamshell phone. One of the slots is between the parts of the clamshell and the hinge replaces the strip. Another slot (if needed) could be added to a place where there are no conductive elements such as display or battery. In [3], there is an antenna structure presented for DVB-H in a clamshell phone, in which the feed is placed between the parts of the clamshell. The operation idea of the antenna in [3] is basically the same as presented in this paper but the presented antenna structure is designed for a more challenging monoblock phone.

The presented idea is system independent. It could be used for ground planes of different size, like e.g. 100 mm x 40 mm, which would be applicable to GSM900 and systems operating at even higher frequencies. The suitability for a transmitting antenna, i.e. the SAR values, is not studied yet.

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