Concentrated Ground Plane Booster Antenna Technology for Multiband Operation in Handset Devices

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Abstract. *The current demand in the handset antenna field requires multiband antennas due to the existence of multiple communication standards and the emergence of new ones. At the same time, antennas with reduced dimensions are strongly required in order to be easily integrated. In this sense, the paper proposes a compact radiating system that uses two non-resonant elements to properly excite the ground plane to solve the abovementioned shortcomings by minimizing the required Printed Circuit Board (PCB) area while ensuring a multiband performance. These non-resonant elements are called here ground plane boosters since they excite an efficient mode of the ground plane. The proposed radiating system comprises two ground plane boosters of small dimensions of 5 mm x 5 mm x 5 mm. One is in charge of the low frequency region (from 0.824 GHz to 0.960 GHz) and the other is in charge of the high frequency region (1.710 GHz–2.170 GHz). With the aim of achieving a compact configuration, the two boosters are placed close to each other in a corner of the ground plane of a handset device (concentrated architecture). Several experiments related to the coupling between boosters have been carried out in two different platforms (barphone and smartphone), and the best position and the required matching network are presented. The novel proposal achieves multiband performance at GSM850/900/1800/1900 and UMTS.*

Keywords

Handset antennas, multi-band, non-resonant antennas, ground plane modes.

1. Introduction

The current requirements in handset antenna design are related to multiband operation and miniaturization. A popular platform which is gaining popularity is the smartphone, which features bigger dimensions than conventional cellular barphones. However, the available space for the antenna is still limited due to the presence of large displays, batteries and related components (multiple cameras, hands-free speakers). The consequences of adding all these functionalities is a challenge for the antenna design because the antenna should have small dimensions in order to be easily integrated with such other elements of the device.

There are different ways of designing multiband and miniature antennas, which basically consist in shaping the geometry of different types of antennas like monopoles [1]–[5], PIFAs [6]–[9], and slots [10], or even adding parasitic elements to the radiating system [11], [12]. However, the antenna is not the only contributor to the radiation since the ground plane also plays a very important role in the overall radiating system [13]–[44].

As it was demonstrated in [14]–[20], the antenna bandwidth can be improved by achieving a ground plane length of approximately 0.4λ at the operating frequencies because the ground plane fundamental mode is efficiently excited. For example, in [17]–[25], slotted ground planes are used in order to achieve a longer electrical path in a shorter physical length with the aim of exciting the fundamental mode of the ground plane which is an efficient radiating mode.

Based on the same principle and knowing that the ground plane is the main contributor, there have been different studies which used the excitation of the ground plane as the principal means to obtain good radiation [29]–[45]. One way of achieving this excitation is through the use of coupling elements, which are strategically located in order to properly excite the ground plane and have a certain C-shape to obtain such coupling [35]–[42]. In [35], a monoband antenna system comprising a microstrip line and a coupling element of 2400 mm^3 was presented, and in [36], two coupling elements occupying a volume of 700 mm^3, a ground plane, and a matching circuitry were needed in order to obtain a quad-band radiating system. One element was required for the GSM850/900 bands and the other for the GSM 1800/1900 bands. Despite those couplers relied on a different principle than common handset antennas, they still featured a significant size similar to those (i.e. a size about the entire shortest edge of a mobile platform), therefore not providing a significant advantage compared to state-of-the-art antennas.

A different way of exciting the ground plane is by means of using very simple and small structures called ground plane boosters, as proposed in [29]–[32] without the need of using said aforementioned C-shaped structures. The ground plane boosters proposed here are solid metallic structures featuring a cube shape and connected with a feeding point to the ground plane. In [31], ground plane boosters have been used to properly excite the ground plane mode to obtain a multiband performance (GSM850/900/1800/1900, and UMTS) with a total volume of only 250 mm^3. In [32], planar booster elements (2D) were used to obtain LTE700, GSM850/900/1800/1900, UMTS, LTE2300/2500 and GPS with a total footprint of only 153 mm^2. These elements feature a non-resonant behavior with a very high quality factor (Q) compared to resonant antennas. Such a high Q explains the non-radiating nature of those elements. The name of ground plane booster was therefore proposed to describe such reactive, high-Q, non-radiating and non-resonating simple elements that are mainly used to excite the ground plane in order to obtain an efficient radiating structure [29]–[33], which can be obtained by exciting the first mode according to the characteristic modes theory [31], [44]. In particular, the modal significance has been computed for a ground plane having 100 mm × 40 mm (Fig. 1). When the modal significance is close to one, the mode is resonant and radiative mode whereas a mode having a modal significance close to zero means a reactive mode. For a ground plane having a 100 mm × 40 mm size, the main mode (J_1) dominates across the frequency region of 800 MHz to 2 GHz. Up to that point, J_1 and J_4 play an important role being still J_1 predominating up to 2.5 GHz. From current simulation shown in the following sections, it will be demonstrated that at the low frequency region the current distribution is mainly determined by J_1 and for the high frequency region is a linear combination of J_1 and J_4.

