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New compact multiband inverted-L frequency reconfigurable antenna for cognitive radio applications

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ABSTRACT

This paper presents, new compact and multiband frequency reconfigurable antenna for cognitive radio applications. A UWB sensing and reconfigurable communicating antennas are contained at the same substrate, where the UWB sensing antenna is an elliptical printed monopole antenna operates on frequency band from (2.65-22.112) GHz which can cover the UWB frequency band from 3.1 to 10.6 GHz, while the communicating antenna is an inverted-L frequency reconfigurable antenna operates on three bands of 1.49 GHz, 5.58 GHz, and 5.6 GHz under (S11 ≤ -10 dB) with a fractional bandwidth of 5.872%, 6.02%, and 6.05% respectively. The proposed antenna used to operate in two modes one for cognitive radio applications to cover WLAN applications at 5.5 GHz and 5.6 GHz and the second mode for wireless Ethernet, GPS synchronization, and Internet of Things that Matter (IoTtM) at 1.49 GHz. The frequency reconfigurability is obtained by using only a single RF switch (PIN diode) for changing the operating frequency. The antenna overall dimensions are 72 x 36 x 1.6 mm^3 printed on an FR-4 epoxy substrate of 4.3 relative-permittivity, loss tangent tan (δ) = 0.002 and 50 Ω micro stripline feed. The obtained simulated gain is ranging from 1.35 to 4.132 dBi. The S11 and isolation (S12) between the two antennas are under -20 dB and -17 dB respectively at the resonant frequencies.

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1. INTRODUCTION

The demand for frequency bands causes the available RF spectrum to become utilized owing to the development of communication systems in the latest years. Also, this utilization makes a shortage in the frequency bands because of the incompetent spectrum allocation management policies, where 70% of the allocated licensed spectrum remains unused noted by the Federal Communications Commission (FCC) in November 2002 [1]. The cognitive radios (CRs) are smart communication systems constructed on a software-defined radio platform, attempt to get better spectral utilization by dynamic interaction with the RF environment and they have the ability to learn from their environment and be familiar with the changes of their surrounds. The CR system has a process of adaptation which consists of operational parameters updating like modulation strategy, carrier frequency, transmission data rate and transmits the power in response to the observed RF environment. The main objectives of the cognitive radios (CRs) can be explained in two points, the first one is the assurance of the communication reliability whenever and wherever needed, and the second is the efficient utilization of the radio spectrum [1, 2]. The main incentive of the CR technology is the improvement and optimization of spectrum utilization because of the 90% of the time the offered channels are ideally free. The CR functioning consists of three main steps, they are spectrum sensing, analysis, decision, and mobility which can be shown in Figure 1 [3].

In the network of the CR system, in order to reduce the interference between primary and secondary users to a minimum, the secondary users (unlicensed users) have the permission to access the spectrum bands of the primary users (licensed users). There are three types of spectrum sharing between primary and secondary users, they are spectrum underlay, spectrum overlay, and spectrum interwave techniques. "In the underlay approach, secondary users must operate below the noise floor of primary users, and thus strict constraints are imposed on the transmission power. Ultra-wideband (UWB) technology is very appropriate for this approach. In spectrum overlay CR, secondary users do search for unused bands of frequency and use them for communication. In the interwave CR, the system allows the secondary users to efficiently utilize the unused spectrum holes while avoiding or limiting, collisions with primary transmissions [1]. To share the spectrum with licensed users without interference with them, and satisfy the various QoS requirements of applications, each CR user in a CR network should perform Spectrum Sensing, Spectrum intelligence or decision, Spectrum Sharing, and Spectrum mobility. Spectrum sensing refers to sense and decides the portion of the spectrum that is available free. Spectrum decision refers to selecting the available channel, and this is known as Spectrum decision and Spectrum sharing refers to let the other users share the available channel, and Spectrum mobility refers to make the channel free when a licensed user is detected" [3-5].

