Planar Wideband Antenna Designs for Wireless Applications in Portable Devices

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Abstract

This paper summarizes the research that has been developed by the authors for the last six years, concerning the design of planar wideband antennas for portable devices. Basic structures combining electric and magnetic elements are proposed, which lead to antennas with large bandwidth. Thus, by using these basic structures, a polarization diversity antenna, a wideband antenna for DVB-H applications and a wideband MIMO antenna have been proposed for wireless applications in mobile terminals. Prototypes of all the antennas have been fabricated and measured at iTEAM and/or CWC facilities.

Keywords: Wideband antenna, complementary antenna, diversity antenna, MIMO antenna, mobile terminals.

1. Introduction

Nowadays there are increased demands for multiple radio interfaces in wireless devices to cover different communication services such as LTE (Long-Term Evolution), UMTS and GSM mobile standards, DVB-H, Radio Frequency Identification (RFID), Bluetooth, Near-Field Communications (NFC), WLAN, and mobile WiMAX.

Moreover, the trend in wireless communications is to increase the number of operating frequency bands when, at the same time, data transmission rate and spectral efficiency must be improved. Multiple antennas can be used to cover multiple frequency bands as well as to provide higher data rate and spectral efficiency. However, the space available for realizing multiple antennas is limited.. Thus, implementing multiple antennas into a small multi-standard device becomes a challenge. One way to address this problem is to reduce the number of antenna elements by covering multiple radio interfaces over a wide frequency range through the use of frequency tunable [1]-[3], multi-band [4]-[6], or wideband antennas [7]-[9].

This paper presents some proposals of wideband antennas that consist of the combination of a magnetic notch with different shapes and an electric dipole or monopole as excitation elements. These antennas can be used as the basis for more complex structures in multistandard mobile terminals.

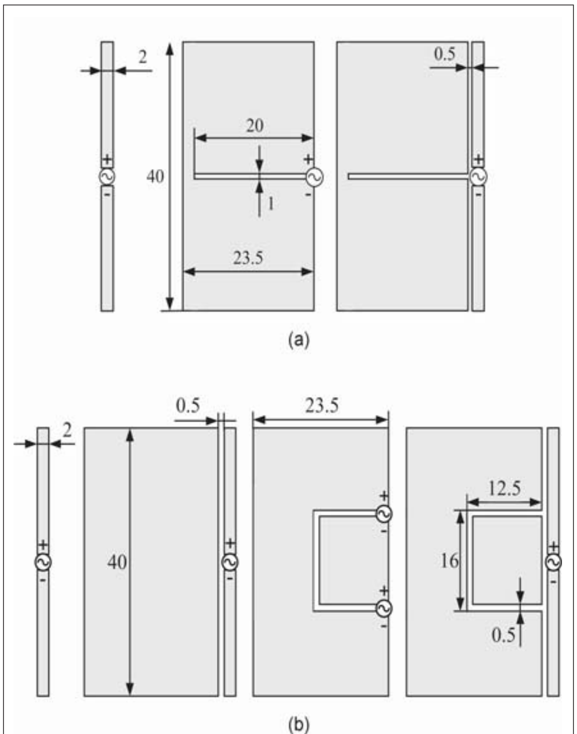
In Section 2, the basic antennas combining a magnetic notch and an electric dipole/monopole are presented. Different notch shapes are proposed and the resulting structures are studied in terms of simulated and/or measured antenna parameters such as input impedance and scattering parameters, to show their wideband behaviour. Then, these antennas are used as the basis for more complex structures in mobile terminals. In Section 3, a wideband antenna with polarization diversity is proposed for mobile terminals to cover UMTS (2.1 GHz), Bluetooth (2.4 GHz), WLAN (2.45 GHz), LTE (1.8–3.8 GHz), and WiMAX (2.3–3.6 GHz) standards. In Section 4, a double-band antenna is proposed to cover DVB-H and LTE standards, and in Section 5 a wideband antenna for Multiple-Input Multiple-Output (MIMO) applications is designed. Finally, Section 6 presents the conclusions of the paper.

Implementing multiple antennas into a small multi-standard device becomes a challenge. One way to address this problem is to reduce the number of antenna elements by covering multiple radio interfaces over a wide frequency range through the use of wideband antennas.

2. Basic wideband radiating structures based on the combination of electric and magnetic elements

This section presents different proposals of wideband antennas based on the combination of an electric dipole and a magnetic slot in a conducting ground plane [10]. Two different slot structures are presented: A notch [11] and a square-shaped slot [12], whose geometries are shown in Fig. 1 (figures at the right ends). A wideband antenna is then obtained by means of creating a sort of magnetic boundary condition [13] with the combination of the dipole and the slot. In order to establish this condition, the electric dipole is used as an excitation element and is closely spaced (0.5 mm) to the conducting ground plane, which includes a magnetic slot.

