Design of Dual-Band Microstrip Patch Antenna with Defected Ground Plane for Modern Wireless Applications

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Abstract—In this paper, we design and analyze a dual-band rectangular microstrip patch antenna with defected ground plane for 2.5 GHz and 3.5 GHz communications. The design concept is to have two slots etched out from the ground plane of a microstrip patch antenna designed for 2.5 GHz operation to enable second frequency band (3.5 GHz) operation. The positions of etched slots are determined using parametric analysis to meet the objectives of large impedance bandwidth and high gains in the desired bands and mismatching in the undesired bands. The proposed antenna provides wide impedance bandwidths of 13.56% (2.3–2.7 GHz) and 10.36% (3.3–3.7 GHz) at center frequencies of 2.5 GHz and 3.5 GHz, respectively. The gains in E-Plane are 6.7 dB and 5.1 dB, and the gains in H-Plane are 6.5 dB and 4.88 dB, for 2.5 GHz and 3.5 GHz, respectively. The proposed dual-band antenna shows monopole-like radiation patterns with higher gains as compared to monopole antennas.

I. INTRODUCTION

The rapidly growing wireless communication applications demand antennas that are low profile, light weight, and low cost. In all of the available pool of antennas, microstrip patch antennas have been well suited for wireless applications because of their simple design, variety of shapes, ease of installation, and compatibility with Microwave and Millimeter wave Integrated Circuits (MMIC) [1]. Microstrip patch antennas have been an active research topic to seek solutions to overcome some critical limitations of these antennas including low gain, narrow bandwidth, low efficiency, and low power handling capabilities [2]. Typical microstrip patch antennas resonate in a single band. However, modern wireless communications require antennas that can operate in multiple frequency bands, e.g., 1575.42/1227.60/1176.45 MHz for Global Positioning System (GPS) [3], 900/1800 MHz for Global System for Mobile Communication (GSM), 2.4/5.2/5.8 GHz for Wireless Local Area Networks (WLANs), 2.5/3.5/5.5 GHz for Interoperability for Microwave Access (WiMAX), 700/2300/2600 MHz for Long Term Evolution (LTE) [4], etc. While using multiple antennas can achieve multiband operation, it increases the cost and complexity of the system. In addition, using multiple antennas creates the coupling problem which in turn degrades the performance of the antennas.

An alternative solution is to modify the antenna such that it can be used for multiband wireless communications.

Techniques such as etching of slots from the radiating element, tapered structure fed by coplanar waveguide, integration of metamaterials with antennas, capacitive coupled patch, and multilayered structure have been proposed [5]. However, these techniques are concerned with modification of the radiating patches and hardly achieve the bandwidth requirements of multiband systems. Another technique, known as the *defected ground plane technique*, modifies the ground plane instead of the radiating patch to meet the multiband requirements. The defected ground plane technique generally produces wider bandwidth as compared to the radiating patch modification technique, since in the latter the etching of slots creates a defect in the ground plane of the radiating patch, resulting in a disturbance to the shield current distribution in the ground plane and consequently the increased effective inductance and capacitance of the transmission line and the input impedance being affected [6]. The defected ground plane technique has been used for monopole and microstrip patch antennas for multiband/wideband applications, which however achieves low gains, typically 1–4 dB [7].

For multiband wireless communications, we consider the use of multiband antennas as opposed to wideband antennas. The reason is that wideband antennas, while meeting the bandwidth requirements in the desired frequency bands, also receive unwanted signals in the undesired bands. As the system works only in certain bands, the receiver has to employ high-order filters to extract the required frequency bands and reject the useless frequency bands. This approach increases the cost and complexity of the receiver. Thus, we consider multiband antennas and design the antennas such that large bandwidth and good gains can be achieved in the desired band to meet the system requirements. Specifically, we modify rectangular microstrip patch antennas by using the defective ground plane technique for 2.5/3.5 GHz dual-band operation, providing: 1) large impedance bandwidth in the desired frequency bands with wideband mismatching in the undesired bands, and 2) good gains as compared to monopole antennas and antennas with monopole-like radiation patterns. The reason for selecting rectangular microstrip patch antenna is its popularity, simplicity, and ease of design and calibration [2].

