

HUMAN HEAD INTERACTION OVER GROUND PLANE BOOSTER ANTENNA TECHNOLOGY: FUNCTIONAL AND BIOLOGICAL ANALYSIS

A. Andújar¹, J. Anguera^{1, 2, *}, C. Picher¹, and C. Puente³

¹Technology and Intellectual Property Rights Department, Fractus, Alcalde Barnils 64, Edificio Testa, Sant Cugat del Vallès, Barcelona 08190, Spain

²Electronics and Telecommunications Department, Universitat Ramon LLull, Barcelona, Spain

³Signal Theory and Communications Department, Universitat Politècnica de Catalunya, Barcelona, Spain

Abstract—Handset antennas strongly interact with the human body. When a user holds a handset during a phone call, the proximity of the human head considerably affects the antenna performance and eventually the quality of the wireless connection. Consequently, the assessment of the antenna parameters regarding free-space conditions is not enough to fully characterize the performance of handset antennas and a further analysis taking into account human head interaction is required. In this sense, this paper presents a study that deals with the human head interaction concerning two aspects: functional and biological. The first one analyzes the effect of the human head over the main antenna parameters (reflection coefficient, efficiency, and radiation pattern) whereas the second one evaluates the impact of the antenna over the human head in terms of Specific Absorption Rate (SAR). Four representative prototypes of radiating structures are measured in both conditions in order to compare their performance: a dual-band Planar Inverted F Antenna (PIFA), a hexa-band PIFA with a slotted ground plane, a set of coupled monopoles, and a new architecture referred as compact radiating system based on the excitation of the ground plane through a set of non-resonant ground plane boosters. A figure of merit that relates the antenna efficiency with the SAR values is proposed for comparison purposes. The results demonstrate that losses caused by the human head power absorption

Received 5 April 2012, Accepted 11 May 2012, Scheduled 2 June 2012

* Corresponding author: Jaume Anguera (Jaume.anguera@fractus.com).

can be minimized if the antennas are placed in the edge located at a higher distance from the human cheek. Furthermore, the study reveals the robustness of the compact radiating system taking into account the human presence. This fact reinforces its position as an alternative solution to current handset antennas, capable of providing penta-band operation (GSM850/900, DCS, PCS, and UMTS) through ground plane boosters featured by their reduced volume of only 250 mm³.

1. INTRODUCTION

The mobile industry is constantly growing and handset antennas are subjected to the new requirements demanded by the market trends based on ultra-slim multifunctional wireless devices [1]. In this sense and in order to facilitate the integration of multiple functionalities, the available space for integrating the handset antenna becomes more and more limited. Consequently, the efforts are oriented to design handset antennas with the challenge of providing operability in multiple communication standards such as GSM850/900, DCS, PCS and UMTS while constrained by physical limitations [2].

As a rough approximation, handset antennas can be grouped into patch/PIFA antennas [3], monopole/IFA antennas [4–6], slots [7], and a combination of them [8]. On one hand, the first ones are featured by a specific volume and are generally located ‘on-ground’, i.e., placed over the ground plane at a certain height. Several techniques have been described to provide dual-band or multi-band operation such as for instance inserting slits in the PIFAs radiating path or using slotted ground planes [9–14]. On the other hand, monopoles and slots are designed to be ‘off-ground’ in such a way that most of the ground plane is removed underneath the antenna enabling, in some cases, substantially coplanar structures which become especially suitable for ultra slim platforms.

Recently, the theory of characteristic modes [15, 16] is acquiring relevance in the handset field and several proposals are focused on the excitation of the efficient radiation mode associated to the ground plane. With this aim, [9–12] propose solutions based on slots capable of tuning said resonant mode to lower frequencies by providing a longer current path, whereas in [17] the resonant mode is tuned to higher frequencies. The proper excitation of the ground plane mode leads to an enhancement of the handset antenna performance regarding bandwidth (BW) and radiation efficiency. Other handset antenna designs are presented in [18, 19], which are based on coupling and small antenna elements capable of efficiently exciting the radiation mode of the ground plane and providing quad-band and penta-band behavior

respectively by the addition of a specific matching network for each frequency region. A novel proposal is described in [20–22] where the small antenna elements are replaced by two non-resonant ground plane boosters featured by a high quality factor (Q) and reduced dimensions ($5\text{ mm} \times 5\text{ mm} \times 5\text{ mm}$). The ground plane, the non-resonant boosters, and the radiofrequency system compose a compact radiating system capable of providing operability in the main communication standards GSM850/900, DCS, PCS, and UMTS. In this case, the challenge lies in the fact that the ground plane resonance is not coupled to the antenna resonance so the efficient radiation is entirely provided by the proper excitation of the ground plane modes. The radiation contribution provided by such small boosters is negligible and they should not be considered antennas. In this sense, said new architecture for wireless handheld devices [20–22] becomes a promising alternative to current antenna technologies since its fundamental principle based on the correct excitation of the ground plane, which is inherent anyway in any wireless device, removes the need of including a dedicated antenna, such as PIFAs or monopoles.

Commonly, handset antenna specifications are given in free-space conditions. However, in practice, the handset antenna performance is strongly affected by other important factors such as hand interaction [23–25] and human head effect [26–37]. The user significantly interacts with the radiating system, especially during a phone call, affecting its performance and causing radiation losses as well as detuning effects. Thus, free-space measurements are not enough to correctly characterize handset antennas and these significant effects of the human head interaction over their performance have to be considered. The purpose of this paper consists in evaluating the performance of a new antenna technology for wireless handheld devices based on the use of ground plane boosters to properly excite the efficient radiation mode of the ground plane concerning the human head interaction. For the sake of comparison, three representative handset antenna topologies together with the new booster-based solution are analyzed not only in free-space but also regarding the human head interaction.

The paper is structured as follows. Firstly, the geometry of the four selected prototypes is described for comparison purposes. Secondly, the human head effect over the performance of these prototypes considering the detuning effect and the power absorption is analyzed. In the next section, the biological impact caused by the electromagnetic fields radiated by the antenna into the human head is presented. Subsequently, a criterion for evaluating the performance of a handset and a figure of merit is proposed. Finally, the conclusions

are discussed.

2. DESCRIPTION OF THE RADIATING SYSTEMS

As stated above, the main antenna parameters are evaluated in free-space conditions. However, this environment emulates an ideal situation that does not occur in practice. For instance, when holding the phone during a call, the proximity of the human head strongly affects the performance of the antenna. At the same time, the electromagnetic fields radiated by the handset antenna produce biological effects over the human head that have to be measured and restricted. Consequently, the human head interaction assessed in this paper considers not only the effect of the human head over the antenna performance but also the biological effect of the antenna over the human head in terms of SAR. Accordingly and in order to completely characterize the handset antenna, its parameters must be evaluated not only in free space conditions but also in more realistic situations, such as those that take into account human head proximity.

With this regard, four representative prototypes have been selected for carrying out the study: a dual-band PIFA antenna for GSM900 and DCS (Fig. 1); an hexa-band PIFA antenna for GSM850/900, DCS, PCS, UMTS, and Bluetooth/Wi-Fi [12] (Fig. 2); a penta-band coupled monopoles set [6] (Fig. 3(a)), and a penta-band compact radiating system for GSM850/900, DCS, PCS, and UMTS [20–22] (Fig. 3(b)). The election of these prototypes as case studies has been done taking into consideration that most of current handset antennas can be grouped into patch/PIFA and monopole antennas. The main difference between both designs lies in the fact that PIFA antennas present a ground plane portion underneath the antenna area and they have to be located at a certain height from said ground plane in order to guarantee good performance.



Figure 1. PIFA antenna for providing dual-band operation with dimensions $W = 15$ mm, $L = 40$ mm, and $h = 6$ mm over a ground plane of 100 mm \times 40 mm.



Figure 2. PIFA antenna with a slotted ground plane for providing hexa-band operation with dimensions $W = 15$ mm, $L = 40$ mm, and $h = 6$ mm over a slotted ground plane of 100 mm \times 40 mm.

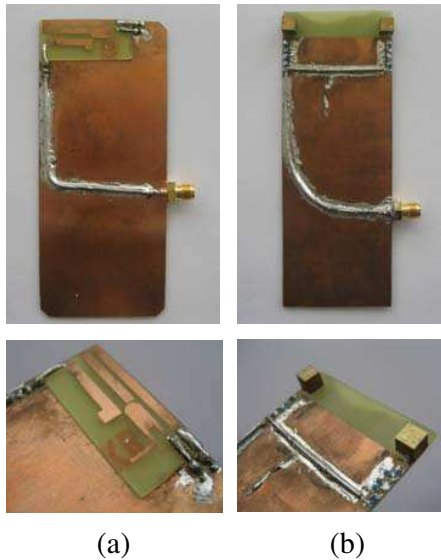


Figure 3. (a) Coupled monopole antenna for providing penta-band operation with dimensions $W = 15$ mm, $L = 33$ mm, and $h = 1$ mm over a ground plane of 110 mm \times 45 mm. (b) Compact radiating system comprising two non-resonant ground plane boosters (5 mm \times 5 mm \times 5 mm), a radiofrequency system, and a ground plane of 100 mm \times 40 mm.

On the other hand, monopole antennas do not present a ground plane portion underneath the antenna and consequently they can be coplanar to it, featuring this way a very low profile. In this sense, two PIFAs and a handset antenna based on coupled monopoles are compared not only between them but also with a new handset antenna concept based on the ground plane mode excitation without the need of a dedicated antenna such as a PIFA or monopole.

The dual-band PIFA antenna is used as a reference antenna for comparisons purposes. It is featured by a width (W) and a length (L) of 15 mm and 40 mm respectively, and is located at a height (h) of 6 mm over a ground plane with dimensions 100 mm \times 40 mm (Fig. 1). The hexa-band PIFA antenna differs from the conventional PIFA in the addition of a mechanism conceived to electrically enlarge the ground plane. Said mechanism is based on the integration of slots in the ground plane intended to enlarge the current path in the low frequency region comprising the communication standards GSM850/900 (824–960 MHz) and for featuring resonant dimensions in the high frequency region including the standards DCS/PCS/UMTS (1710–2170 MHz) (Fig. 2).

