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Compact 3x1 Elements Reconfigurable MIMO Antenna for Cognitive Radio Applications

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Abstract. This paper presents, compact multiband frequency reconfigurable 3x1 MIMO antenna for cognitive radio applications. The antenna comprises 3-elements reconfigurable MIMO antenna and single element UWB sensing antenna. The frequency reconfigurability range under (S11 $\leq$ -10 dB) from 7-14.8 GHz using single PIN diode, while the UWB frequency range from 2.597-23.08 GHz. The antenna is designed and optimized to cover such wireless applications such as WiMAX, international telecommunication union (ITU), satellite, and broadband applications. The antenna is optimized using a Genetic Algorithm to operate in the MIMO and cognitive radio systems. The antenna dimensions for 3-elements MIMO antenna are 55 x 65 x 1.6 mm^3 printed on an FR-4 epoxy substrate with relative dielectric constant εr = 4.3, loss tangent tan (δ) =0.002 and 50 Ω microstrip feed line. The obtained simulated gain is ranging from 2.8-8.25 dB and the maximum simulated gain is 8.25 dB at 8.5 GHz. The return loss, Envelope Correlation Coefficient ECC, and Isolation are obtained to be less than -25 dB, less than 0.018, and less than -17 dB respectively. Detailed simulation results are explored and studied in this research. The CST software is used to simulate and optimize the proposed antenna.

1. Introduction
The significant consideration from the research community in the past years has drawn toward the advent of Multiple Input Multiple Output (MIMO) in present and future wireless communications standards [1]. The MIMO system is used to improve the throughput and increase the transmission rate in wireless communications such as cellular, wireless local area network WLAN, and satellite communications without requiring any additional bandwidth [2]-[6].
There are a lot of features that find application in the spectrum sensing and spectrum allocation in cognitive radios such as compact size, high data rate wireless transmission, wide spectrum, diversity, low power consumption, and multiple access capabilities [7].

The reconfigurable antennas are being used in single and multiple in the same substrate to produce MIMO configuration and the used widely in the MIMO system to enhance the characteristics of the system such as improve the quality of the communication path, the efficient of spectrum utilization, compact size, multipath effects, and interference reduction. The frequency reconfigurability is achieved by using RF switches such as PIN and varactor diodes, RF MEMS, switched capacitors, and field-effect transistors switches [2]-[10].

The important parameters in the reconfigurable MIMO antenna are the compact size, the isolation greater than 12 dB [2]-[8], Envelope Correlation Coefficients ECC is the criterion of the MIMO antenna that is able to confirm similarity in the radiation pattern and it’s less than 0.5 [11] and

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some researches proposed ECC less than 0.3 [2], and diversity gain DV around 10 [12]. The ECC is related to the S-parameter and is used to measure the field coupling between the antenna elements [12]. The diversity gain DV is related to the ECC and they can be calculated from the equations below [2-11], [12]:

$$\rho_e = \frac{|S^*_{11}S_{12} - S^*_{21}S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$DV = 10\sqrt{1-|\rho_e|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: ρe is the ECC, S11, and S22 are the S-parameters of the antenna, S12, and S21 are the coupling coefficients between the antenna elements.

The literature used in this paper is to focus on the researches that have two or greater reconfigurable MIMO antenna with single or multiple UWB sensing antennae for cognitive radio applications.