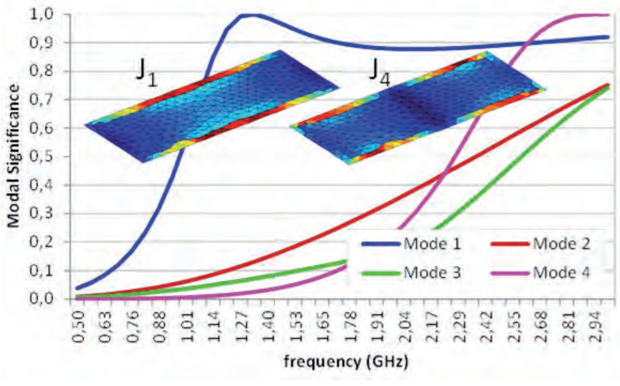


Fig. 1. Computed modal significance for the first eigen-modes for a ground plane of 100 mm × 40 mm. Current distribution associated to the first J_1 and fourth J_4 eigen vectors.

In the present study, such ground plane boosters have been used with the aim of achieving good radiation performance in several frequency bands in a novel configuration featuring a concentrated architecture [32]. In [31], a distributed configuration (Fig. 2a) was presented. Since the antenna engineer has a lot of constrains in terms of available area for the antenna, a further research has been carried out to obtain a different solution capable of reducing the required PCB area. In this case, a novel concentrated solution (Fig. 2-b) using two closely spaced ground plane boosters has been designed and analyzed. In principle, since both boosters are closely spaced, mutual coupling drastically degrades the performance compared to the distributed solution. Therefore, this paper analyzes different configurations and filter schemes capable of mitigating the mutual coupling while obtaining a multiband performance at the low and high frequency region in two different topologies of ground planes: a barphone and a smartphone. The latter has been included in order to establish the behavior of the proposed technology in one of the most popular devices of the current market demand.

The paper is divided as follows. Section 2 explains the behavior of the boosters that form the radiating system. Section 3 illustrates the measurements of the built prototype in order to validate the simulation results shown in the previous section. Finally, in Section 4, the conclusions are presented.

2. The Radiating System

The radiating structure of a first proposed design consists of a 100 mm × 40 mm ground plane, which is a typical size of a conventional barphone, and two metallic ground plane boosters of 5 mm × 5 mm × 5 mm located in one corner of the ground plane (Fig. 2-b). Owing to the reduced dimensions of the boosters and their close arrangement, the solution confines the multiband radiating solution of the mobile platform in an extremely concentrated configuration.

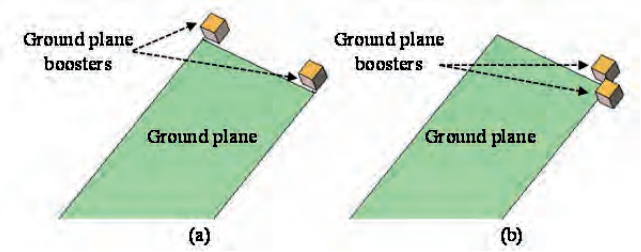


Fig. 2. (a) Two ground plane boosters distributed in each corner of the ground plane of a handset device; (b) concentrated configuration having both boosters close to each other (without being connected).