As aforementioned, coupled monopoles are evaluated as a representative sample of a penta-band antenna especially designed for being integrated in slim platform thanks to its characteristic low profile (Fig. 3(a)).

Finally, a novel compact radiating system based on the excitation of the ground plane is compared with previous techniques already consolidated in the handset market. The compact radiating system comprises two booster elements with very small dimensions of just 5 mm \times 5 mm \times 5 mm, soldered at a distance of 2 mm from the edge of a ground plane (100 mm \times 40 mm) (Fig. 3(b)). It is worthy to emphasize the small volume featured by the compact solution of 250 mm³ compared to the approximately 3600 mm³ associated to the PIFA. The full description this compact radiating system can be found in [22].

Note that all the prototypes are etched over a 1 mm FR4 piece ($\epsilon_r = 4.15$, $\tan \delta = 0.013$).

3. FUNCTIONAL ANALYSIS

This section is focused on analyzing the human head effect over the handset antenna performance. With this regard, the main antenna parameters (reflection coefficient, efficiency, radiation pattern, and directivity) are measured in free-space conditions and human head interaction. For the last case, the talk positions tested are right-cheek. These are positions included in the new European Standard for SAR measurements [38]. Accordingly, for the right location two different positions have been evaluated (Fig. 4): on one hand, the antenna is arranged near the phantom ear (Antenna Up), and on the other hand, the prototype is rotated 180° with respect to the previous position (Antenna Down).

The Printed Circuit Board (PCB) is spaced apart 1 mm from the phantom head for all the prototypes under study thanks to the use of

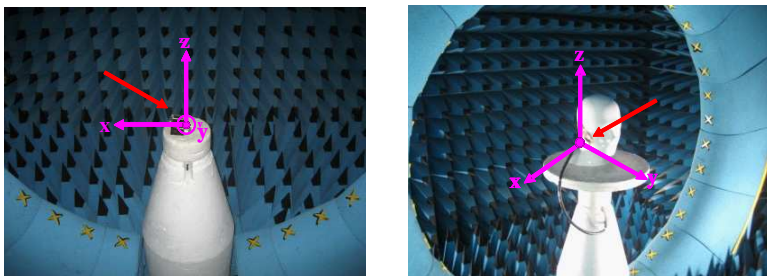


Figure 4. Set-up for radiation measurement in the anechoic chamber Satimo Stargate-32 showing the coordinate system in free-space and the human head presence for the Antenna Down position.

a methacrylate piece. It is important to notice that this is a critical situation because in practice the distance between the PCB and the human head is usually higher.

The phantom head is filled with lossy liquids emulating the electromagnetic properties of the human tissue according to the standard defined by CENELEC [38] and for the frequency range under study: low frequency region comprising the communication standards GSM850 and GSM900 (824–960 MHz), and high frequency region allocating the communication standards GSM1800/DCS, GSM1900/PCS, and UMTS (1710–2170 MHz).

3.1. Reflection Coefficient: S_{11}

As the lossy liquids are frequency dependent, the reflection coefficient has to be measured in two steps by means of a network analyzer.

Firstly the low frequency region is measured using CENELEC liquid @ 900 MHz ($\epsilon_r = 41.5$, $\sigma = 0.97$ S/m) and secondly CENELEC liquid @ 1800 MHz ($\epsilon_r = 40$, $\sigma = 1.4$ S/m) is used for the high frequency region [38].

Some minor variations of BW are observed for the dual-band PIFA, hexa-band PIFA, and the compact radiating system. However, coupled monopoles experiment an increment in BW at both frequency regions, which can be directly understood as an increment of losses caused by the power absorbed by the human head, as the following sections will demonstrate.

Analyzing each prototype particularly, it is possible to state that the presence of the human head does not significantly disturb the low frequency region and even less the high frequency region in the dual-band PIFA case (Fig. 1) since no significant detuning effects are observed (Fig. 5).

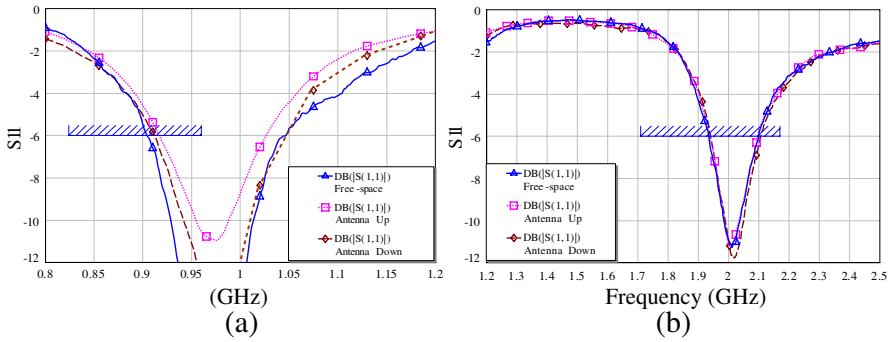


Figure 5. S_{11} referred to the dual-band PIFA (Fig. 1) regarding free-space and head interaction: Antenna Up and Antenna Down for the low frequency region (a) and for the high frequency region (b).

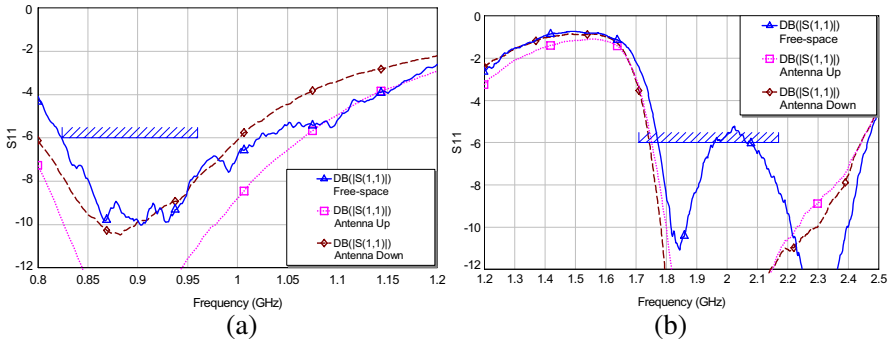


Figure 6. S_{11} referred to the hexa-band PIFA (Fig. 2) according to the conditions described in the caption of Fig. 5.

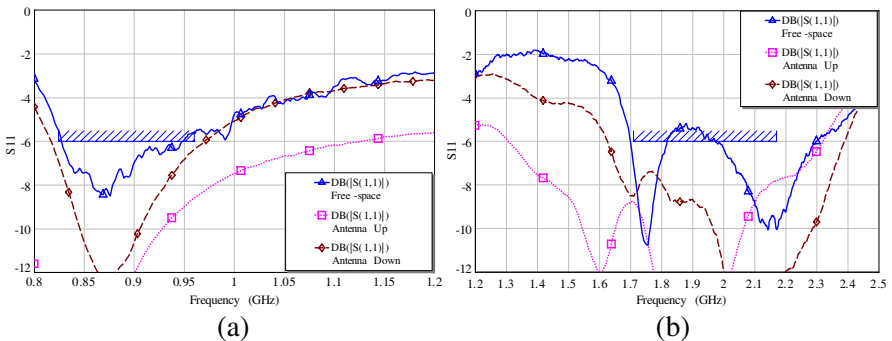


Figure 7. S_{11} referred to the coupled monopoles (Fig. 3(a)) according to the conditions described in the caption of Fig. 5.

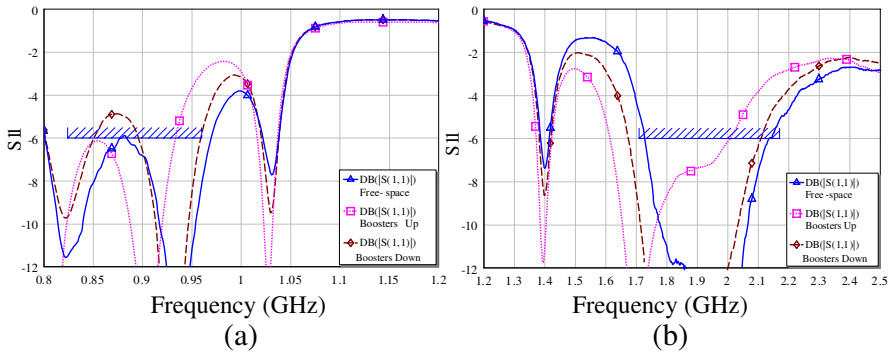


Figure 8. S_{11} referred to the compact radiating system (Fig. 3(b)) according to the conditions described in the caption of Fig. 5.

Accordingly, for the hexa-band PIFA (Fig. 2) higher losses are likely for the low frequency region and considering the Antenna Up position.

However, no significant detuning effect neither in the low frequency region neither in the high frequency region is observed (Fig. 6).

As aforementioned, higher losses are expected in the coupled monopoles case (Fig. 3(a)) for both frequency regions since a significant BW increment is observed (Fig. 7).

In the compact radiating system case (Fig. 3(b)), some detuning effect is observed in both frequency regions but particularly in the high frequency region when the Boosters Up position is evaluated (Fig. 8).

It is important to notice that for PIFA-based solutions and coupled monopoles no mismatching effect is appreciated, which means that the BW in all cases is equal or larger. However, for the compact radiating system (Fig. 3(b)) and regarding the Boosters Up position a detuning effect to lower frequencies is observed. Nevertheless, said effect can be overcome by the proper adjustment of the reactive elements that compose the radiofrequency system.

The quantitative values of the power absorbed by the human head are discussed in the following section.