In [13]-[20], reconfigurable MIMO antennas are presented for cognitive radio applications. In [13], the antenna works with sensing UWB band from 3-6 GHz and frequency reconfigurability from 3.8-4.3 GHz with isolation less than 15 dB and ECC less than 0.04. In [14], the antenna consists of 2-elements reconfigurable antennas operate with frequency tuning from 0.7-2.8 GHz using varactor diodes and a single UWB sensing antenna can cover a band from 0.74-3.44 GHz with isolation less than 11.5 dB and ECC less than 0.015. In [15], a 4-elements reconfigurable MIMO antenna operates on 1.77-2.51 GHz tuning using varactor diodes and an UWB sensing antenna covers a band from 0.75-7.65 GHz with isolation < 10 dB and ECC < 0.248. In [16], a 4-elements reconfigurable MIMO antenna operates on 743-1240 and 2400 MHz tuning using combination of PIN and varactor diodes with isolation < 12 dB and ECC < 0.027. In [17], a 2-elements reconfigurable MIMO antenna operates on 1.75-2.48 GHz tuning using varactor diodes and an UWB sensing antenna covers a band from 0.75-7.65 GHz with isolation < 10 dB and ECC < 0.1815. In [18], a 2-elements hexagonal-shaped frequency reconfigurable MIMO antenna and UWB sensing antenna with defective GND plane structure DGS to enhance isolation and for size reduction are presented for cognitive radio applications. The antenna operates with a frequency tuning range from 1.41-2.26 GHz with isolation better than 12 dB and ECC less than 0.2. In [19], a frequency reconfigurable 2-elements MIMO antenna with wideband 2-elements MIMO antenna for cognitive radio applications. The wideband sensing antenna operates with a frequency range from 2.35-5.9 GHz, while the reconfigurable antenna operates from 2.6-3.6 GHz using varactor diodes. The antenna operates with gain ranging from 3.5-5 dBi, ECC < 0.5, isolation better than 15 dB. In [20], a 2x2 frequency reconfigurable MIMO with UWB MIMO antenna for cognitive radio applications. The proposed antenna operates in three modes, UWB sensing mode, MIMO reconfigurable mode, and MIMO UWB mode. The UWB and reconfigurable modes are obtained from switching on and off states of the PIN and varactor diodes, where it achieves the UWB spectrum from 1-4.5 GHz and reconfigurability range from 0.9-2.6 GHz. The antenna has an isolation of less than 12 dB and ECC less than 0.19 for all operating bands.

In this paper, a new compact multiband 3x1-elements frequency reconfigurable MIMO antenna for WiMAX, international telecommunication union (ITU), satellite, Radar, and broadband applications is designed and optimized with two and four polarized configurations. The proposed design is different from the literature and the contributions in this paper are:

1. A 3-elements frequency reconfigurable antenna with wide frequency reconfigurability range from 7-14.8 GHz, and gain ranging from 2.8-8.25 dBi, so that its application in the MIMO and cognitive radio applications.
2. A compact single element design having a single patch and partial GND plane with areas of 10 x 21 mm^2 and 14 x 30 mm^2 respectively.
3. The compact overall design of 3x1-elements with an optimized size of 55 x 65 x 1.6 mm3 while providing isolation greater than 17 dB.

4. The GND plane dimensions of the proposed antenna are optimized using the Genetic Algorithm to be 30 x 13.86 mm^2 in order for the antenna operates on the MIMO system and cognitive radio applications.

2. Proposed MIMO Antenna Design and PIN Diode Modeling

2.1. Proposed Cognitive Radio Antenna Design

2.1.1. Reconfigurable MIMO Antenna Design

The proposed structure is designed for a 3-elements T-shaped frequency reconfigurable antenna with a single element UWB sensing antenna. The proposed design of 3-elements is shown in Fig. (1). After the study of the latest researches and determine which applications to cover by the antenna the proposed antenna shape is chosen after some parametric study and optimization algorithm of the GND plane dimensions to be completely different from the literature. The Genetic Algorithm is used after using the parametric study to optimize the GND plane dimensions for the best operation in the MIMO system and cognitive radio. The optimized dimensions of the GND plane of the reconfigurable antenna become 30 x 13.86 mm^2 instead of 30x14 mm^2. In addition the patch radii of the UWB sensing antenna are optimized to be (9.5, 7) mm instead of (10, 7) mm. The antenna consists of a patch printed on an FR-4 substrate with εr = 4.3, tan (δ) = 0.002 relative dielectric constant and loss tangent respectively, the thickness of 1.6 mm and 50 Ω microstrip feed line. The overall antenna size of 3x1-element which is applicable in the MIMO wireless and cognitive radio applications and meet the compact antenna properties and classifications. All optimum parameters of the multiband 3x1 MIMO antenna are summarized in table (1). Only single (DSM8100-000 Mesa Beam-Lead) from Skyworks PIN diode used to modify the length of the patch to reconfigure the resonant frequency to meet other bands of frequencies. The PIN diode is placed in an optimized position to achieve the desired operation. The design equations of the communicating antenna can be listed at equations from (3) to (7) respectively, while the sensing antenna design according to equations (8) and (9) respectively [21].