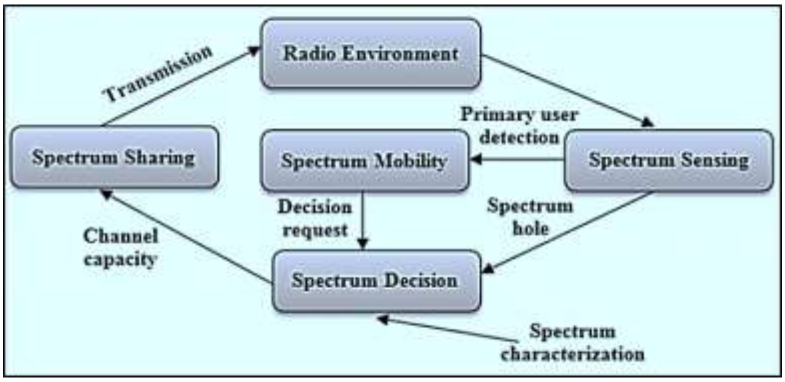


Figure 1. Cognitive radio functioning flow chart [3]

Sensing and communicating antennas are the basic RF structure of a CR system, where the sensing antenna always a UWB antenna used for wireless channel continuous monitoring of unutilized frequency bands, while the communicating antenna performs the communication through those channels [6]. There are four techniques applied to produce frequency reconfigurable antennas, they are electrical, optical, physical, and smart materials reconfigurations. The electrical reconfiguration is attained by RF switches such as MEMS, PIN, and varactor diodes, while an optical reconfigurations use photoconductive switching elements such as silicon switches. Structural adjustment of the antenna using slots, cuts, etc. is used for physical reconfiguration, while the smart materials reconfigurability can be implemented using smart materials such as ferrites, liquid crystals, etc. [7, 8].

The cognitive radio antenna design can be classified into three main parts, the first and the second classes are two ports one for UWB sensing antenna and the second for communicating antenna for the electrical and mechanical reconfigurations, while the third class is a single port of a UWB/narrowband antenna with reconfigurable slots [3, 4]. In [9-10] a CR system is presented based on two-port mechanical reconfigurability wherein [9] the sensing UWB and reconfigurable antennas are fabricated on the same substrate. The antenna uses an egg-shaped UWB sensing antenna and stepper motor to rotate five patches of the communicating antenna to produce five resonance frequencies of (3.44, 4.5, 5.36, 7.29, and 10.2) GHz. The peak gain obtained is 11.17 at 5.36 GHz and coupling less than -20 dB. In [10] also an egg-shaped UWB sensing antenna being used and five communicating patches are rotated for frequency reconfigurability of the whole 2-10 GHz.

In [11, 12] a CR antenna of two ports based on an electrical reconfigurable antenna is proposed. In [11] the antenna comprises a UWB sensing antenna of half egg-shaped with a reconfigurable monopole antenna. Three switches are used for frequency tuning with frequency bands of (3.7 to 4.2 GHz, 5 to 5.85 GHz, and 7.46 to 8.5 GHz). The isolation between the two antennas is better than -10 dB. In [12] the antenna supports frequency reconfigurability from 5-6 GHz. The antenna gain and mutual coupling between the sensing and communicating antenna are 0.5 dBi and less than -20 dB respectively.