3.2. Absorption Ratios and Free-space Efficiency

The free-space antenna efficiency (Fig. 9) of the four prototypes has been measured using the anechoic chamber Satimo Stargate-32. Subsequently, these values have been processed according to the former reflection coefficients measured in free space (Fig. 5–Fig. 8) in order to obtain the radiation efficiency $\eta_r = \eta_a / (1 - |S_{11}|^2)$. In this sense,

the mismatching effect is removed and the prototypes can be compared just taking into account losses without the need of considering whether the antenna is well matched or not (Fig. 10).

The four prototypes present similar radiation efficiency (Fig. 10)

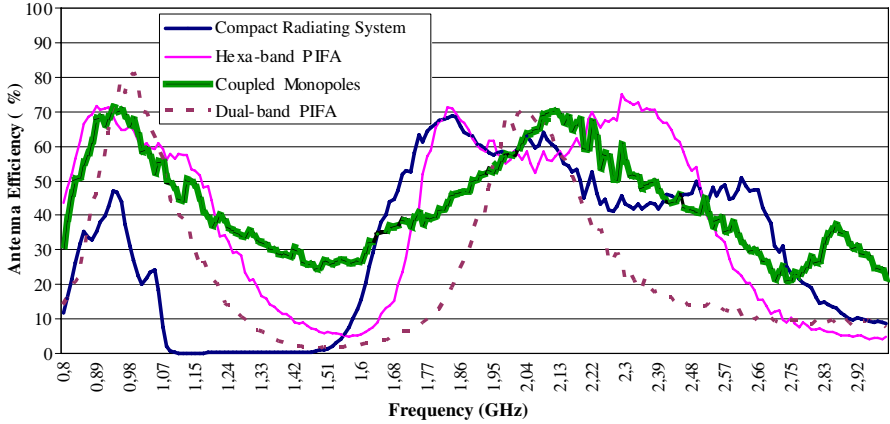


Figure 9. Antenna efficiency measured by 3D integration pattern in the anechoic chamber Satimo Stargate-32 for the: Dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) in free-space. The antenna efficiency takes into account the mismatch losses since it is defined as $\eta_a = \eta_r \cdot (1 - |S_{11}|^2)$.

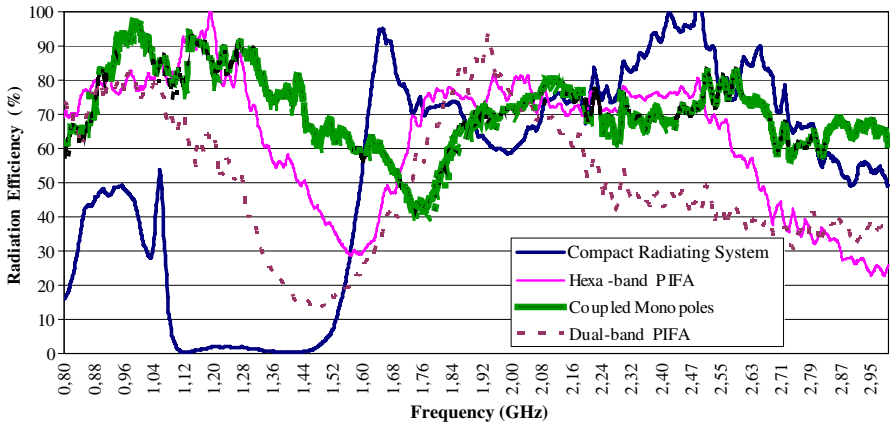


Figure 10. Radiation Efficiency associated with the dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) in free-space.

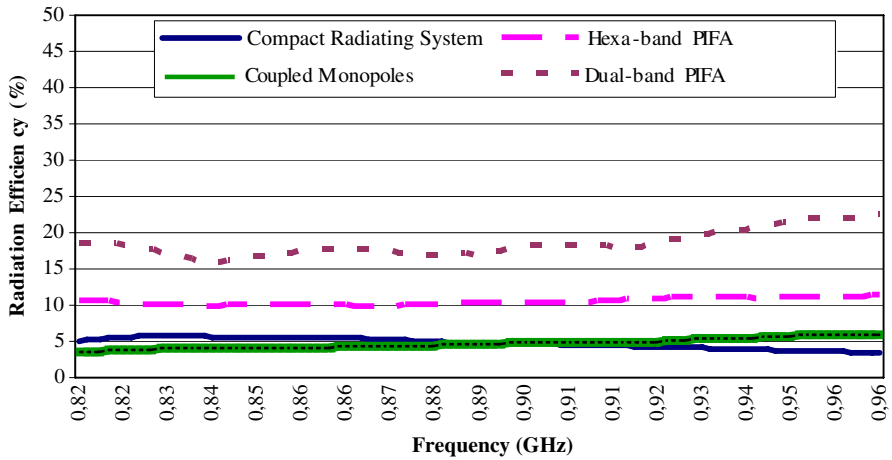


Figure 11. Measured radiation efficiency in the high frequency region for the: Dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) regarding human head for the Antenna Up position.

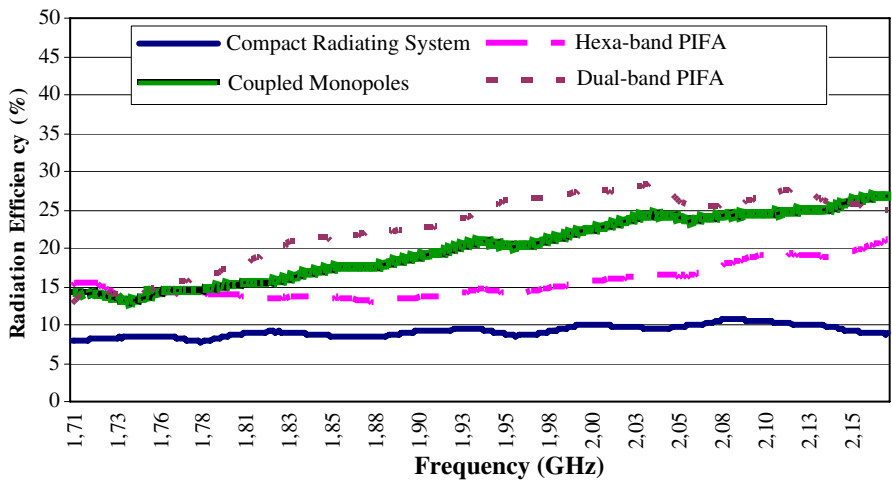


Figure 12. Measured radiation efficiency in the low frequency region for the: Dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) regarding human head for the Antenna Up position.

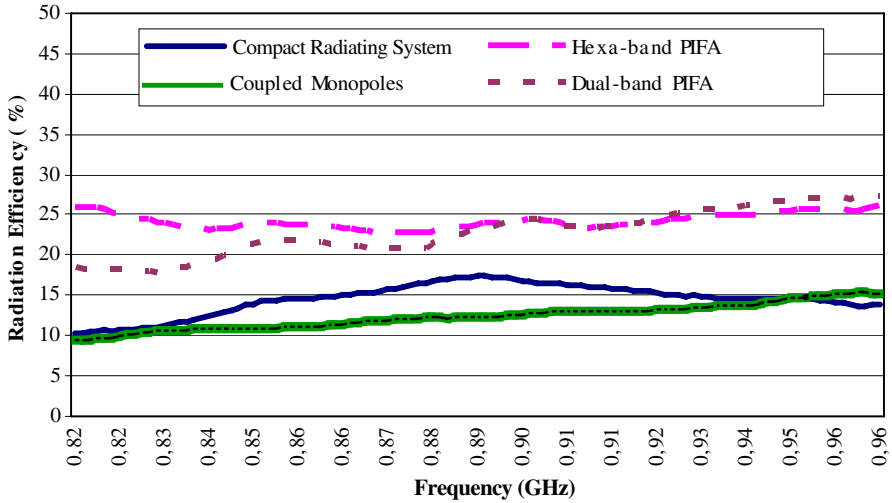


Figure 13. Measured radiation efficiency in the low frequency region for the: Dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) regarding human head for the Antenna Down position.

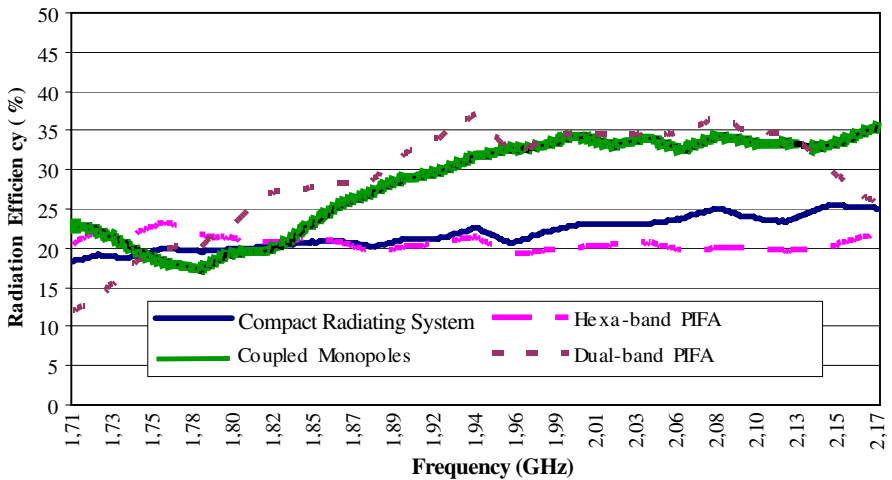


Figure 14. Measured radiation efficiency in the high frequency region for the: Dual-band PIFA (Fig. 1), hexa-band PIFA (Fig. 2), coupled monopoles (Fig. 3(a)), and compact radiating system (Fig. 3(b)) regarding human head for the Antenna Down position.

in the high frequency region but not in the low frequency region, where the radiation efficiency of the compact radiating system drops to lower values which however are still considered acceptable for mobile communications [39–42]. This effect is caused by the losses associated to the reactive components that compose the radiofrequency system, which feature a low Q especially in the low frequency region.