$$\mathrm{W} = \frac{\mathrm{V0}}{2fr}\sqrt{\frac{2}{\varepsilon r+1}} \qquad (3)$$

$$\varepsilon eff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}} \qquad (4)$$

$$\Delta \mathrm{L} = 0.412\,\mathrm{h}\frac{(\varepsilon reff+0.3)(\frac{w}{h}+0.264)}{(\varepsilon reff-0.258)(\frac{w}{h}+0.8)} \qquad (5)$$

$$Leff = L + 2\Delta L \qquad (6)$$

$$L = \frac{V0}{2fr\sqrt{\varepsilon eff}} - 2\Delta L \qquad (7)$$

$$a = \frac{F}{\{1+\frac{2h}{\pi\varepsilon rF}[\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\}^{\frac{1}{2}}} \qquad (8)$$

$$F = 8.791 * \frac{10^9}{fr\sqrt{\varepsilon r}} \qquad (9)$$

Where:
W: the width of the patch.
V0: velocity of light.
εr: the dielectric constant.
fr: the resonant frequency.
εreff: the effective dielectric constant.
h: the substrate height.
ΔL: length due to the fringing effect.
Leff: the effect patch and
L: the actual length of the patch.
a: the radius of the circular patch.

2.1.2 UWB Sensing Antenna Design

The structure of the UWB sensing antenna is an elliptical printed monopole antenna that can be shown in Fig. 1. The optimized antenna operates with a frequency band that covers the UWB from (3.1-10.6) GHz and covers the broadband up to 23.3 GHz so that the proposed antenna shape is chosen and optimized parameters are shown in Table 1. The antenna consists of an optimized elliptical monopole patch of (9.5 mm, 7 mm) radii, 50 Ω microstrip line feed and a half elliptical ground plane of (15 mm, 7 mm) radii.

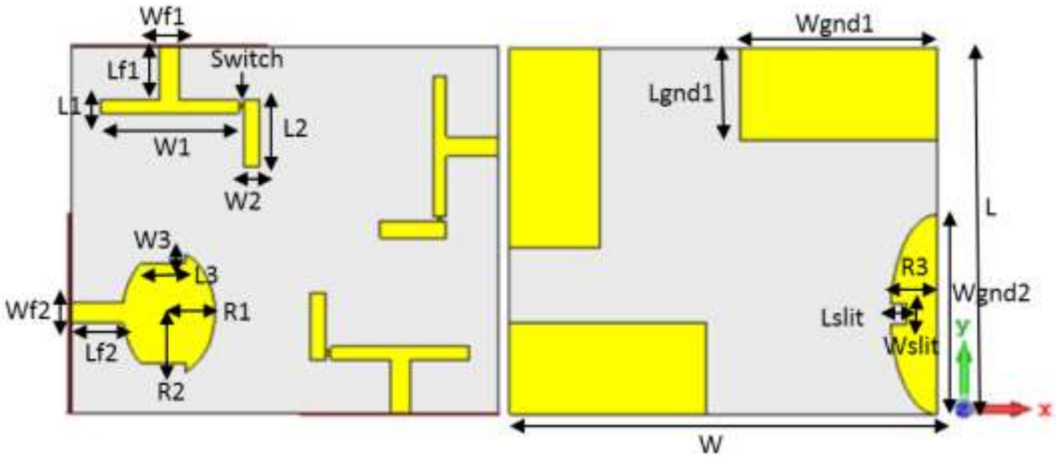


Figure 1. The proposed 3x1 multiband MIMO reconfigurable antenna.

Table 1. The Optimum Parameters of multiband 3-elements Reconfigurable MIMO Antenna

Parameters	Values in mm	Parameters	Values in mm
W	65	Wsw	0.7
L	55	Lsw	0.7
Wgnd1	30	Lf1	8
Lgnd2	13.86	Wf1	3
L1	2	t	0.035
W1	21	h	1.6
L2	10	W2	2.5
R1	9.5	R2	7
R3	7	Wgnd2	30
Lslit	3	Wslit	3
Wf2	3	Lf2	8
L3	6	W3	2.5

2.2. Pin Diode Modelling

The states of the electronic switch are ON and OFF. They can be realized by biasing the PIN diode in the forward or reverse bias. At the ON state, the switch is forward bias and it has low impedance acts as a short circuit and the current can pass through the diode, while in the OFF state the switch is reversed bias and it presents a high impedance and acts as an open circuit which indicates no current flown through the diode. An electrical circuit is shown in Fig. (2), which explain the forward and reverse biased, where the only resistor of (3.5 ohms) in series with an inductor of (0.15 nH) in the ON state and a combination of (1Kohm) resistor in parallel with the capacitance of (0.025 pF) all in series with an inductor of (0.15 nH) [22].