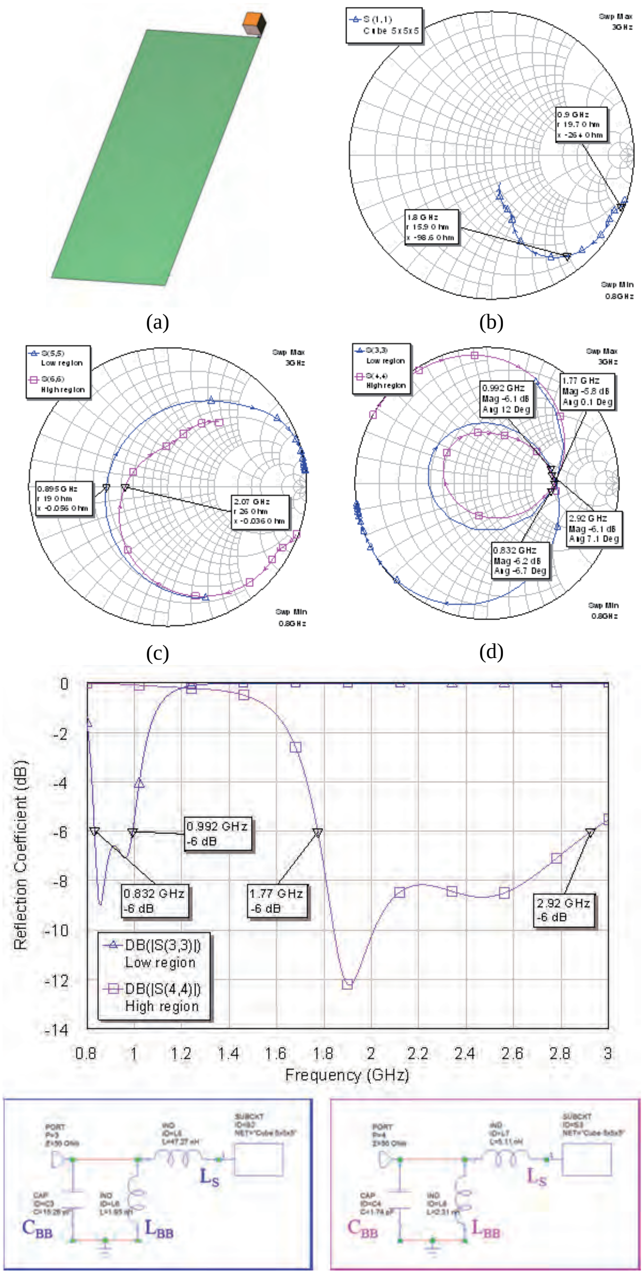
2.1 Functional Analysis

The position of the boosters and their separation is a critical factor that needs to be taken into account in the design process as it is explained next.

The radiating system needs to offer a multiband performance able to satisfy the current market demand. Thus, it should operate in the common cellular frequency bands, such as GSM850/900/1800/1900, and UMTS.

As discussed, the ground plane boosters are non-resonant and non-radiating elements, as they feature a high quality factor in each of the target frequency bands

(Q ≈ 2250 @0.9 GHz and Q ≈ 265 @1.8 GHz) [31]. However, their position helps the radiation modes in the ground plane to be efficiently excited and provide good radiation performance. Therefore, the radiating structure comprises the ground plane boosters and the ground plane. A matching network is then added to provide the impedance matching at the desired frequency bands.



(a) (b) (c) (d) (e)

Fig. 3. Matching procedure applied at both frequency regions. (a) 3D view of the radiating structure. (b) Impedance of the radiating structure without any matching network. The ground plane booster has a strong capacitive behavior at both frequency regions. (c) The radiating structure resonates at 0.9 GHz or 2.0 GHz depending on the value of the series inductor. (d, e) The ground plane booster can be matched at both frequency regions offering good bandwidth results by means of different broadband matching networks.

First of all, it is necessary to understand the behavior of each booster in each frequency region independently, that is, having only one ground plane booster (Fig. 3-a). These ground plane boosters are highly reactive elements with a strong capacitive behavior across the desired frequencies (Fig. 3-b). In order to make them resonant, a series inductor (L_S) is added which results in an input impedance as an RLC series circuit (Fig. 3-c). After that, a broadband matching network (L_{BB} and C_{BB}) [45], [46] is added to enhance the bandwidth. The objective of the broadband matching network (a shunt LC circuit) is to create an input impedance loop that can be inscribed within the SWR = 3 circle of the Smith chart. With the proposed matching network, the bandwidth can be enhanced by a factor of 2.45 (SWR = 3), which is significant taking into account that only two components are used [47].

In the case of the booster for the low frequency region, good bandwidth results are obtained with a series inductor (L_S) of 47.3 nH, and a broadband matching network comprising a 1.9 nH inductor (L_{BB}) and a 15.3 pF capacitor (C_{BB}) (Fig. 3-d, e). For the booster in charge of the high frequency region, a similar matching network topology is applied, consisting of a series inductor of 5.1 nH (L_S) and a broadband matching network composed of a 2.3 nH inductor (L_{BB}) and a 1.7 pF capacitor (C_{BB}) (Fig. 3-d, e).

It has been found that the optimum position is in the shortest edge of the ground plane [31] because it is the place where the ground plane mode is efficiently excited.

With the objective to simultaneously cover the desired frequency bands, a modular radiating system is preferred. This means that two ground plane boosters are needed to match each one at one frequency region as in Fig. 2-b.

Each booster behaves correctly when it is alone and in the optimum position (Fig. 3). However, since a concentrated and multiband radiating system is needed, both boosters need to be working simultaneously and occupy the minimum possible area. Therefore, the first approach is to place them close to each other in the same edge (Fig. 4). Note that the advantage of the concentrated configuration having both boosters close together (compared to other configurations [27]) relies on the fact that the connection to a multiband front-end module is simplified since the feeding lines for each booster may be short. As it can be observed after simulating the radiating system using the electric scheme of Fig. 3-e, the required performance is not achieved (Fig. 4). In the low frequency region, the S_{11} is above -6 dB and the S_{21} presents unsatisfactory values (-0.28 dB), which means that this particular configuration as it is becomes completely useless for a modern multiband phone. In order to guarantee the same behavior as the one shown in Fig. 3, both boosters should have low S_{21} values ($S_{21} < -20$ dB) in both frequency regions and therefore, be less coupled. In this sense, and as presented in the following section, the purpose of this paper relies on providing a proper isolation in order to guarantee the performance of this novel concentrated solution.