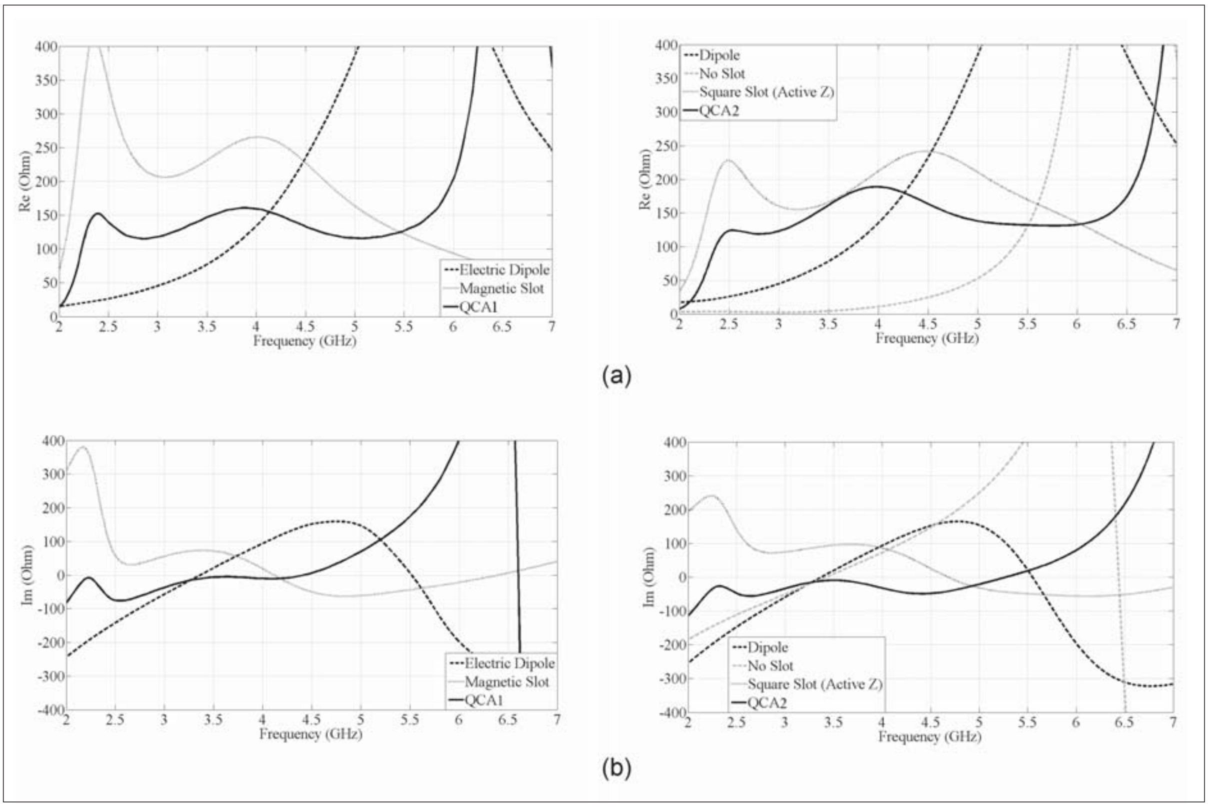
Fig. 1 (a) shows three different antenna structures that will be compared in terms of the input impedance (real and imaginary parts separately) and reflection coefficient. Analysis of the structures will be made using commercial CST Microwave Studio electromagnetic simulation tool [14]. The compared antennas are a simple electric dipole (left), a magnetic slot cut into an electric conductor (middle) and a combination of both (right), which results in the proposed wideband structure. This structure behaves similar as a complementary antenna, so it will be referred as Quasi-Complementary Antenna 1 (QCA1). Additionally, Fig. 1 (b) presents an electric dipole with a magnetic square-shaped slot cut into a conducting ground plane. The antenna is considered to be an improved structure of that presented in Fig. 1(a) and it will be referred as Quasi-Complementary Antenna 2 (QCA2). The distance of the electric dipole from the conducting ground plane is 0.5 mm, as in the notch case. This structure is compared in the same terms as the notch structure: to a dipole, to a dipole closely spaced to an electric conductor, and to a symmetrically excited square slot. Symmetrical excitation means that both sources have the same amplitude and phase.



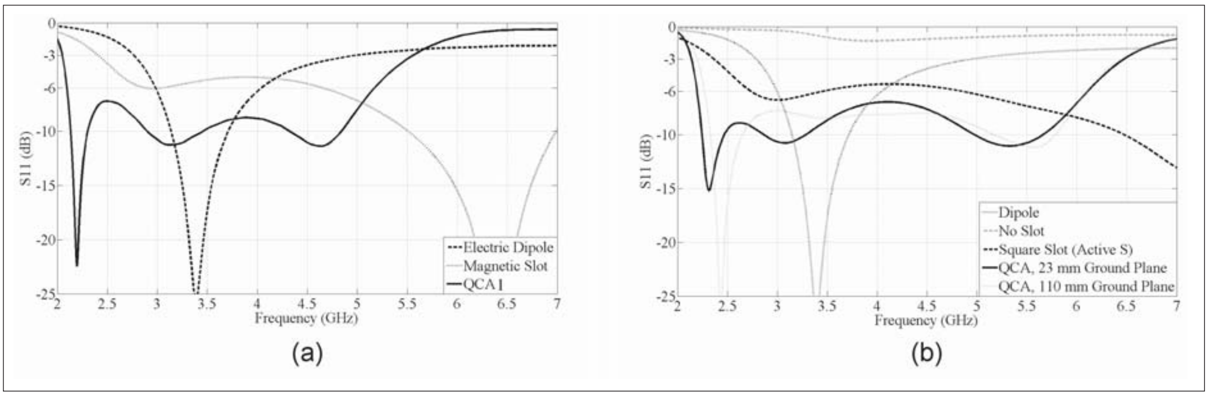
■ **Figure 1.** Basic wideband radiating structures with (a) a notch (QCA1) and (b) a square-shaped slot (QCA2). Antenna structures to be compared with the basic structures are presented in the same figure.

In Fig. 2, the antennas are compared in terms of the real and imaginary parts of the input impedance. Notice that Active Z is determined here as (Z_{11}+Z_{12}), being Z_{11} and Z_{12} the self and mutual port impedance, respectively. Active Z parameter represents a symmetrical excitation (with same amplitude and phase) of both sources in the square slot shown in Fig. 1 (b). As it can be observed in the imaginary part plot in Fig. 2 (b), the complementary behavior of the electric dipole and the magnetic slot compensates each other, in terms of capacitive (magnetic slot) and inductive behavior (electric dipole), over a wide frequency range. This is the main reason for the wideband characteristics of the antennas. At the same time, the average value of the real part of the antenna impedance with the notch in Fig. 2 (a) is approximately 125 Ω, in contrast to the magnetic slot with 250 Ω. Similarly, for the structure with the square-shaped slot, the same values are approximately 150 Ω and 200 Ω.