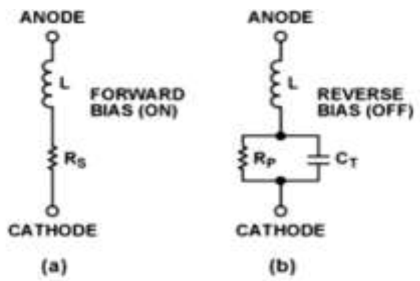
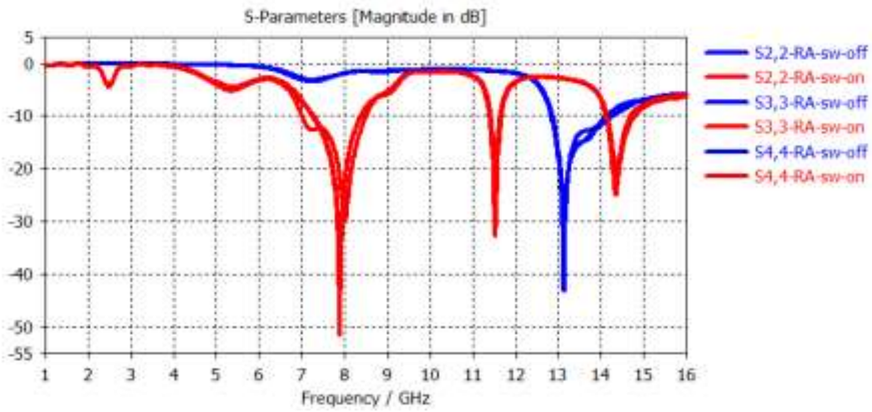


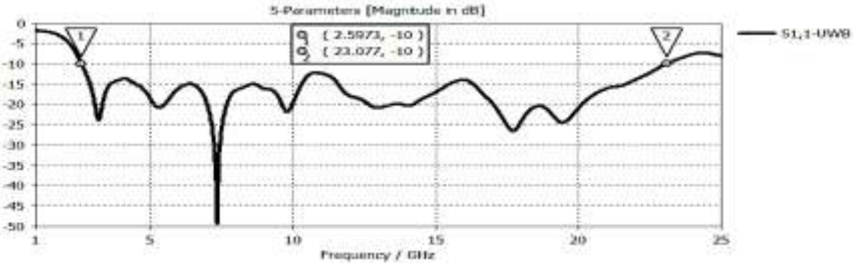
Figure 2. PIN diode modelling under (a) forward (b) reversed biased condition

3. Results and Analysis

The CST software is used to design, optimize, and simulate the proposed reconfigurable multiband MIMO antennas. The obtained multi-bands of the 3x1 MIMO reconfigurable antenna with the (S11) through the two states of the PIN diode are pragmatically shown in Fig. (3-a), where obtained lowest S11 of (-52 dB) in the (7.8 GHz). The simulated S-parameter of the UWB sensing antenna is presented in Fig. (3-b) with a band from 2.597-23.08 GHz. There are four resonant frequencies under the (S11 ≤ -10 dB) condition have resulted in the ON and OFF states of the PIN diode, they are (7.8, 11.5, 13.12, and 14.35) GHz, which are applicable to cover WiMAX, international telecommunication union (ITU), satellite, Radar, and broadband applications, where the 13.12 GHz frequency is obtained from the T-shaped while the other 7.8, 11.5 GHz and 14.35 GHz frequencies are obtained from the inverted-L shaped side arms of the patch, after some important parametric study and optimization with Genetic algorithm inside the CST software on the antenna dimensions to make the proposed antenna applicable in the MIMO and cognitive radio systems. The gain is ranging from (2.8 to 8.25) dBi and the maximum simulated gain is 8.25 dB at 8.5 GHz as shown in Fig. (4). The isolation between the 3-elements is ≤ -17 dB for all the bands as shown in Fig. (5). The simulated envelope correlation coefficient (ECC) of the proposed 3x1-elements MIMO antenna is obtained < 0.5 at all resonant frequencies where the worst-case produces (ECC = 0.018) as shown in Fig. (6), which make the proposed antenna can operate in the MIMO system properly. The diversity gain is around 10 for all the frequency bands as shown in Fig. (7), which is one of the requirements of the MIMO system. The simulated VSWR of the proposed antenna meets the practical requirements of (VSWR ≤ 2) at all the resulted multiband frequencies, where the VSWR is a measure for how the line is matching with the load.