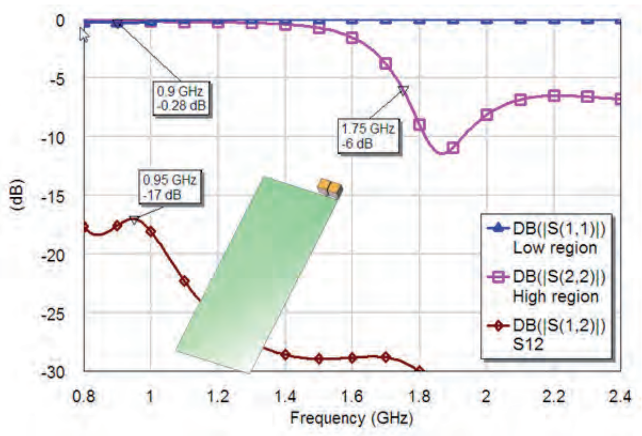


Fig. 4. Impedance response of the radiating system comprising two boosters close to each other. They use the same matching network as the one shown in Fig. 3. Multiband performance is not achieved in the low frequency region due to the strong mutual coupling.

2.2 Coupling Analysis

Commonly, the coupling of a determined circuit is directly measured by the S_{21} parameter. However, in this case, it would not be fair to rely on it because the boosters are non-resonant elements presenting very high impedance at the frequencies of interest and therefore they are totally mismatched when no matching network is used. Since they are not matched, they do not interfere to each other and therefore, the S_{21} is very low and therefore is not realistic [48]. For this reason, the maximum available gain (MAG) is calculated [49]. Maximum available gain takes into account conjugate matching at both ports.

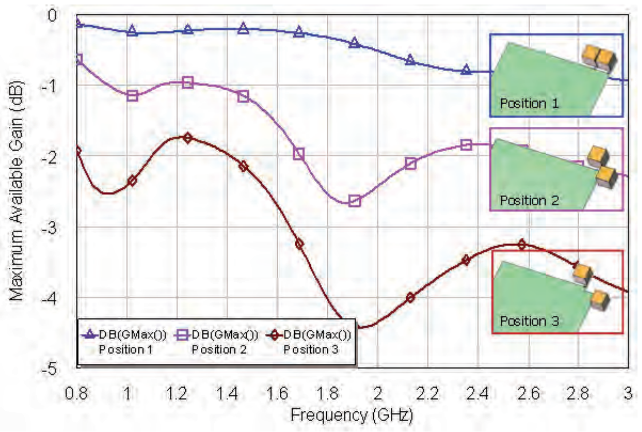


Fig. 5. Maximum available gain values obtained for the three experiments gathering different ground plane boosters' arrangements. The coupling decreases (the maximum available gain decreases) from position 1 (the worst) to position 3 (the best).

Without losing the objective of achieving a concentrated configuration, three different positions have been analyzed in terms of MAG. The first one (position 1) has both boosters next to each other in the same axis separated by 1.5 mm (Fig. 5). On the contrary, the second and third positions (position 2 and 3) feature a different configuration because both boosters minimize the area of close contact as they are orthogonal to each other. In the second position, each booster is aligned with one of the edges of the ground plane (Fig. 5), and in the third position, they follow the same configuration but one of the boosters is located 5 mm away from the ground plane's corner (Fig. 5).

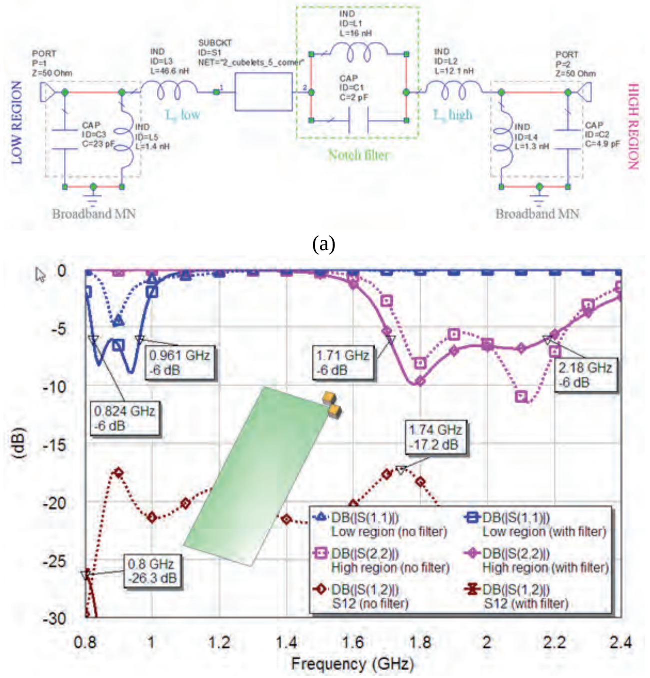
The best position is 'position 3' because it is the one where the radiating structure presents the lowest MAG between boosters, that is, less coupling. However, the configuration is not as concentrated as the other ones. On the contrary, 'position 1' presents the highest (worst) MAG values because the area of contact between boosters is larger. Hence, the chosen position is 'position 2' because it presents the best trade-off between compactness and coupling. This position shows lower MAG values compared to 'position 1' because the area of contact between boosters is lower.