In [13-19] the proposed CR systems based on single port UWB antenna with reconfigurable slots and switches between them for frequency reconfigurability. In [13] a UWB antenna with a T-shaped slot placed between pair of symmetrical gaps with six electronic switches to produce bandpass structure for frequency tuning from 6-9 GHz with a peak gain of 5.4 dB at 7.6 GHz. In [14] a UWB antenna with four slots and a ring slot with two electronic switches for frequency reconfiguration. The resonance frequencies of 2.75, 2.9, 3.7, 4.4, and 4.6 GHz for two states. In [15] a UWB antenna with six parasitic coplanar elements connected by six electronic switches to produce six bands with frequency reconfigurability range from 6.4-12 GHz. In [16] the designed semicircular shaped UWB antenna with a T-shaped slot filter with six switches in the feeding for adjusting the bandwidth to select sub-band and pre-filter the others. The six cases of the switches produce six reconfigurable bands from 5-10 GHz and the peak gain is 4.14 dB. In [17] a compact UWB antenna with reconfigurable band-notched with two switches for frequency tuning from 3.3 to 4.1 GHz. The peak average gain is 3 dB. In [18] two configurations of a UWB reconfigurable antenna were having the same patch but different GND plane with five and six PIN diodes respectively. The first design can operate in UWB, single, and double bands, while the second design also operates in three modes but more cases than the first one. Both structures operate with frequency reconfigurability from 5-9 GHz. In [19] a UWB and double bands frequency reconfigurable antenna are presented. By using the circular patch with C slot attached with a rectangular L-shaped and defected ground plane and inserting two parasitic surfaces the antenna operates with frequency reconfigurability range from 2.8-5.94 GHz.

In [20-23] reconfigurable MIMO antennas for CR applications. In [20, 21] a compact multi-band frequency reconfigurable antenna is presented. The antenna comprises two elements and four elements integrated with PIN and varactor diodes. According to the states of the PIN diode and controlling the bias voltage of the varactor diode the antenna operates with frequency tuning from (0.573-2.48) GHz and (0743-2.42) GHz with peak gain and isolation of 3.15 dB, 3.52 dB and better than -15 dB respectively. In [22] a MIMO antenna is suggested for CR applications. The antenna consists of two arrangements of patches the first comprises two reconfigurable antennas with four PIN diodes between the T-shaped slots for frequency tuning while the other is two sensing antennas that cover the band from 3-6 GHz. The maximum coupling between the elements is better than -15 dB. In [23] a MIMO antenna is designed for the CR system. A wideband structure in the middle is used to enhance the isolation between the two antenna elements. The sensing antenna can cover two bands one for the lower band of 2.3-6.3 GHz and the other for the higher band from 2.2-7 GHz. The antenna can tune the operating frequency from 2.3-6.3 GHz by using two pairs of varactor diodes.

In this paper, compact multiband two ports inverted-L antenna is proposed for cognitive radio (CR) applications and some other wireless applications. The proposed design is different from the literature and the contributions in this paper are:

a. The proposed antenna is completely different from the literature.
b. A compact frequency reconfigurable antenna with wide frequency reconfigurability range from 1.3-5.8 GHz, which can be used to cover various wireless applications such as wireless Ethernet, GPS synchronization, Internet of Things that Matter (IoTtM), and WLAN/WiFi systems using only single PIN diode for frequency reconfigurability.
c. A compact design having a single patch and partial GND plane with areas of 32 x 25 mm^2 and 20.6 x 30 mm^2 respectively.
d. The compact overall design of 2-elements with an optimized size of 36 x 72.5 x 1.6 mm^3, while providing isolation greater than 17 dB.
e. A compact UWB sensing antenna with patch and half elliptical GND plane of radii (10 mm, 7 mm) and (15 mm, 7 mm) which provides a wide band from 2.65-22.112 GHz.

2. PROPOSED COGNITIVE RADIO ANTENNA DESIGN AND PIN DIODE MODELING

2.1. Proposed CR Antenna Design

The overall structure is shown in Figure 2, which illustrates the front and back views of the proposed antenna. The front side of the antenna consists of UWB printed elliptical monopole antenna and inverted-L microstrip reconfigurable communicating antenna. The backside of the antenna shows partial ground for both structures, where the UWB sensing antenna has partial elliptical GND plane and the communicating antenna has a rectangular partial ground plane. The two antennas are printed on the FR4 epoxy substrate with relative permittivity of 4.3, 1.6 mm height (h), 0.002loss tangent as in [24, 25], and overall dimensions of 70 mm x 36 mm. The design equations of the communicating antenna can be listed at equations from (1) to (5) respectively, while the sensing antenna design according to (6) and (2) respectively [26].