(a)



(b)

Figure 3. The simulated (S11) parameter versus frequency of (a) 3-elements reconfigurable MIMO antenna, (b) single elements UWB sensing antenna.

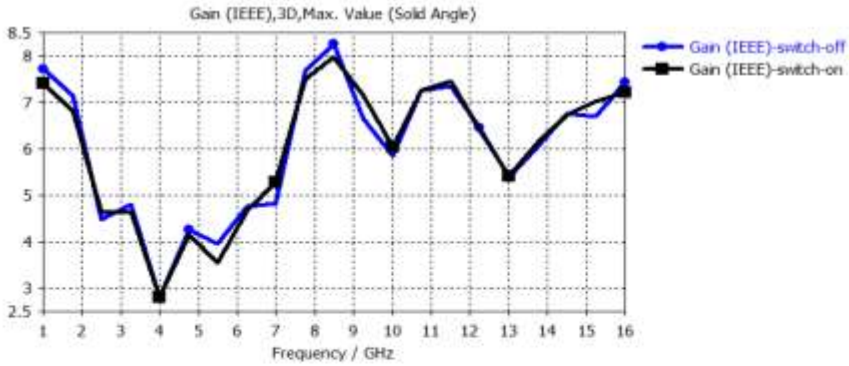


Figure 4. The gain variation with the frequency of the proposed reconfigurable MIMO antenna

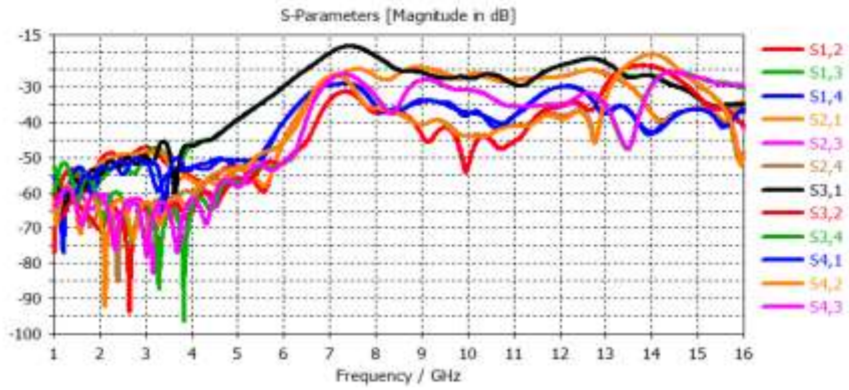


Figure 5. The simulated isolation of the 3x1 multiband reconfigurable MIMO antenna.

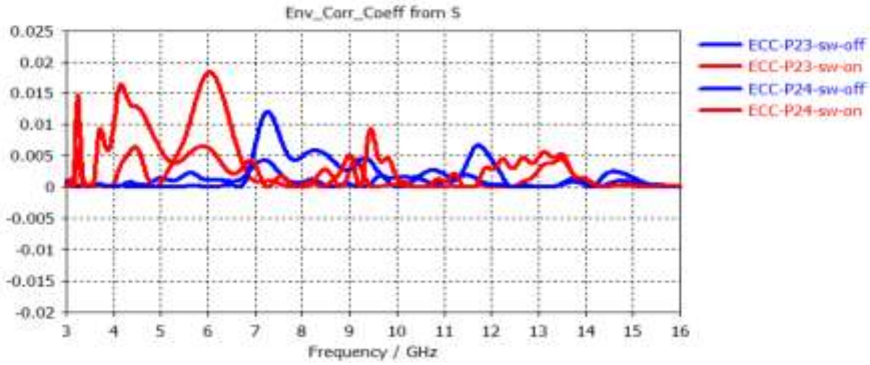


Figure 6. The simulated envelope correlation coefficients (ECC) of the 3-elements multiband MIMO antenna.