2.3 Multiband Performance

Once the location for both boosters is chosen, it is important to establish the matching network needed for each frequency region (Fig. 6-a). As it has been explained in Section 2, each booster needs a series inductor in order to make it resonant at a given frequency within the band of operation, and a broadband matching network to achieve good bandwidth.

The booster located in the upper part of the shortest edge of the ground plane (Fig. 6-b) is responsible for the low frequency region, and the booster located next to the left side of the longer edge (Fig. 6-b) is in charge of the high frequency region. The radiating system has two input ports, one for each frequency region. This may be useful for front-end modules having separate entries for each frequency region/band as some used in some cellular phones. If needed, both ports can be merged into one by means of combining filters [31].

Based on the study of the MAG, 'position 2' reduces coupling compared to 'position 1'. However, they still do not behave as if they were alone and some kind of filtering to reduce coupling is needed. For the series inductor (L_{Slow}) corresponding to the low frequency region acts as high impedance at the high frequency region (its value of the order of 40 nH is a high impedance at the high frequency region), no filters are required to obtain better isolation at the high frequency region. However, the series inductor (L_{Shigh}) corresponding to the high frequency region is low (of the order of 12 nH) and it does not present high impedance in the low frequency region (12 nH is not a high impedance at the low frequency region). That is why a notch filter is needed in this case to achieve a good isolation at the low frequency region. In this sense and thanks to the lower coupling values between boosters obtained due to their relative location, only a simple notch filter (one stage) is added.



(a)

(b)

Fig. 6. (a) The matching network consists of 8 lumped elements. (b) Thanks to the notch filter (high impedance at frequencies around 0.9 GHz) and the broadband matching networks, multiband operation and good isolation between boosters is obtained. When no filter is used (dashed lines), coupling increases and operation in the low frequency region is lost.

After optimizing the components' values of the matching network, the multiband performance is achieved with occupying only 250 mm^3 (Fig. 6-a). Simulation results show that the radiating system is matched (SWR $\leq$ 3) from 0.824 GHz to 0.961 GHz (GSM850 and GSM900 as well as some LTE standard within this range such as LTE900) and from 1.71 GHz to 2.18 GHz (GSM1800, GSM1900, UMTS, as well as some LTE standards within this range such as LTE1800, 1900, 2100) (Fig. 6-b). S_{21} is below -26 dB along the desired frequency bands (Fig. 6-b).

It is important to remark that without the filter it is not possible to keep the desired multiband behavior, especially in the low frequency region due to the mutual coupling (Fig. 6). Thanks to the notch filter, coupling decreases 10 dB with respect the solution without the notch filter and better performance from 0.824 GHz to 0.960 GHz is achieved.

Although the notch filter plays an important role in the performance of the radiating system, the position is also a key factor in terms of coupling. When both boosters are in 'position 1', despite having the notch filter, the multiband response gets worsen and out of the required specs, especially in the low frequency region, where GSM900 is lost (Fig. 7). Therefore, both the position and the filter play an important role in determining the multiband performance with highly isolated ports.

Since the smartphone platform is gaining interest, a new experiment considering a ground plane of 120 mm × 50 mm, which is a typical size of said platform, has been carried out. Using the same ground plane booster architecture and the same matching network, the performance of the new radiating system has been also simulated (Fig. 8). As it is observed in Fig. 8, the impedance performance of the concentrated ground booster antenna technology in the new platform is not altered in the low frequency region and even enhanced in the high frequency region, which means that the proposed architecture is a standard solution for both types of platforms.

Current distributions on the ground plane (Fig. 9) also show that the predominant mode (first mode) of the radiating structure at 0.9 GHz presents a current distribution similar to that produced by a half-wavelength dipole, that is, null at the short edges of the ground plane and maximum at the center on the long edge. At 1.8 GHz, although the current distribution slightly differs from the one obtained in the low frequency region, the first mode J_1 is still predominant (main current follows the y-direction) and also the J_4 mode appears.