The power absorption caused by the human head presence considerably reduces the radiation efficiency values (Fig. 11, Fig. 12, Fig. 13, Fig. 14) with respect to those values achieved in free-space conditions (Fig. 10). The ratio between the radiation efficiency values obtained in free-space and those obtained taking into account the phantom head gives a quantitative vision of the losses introduced by the human head.

In order to demonstrate the aforementioned statement, the power absorption ratios associated to each prototype are calculated according to Equation (1).

$$\text{Absorption_ratio[dB]} = 10 \cdot \log_{10} \left(\frac{\eta_{\text{rad-free-space}}}{\eta_{\text{rad-head-position}}} \right) \quad (1)$$

The absorption ratios are calculated using the measured radiation efficiencies as discussed above using the radiation efficiency for free-space (Fig. 10) and radiation efficiencies taking into account the phantom head (Fig. 11, Fig. 12, Fig. 13, Fig. 14). The ratio is computed at both the low and high frequency region. In order to obtain a single representative absorption ratio, average is computed in the low frequency region from 824–960 MHz and from 1710–2170 MHz at the high-frequency region (Fig. 15–Fig. 16).

An important aspect to remark at this point is that although the radiation efficiency of the compact radiating system prototype in free-space is lower than that of the other handset antenna designs in the low frequency region; its performance remains comparable to the other prototypes when the interaction of the human head is considered. For example, radiation efficiency is similar to the coupled monopoles at the low frequency region for Antenna Up position and slightly better considering Antenna Down position. In this position, the compact radiating system also offers similar performance for the high frequency region than the hexa-band PIFA. Therefore, it is possible to state that the compact radiating system prototype presents higher robustness to the human head effect than that offered by other common antenna designs such as the hexa-band PIFA or the coupled monopoles. The benefits of the compact radiating system not only lie in said robustness, but also in its reduced size that allow the integration of multiple components in the wireless platform as strongly required by the handset industry.

The computed average of the absorption ratios for each frequency region and for all the prototypes concludes that the power absorption is higher for the Antenna Up position than for the Antenna Down position. This last becomes preferred since for this position the distance between the antenna and the human head is farther.

At the same time and perfectly aligned with the results gathered in previous section, the absorption ratio is higher in the low frequency region than in the high frequency region, except for the compact radiating system prototype, which presents similar behavior in both cases, Antenna Up (Fig. 15) and Antenna Down (Fig. 16).

In the preferred situation (Antenna Down), the compact radiating system becomes the best option concerning losses, operation, and volume, since it provides penta-band behavior through the use of non-

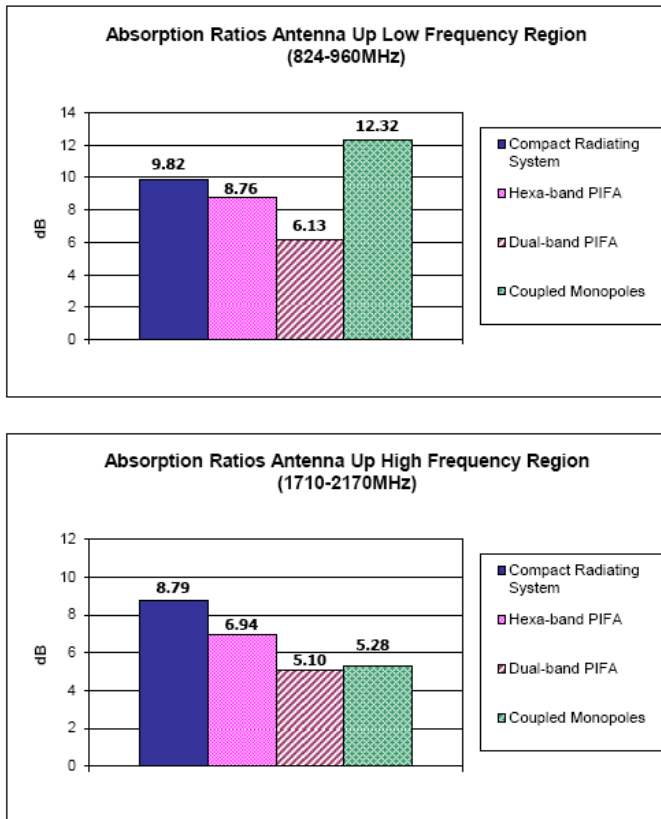


Figure 15. Absorption ratios regarding human head for the Antenna Up position for both frequency regions.

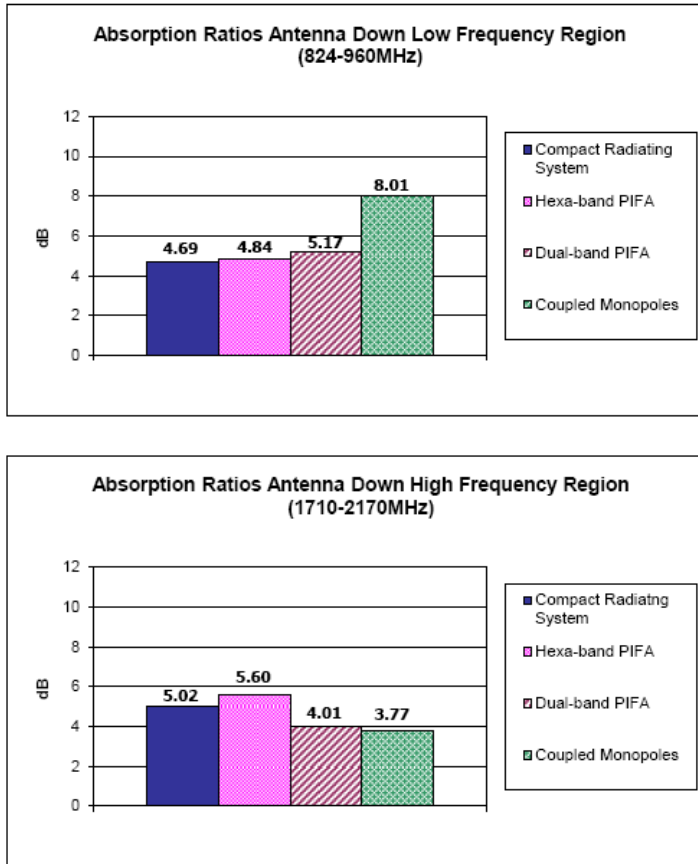


Figure 16. Absorption ratios regarding human head for the Antenna Down position for both frequency regions.

resonant ground plane boosters featuring a significant reduced size of 250 mm^3 , whereas the dual-band PIFA only presents dual-band operation regarding a considerable volume of 3600 mm^3 . At the same time, power absorption is reduced with respect to that experimented by the other handset antenna designs in the low frequency region.

Referring now to the low frequency region case and concerning the worst configuration (Antenna Up position), losses are higher for the coupled monopoles being around 12 dB in average. This fact coincides with the predictions extracted from reflection coefficient measurements (Fig. 7) where a considerable BW increment was observed.

3.3. Antenna Efficiency Considering the Human Head

In this section, the antenna efficiency is measured taken into account the human head interaction. Thus, losses associated to the amount of power absorbed by the human head are considered as well as the mismatching effects regarding both talking positions under study: Antenna Up and Antenna Down.

As aforementioned, the Antenna Up position becomes the configuration that experiments higher losses in all cases mainly due to the proximity of the antenna to the human head. Thus, the antenna efficiency is noticeably reduced with respect to the free-space conditions (Fig. 9) in both frequency regions (Fig. 17 and Fig. 18).

It is important to remark that despite the antenna efficiency of the compact radiating system prototype is lower than that presented by the other cases referring free-space measurements, the difference diminishes when the human head presence is considered. In this sense, the antenna efficiency attained in the low frequency region considering Antenna Up position is comparable to that obtained by the coupled monopoles especially in the frequency band associated to the GSM850 mobile communication service.

This fact reinforces the statement that coupled monopoles present higher losses since they attain similar antenna efficiency than the compact radiating system despite its higher values in free-space

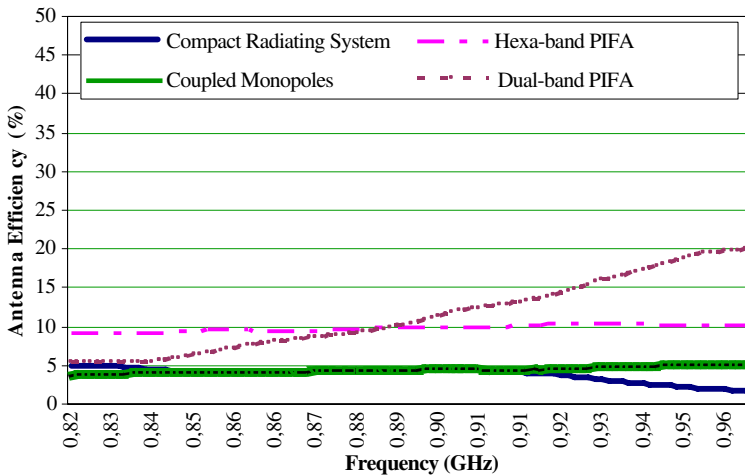


Figure 17. Measured antenna efficiency in the low frequency region for the: Dual-band PIFA, hexa-band PIFA, coupled monopoles, and compact radiating system regarding human head for the Antenna Up position.