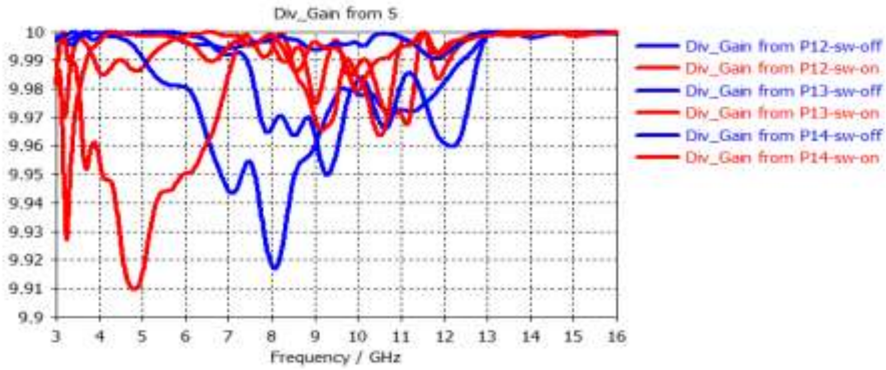
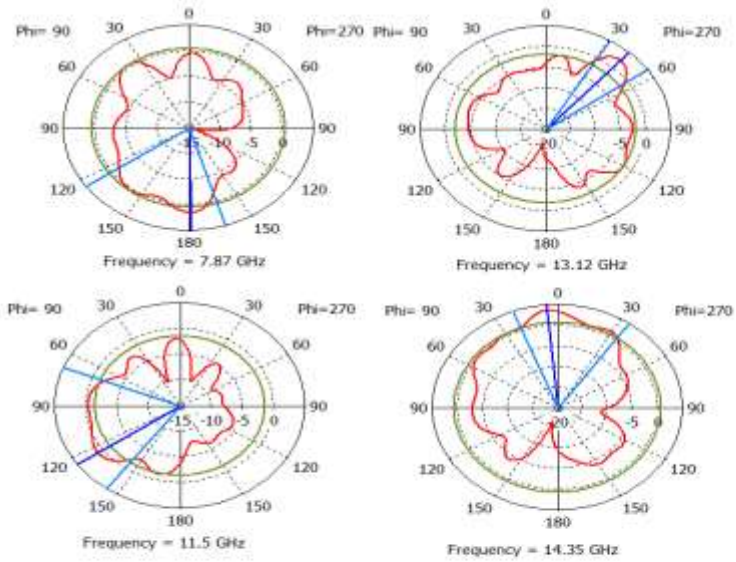
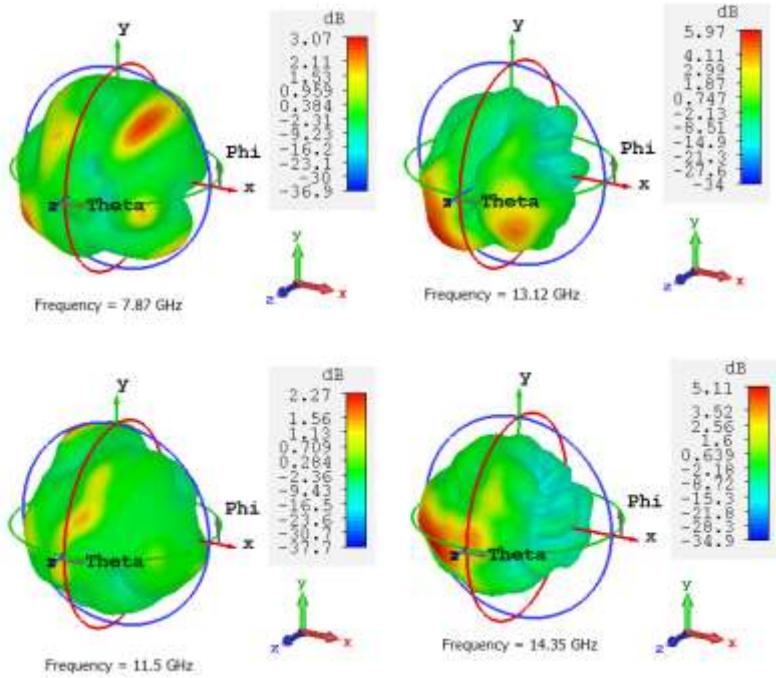


Figure 7. The simulated diversity gain of the 3x1 multiband reconfigurable MIMO antenna.