Fig. 3 represents the reflection coefficient of the antenna structures shown in Fig. 1. For comparison, the input impedance of a resonant dipole (75 Ω approximately) is chosen as the reference impedance for all the analyzed structures. As observed, the -6 dB impedance bandwidth of the antenna with the notch (Fig 3(a)) is from 2.1 to 5.2 GHz, which represents a 85% relative bandwidth. For the antenna with the square-shaped notch (Fig. 3(b)), the -6 dB impedance bandwidth is from 2.2 GHz to 6.1 GHz, corresponding to a 94% relative bandwidth, whereas the -6 dB relative impedance bandwidth of the isolated dipole is limited to 28.5%. The symmetrically excited square slot is presented as the Active S-parameter (S_{11}+S_{12}) and since as can be seen, it operates at a higher frequency band. As observed, the dipole close to the electric conductor without a slot (Fig. 3(b)) is unmatched over the whole bandwidth.



■ **Figure 2.** Simulated (a) real part and (b) imaginary part of the input impedance of the antenna structures presented in Fig. 1 (a) (left) and Fig. 1(b) (right).

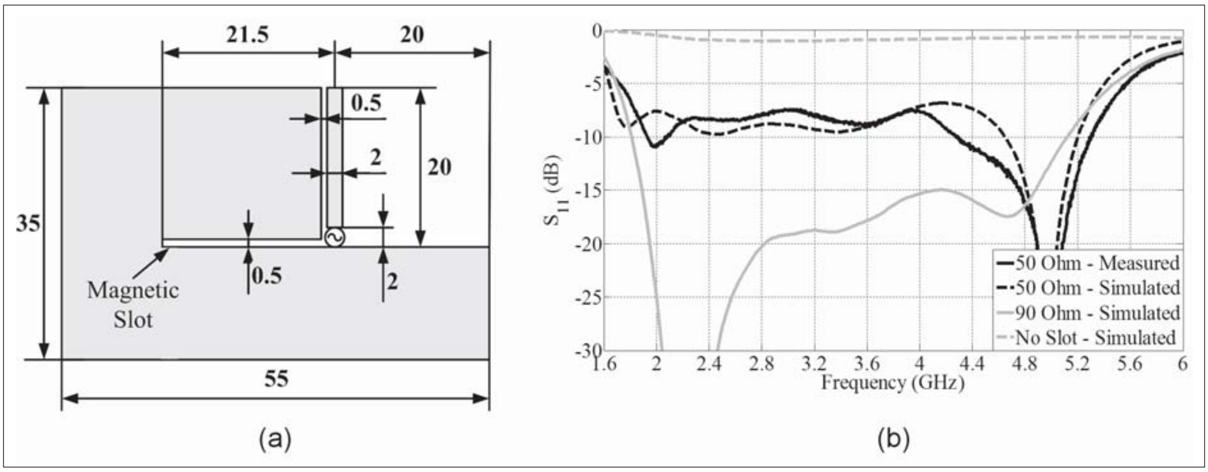


■ **Figure 3.** Simulated reflection coefficient of the antenna structures presented in Fig. 1: (a) QCA1 and (b) QCA2.

For mobile terminals, a typical reference value of -6 dB in reflection coefficient is considered for impedance bandwidth [8]. The effect of the length of a mobile ground plane in the square-shaped notch structure is compared by simulations in Fig. 3. A typical length of 110 mm is compared to a 23 mm length ground plane. It is interesting to notice how the length of the conducting ground plane does not significantly affect the -6 dB impedance bandwidth of the antenna. This is due to the fact that the radiating currents in the ground plane are concentrated around or close to the slot [12].

Recently [15], a new proposal for a basic wideband radiating structure combining electric and magnetic structures has been made, which consists of simplifying the antenna structure by means of changing the excitation element to a monopole, as shown in Fig. 4(a). The usage of a balun becomes then unnecessary and the structure becomes simpler.

Fig. 4 (b) presents the measured and simulated reflection coefficient for the antenna. As it can be shown, the measured -6 dB impedance bandwidth is from 1.78 GHz to 5.5 GHz for 50 reference impedance, corresponding to a 103% relative bandwidth. Therefore the relative -6 dB impedance bandwidth has been increased from 95% using dipole excitation [12] to 103%. The radiation patterns present an omnidirectional behavior over the whole operating frequency range [15], as is a desired feature for wireless applications.



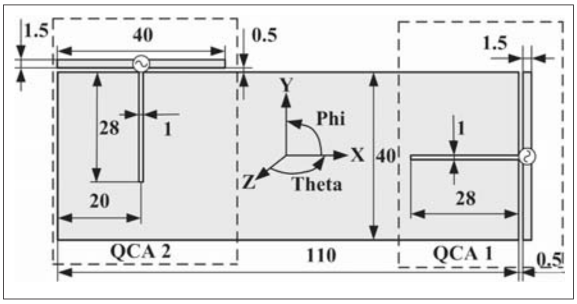
■ **Figure 4.** (a) Novel basic antenna combining an electric monopole and a magnetic notch. Dimensions in mm.(b) Measured and simulated reflection coefficient and comparison to the cases with 90 reference input impedance and without magnetic slot.

3. Polarization diversity antenna for mobile terminals

This section proposes the use of the basic wideband antenna based in the combination of an electric dipole and a magnetic notch proposed in section 2 and shown in Fig. 1 (a), to design a novel wideband planar antenna with polarization diversity for mobile terminals [10][11].

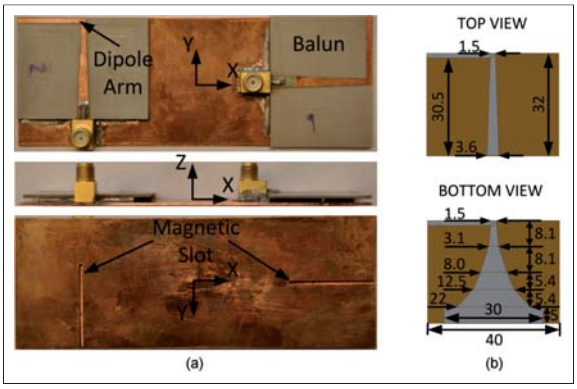
3.1. Antenna geometry

The antenna consists of two orthogonally oriented basic radiating elements combining a dipole and a notch, that will be referred again as Quasi-Complementary Antenna 1 and 2 (QCA 1 and QCA2). As observed, they are located at the separate ends of a mobile ground plane. The geometry of the antenna structure together with its dimensions is presented in Fig. 5. Thickness of the ground plane is 0.8 mm to make the structure more robust.