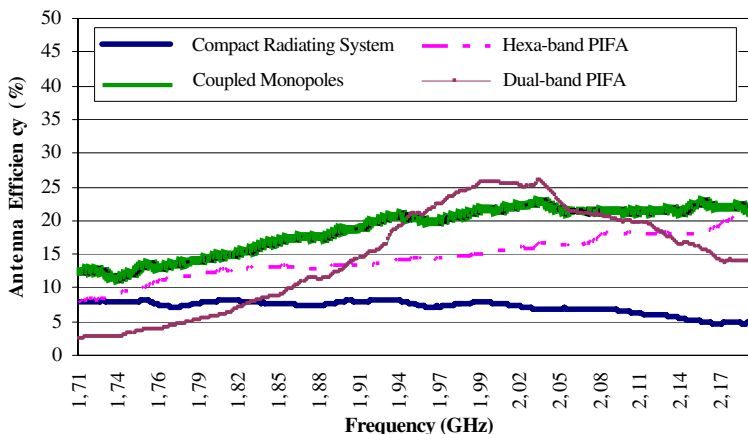


Figure 18. Measured antenna efficiency in the high frequency region for the: Dual-band PIFA, hexa-band PIFA, coupled monopoles, and compact radiating system regarding human head for the Antenna Up position.

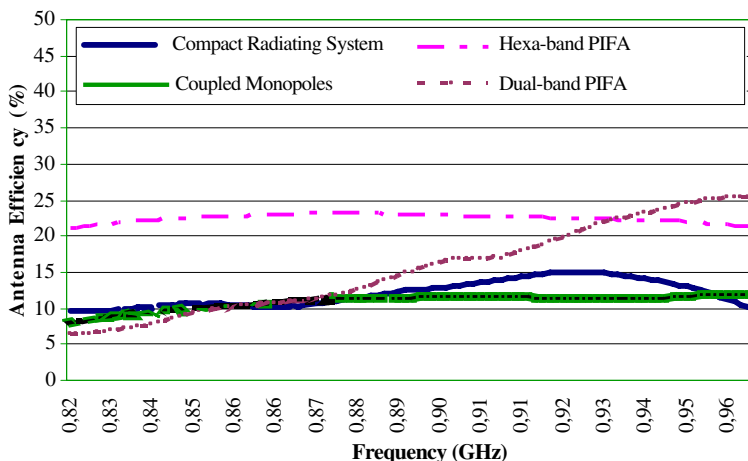


Figure 19. Measured antenna efficiency in the low frequency region for the: Dual-band PIFA, hexa-band PIFA, coupled monopoles, and compact radiating system regarding human head for the Antenna Down position.

conditions (approximately 60% of antenna efficiency in free-space versus the 40% achieved by the compact radiating system). In the high frequency region and still regarding the Antenna Up position, antenna efficiency concerning the compact radiating system could be

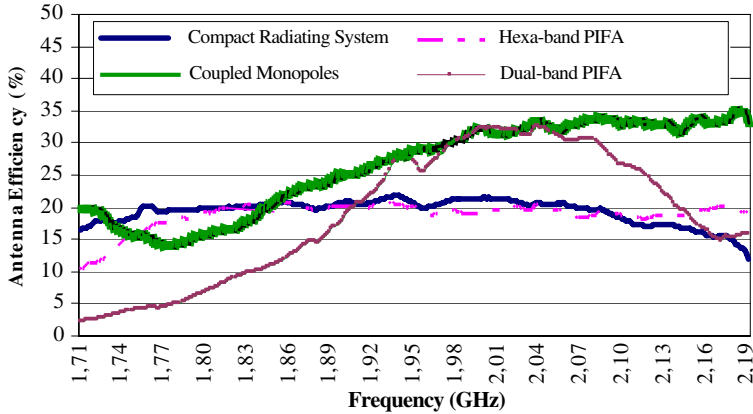


Figure 20. Measured antenna efficiency in the high frequency region for the: Dual-band PIFA, hexa-band PIFA, coupled monopoles, and compact radiating system regarding human head for the Antenna Down position.

improved if the detuning effect is corrected through the appropriate adjustment of the matching network components.

In the preferred configuration (Antenna Down), the compact radiating system prototype exhibits less additional loss than the other antenna designs and as expected, the antenna efficiency achieved in the low frequency region is comparable to that values attained by other common handset antenna designs such as the coupled monopoles (Fig. 19 and Fig. 20).

The best values are those achieved by the hexa-band PIFA and are comparable to that obtained by the dual-band PIFA at those frequencies for which the antenna is matched. In the high frequency region, the compact radiating system prototype competes directly with the hexa-band PIFA prototype since similar values are obtained with the added advantage of its reduced volume (250 mm^3) compared to the 3600 mm^3 of the hexa-band PIFA.

3.4. Radiation Patterns

Following with the study of the human head effect over the main antenna parameters, radiation patterns are evaluated and presented along this section.

Although the four prototypes have been measured in free-space conditions and human head interaction for both positions (Antenna Up and Antenna Down), only the most significant results related to the

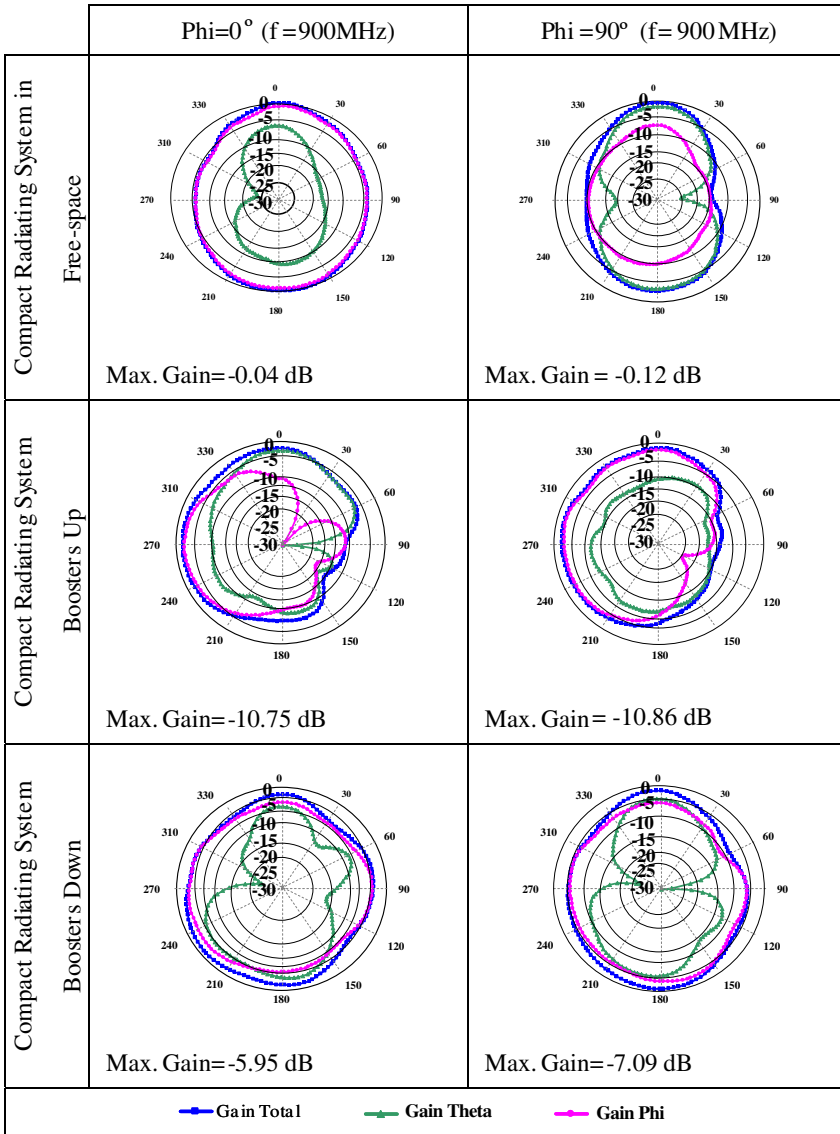


Figure 21. Main cuts (Phi = 0° and Phi = 90°) of the radiation pattern provided by the compact radiating system prototype (Fig. 3(b)) measured at the frequency of $f = 900$ MHz in free-space and human head for both positions: Boosters Up and Boosters Down. See coordinate axis at Fig. 4.

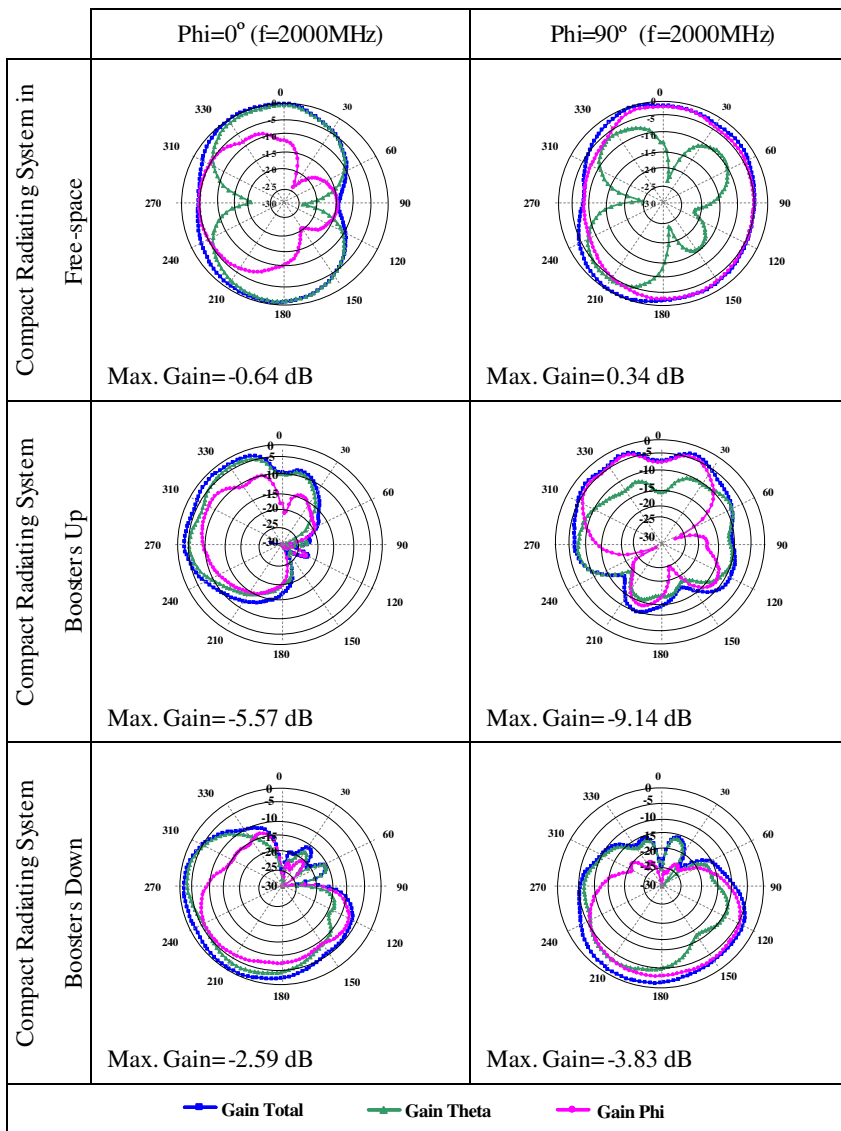


Figure 22. Main cuts (Phi = 0° and Phi = 90°) of the radiation pattern provided by the compact radiating system prototype (Fig. 3(b)) measured at the frequency of $f = 2000$ MHz in free-space and human head for both positions: Boosters Up and Boosters Down. See coordinate axis at Fig. 4.