This paper is organized as follows. Sec. II highlights the design challenges and drawbacks of multiband/wideband an-

tennas that motivate this work. Sec. III presents the proposed design methodology for dual-band operation with a detailed parametric analysis. Sec. IV presents the simulation results. Sec. V concludes the paper.

II. MULTIBAND/WIDEBAND ANTENNAS

Various types of monopole patch antennas have been designed for multiband/wideband applications. The design of multiband antennas is challenging especially when the frequency bands are closer to each other. Multiband antennas show impedance matching only in the desired frequency bands and provide impedance bandwidth according to the system requirements. Monopole patch antennas with defected ground plane for multiband resonance achieve good impedance bandwidth; however, the gains are low in the desired frequency bands. A dual-band patch antenna was designed [8] for 0.95 GHz and 2.45 GHz bands with monopole-like radiation pattern. The gain of the proposed antenna is -3.6 dB and 0.6 dB for 0.95 GHz and 2.45 GHz, respectively. A triple-band antenna was designed [9] for WLAN (2.4/5.2/5.8 GHz) and WiMAX (2.5/3.5/5.5 GHz), but the peak gain in all three bands is only 1.85 dB. A dual-polarized dual-band patch antenna was designed [10] with defected ground plane for frequency bands of 2.0 GHz and 2.5 GHz with a peak gain of 4.83 dB.

Since designing multiband antennas for close multiple bands is a difficult task, wideband techniques have been used to achieve large impedance bandwidth in the desired as well as undesired bands. This technique provides large bandwidth with good impedance matching; however, it forces the antenna to receive signals in all frequency bands (desired or undesired). A ground plane defected patch antenna was proposed [11] to cover frequency bands of WiMAX/WLAN (3.5/5.2/5.8 GHz). The proposed wideband antenna has a wide impedance bandwidth from 3.07–6.15 GHz in order to cover the mentioned three bands, which creates problems for the receiver during filtration of useful bands from useless bands. The gain of the antenna varies from 2.47 dB to 4.86 dB. A wideband monopole antenna was designed [12] for WLANs (2.4/5.2/5.8 GHz), which has a very large impedance bandwidth from 3.1–9.0 GHz only for covering the mentioned three bands. A wideband monopole antenna was proposed [13] which provides wide impedance bandwidth from 1.78–5.5 GHz covering multiband systems of Digital Video Broadcasting (DVB), Universal Mobile Telephone System (UMTS), WiMAX, LTE, and WLAN, with a peak gain of 3.1 dB.

In summary, for multiband communications, wideband monopole antennas have the drawbacks of low gains and the need to adopt highly selective filters at the receiver, and multiband monopole antennas have the drawbacks of low gains and difficult design for close frequency bands. This paper reports the design method for dual-band microstrip patch antennas for two close bands of 2.5 GHz and 3.5 GHz (WLAN/WiMAX) using the defected ground plane technique. The proposed design concept applies to any two or three adjacent or nonadjacent frequency bands. The proposed dual-band antenna not only provides high gains as compared to monopole antennas, but also achieves large impedance bandwidth in the desired frequency bands.

Fig. 1. Geometry of the single-band rectangular microstrip patch antenna for 2.5 GHz.

III. THE PROPOSED DESIGN

The proposed dual-band antenna design is based on first designing a single-band patch antenna using the equations of microstrip patch antennas and then modifying the geometry of the single-band antenna to achieve the desired resonance frequencies.

A. Single-Band Microstrip Patch Antenna

The geometry of the rectangular microstrip patch antenna for single band operation is shown in Fig. 1. The substrate used for the microstrip patch antenna is RT Duriod 5880 of dimensions $96 \times 96 \text{ mm}^2$ with height $h = 1.6 \text{ mm}$, dielectric constant $\epsilon_r = 2.2$, and loss tangent $\tan \delta = 0.0009$. The dimensions and parameters of the rectangular microstrip patch antenna can be calculated as follows for the central resonance frequency (f_r) of 2.5 GHz [1]. The width (W) of the patch antenna is calculated by

$$W = \frac{v_0}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

where v_0 is the free space velocity of light. The actual physical length (L) of the patch antenna is calculated by

$$L = L_{\text{eff}} - 2\Delta L \quad (2)$$

where L_{eff} is the effective length of patch antenna caused by fringing fields and ΔL is the extended length due to fringing fields. L_{eff} and ΔL are given by

$$L_{\text{eff}} = \frac{v_0}{2f_r \sqrt{\epsilon_{\text{reff}}}} \quad (3)$$

$$\Delta L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3)(W/h + 0.264)}{(\epsilon_{\text{reff}} - 0.258)(W/h + 0.8)} \quad (4)$$

where ϵ_{reff} is the effective dielectric constant of microstrip patch antennas on dielectric substrate