■ **Figure 5.** Polarization diversity antenna with two orthogonal quasi-complementary antennas. Dimension are in mm.

A prototype of the proposed antenna structure was fabricated [Fig. 6(a)] together with a wideband tapered microstripline balun [Fig. 6(b)] to excite the antennas. The feeding of the prototype antenna has been optimized by simulations taking into account the relative dielectric constant of the substrate (ε_r=2.2) used in the balun and the dipole. In addition, the slot length has been optimized to match the increased electric length of the dipole (compare to Fig. 1) affected by the substrate and the thickness of the ground plane.

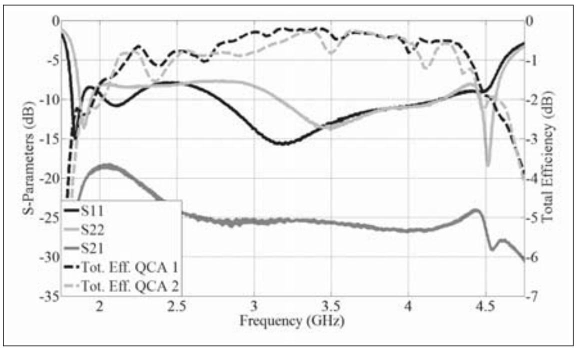


■ **Figure 6.** (a) Polarization diversity antenna prototype (top view, side view and bottom view); (b) Balun topology.

3.2. Results

In Fig. 7, the measured S-parameters and total efficiency are presented. As observed, both antennas have approximately a -6 dB impedance bandwidth that ranges from 1.8 to 4.6 GHz, corresponding to a 87.5% relative bandwidth. At the same time, the measured coupling coefficient (S_{21}) at the operating bandwidth is less than -18 dB.

When comparing the measured S_{11} to the simulated one in Fig. 3(a), it can be noticed that the size of the mobile ground plane does not have significant effect on the relative bandwidth of the antenna structure. The matching of the QCA 2 can be observed to be slightly different to that of QCA 1 due to the effect of the different orientation of the antenna within the ground plane. The shift in the center frequency, compared to the simulated results in Fig. 3(a), is caused by the increased electric length of the dipole and the slot.



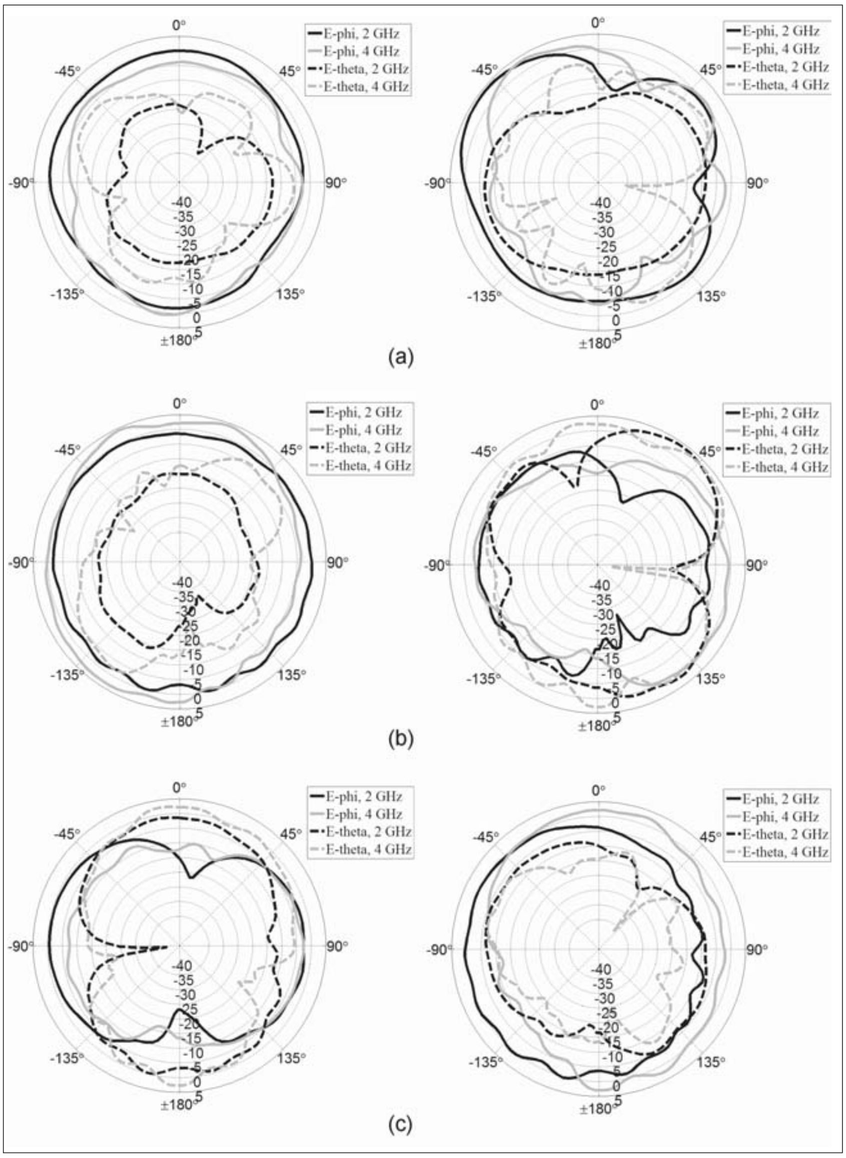
■ **Figure 7.** Measured S-parameters and total efficiency of QCA 1 and QCA 2 shown in Fig. 5.