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

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

$$\Delta L = 0.412\,h\frac{(\varepsilon reff+0.3)(\frac{w}{h}+0.264)}{(\varepsilon reff-0.258)(\frac{w}{h}+0.8)} \quad (3)$$

$$Leff = L + 2\Delta L \quad (4)$$

$$L = \frac{V0}{2fr\sqrt{\varepsilon eff}} - 2\Delta L \quad (5)$$

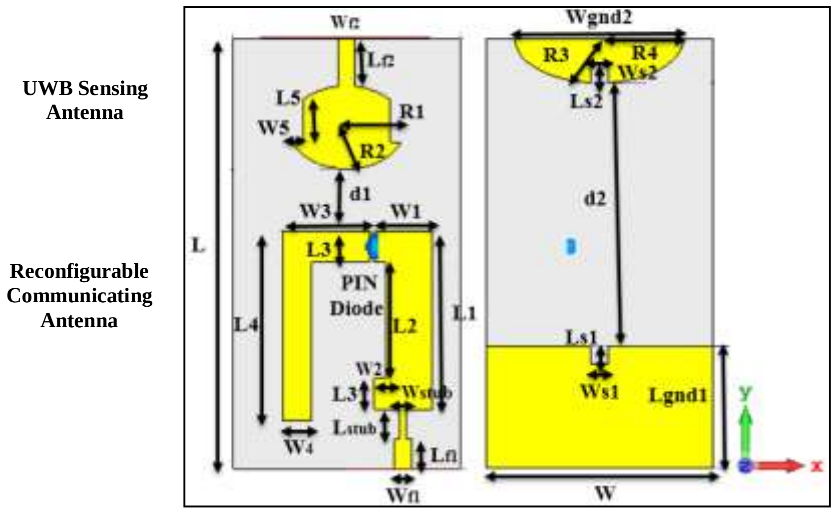
$$a = \frac{F}{\{1+\frac{2h}{\pi\varepsilon rF}[\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\}^{\frac{1}{2}}} \quad (6)$$

$$F = 8.791 * \frac{10^9}{fr\sqrt{\varepsilon r}} \quad (7)$$

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.

2.1.1. UWB Sensing Antenna Design

The structure of the UWB sensing antenna is an elliptical printed monopole antenna that illustrated in Figure 2. The optimized antenna operates with a frequency band that covers the UWB from (3.1-10.6) GHz so that the proposed antenna shape is chosen and optimized parameters are shown in Table 1. The antenna consists of an elliptical monopole patch of (10 mm, 7 mm) radii, 50 Ω micro stripline feed and a half elliptical ground plane of (15 mm, 7 mm) radii.



(a) (b)

Figure 2. The proposed multi-band cognitive radio antenna, (a) Front side, (b) Backside

Table 1. The optimum parameters of CR antenna

Parameters	Values in (mm)	Parameters	Values in (mm)
W	36	d1	11
L	72.5	d2	44.42
L1	30	t	0.035
W1	10	h	1.6
L2	19.6	R1	10
W2	2	R2	7
L3	5.2	R3	7
W3	15	R4	15
Ld	0.7	L5	7.13
Ws	4	W5	2.5
L4	32	Ls1	3
W4	5	Ws1	3
Lstub	5	Ls2	3
Wstub	1.2	Ws2	3
Lf1	5	Lgnd2	7
Wf1,2	3	Wgnd2	30
Lgnd1	20.6	Wgnd1	36

2.1.2. Communicating Antenna Design

The proposed design of a multi-band reconfigurable inverted-L antenna can be shown in Figue 1(a) and 1(b). 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 of the patch and GND plane dimensions to be completely different from the literature. The overall patch dimensions are 32 mm x 25.7 mm, which is compact and suitable for many wireless applications. All the antenna optimum parameters are summarized in Table 1. The antenna has only single (DSM8100-000 Mesa Beam-Lead) from Skyworks PIN diode used to modify the length of the proposed inverted-L antenna 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.