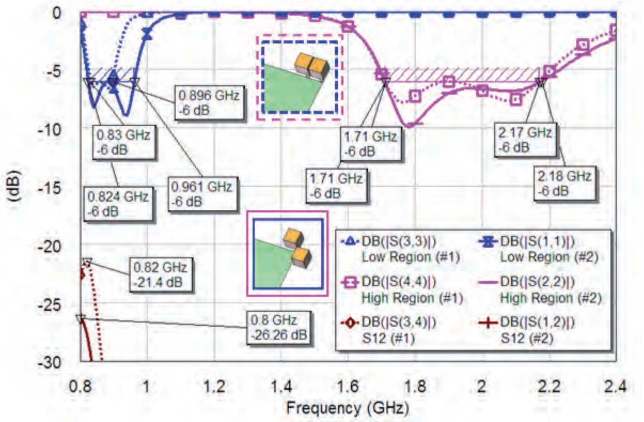


Fig. 7. The radiating system with the optimized matching network that uses a notch filter has less bandwidth in the low frequency region when boosters are in 'position 1' compared to the proposed 'position 2'.

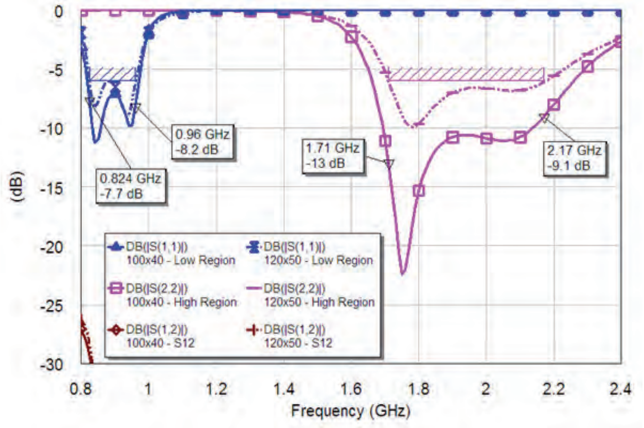


Fig. 8. The multiband behavior is perfectly achieved using a smartphone platform of 120 mm × 50 mm. Impedance matching is enhanced in the case of the largest ground plane, especially in the high frequency region. Both platforms offer good isolation at both frequency regions (> 26 dB).

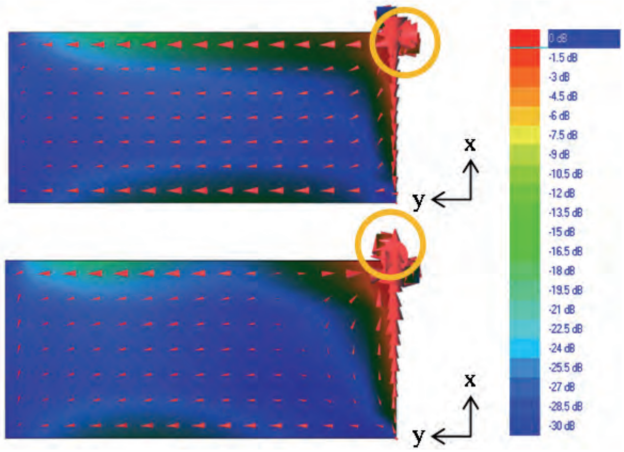


Fig. 9. Current distribution of the radiating system (also taking into account the matching network) at 0.9 GHz (top) and 1.8 GHz (bottom) (current max: 4 A/m). The circle indicates the booster with stronger excitation.

It is also useful to see the current distribution in both frequency regions to show that both boosters work closely to each other without being interfered (Fig. 9). At 0.9 GHz, the main player of the radiation is the booster aligned with the longest edge of the ground plane (Fig. 9, top) because it is more excited. Since the other booster has density current values below -20 dB, good isolation is demonstrated. At 1.8 GHz, the same phenomenon is observed (Fig. 9, bottom) although now, the main player is the booster aligned with the shortest edge of the ground plane.

3. Measurements

With the purpose of validating the simulation results, two prototypes made of FR4 with solid metallic boosters has been built and measured. Each ground plane booster of 5 mm × 5 mm × 5 mm is located (orthogonal disposal) in one side of a corner of the 100 mm × 40 mm and 120 mm × 50 mm ground plane respectively featuring the concentrated solution (Fig. 10).

The radiating system has been matched following the teachings of the simulation results. The final matching network of the built prototype consists of 9 lumped elements from Murata (high Q tight tolerance). For the low frequency region, a series inductor ($L_{Slow} = 36$ nH) and a broadband matching network ($L_{BB} = 2.2$ nH and $C_{BB} = 15$ pF) are needed. For the high frequency region, a notch filter ($L_N = 18$ nH and $C_N = 1.8$ pF), a series inductor ($L_{Shigh} = 8.7$ nH), and a broadband matching network ($L_{BB} = 1.3$ nH, $C_{BB} = 5.1$ pF) with some fine-tuning components ($C_S = 7$ pF, $C_P = 1.5$ pF) are used.

The measured reflection coefficient (Fig. 11) in both prototypes is below -6 dB from 0.819 GHz to 0.969 GHz, and from 1.71 GHz to 2.2 GHz, which means that the radiating system may be operative in many frequency bands such as GSM850, GSM900, GSM1800, GSM1900, and UMTS. S_{21} is below -21 dB among the low and high frequency regions in both prototypes, ensuring a good isolation between ports, which agrees with the simulation.