Furthermore, the measured total efficiency shown in Fig. 7 for both antennas is between -0.3 and -3.5 dB (average -0.95 dB) within the studied -6 dB impedance bandwidth. The total efficiency is measured by terminating the passive antenna element with a standard 50 Ω-load. The measurements are done with the commercial Satimo Starlab antenna measurement system at University of Oulu [16].

A basic wideband antenna based in the combination of an electric dipole and a magnetic notch proposed in section 2 is used to design a novel wideband planar antenna with polarization diversity for mobile terminals.

Measured radiation patterns of the antenna prototype are presented at 2 and 4 GHz in Fig. 8. The method to measure radiation patterns is the same as that used for the total efficiency. The maximum radiated field, depending on the cut, the frequency, and the measured antenna, is between 0.1 and 4.5 dB. It can be noticed that the amplitude of the radiated fields varies between the cuts at the two measured frequencies.

Fig. 9 shows the envelope correlation between QCA 1 and QCA 2 calculated from measured S-parameters by using (1) [17]. The formula assumes that the radio channel is uniformly distributed.



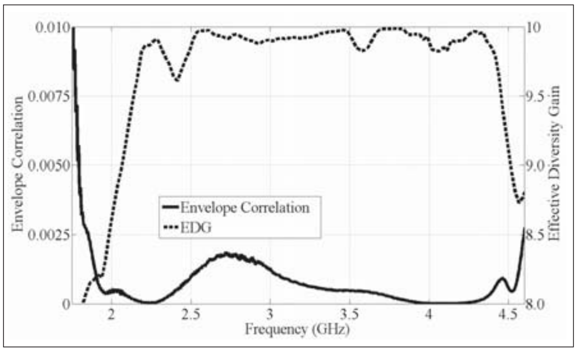
■ **Figure 8.** Radiation patterns (in dB) for Phi and Theta components at 2 GHz and 4 GHz in (a) XY-cut, (b) XZ-cut, and (c) YZ-cut. The legend of the lines is as follows: (——) E-phi at 2 GHz, (——) E-phi at 4 GHz, (- - -) E-theta at 2 GHz, and (- - -) E-theta at 4 GHz.

$$\rho_e = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^2}{(1-(\left|S_{11}\right|^2+\left|S_{21}\right|^2))(1-(\left|S_{22}\right|^2\left|S_{12}\right|^2))} \quad (1)$$

As it can be observed in Fig. 9, the envelope correlation is less than 0.01 over the studied -6 dB impedance bandwidth. This small correlation was expected because of the orthogonal antenna orientations. In the same figure, the effective diversity gain (EDG) is presented based on (2). The diversity gain is calculated by using a selection combining criteria with maximum apparent diversity gain at 1% outage rate [17]. In the calculations, the relation between the complex cross-correlation coefficient and envelope correlation coefficient ρ_e is $|\rho|^2 \approx \rho_e$ [18]. Finally, the EDG is calculated by multiplying the diversity gain with the radiation efficiency (e_{rad}) of the most efficient QCA element.

$$\mathrm{EDG} = e_{rad} \cdot 10\sqrt{1-|\rho|^2} \quad (2)$$

It can be notice the EDG is more than 8.0 dB over the -6 dB bandwidth. This is expected because of the small envelope correlation and high radiation efficiency.



■ **Figure 9.** Measured envelope correlation and effective diversity gain.

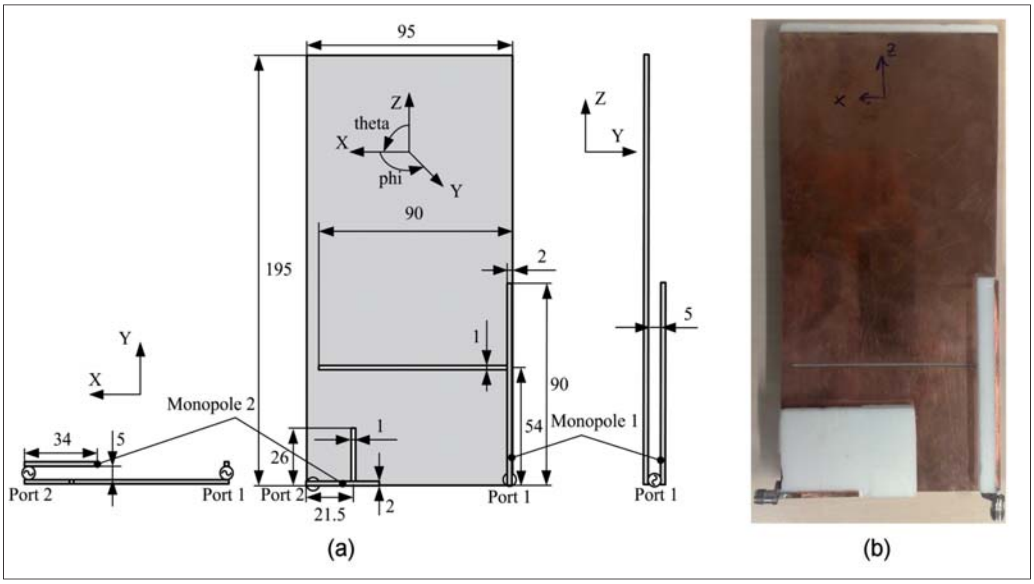
4. Dual-band antenna for DVB-H and LTE applications in portable devices

In this section, a radiating structure based on the QCA presented in Fig. 1(a) is used to design a dual-band antenna for portable devices. In this case, the basic radiating structure consists of the combination of a radiating monopole and a notch in a planar ground plane. By using two monopoles with different lengths, two different operating frequency bands are created in a portable device by exciting different current distributions in the radiating ground plane [19] .