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 Figure 3, 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) [27].

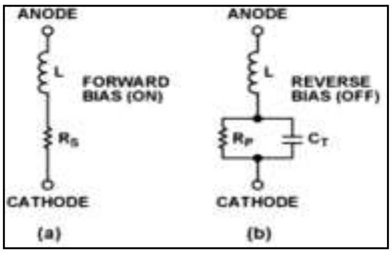
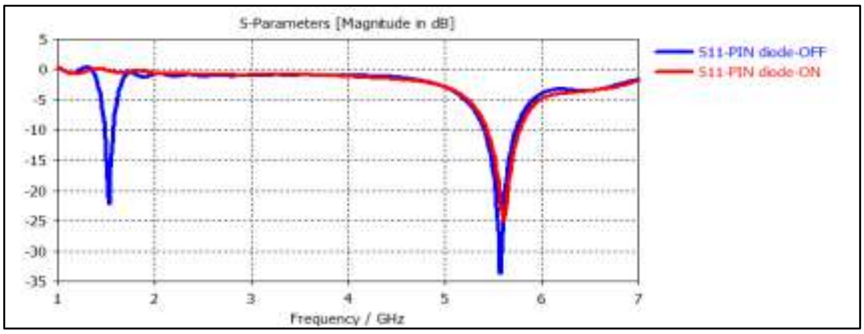


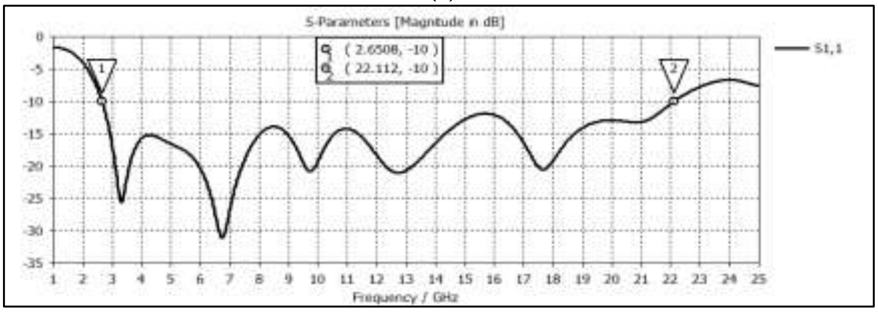
Figure 3. PIN diode modeling under, (a) Forward, (b) Reversed biased condition

3. RESULTS AND DISCUSSIONS

The simulation results of the proposed CR antenna are obtained by using the CST software. The (S11) parameter which belongs to the UWB sensing antenna can be shown in Figure 4(b), which has an operating band cover the UWB (3.1-10.6) GHz. The obtained multi-bands with the (S11) through the two states of the PIN diode are pragmatically shown in Figure 3(a), where obtained lowest S11 of (-37.5 dB) in the (5.58 GHz). There are three frequency bands under the (S11 ≤ -10 dB) condition have resulted in the ON and OFF states of the PIN diode, they are (1.49, 5.58, and 5.6) GHz, which are applicable to cover (wireless Ethernet, GPS synchronization, Internet of Things that Matter (IoTtM), and WLAN/WiFi) systems respectively. The first two bands (1.49, 5.58) GHz are obtained from the inverted C-shaped sidearm of the patch at the OFF state, while the last one (5.6) GHz is obtained from the ON state of the PIN diode after some important parametric study on the antenna dimensions. The simulated coupling effect (S12) between the two antennas is illustrated in Figure 5, that it shows a coupling less than -17 dB for all resonant frequencies. The simulated gain is ranging from (1.35 to 4.13) dBi as shown in Figure 6. The simulated VSWR of the proposed CR antenna meets the practical requirements of (VSWR $\leq$ 2) at all the resulted in multiband frequencies, where the VSWR is a measure for how the line is matching with the load.