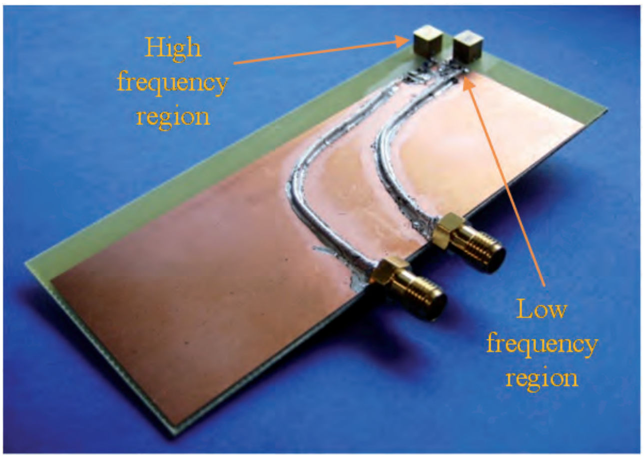


Fig. 10. Built prototype. Ground plane is 100 mm × 40 mm printed over a 1 mm thick FR4 substrate. Ground plane boosters are 5 mm × 5 mm × 5 mm. The same scheme is used for the ground plane of 120 mm × 50 mm representative of the smartphone.

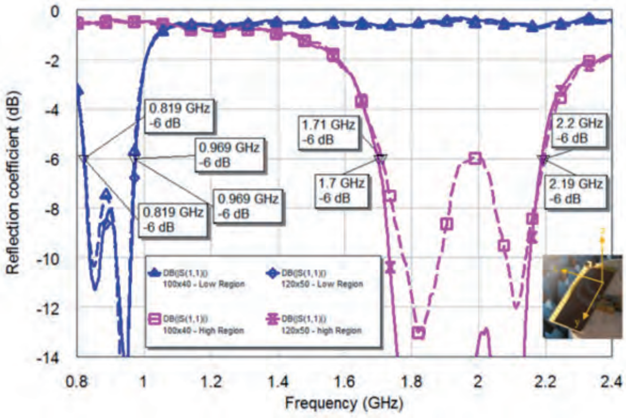


Fig. 11. The radiating system is matched from 0.824 GHz to 0.960 GHz and from 1.71 GHz to 2.17 GHz in both platforms.

The efficiency has been measured using 3D pattern integration using the anechoic chamber Satimo Stargate 32. Regarding the radiation efficiency values (η_r) of the 100 mm × 40 mm prototype (Fig. 12 and Fig. 13), acceptable results have been obtained among the low and high frequency region, offering average values of 49 % and 64 %, respectively. The total antenna efficiency (η_a) (Fig. 12 and Fig. 13 which also takes into account the mismatch losses ($\eta_a = \eta_r \cdot (1 - |S_{11}|^2)$), reaches a peak of 55 % in the low frequency region and 63 % in the high frequency region, which is a high value considering the small volume of the booster element.

Regarding the smartphone prototype, the efficiency results (Fig. 12 and Fig. 13) are considerably better than in the previous prototype of 100 mm × 40 mm because the ground plane fundamental mode is better excited due to its larger size (more close to 0.4λ at the operating frequencies [14], [46]). Based on the characteristic mode analysis in [46], the smartphone platform presents better modal significance values (closer to 1) in the low frequency region than the barphone platform. This results in a better efficiency of the smartphone case. In this case, the impedance matching is similar but the radiation efficiency is much higher because the whole radiating system radiates more efficiently. Therefore, the smartphone provides an average total antenna efficiency of 51 % in the low frequency region and a 70 % in the high frequency region.

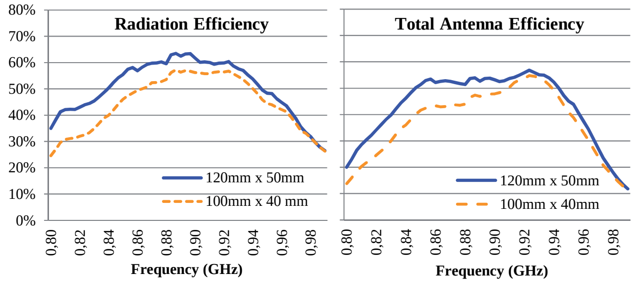


Fig. 12. Measured efficiency values in the low frequency region of both prototypes. Highlighted area indicates the frequencies range of 0.824 GHz–0.960 GHz.

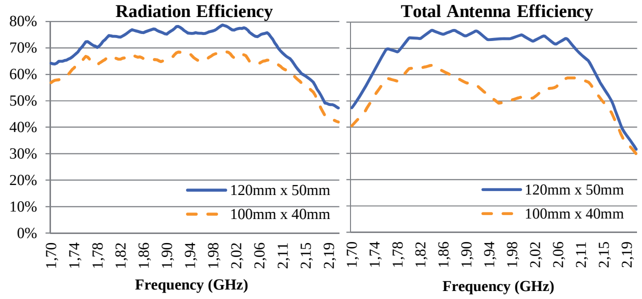


Fig. 13. Measured efficiency values in the high frequency region of both prototypes. Highlighted area indicates the frequency range of 1.71 GHz–2.17 GHz.