4.1. Antenna geometry

Fig. 10 (a) presents the structure and dimensions of the planar radiating ground plane. The dimensions of the ground plane are designed to correspond approximately to those of a mini-laptop, large PDA (Personal Digital Assistant) or a tablet. The radiating ground plane is excited by two monopoles, of 90 mm (Monopole 1) and 34 mm in length (Monopole 2), which act as coupling elements. Moreover, two complementary slots (measuring 90 and 26 mm in length, respectively) are implemented orthogonally to the corresponding monopoles into the radiating ground plane. The height of both monopoles from the ground plane is 5 mm, corresponding to 0.008–0.05λ, depending on the frequency. The positions of the slots in the ground plane were optimized using CST Microwave Studio [14], to cover DVB-H, GSM850 and GSM900 frequency bands with Monopole 1, and GSM1800, UMTS, LTE and 2.4 GHz bands with Monopole 2 . Alternatively, the monopole can be implemented to the side of the ground plane to make the structure coplanar.

The prototype of the fabricated antenna is shown in Fig. 10(b), where both monopoles are supported by a small piece of white foam (ε_r = 1). As observed, the slot associated to Monopole 2 in Fig. 10 (a) is hidden by one of



■ **Figure 10.** (a) Planar radiating ground plane with monopoles of two different lengths as coupling elements. The gray color is metal, whereas the white color is air. Dimensions are in mm. (b) Prototype of the antenna.

the pieces.

4.2. Results

The simulated and measured reflection coefficient and measured maximum gain of Monopole 1 are represented in Fig. 11 (a). The measured total gain in the DVB-H band is approximately -5 dBi at 474 MHz and -4 dBi at 858 MHz. The maximum gain is 5–10 dB higher than the minimum requirements of the DVB-H standard and, thus, exceedingly satisfies the standard, as presented in the figure. The impedance matching at 474 MHz is -1.8 dB, which also satisfies the standard, based on studies presented in [20].

Apart from the DVB-H standard (474–858 MHz), the GSM850 and GSM900 bands can be covered within the -6 dB impedance bandwidth with Monopole 1. The relative -6 dB bandwidth of Monopole 1 is 57%. Additionally, the measured isolation between Monopoles 1 and 2 is higher than 25 dB over the whole operating bandwidth.

Fig. 11 (b) presents the measured and simulated reflection coefficient for Monopole 2. The measured -6 dB impedance bandwidth ranges from 1.53 to 3.0 GHz and the simulations predicted the same bandwidth with a slightly better matching. The measured relative bandwidth in the case of Monopole 2 is 65%. The measured isolation over the operating bandwidth is once again over 25 dB, as in the lower frequency band. As previously, the case with the slot in the ground plane is compared with the case without the slot. As shown, matching is dramatically improved in this case as well. Fig. 11(b) presents also the measured total efficiency of Monopole 2. As it can be observed, the total efficiency is more than -3 dB over the operating impedance bandwidth, and the average is -1.81 dB.

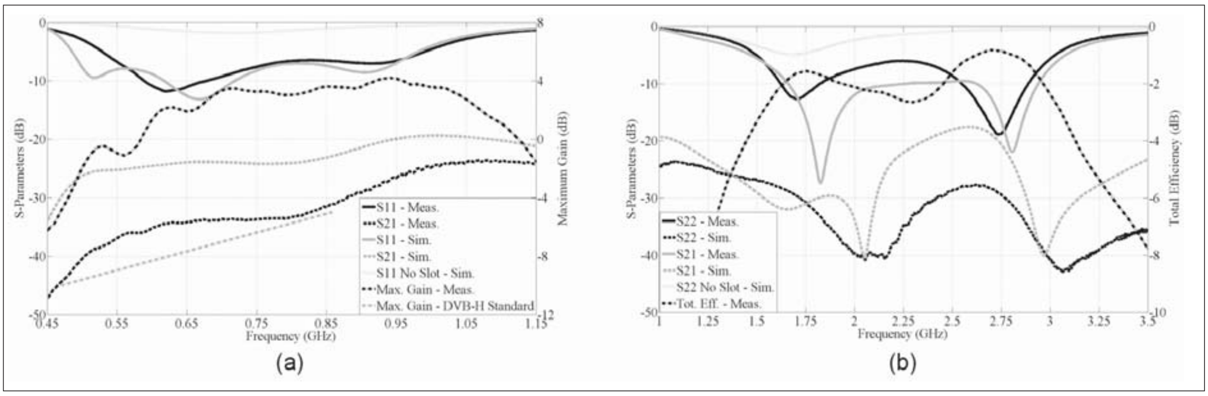


Figure 11. Measured and simulated S-parameters (a) for Monopole 1, with measured maximum gain and (b) for Monopole 2, with measured total efficiency. Simulated S-parameters are compared with the case without slot.