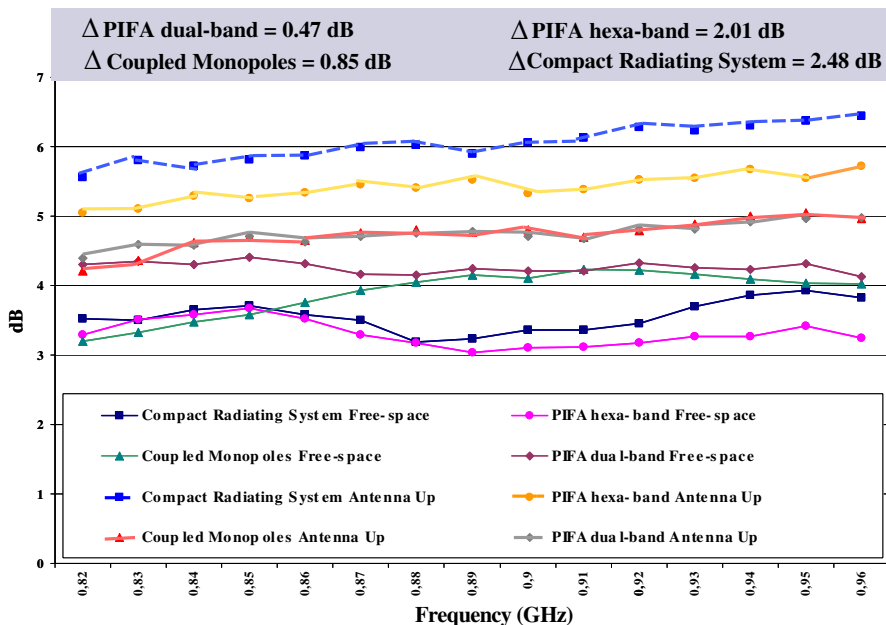


Figure 23. Measured directivity in the low frequency region for the four prototypes in free-space and human head conditions.

new compact radiating system prototype are presented herein (Fig. 21 and Fig. 22).

The effect of the human head over the radiation pattern is quite similar for all the cases. The omnidirectional behavior found in free-space conditions is modified with the human head presence resulting in a directivity increment (depicted in Fig. 23 and Fig. 24 as an average Δ) for all the prototypes under study. This effect is mainly produced by the fact that at these frequencies the phantom head acts as a lossy reflector. The impact is more evident in the high frequency region since for this frequency range the head is electrically larger.

Thus, the directivity for the three prototypes in free-space conditions remains around 3.5 dB in the low frequency region and slightly increases with the frequency. As aforementioned, the effect caused by the human head presence traduces in a directivity increment in both frequency regions for all the prototypes under study, concluding that it affects in a similar way to their radiation patterns.

Note that for simplicity purposes the Antenna Up position is considered since it produces more significant effects over the directivity. The Antenna Down case also increases the directivity but their effects are not so noteworthy.

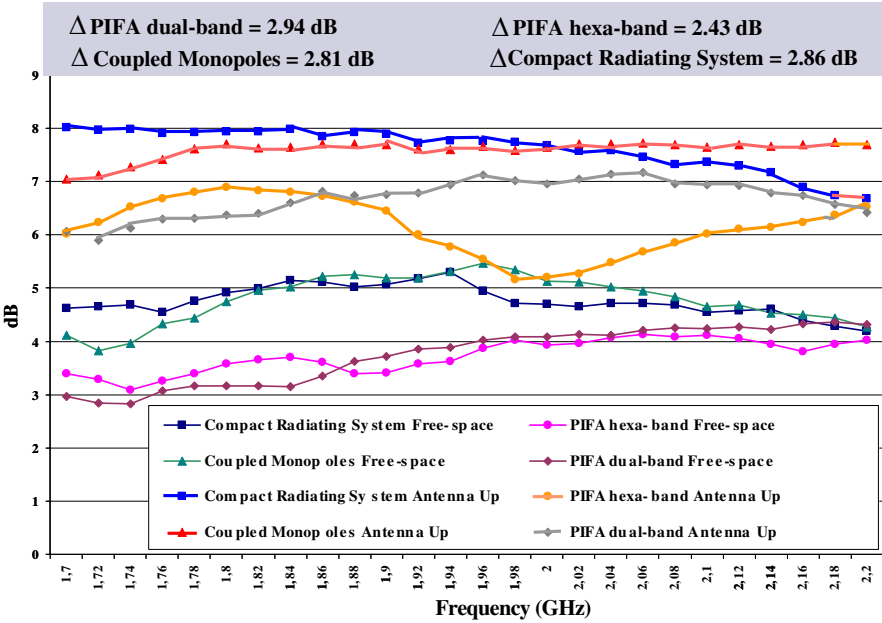


Figure 24. Measured directivity in the high frequency region for the four prototypes in free-space and human head conditions.

4. BIOLOGICAL COMPATIBILITY

As already introduced in Section 2, the assessment of the human head impact must be carried out regarding two main aspects. On one hand, the effect over the performance of the handset antenna, which takes into account absorption losses and detuning effects (former section), and on the other hand, the biological impact over the human head, which is the object of the present section.

SAR is the parameter used to evaluate the biological impact over the human head caused by the electromagnetic fields radiated by a handset antenna. Hence, SAR is related to biological effects since it is directly related with temperature increments within the head [34, 35]. Namely, SAR is a measure of the localized maximum value of the power absorbed by the human head by unity of mass and its dimensions are mW/g. This point of maximum absorption receives the name of hot-spot. Due to the fact that this absorption is produced in the near field, SAR can be measured from the electric near field according to Equation (2), where σ_{eff} , and ρ are the human tissue effective conductivity and the tissue volumetric density, respectively. It is significant to note that the magnetic field is not considered in

Equation (2) since the head features $\mu'' = 0$.

$$SAR = \frac{\sigma_{eff}}{\rho} |\vec{E}|^2 \tag{2}$$

In this sense, the SAR values associated with the four prototypes under study have been measured using the DASY4 equipment. Since maximum transmitted power of mobile phones at 900 MHz (GSM900) is 2 W and taking into account that a channel used 1/8 of the time slot, SAR at 900 MHz is measured injecting 24 dBm to the radiating systems under test. For the high frequencies region, since maximum transmitted power is 1 W, SAR is measured injecting 21 dBm to the radiating systems under test.

SAR distribution is depicted at two representative frequencies, one associated to the low frequency region (900 MHz) and the other one located in the high frequency region (1900 MHz) considering both positions: Antenna Up and Antenna Down (Table 1–Table 4).

As a common feature, SAR values are higher in the Antenna Up position since the antenna is nearer the human head. In this sense, the fact of rotating the prototype 180° causes a significant reduction that considerably minimizes the SAR. This effect is observed in all the prototypes and more significantly in the high frequency region where the maximum electric field appears localized in the shorter edge of the PCB at a certain distance from its center. Otherwise, in the

Table 1. SAR measurements: Dual-band PIFA.

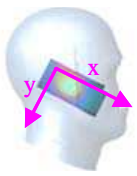



Antenna Up (f=900MHz)	Antenna Down (f=900MHz)	Antenna Up (f=1900MHz)	Antenna Down (f=1900MHz)
			
SAR(1g): 2.46 mW/g	SAR (1g) : 2.29 mW/g	SAR(1g): 2.68 mW/g	SAR (1g): 0.79 mW/g
SAR(10g): 1.65 mW/g	SAR (10g): 1.52 mW/g	SAR (10g) : 1.36 1.36 mW/g	SAR (10g): 0.44 mW/g
Hotspot: (38,20)	Hotspot: (64,14)	Hotspot: (9,8)	Hotspot: (91,30)

Table 2. SAR measurements: HEXA-band PIFA.





Antenna Up (f=900MHz)	Antenna Down (f=900MHz)	Antenna Up (f=1900MHz)	Antenna Down (f=1900MHz)
			
SAR (1g): 2.42 mW/g	SAR (1g): 2.02 mW/g	SAR (1g) : 3.28 mW/g	SAR (1g): 1.63 mW/g
SAR (10g): 1.61 mW/g	SAR (10g): 1.39 mW/g	SAR (10g) : 1.50 mW/g	SAR (10g): 0.89 mW/g
Hotspot: (3 5,19)	Hotspot: (65,13)	Hotspot: (13, 14)	Hotspot: (92,20)

Table 3. SAR measurements: Coupled monopoles.