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W}\right)^{-\frac{1}{2}} \quad (5)$$

The resonant input resistance R_{in} at distance $y = y_0$ from the edge for the inset feed line is

$$R_{\text{in}}(y = y_0) = R_{\text{in}}(y = 0) \cdot \cos^2 \left(\pi \frac{y_0}{L} \right) \quad (6)$$

TABLE I
CALCULATED PARAMETERS FOR THE RECTANGULAR MICROSTRIP PATCH
ANTENNA FOR 2.5 GHz

Parameter	Value
1. Length of patch (L)	39.67 mm
2. Width of patch (W)	47.42 mm
3. Width of microstrip feed line (W_0)	4.852 mm
4. Inset feed distance (IFD)	12.50 mm
5. Inset feed gap (IFG)	2.426 mm

The required value of $R_{in}(y = y_0) = 50$ ohms for the patch antenna as the feed line is also of 50 ohms. Thus, the value of y_0 can be determined which is the distance at which the patch antenna has $R_{in} = 50$ ohms. $R_{in}(y = 0)$, which is the resonant input resistance at the edge, is determined by

$$R_{in}(y = 0) = \frac{1}{2(G_1 \pm G_{12})} \quad (7)$$

where G_1 is the self conductance of slots when the microstrip patch antenna is represented by two radiating slots, and G_{12} is the mutual conductance between slots, as given by

$$G_1 = \begin{cases} \frac{1}{90} \left(\frac{W}{\lambda_0} \right)^2, & \text{if } W \ll \lambda_0 \\ \frac{1}{120} \left(\frac{W}{\lambda_0} \right), & \text{if } W \gg \lambda_0 \end{cases} \quad (8)$$

$$G_{12} = \frac{1}{120\pi^2} \int_0^\pi \left[\frac{\sin(\frac{k_0 W}{2} \cos \theta)}{\cos \theta} \right]^2 j_0(k_0 L \sin \theta) \sin^3 \theta d\theta \quad (9)$$

where λ_0 is the free-space wavelength, j_0 is the Bessel function of the first kind of order zero, and k_0 is the wavenumber. The mutual conductance (G_{12}) is typically very small as compared to self inductance (G_1) and usually omitted in (7). The width of microstrip feed line (W_0) for the characteristic resistance of $Z_c = 50$ ohms is calculated below by arranging terms.

$$Z_c = \begin{cases} \frac{60}{\sqrt{\epsilon_{reff}}} \ln \left(\frac{8h}{W_0} + \frac{W_0}{4h} \right), & \text{if } \frac{W_0}{h} \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_{reff}}} \left[\frac{W_0}{h} + 1.393 + 0.667 \ln \left(\frac{W_0}{h} + 1.444 \right) \right], & \text{if } \frac{W_0}{h} > 1 \end{cases} \quad (10)$$

The junction capacitance is produced because of the physical notch of inset feed and patch which disturb the resonance frequency. Therefore, inset feed gap (IFG) is set to $W_0/2$ mm to overcome the produced capacitance. The calculated parameters are summarized in Table I.

B. Dual-Band Microstrip Patch Antenna

The geometry of the patch antenna for dual-band operation is shown in Fig. 2(a) (front view) and Fig. 2(b) (back view). Two slots are etched out from the ground plane for dual-band operation. They are designated as Slot A and Slot B where Slot B is further divided into Slot B₁ and Slot B₂. The etching of slots creates defect in the ground plane of the radiating patch which disturbs the shield current distribution in the ground plane. This disturbance affects the input impedance and increases the effective inductance and capacitance of the transmission line [6]. The etching of slots from the ground

Fig. 2. Geometry of the proposed dual-band rectangular microstrip patch antenna for 2.5 GHz and 3.5 GHz. (a) Front view. (b) Back view.