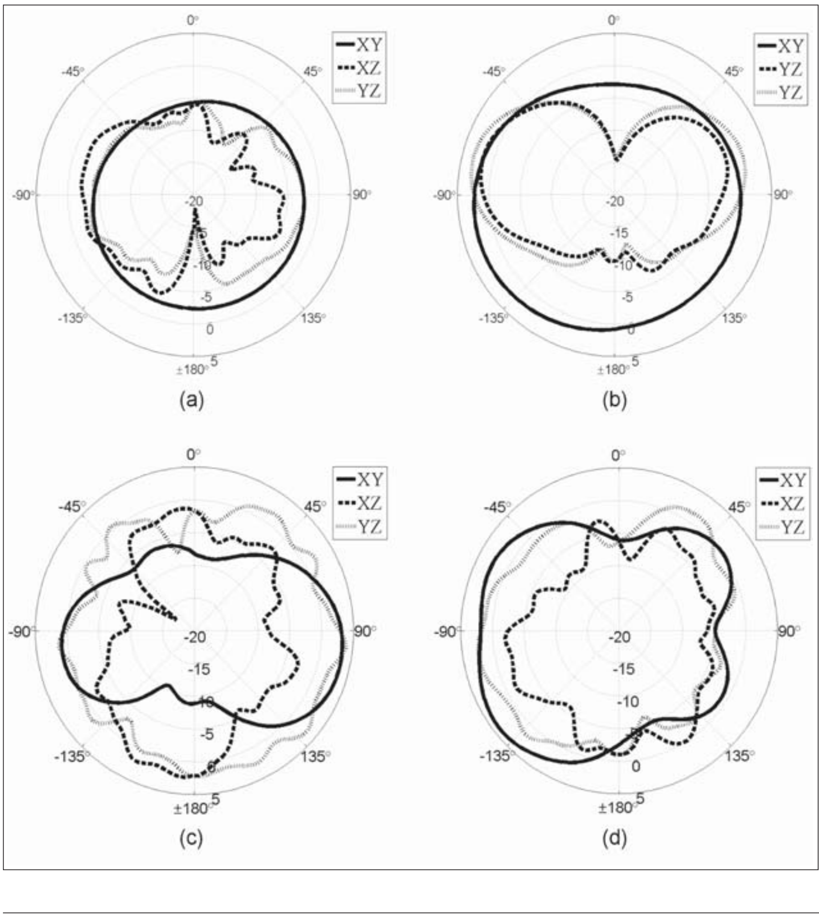


Figure 12. Measured radiation patterns in total gain at (a) 500 MHz, (b) 900 MHz, (c) 1.70 GHz, and (d) 2.75 GHz.

By adding two basic radiating elements formed by the combination of a dipole and a square-shaped notch to the opposite ends of the mobile ground plane, an efficient MIMO antenna structure with high isolation and low correlation can be created.

The measured radiation patterns of Monopole 1 at 500 and 900 MHz are presented in Fig.12 (a) and Fig.12 (b), respectively. As it can be noticed, the radiation patterns at the measured frequencies do not show very deep nulls, so the propagated signal can be easily received from all directions. The maximum gain at 500 MHz is -2.3 dBi, which is approximately the same in every cut. The radiation pattern can be observed as being dipole-like. The maximum 3.2 dBi gain at 900 MHz can be found in the YZ plane. It is also notable that the radiation pattern at 900 MHz corresponds well with the radiation of a monopole on a ground plane.

Fig.12 (c) and Fig.12 (d) depict the measured radiation patterns of Monopole 2 at 1.70 and 2.75 GHz, respectively. A 3.9 dBi maximum gain at 1.7 GHz can be observed at the intersection of the XY and YZ planes, while a 4.1 dBi maximum at 2.75 GHz can be found in the XY plane. It is also notable that the radiation patterns at both measured frequencies have no deep nulls. The same was observed with Monopole 1 in the lower frequency band.

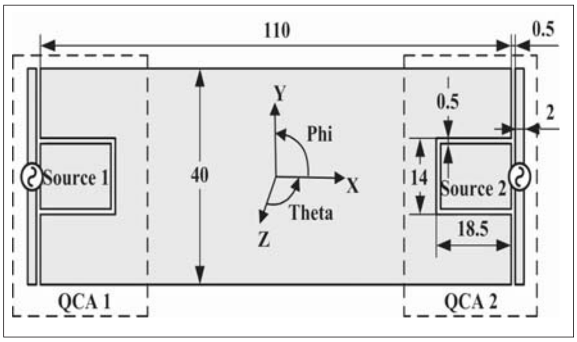
5. Wideband MIMO antenna for mobile terminals

This section presents the use of the QCA basic structure shown in Fig. 1(b) to design a wideband planar MIMO antenna for mobile terminals [12].

5.1. Antenna geometry

By adding two basic radiating elements formed by the combination of a dipole and a square-shaped notch to the opposite ends of the mobile ground plane, an efficient MIMO antenna structure with high isolation and low correlation can be created. The geometry of the MIMO antenna is shown in Fig. 13.

Fig. 14 shows the prototype of the MIMO antenna using a wideband tapered microstripline balun. The relative dielectric constant of the substrate used in the balun is ε_r=2.2. The balun was optimized by simulations, by taking into account the combined effect of the slot and the thickness of the ground plane [12].

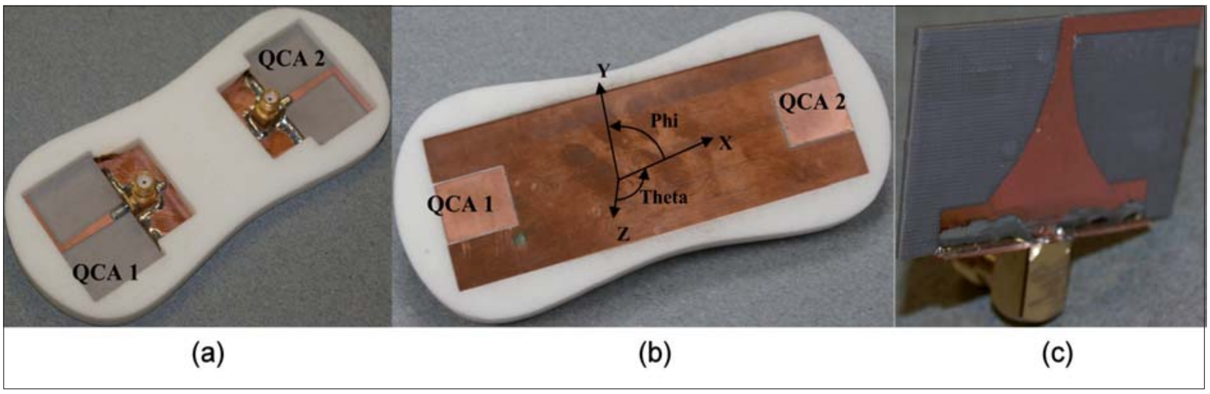


■ **Figure 13.** MIMO prototype antenna with two QCA basic structures at both end of the ground plane. Dimensions are in mm.