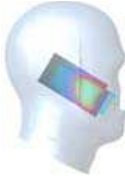

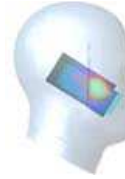




Antenna Up (f=900MHz)	Antenna Down (f=900MHz)	Antenna Up (f=1900MHz)	Antenna Down (f=1900MHz)
			
SAR (1g): 3.58 mW/g	SAR (1g): 2.36 mW/g	SAR (1g) : 2.93 mW/g	SAR (1g): 1.47 mW/g
SAR (10g): 2.48 mW/g	SAR (10g): 1.67 mW/g	SAR (10g) : 1.66 mW/g	SAR (10g): 0.92 mW/g
Hotspot: (27,29)	Hotspot: (68,18)	Hotspot: (18,23)	Hotspot: (68,16)

Table 4. SAR measurements: Compact radiating system.

Boosters Up (f=900MHz)	Boosters Down (f=900MHz)	Boosters Up (f=1900MHz)	Boosters Down (f=1900MHz)
			
SAR(1g): 1.11 mW/g	SAR(1g): 0.59 mW/g	SAR(1g): 2.15 mW/g	SAR(1g): 0.98 mW/g
SAR(10g): 0.77 mW/g	SAR(10g): 0.41 mW/g	SAR(10g): 1.27 mW/g	SAR(10g): 0.59 mW/g
Hotspot: (26,26)	Hotspot: (66,16)	Hotspot: (24,27)	Hotspot: (79,5)

low frequency, region SAR reduction is less significant since for these frequencies the electric field is distributed along the PCB and the hot-spot is located near the PCB center [12].

In the case of the low frequency region, the SAR values regarding both positions are located below the standards (American standard (ANSI/IEEE C95.1 2005): 1.6 mW/g (1 g) and European guidelines (ICNIRP 1998) 2 mW/g (10 g)). However, for the high frequency region the antenna down position is preferred.

5. EVALUATION CRITERIA

5.1. SAR vs Power Absorption and Antenna Efficiency

In order to complete the study it is interesting to deeply analyze the correlation between the SAR values and the power absorption. A priori, the statement, the higher the SAR, the higher the absorption losses are, seems reasonable. However, the experiments carried out demonstrate that this is an invalid affirmation.

SAR is a measure of the peak power absorption per unit of weight as defined in (2). Consequently, it only gives information about the maximum value of absorption and the location where it takes place. On the contrary, the total power absorption as given in (3) is calculated

as the integral along all the head volume (V') so it is directly connected with the distribution of the near electrical fields thereof. On one hand, SAR is an electromagnetic magnitude useful for biological analysis since it is directly related to temperature elevation inside the human's head [34, 35]. On the other hand, power absorption is referred to the antenna performance that in the end, determines the phone behavior. Power absorption determines battery life and coverage for example.

$$\text{Power_absorption} = \int_{V'} \sigma_{eff} \cdot |E|^2 dV' \quad (3)$$

In this sense, it is possible to find a prototype having maximum SAR but minimum power absorption. This is the case of the hexa-band PIFA, which presents at a frequency of 2000 MHz regarding the Antenna Up position a high level of SAR (2.81 mW/g (1 g)) and losses around 7.11 dB. On the contrary, the behavior of the compact radiating system prototype at 900 MHz shows that it is possible to have low SAR (1.11 mW/g (1 g)) but higher losses (around 10.07 dB). This fact demonstrates that both values are not necessarily correlated, high values of SAR do not imply high losses, since they are only defined by the distribution of the near fields along the PCB.

The conclusion that can be extracted from the compact radiating system results gathered in Table 5 and Table 6 is that insofar the frequency increases, the near electric field distribution concentrates nearer the boosters providing high values of SAR. At the same time since the hot-spot is located nearer the booster and at a significant distance from the PCB midpoint, the rotation of the PCB (Boosters Down position) not only reduces the SAR values but also the power absorption levels.

The compact radiating system presents lower SAR values for the

Table 5. SAR and absorption losses for boosters up.

Compact Radiating System	Boosters Up			
	SAR (1 g) (mW/g)	Hot Spot	Absorption Losses (dB)	η_a (%)
835	1.81	32,28	7.06	4.75
900	1.11	26,26	10.07	4.58
1800	2.42	20,28	9.23	7.82
1900	2.15	24,27	8.57	8.03
2000	2.19	26,23	7.71	7.90

Table 6. SAR and absorption losses for boosters down.

Compact Radiating System	Boosters Down			
Frequency MHz	SAR (1 g) (mW/g)	Hot Spot	Absorption Losses (dB)	η_a (%)
835	0.88	66,12	4.03	9.91
900	0.59	66,16	4.61	13.01
1800	0.97	81,6	5.62	19.85
1900	0.98	79,5	4.91	20.76
2000	1.03	79,5	4.14	21.41

Table 7. SAR (1 G) comparison for antenna down position.

Prototype	(900 MHz)	(1900 MHz)
Dual-band PIFA	2.29 mW/g	0.79 mW/g
Hexa-band PIFA	2.02 mW/g	1.63 mW/g
Cpupled monopoles	2.36 mW/g	1.47 mW/g
Compact Radiating System	0.59 mW/g	0.98 mW/g

preferred position (Boosters Down) when it is compared with those achieved by the other prototypes.

This fact, depicted in Table 7, leads to an important conclusion since for approximately the same antenna efficiency (especially comparing the compact radiating system with the coupled monopole in the low frequency region and with the hexa-band PIFA in the high frequency region (Fig. 19 and Fig. 20) the SAR values obtained with the booster-based solution are noticeably reduced. Accordingly, and in order to define a criteria for evaluating the performance of the four prototypes in both biological and functional effects in terms of SAR and power absorption, a new figure of merit is proposed and discussed in the following section.

5.2. Figure of Merit

The proposed figure of merit is defined as the ratio between the antenna efficiency and the SAR values for a given frequency. The larger the figure of merit, the better.

As aforementioned, the absorption ratios and SAR values are not necessarily correlated. However, SAR values are directly related with

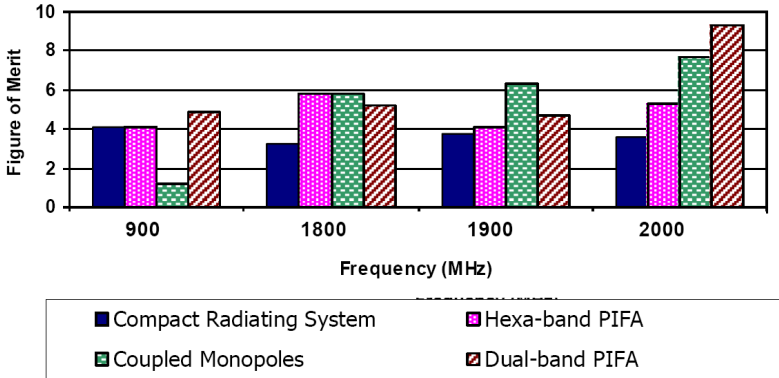


Figure 25. Figure of merit related to the four prototypes regarding the Antenna Up position.

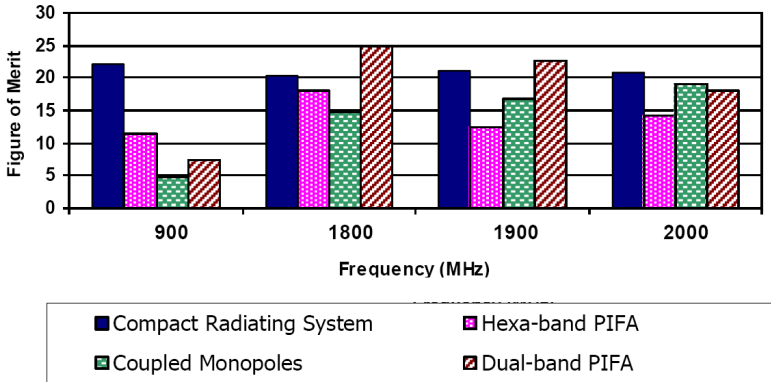


Figure 26. Figure of merit related to the four prototypes regarding the Antenna Down position.

the antenna efficiency. Thus, for a given device, the higher the power radiated by the antenna, the higher the SAR values attainable.

In this sense and in order to establish a fair comparison between prototypes, a figure of merit that relates antenna efficiency and SAR values is provided in Fig. 25 and Fig. 26 for both positions: Antenna Up and Antenna Down respectively. Accordingly, the prototype with better performance is the one that presents higher antenna efficiency and low SAR values.

In the Antenna Up case, the compact radiating system does not present the best trade-off in any cases. However, for the low frequency region the values obtained are comparable with those achieved by the hexa-band PIFA. In the Antenna Up case, the dual-band PIFA is the prototype that maximizes antenna efficiency while minimizing SAR at

those frequencies for which the antenna is well-matched. Otherwise coupled monopoles and hexa-band PIFA alternate their performance since for the low frequency region, the hexa-band PIFA would be preferred while for frequencies around 1900 MHz, coupled monopoles are favorite. Nevertheless and taking into account the preferred position: Antenna Down, the compact radiating system stands out over the hexa-band PIFA and the coupled monopoles as the better solution considering both frequency regions but especially for the low frequency region. In the high frequency region, the values obtained are comparable with those achieved by the dual-band PIFA but with the advantage of the reduced volume and the penta-band operation of the compact radiating system. This fact turns the compact radiating system in a good alternative to the already existing handset antennas technologies since it is able not only to provide penta-band operation with a reduced volume (250 mm^3) but also to ensure robustness to the human head effect guarantying low SAR values.