TABLE II
PARAMETERS RESPONSIBLE FOR WIDENING UNDESIRABLE FREQUENCY BANDS

Parameter	Value
1. Length of Slot A (L_{SA})	78 mm
2. Width of Slot A (W_{SA})	16 mm
3. Length of Slot B ₁ (L_{SB1})	33 mm
4. Width of Slot B ₁ (W_{SB1})	16 mm
5. Length of Slot B ₂ (L_{SB2})	33 mm
6. Width of Slot B ₂ (W_{SB2})	16 mm
7. Distance between Slot B ₁ and Slot B ₂ ($DBS(B_1, B_2)$)	12 mm

plane enhances the bandwidth [14]. The etching of slots leads to many parameters to be examined for dual-band operation. Our objective, as mentioned earlier, is not to design wide-band antennas (that cover bandwidth from 2.5–3.5 GHz) but design antennas for dual bands of 2.5 GHz and 3.5 GHz with large impedance bandwidths and good gains. Therefore, careful parametric analysis is carried out for identifying the parameters responsible for producing large bandwidths in the desired bands and those contributing to the widening of undesired frequency bands. After extensive experiments, some parameters that contribute to widening unnecessary frequency bands are identified with proper values listed in Table II. These parameters are given fixed values to not contribute

Fig. 3. Return loss of the proposed dual-band microstrip patch antenna for different (a) DFE, (b) DBS, and (c) IFD values.

in the matching of undesired frequency bands at -10 dB. Furthermore, it is empirically observed that parameters such as distance from the edge (DFE) for Slot A (from the substrate edge), distance between slots (DBS), and inset feed distance (IFD) are crucial in dual-band operation. A parametric study is conducted for these three parameters to find the best values for dual-band resonance. Due to the numerous possibilities and complexity of examining all three parameters simultaneously, these parameters are studied individually and alternately to examine their unilateral contribution and obtain the best value with the other two parameters fixed. The criteria for choosing the best value are: 1) the resonance frequencies should be near the desired bands of 2.5 GHz and 3.5 GHz, and 2) the return loss near the desired bands should be low. Priority is given to the former when a compromise is needed. The two resonance frequencies near 2.5 GHz and 3.5 GHz are denoted by f_{r1} and f_{r2} , respectively. The antenna is simulated in Higher Frequency Structure Simulation (HFSS) software.

1) *Effects of changing the distance from the edge (DFE)*: With parameter values in Table II and the value of IFD = 12.5 mm from the single-band patch antenna, signs of dual-band resonance appeared when DBS = 21.5 mm and DFE = 40 mm in initial experiments. Therefore, to examine the effects of all three parameters of IFD, DBS, and DFE on dual-band resonance separately, first the DFE is changed from 40 mm to 33 mm (with a step size of 1 mm) using parametric analysis while IFD and DBS are fixed at mentioned values. As a result of change in DFE, f_{r1} varies from 1.77 GHz to 1.83 GHz and f_{r2} varies from 3.65 GHz to 3.93 GHz with different return losses, as shown in Fig. 3(a). DFE = 34 mm is selected according to the established criteria. With DFE = 34 mm, f_{r1} is 1.82 GHz with a return loss of -12.23 dB and f_{r2} is 3.72 GHz with a return loss of -8.72 dB.

2) *Effects of changing the distance between slots (DBS)*: With DFE = 34 mm and IFD = 12.5 mm, the DBS is varied from 21.25 mm to 27.25 mm with a step size of 1 mm using parametric analysis. As can be seen in Fig. 3(b), f_{r1} varies from 1.81 GHz to 2.48 GHz and f_{r2} varies from 3.66 GHz to 3.91 GHz for different values of DBS. DBS = 25.25 mm is selected, where f_{r1} is 2.40 GHz with a return loss of -5.8 dB and f_{r2} is 3.68 GHz with a return loss of -22.19 dB.