(a)



(b)

Figure 4. (a) The simulated (S11) parameter versus frequency of the communicating antenna, (b) The simulated (S11) parameter versus frequency of the UWB sensing antenna

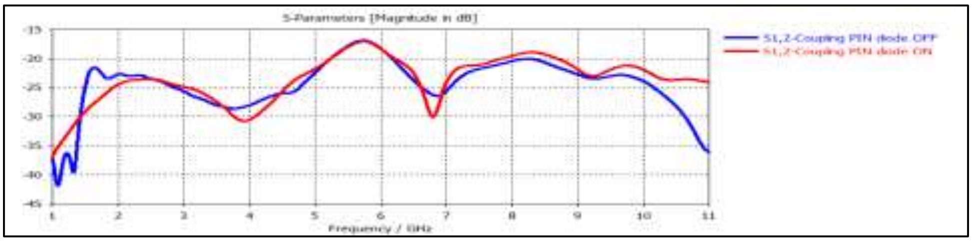


Figure 5. The simulated (S12) parameter (Coupling effect) between the two antennas versus frequency

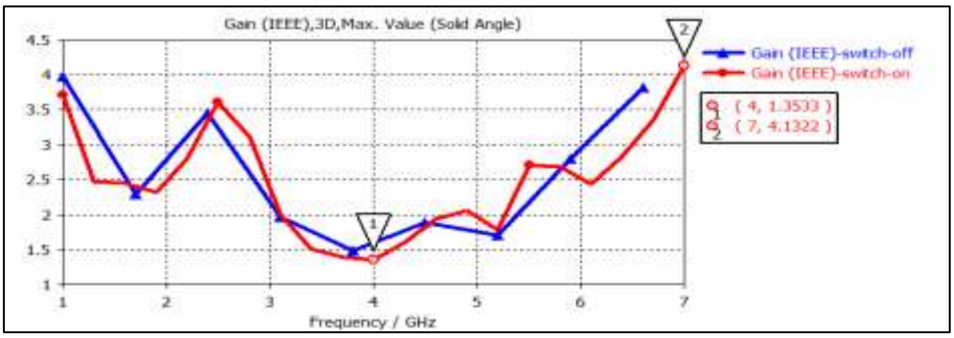


Figure 6. The gain variation with the frequency of the CR antenna

The radiation pattern and surface current distribution of the proposed CR are shown in Figure 7 and Figure 8 respectively, they represent the 2D/3D results. The surface current distribution presented in Figure 8 shows the OFF state of the PIN diode on the right side, where no current flown to the second arm of the patch, while the only single state on the left side represents the ON state. The proposed antenna can be compared with the literature to produce the strength of the system and is listed in Table 2.