The 2D/3D radiation patterns of the proposed antenna are shown in Fig. (8), and the 3D surface current distribution for both cases of the PIN diode is shown in Fig. (9). It is noted that the ON-state of the PIN diode is at 7.87 GHz, 11.5 GHz and 14.35 GHz while the OFF-state is at 13.12 GHz due to the current flow in the patch arms.

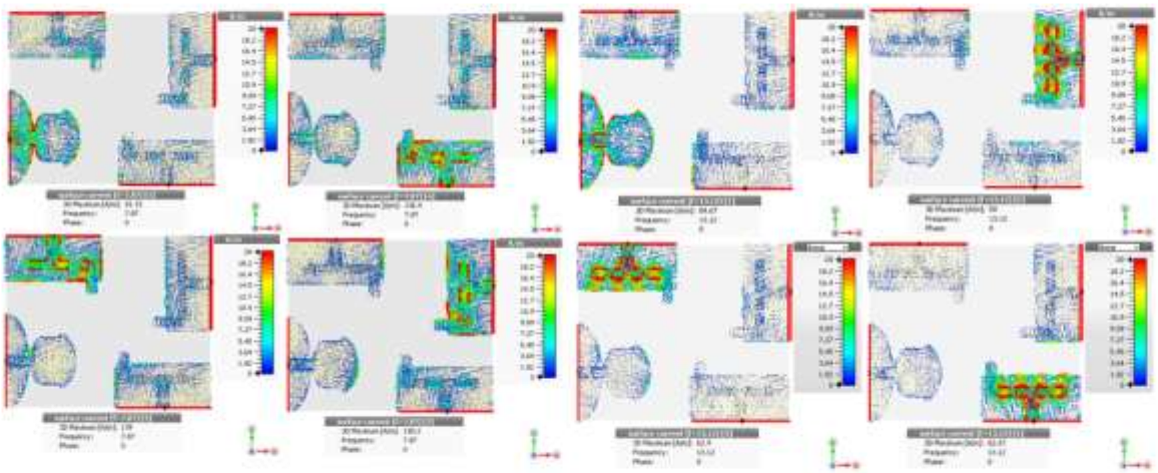


(b)



(b)

Figure 8. The (2D/3D) radiation pattern of the proposed reconfigurable MIMO antenna, (a) 2D radiation pattern, (b) 3D radiation pattern.



(a) (b)

Figure 9. The (3D) surface current distribution of the proposed MIMO antenna, (a) ON-state of the PIN diode switch, (b) OFF-state of the PIN diode switch.

The proposed antenna is compared with papers published in the literature as shown in Table 2. The comparisons show that the proposed design has better performance than the used references in Table (2) such as lower ECC, better isolation, very wide band spectrum sensing, and higher gain.

Table 2. A Comparison between the Proposed MIMO Antenna and other references.

References	No. of Elements	No. and type of switches	ECC (≤)	Isolation (dB) (≤)	UWB Band (GHz)	Reconfigurable Band (GHz)	Peak gain (dB)
14	2	2-PIN	0.05	-15	3-6	3.8-4.5	----------
15	4	2-varactor	0.248	-12	0.75-7.65	1.77-2.51	3.89
16	4	4-PIN 4-varactor	0.027	-12	--------	1.75-2.48	3.521
17	2	2-varactor	0.1815	-9.5	0.75-7.65	1.75-2.48	----------
18	2	2-varactor	0.2	-12	--------	1.41-2.26	2.12
19	4	2-varactor	0.06	-15	2.35-5.9	2.6-3.6	5
20	2	2-varactor	0.19	-12.5	1-4.5	0.9-2.6	3.7
Proposed MIMO Antenna	4	3-PIN	0.018	-17	2.7-22.3	7-14.8	8.25

4. Conclusion

A new compact multiband 3x1-elements reconfigurable MIMO antenna for cognitive radio applications is presented in this paper with a compact size to meet the requirements for the MIMO and cognitive radio systems. The proposed structure operates with only a single PIN diode to obtain four resonant frequency bands appropriate for various wireless applications such as WiMAX, international telecommunication union (ITU), satellite, and broadband applications. The proposed antenna can be fabricated simply due to a compact size and planar structure, good characteristics such as gain, efficiency, radiation pattern, return loss, ECC, Isolation, diversity gain and VSWR. The system has accepted properties to operate in the MIMO system and cognitive radio applications where the worst case of the isolation and ECC are -17 dB and 0.018 < 0.5 respectively.

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