3) *Effects of changing the inset feed distance (IFD)*: According to [14], the shift in frequencies due to etching

Fig. 4. (a) Return loss, and (b) rectangular plot of gains in E-Plane ($\Phi = 0^\circ$) and H-Plane ($\Phi = 90^\circ$), for the single-band microstrip patch antenna for 2.5 GHz.

slots from the ground plane can be overcome by changing the position of inset feed. With DFE = 34 mm and DBS = 25.25 mm obtained previously, IFD is varied from 14.5 mm to 6.5 mm with a step size of 1 mm using parametric analysis. As can be seen in Fig. 3(c), f_{r1} varies from 2.38 GHz to 2.50 GHz and f_{r2} varies from 3.86 GHz to 3.50 GHz with different return losses. IFD = 6.5 mm is selected, where f_{r1} is 2.50 GHz with a return loss of -25.45 dB and f_{r2} is 3.50 GHz with a return loss of -23.2 dB. This meets the desired objective established in this paper.

IV. SIMULATION RESULTS

A. Single-Band Antenna

The return loss (in dB) of the single-band patch antenna is shown in Fig. 4(a). The return loss is -24.5 dB at 2.5 GHz which shows a good matching between the antenna and the feed line. The bandwidth at -10 dB is equal to 39.4 MHz at the center frequency of 2.5 GHz (1.576% of the center frequency). The 2-D radiation pattern is shown in Fig. 4(b) for E-Plane ($\Phi = 0^\circ$) and H-Plane ($\Phi = 90^\circ$) in a rectangular plot. The maximum gain of the single-band patch antenna is 7.8 dB at $\Theta = 0^\circ$.

B. Dual-Band Antenna

The return loss (in dB) of the proposed dual-band patch antenna is shown in Fig. 5(a), which is obtained by using the final design parameters given in Table III. The bandwidth at -10 dB is equal to 339.4 MHz (2.3 – 2.7 GHz) at center frequency $f_{r1} = 2.5$ GHz (13.56% of the center frequency),

Fig. 5. (a) Return loss, (b) rectangular plot of gains in E-Plane ($\Phi = 0^\circ$), and (c) rectangular plot of gains in H-Plane ($\Phi = 90^\circ$), for the proposed dual-band microstrip patch antenna for 2.5 GHz and 3.5 GHz.

TABLE III
FINAL DESIGN PARAMETERS FOR PROPOSED DUAL-BAND PATCH ANTENNA

Parameter	Value
1. Length of ground plane (L_G)	96.00 mm
2. Width of ground plane (W_G)	96.00 mm
3. Length of patch (L)	39.67 mm
4. Width of patch (W)	47.42 mm
5. Width of microstrip feed line (W_0)	4.852 mm
6. Inset feed gap (IFG)	2.426 mm
7. Distance from the edge (DFE)	34.00 mm
8. Distance between slots (DBS)	25.25 mm
9. Inset feed distance (IFD)	6.500 mm
10. Length of Slot A (L_{SA})	78.00 mm
11. Width of Slot A (W_{SA})	16.00 mm
12. Length of Slot B_1 (L_{SB_1})	33.00 mm
13. Width of Slot B_1 (W_{SB_1})	16.00 mm
14. Length of Slot B_2 (L_{SB_2})	33.00 mm
15. Width of Slot B_2 (W_{SB_2})	16.00 mm
16. Distance between Slot B_1 and Slot B_2 ($DBS(B_1, B_2)$)	12.00 mm

and 362.8 MHz (3.3–3.7 GHz) at center frequency $f_{r2} = 3.5$ GHz (10.36% of the center frequency). As can be seen, the proposed antenna achieves one desired objective of producing wide impedance bandwidths in useful frequency bands and mismatching in the unwanted frequency band of 2.7–3.3 GHz. Thus the receiver will receive all frequencies of useful bands and will not pick up unwanted signals in these undesired frequency bands.

Fig. 5(b) and Fig. 5(c) show the 2-D radiation pattern in E-Plane ($\Phi = 0^\circ$) and H-Plane ($\Phi = 90^\circ$) in rectangular plots, respectively, for the proposed dual-band patch antenna. The maximum gain in E-Plane is 6.7 dB for 2.5 GHz and 5.1 dB for 3.5 GHz, while the maximum gain in H-Plane is 6.5 dB for 2.5 GHz and 4.88 dB for 3.5 GHz. The directive radiation pattern of microstrip patch antenna is changed to monopole-like radiation pattern with slight distortion due to etching of slots from the ground plane. The gains in both planes are higher than prior art with defected ground plane antennas reported in [7]–[11], [13].