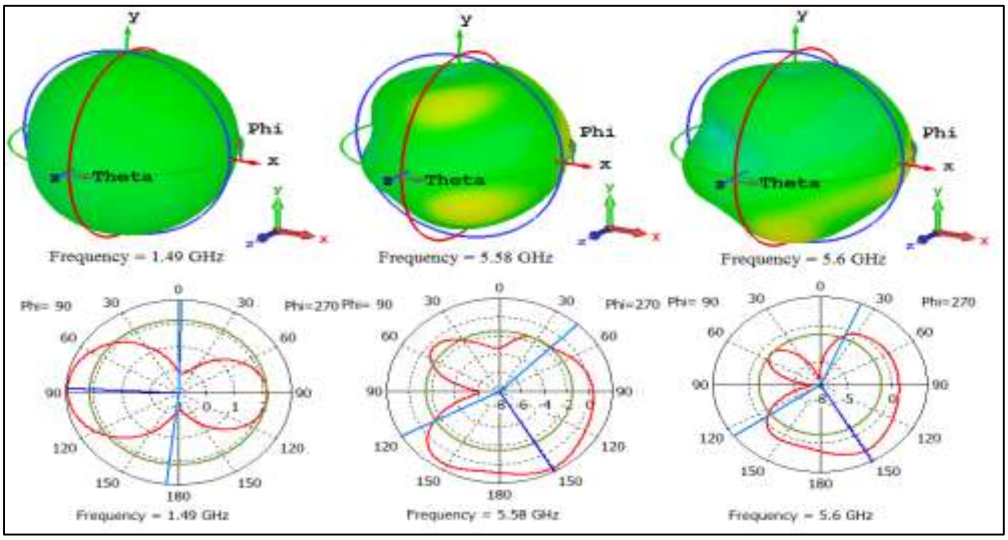


Figure 7. The 2D/3D CR antenna radiation pattern

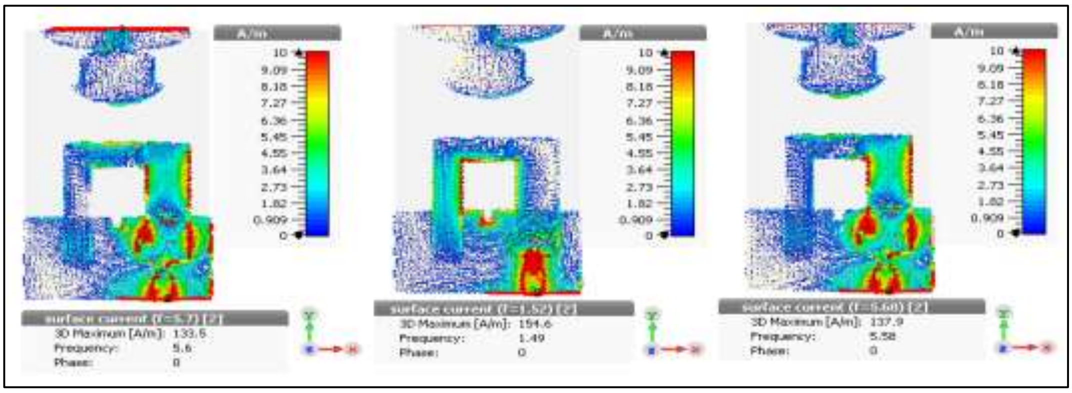


Figure 8. The 3D CR antenna surface current distribution

Table 2. Proposed antenna compared with literature

References	Type of The Antenna	No. of Switches	Type of Reconfigurability	Frequency Bands (GHz)	Peak gain (dB)	Max. Isolation (dB)
[8]	Two ports	------	Rotating by Stepper motor	2.56, 3.32, 3.91, 5.81, 7.82	4.62	-45
[11]	Two ports	3-switches	Electrical	3.9, 5.5, 7 .9	----	≤ -20
[12]	Two ports	1-varactor diode	Electrical	5.1, 5.2, 5.3, 5.51, 5.6, 5.8	2.72	-22
[13]	Single port	7-PIN diodes	Electrical	6.11, 6.52, 7.15, 7.6, 8.2	5.4	------
[15]	Single port	6-switches	Electrical	3.5, 5.8, 6.5, 7.5, 8.5, 10.3	----	-------
[16]	Single port	7-PIN diodes	Electrical	5.35, 5.7, 6.6, 6.8, 7.1, 9.5	4.14	--------
[20]	Four ports	8-PIN diodes and 4-varactor diodes	Electrical	0.743 to 2.4	3.52	≤ -17
Proposed CR Ant.	Two ports	1-PIN diode	Electrical	1.49, 5.58, 5.6	2.5	-22

4. CONCLUSION

A new compact multiband CR antenna for wireless communication applications is presented in this paper with a compact size to meet the requirements for several wireless applications. The proposed structure operates with only a single PIN diode to obtain three resonant frequency bands appropriate for various wireless devices applications. The proposed structure can be fabricated simply due to a compact size and planar structure, good characteristics such as gain, efficiency, radiation pattern return loss less than (-20 dB), coupling less than (-20 dB), and VSWR less than or equal to (2). The system can be fabricated in the nearest future in order to compare the obtained results from the simulation with the fabricated one.

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