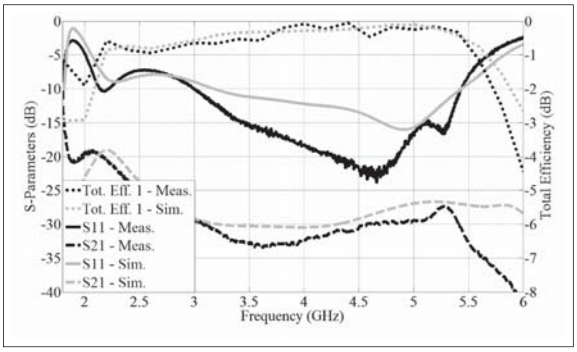
5.2. Results

The simulated and measured S-parameters and the total efficiency of the antenna prototype are shown in Fig. 15. It can be observed that the measured relative -6 dB impedance bandwidth (S_{11}) is 95%, ranging from 2.0 to 5.6 GHz. The measured S_{21} at the same bandwidth is less than -19 dB. The results are well correlated with the numerical results presented in Fig. 3(b). The measured total efficiency is between -2.3 and -0.1 dB, having an average of -0.85 dB within the -6 dB impedance bandwidth. The total efficiency is measured by terminating the other antenna element with a standard 50 Ω load.

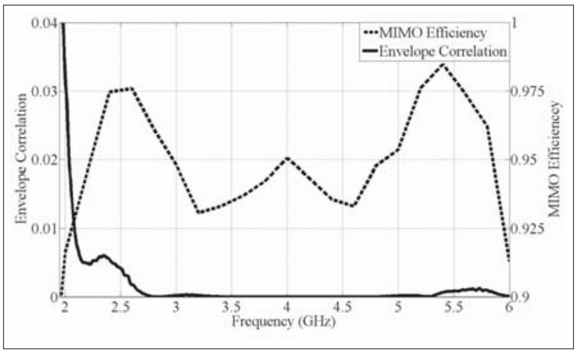
Fig. 16 presents the measured radiation patterns of the QCA 2 element in terms of the total gain at 2 and 5 GHz. It can be observed that the antenna radiation patterns do not have deep nulls at any of the both frequencies, which is desired in mobile applications. Especially at 2 GHz, the radiation pattern is almost isotropic, which agrees with the radiation of a complementary antenna. The maximum total gains are 2.8 dBi and 5.7 dBi at 2



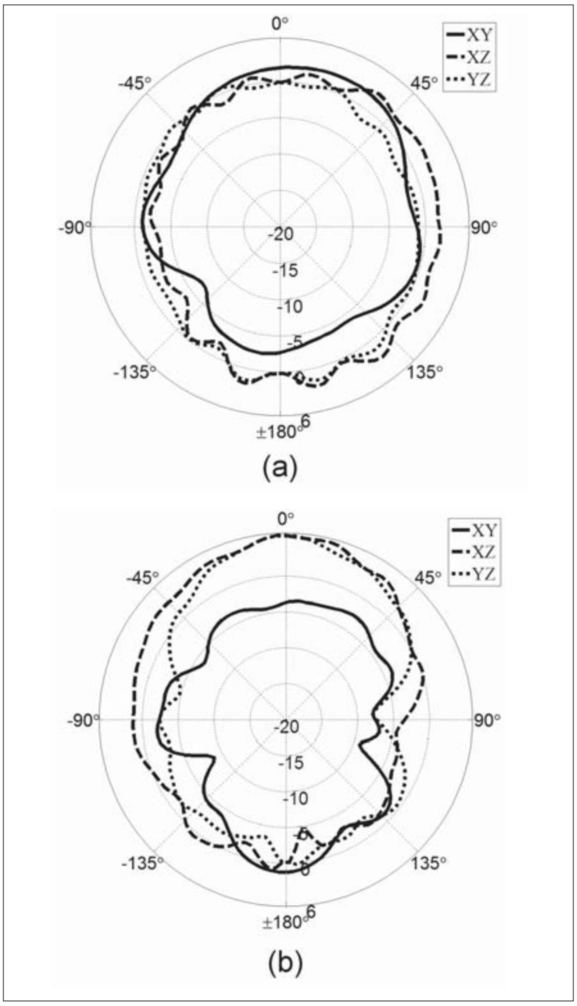
■ **Figure 14.** Picture of the MIMO antenna prototype: (a) Upper view; (b) Bottom view. The ground plane of the tapered microstrip line balun is presented in (c).



■ **Figure 15.** Simulated and measured S-parameters (dB), and measured total efficiency (dB).



■ **Figure 17.** SMeasured envelope correlation and MIMO multiplexing efficiency of the antenna shown in Fig. 14.



■ **Figure 16.** Measured radiation patterns of QCA 2 at (a) 2 GHz and (b) 5 GHz in terms of total gain (dBi).
GHz
and
5 GHz, respectively.

In Fig. 17, the measured envelope correlation and MIMO multiplexing efficiency [21] are shown. The envelope correlation as a function of frequency is calculated by using S-parameters [17], as in Section 3. This formula assumes a uniformly distributed radio channel. Additionally, port 2 is terminated with a 50 load when port 1 is excited, and the antenna system is a lossless structure [22]. The antenna system proposed in this letter exhibits high total efficiency with good impedance matching and low mutual coupling. Thus, the lossless formulation can be used to calculate the envelope correlation [21]. As observed, the measured envelope correlation is less than 0.04, and the measured MIMO efficiency is better than 90% over the whole bandwidth.

6. Conclusions

Simple designs of wideband antennas based on the use of an electric conductor (inductive behaviour) close to a magnetic slot cut into a conducting ground plane (capacitive behaviour) have been presented. A notch and a square-shaped slot in combination to an electric dipole or monopole have been proposed as simple wideband structures. Complex wideband antennas have been then proposed for mobile terminals based on the use of these simple wideband antennas. Thus, a wideband antenna with polarization diversity for UMTS, Bluetooth, WLAN, LTE and WiMAX standards, a dual-band antenna for DVB-H and LTE standards, and a wideband antenna for MIMO applications have been designed. Prototypes of all the antennas have been fabricated and real measurements performed, which show the suitability of the proposed basic structures to implement more complex wideband antennas for multi-standard portable devices.

Acknowledgments

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