V. CONCLUSION

A dual-band rectangular microstrip patch antenna has been designed and simulated for 2.5 GHz and 3.5 GHz communications. The dual-band resonance is achieved by etching of slots from the ground plane. Complete parametric analyses

are carried out to select proper slot positions and sizes. The proposed antenna achieves dual-band operation with large useful bandwidths (13.56% at 2.5 GHz and 10.36% at 3.5 GHz), as well as wideband mismatching in the undesired frequency band of 2.7–3.3 GHz. The gain of the proposed antenna is higher than that of previously reported antennas using the defected ground plane technique.

REFERENCES

- [1] C. A. Balanis, *Antenna theory: analysis and design*. John Wiley & Sons, 2012.
- [2] R. Garg, *Microstrip Antenna Design Handbook*. Artech House, 2001.
- [3] E. G. Doust, M. Clénet, V. Hemmati, and J. Wight, "An aperture-coupled circularly polarized stacked microstrip antenna for GPS frequency bands L1, L2, and L5," in *IEEE Antennas and Propag. Soc. Int. Symp.*, 2008, pp. 1–4.
- [4] H. Liu, R. Li, Y. Pan, X. Quan, L. Yang, and L. Zheng, "A multi-broadband planar antenna for gsm/umts/lte and wlan/wimax handsets," *IEEE Trans. Antennas and Propag.*, vol. 62, no. 5, pp. 2856–2860, 2014.
- [5] M. R. Ahsan, M. T. Islam, M. Habib Ullah, H. Arshad, and M. F. Mansor, "Low-cost dielectric substrate for designing low profile multiband monopole microstrip antenna," *The Scientific World Journal*, vol. 2014, 2014.
- [6] L. H. Weng, Y.-C. Guo, X.-W. Shi, and X.-Q. Chen, "An overview on defected ground structure," *Prog. Electromagn. Res.*, vol. 7, pp. 173–189, 2008.
- [7] C.-Y. Pan, T.-S. Horng, W.-S. Chen, and C.-H. Huang, "Dual wideband printed monopole antenna for WLAN/WiMAX applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 149–151, 2007.
- [8] A. Andrenko, I. Ida, and T. Kikuzuki, "Dual-band patch antenna with monopole-like radiation patterns for BAN communications," in *7th European Conf. on Antennas and Propag. (EuCAP)*, 2013, pp. 1922–1926.
- [9] J. Pei, A.-G. Wang, S. Gao, and W. Leng, "Miniaturized triple-band antenna with a defected ground plane for WLAN/WiMAX applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 298–301, 2011.
- [10] Y. Chung, S.-S. Jeon, D. Ahn, J.-I. Choi, and T. Itoh, "High isolation dual-polarized patch antenna using integrated defected ground structure," *IEEE Microw. Compon. Lett.*, vol. 14, no. 1, pp. 4–6, 2004.
- [11] M. Samsuzzaman, M. Islam, J. Mandeep, and N. Misran, "Printed wide-slot antenna design with bandwidth and gain enhancement on low-cost substrate," *The Scientific World Journal*, vol. 2014, 2014.
- [12] M. H. Al Sharkawy, "Miniaturized wideband slotted monopole antenna for WLAN applications," in *IEEE Middle East Conf. on Antennas and Propag. (MECAP)*, 2010, pp. 1–5.
- [13] M. Sonkki, E. Antonino-Daviu, M. Ferrando-Bataller, and E. Salonen, "Wideband planar antenna with monopole excitation for wireless applications," in *8th European Conf. on Antennas and Propag. (EuCAP)*, 2014, pp. 2380–2383.
- [14] S. Sathamsakul, S. Puntheeranurak, C. Benjankaprasert, N. Anantrasirichai, and T. Wakabayashi, "Improvement microstrip patch antenna for ultra-wideband by C-shaped wide slot," in *IEEE Int. Conf. on Control Automation and Syst. (ICCAS)*, 2010, pp. 2214–2217.