6. CONCLUSION

Free-space measurements are not enough to fully characterize a handset device since the presence of the human head in the vicinity of a handset antenna strongly affects its performance. This effect must be taken into account regarding two main aspects: functional and biological. The first one considers the effect of the human head over the main antenna parameters whereas the second one relates to the effect of the radiated fields into the human head in terms of SAR and temperature elevation. On one hand, power absorption losses and SAR values can be minimized if the antenna is placed in the PCB edge located at a higher distance from the human cheek. On the other hand, the results show that SAR values are not necessarily associated with power absorption since while SAR is a measure of the peak power absorption per unit of weight, the power absorption is defined as the integral along all the head volume so it is directly connected with the near electrical fields distribution. It means that a prototype can present high losses but low SAR values, and in this sense, a figure of merit is required for the sake of comparison since the best solution is the one that maximizes antenna efficiency while minimizing SAR. The results demonstrate that the proposed compact radiating system based on the excitation of the ground plane mode becomes a promising solution that directly competes with other common handset antenna designs regarding functional performance and with the advantage of a reduced volume (250 mm^3). Hence, it is possible to conclude that the compact radiating system becomes a robust solution to the human

head able to provide penta-band operation (GSM850/900, DCS, PCS, and UMTS) while increasing the available PCB space for integrating new and multiple functionalities.

REFERENCES

1. Frost, F. and Sullivan, *Antennas Systems*, Washington, USA, 2006.
2. Geissier, M., D. Heberling, and I. Wolff, "Bandwidth and radiating properties of internal handset antennas," *IEEE Antennas and Propagation Society International Symposium*, Vol. 4, 2246–2249, July 2000.
3. Wong, K. L., *Planar Antennas for Wireless Communications*, John Wiley & Sons, New York, 2003.
4. Puente, C., J. Anguera, J. Soler, and A. Condes, "Coupled multi-band antennas," *Patent Appl. WO2004/025778*, September 10, 2002.
5. Lin, C. and K. L. Wong, "Printed monopole slot antenna for internal multiband mobile phone antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 12, 3690–3697, December 2007.
6. Risco, S., J. Anguera, A. Andújar, A. Pérez, and C. Puente, "Coupled monopole antenna design for multiband handset devices," *Microwave and Optical Technology Letters*, Vol. 52, No. 2, 359–364, February 2010.
7. Wu, C. and K. Wong, "Hexa-band internal printed slot antenna for mobile phone application," *Microwave and Optical Technology Letters*, Vol. 50, No. 1, 35–38, January 2008.
8. Anguera, J., I. Sanz, J. Mumbrú, and C. Puente, "Multi-band handset antenna with a parallel excitation of PIFA and slot radiators," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 2, 348–356, February 2010.
9. Anguera, J., I. Sanz, A. Sanz, A. Condes, D. Gala, C. Puente, and J. Soler, "Enhancing the performance of handset antennas by means of groundplane design," *IEEE International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials (iWAT)*, New York, USA, March 2006.
10. Anguera, J., A. Cabedo, C. Picher, I. Sanz, M. Ribó, and C. Puente, "Multiband handset antennas by means of groundplane modification," *IEEE Antennas and Propagation Society International Symposium*, Honolulu, Hawaii, USA, June 2007.

11. Picher, C., J. Anguera, A. Cabedo, C. Puente, and S. Kahng, "Multiband handset antenna using slots on the ground plane: Considerations to facilitate the integration of the feeding transmission line," *Progress In Electromagnetics Research C*, Vol. 7, 95–109, 2009.
12. Cabedo, A., J. Anguera, C. Picher, M. Ribó, and C. Puente, "Multi-band handset antenna combining a PIFA, slots, and ground plane modes," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 9, 2526–2533, September 2009.
13. Quintero, R. and C. Puente, "Multilevel and space-filling ground planes for miniature and multiband antennas," *Patent Appl. WO2003/023900*, September 13, 2001.
14. Anguera, J. and C. Puente, "Shaped ground plane for radio apparatus," *Patent Appl. WO2006/070017*, December 29, 2005.
15. Cabedo-Fabrés, M., E. Antonino-Daviu, A. Valero-Nogueira, and M. F. Bataller, "The theory of characteristic modes revisited: A contribution to the design of antennas for modern applications," *IEEE Antennas and Propagation Magazine*, Vol. 49, No. 5, 52–68, October 2007.
16. Schroeder, W. L., C. T. Famdje, and K. Solbach, "Utilization and tuning of the chassis modes of a handheld terminal for the design of multiband radiation characteristics," *IEEE Transactions on Antennas and Propagation*, Vol. 50, No. 10, 1433–1444, October 2002.
17. Puente, C. and J. Anguera, "Handset with electromagnetic bra," *Patent Appl. WO2005/083833*, February 28, 2005.
18. Ozden, S., B. K. Nielsen, C. H. Jorgensen, J. Villanen, C. Icheln, and P. Vainikainen, "Quad-band coupling element antenna structure," U.S. Patent 7,274,340, September 25, 2007.
19. Anguera, J., I. Sanz, C. Puente, and J. Mumbrú, "Wireless device including a multiband antenna system," *Patent Appl. WO2008/119699*, March 26, 2008.
20. Anguera, J., A. Andújar, C. Puente, and J. Mumbrú, "Antennaless wireless device," *Patent Appl. WO2010/015365*, July 31, 2009.
21. Anguera, J., A. Andújar, C. Puente, and J. Mumbrú, "Antennaless wireless device capable of operation in multiple frequency regions," *Patent Appl. WO2010/015364*, July 31, 2009.
22. Andújar, A., J. Anguera, and C. Puente, "Ground plane boosters as a compact antenna technology for wireless handheld devices," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 5,

- 1668–1677, May 2011.
23. Anguera, J., A. Camps, A. Andújar, and C. Puente, “Enhancing the robustness of handset antennas to finger loading effects,” *Electronics Letters*, Vol. 45, No. 15, 770–771, July 2009.
 24. Jung, J. M., S. Kim, K. Kong, J. Lee, and B. Lee, “Designing ground plane to reduce hand effects on mobile handsets,” *IEEE Antennas and Propagation Society International Symposium*, 1040–1043, Honolulu, USA, June 2007.
 25. Su, C., C. Wu, and K. Wong, “User’s hand effects on EMC internal GSM/DCS mobile phone antenna,” *IEEE Antennas and Propagation Society International Symposium*, 2097–2100, Albuquerque, USA, July 2006.
 26. Toftgard, J., S. N. Hornsleth, and J. B. Andersen, “Effects on portable antennas of the presence of a person,” *IEEE Transaction on Antennas and Propagation*, Vol. 41, No. 6, 739–746, 1993.
 27. Okoniewski, M. and M. A. Stuchly, “A study of the handset antenna and human body interaction,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 44, No. 10, 1855–1864, October 1996.
 28. Kildal, P. S. and C. Carlsson, “Comparison between head losses of 20 phones with external and built-in antennas measured in reverberation chamber,” *IEEE Antennas and Propagation Society International Symposium*, Vol. 1, 436–439, August 2002.
 29. Boyle, K. R., Y. Yuan, and L. P. Ligthart, “Analysis of mobile phone antenna impedance variations with user proximity,” *IEEE Transaction on Antennas and Propagation*, Vol. 55, No. 2, 364–372, February 2007.
 30. Huang, T. and K. R. Boyle, “User interaction studies on handset antennas,” *European Conference on Antennas and Propagation — EuCAP*, Edinburgh, United Kingdom, 2007.
 31. Lu, D., D. Fisk, and A. Wang, “A mobile antenna design for optimal performance in human head and hand configuration,” *IEEE Antennas and Propagation Society International Symposium*, 1048–1048, Honolulu, USA, June 2007.
 32. Ebrahimi-Ganjeh, M. A. and A. R. Attari, “Interaction of dual band helical and pifa handset antennas with human head and hand,” *Progress In Electromagnetics Research*, Vol. 77, 225–242, 2007.
 33. Schiavoni, A., P. Bertotto, G. Richiardi, and P. Bielli, “SAR generated by commercial cellular phones — Phone modeling, head modeling, and measurements,” *IEEE Transactions on*

- Microwave Theory and Techniques*, Vol. 18, No. 11, 2064–2071, November 2000.
34. Bernardi, P., M. Cavagnaro, S. Pisa, and E. Piuzzi, “Power absorption and temperature elevations induced in the human head by a dual-band monopole-helix antenna phone,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 49, No. 12, 2539–2546, December 2001.
 35. Hirata, A. and T. Shiozawa, “Correlation of maximum temperature increase and peak SAR in the human head due to handset antennas,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, No. 7, 1834–1841, July 2003.
 36. Khodabakhshi, H. and A. Cheldavi, “Human head interaction with a PIFA in cellular mobile communication,” *European Conference on Antennas and Propagation — EuCAP*, Barcelona, Spain, 2010.
 37. Risco, S., J. Anguera, A. Andjar, C. Picher, and J. Pajares, “Comparison of a monopole and a PIFA handset antenna in the presence of the human head,” *Microwave and Optical Technology Letters*, Vol. 54, No. 2, 454–459, Feb. 2012.
 38. CENELEC-European Committee for Electro technical Standardization Std. EN 62209-1 2006, “Basic standard for the measurement of specific absorption rate related to human exposure to Electromagnetic fields from mobile phones (300 MHz–3 GHz),” July 2001.
 39. Martínez, M., O. Letschke, M. Geissler, D. Heberling, A. M. Martínez, and D. Sánchez, “Integrated planar multiband antennas for personal communication handsets,” *IEEE Transactions on Antennas and Propagation*, Vol. 54, No. 2, 384–391, February 2006.
 40. Kim, B., S. Park, Y. Yoon, J. Oh, K. Lee, and G. Koo, “Hexaband planar inverted- f antenna with novel feed structure for wireless terminals,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 66–69, 2007.
 41. Hsieh, H., Y. Lee, K. Tiong, and J. Sun, “Design of a multiband antenna for mobile handset operations,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 200–203, 2009.
 42. Li, Z. and Y. Rahmat-Samii, “Optimization of pifa-ifa combination in handset antenna designs,” *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 5, 1770–1778, May 2005.