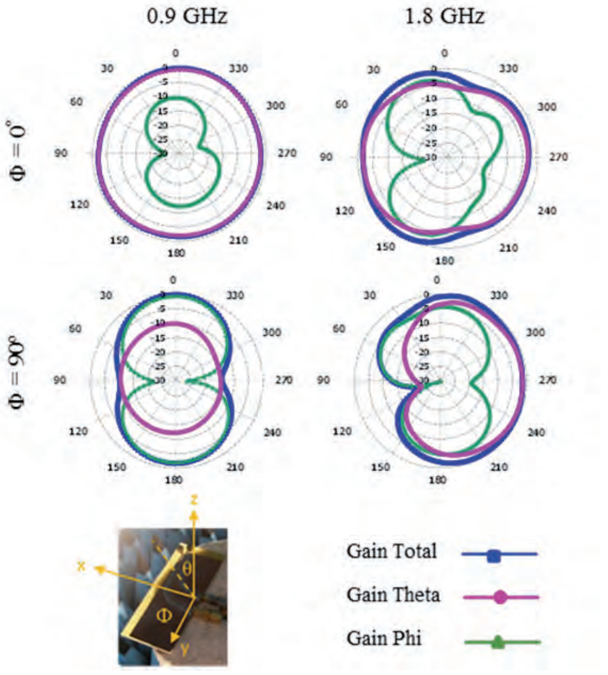


Fig. 14. Measured radiation patterns at 0.9 GHz and 1.8 GHz. The radiation patterns of the 120 mm × 50 mm ground plane feature a similar shape but they have not been included for the sake of brevity.

Finally, radiation patterns have also been measured in the same anechoic chamber. The main cuts normalized to the maximum gain (φ = 0º and φ = 90º) are shown at 0.9 GHz and 1.8 GHz. Both prototypes present an omnidirectional behavior in φ = 0º and a deep in the y-axis at both frequency regions (Fig. 14) which is the typical dipole type pattern for this kind of handset platforms. Although a slightly different shape is observed in 1.8 GHz, the radiation pattern is still omnidirectional and no directional lobes are observed.

It is remarkable the small size of only 250 mm^3, which is much smaller than other existing antennas providing also operability at 5 frequency bands, such as typical PIFA antennas with an average volume of 6600 mm^3 and monopole antennas with an average volume of 2200 mm^3 [47]. This makes this solution interesting for the new generation of wireless handheld devices including smartphones.

4. Conclusions

A new radiating system based on ground plane booster technology has been presented. Basically, this technology uses simple elements called ground plane boosters for exciting the efficient radiation mode of the ground plane, which presents high radiation efficiency at the frequencies of interest.

Although each ground plane booster can satisfactory operate in one frequency region, when they work close to each other with the purpose of obtaining a concentrated and a multiband radiating system, coupling between them increases and its operability becomes severely degraded. In order to overcome such a limitation, a new architecture where boosters are orthogonally disposed in a corner of the PCB has been proposed. This new solution satisfies the two main requirements: low coupling between boosters and compactness.

While the orthogonal arrangement of the boosters with respect to the ground plane improves the coupling, it is still not sufficient to guarantee operation since the input impedance and isolation levels are still out of bounds. In this sense, the proposed radiating system for the 100 mm × 40 mm platform further includes a matching network with a notch filter. Such a notch filter, when combined with the specific arrangement of boosters and the ground plane, results in a significant improvement of the overall performance, particularly in the low frequency region.

The present research has also been focused on analyzing how this technology behaves in a smartphone platform and it has been concluded that there is no need to change the radiofrequency system because the new platform does not affect the impedance response, while at the same time the efficiency becomes significantly improved. That is, the proposed architecture performs robustly across different platforms, which suggest the potential advantage of a standardized solution. This would in turn become a very significant advantage as mobile devices currently require a customized platform and a specific antenna system. The measured results demonstrate that good matching and satisfactory efficiency values can be obtained at least from 0.824 GHz to 0.96 GHz and from 1.71 GHz to 2.17 GHz, which means that the proposed radiating system can operate in many frequency bands such as GSM850, GSM900, GSM1800, GSM1900, and UMTS, as well as in many LTE standards within the above frequency range. Furthermore, the volume is only 250 mm^3 compared to the average of 6600 mm^3 of PIFA and 2200 mm^3 of monopoles used in many commercial phones.

Based on the obtained results, it is concluded that the proposed technique is a useful and promising antenna solution offering a concentrated configuration, operating in multiple frequency bands, and only requiring a small volume (250 mm^3) of the handset device.

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