On the Design of a Novel Fractal Antenna for Spectrum Sensing in Cognitive Radio

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Abstract ─ The present paper reports on the development of a novel compact fractal microstrip patch antenna for spectrum sensing in cognitive radio. The geometrical design of the proposed fractal antenna is optimized using nature inspired Moth Flame Optimization (MFO) method. The optimized antenna is having broadband characteristic within two bands (6.206 - 7.864 GHz, 23.56%) and (14.95 - 20 GHz, 28.89%), which are specified for IEEE C-band, Ku-band and K-band applications respectively. The proposed fractal antenna is also having high peak gain of 7.26 dBi at 18.04 GHz and omnidirectional radiation pattern at all frequencies. The performance of the proposed antenna is also validated experimentally by having a comparison of simulated results with the measured results. The proposed design offers 45.54% reduction in antenna physical size (copper required) as compare to a rectangular patch antenna of same size.

Index Terms ─ Cognitive radio, CPW feed, fractals, IFS, method of moment, microstrip patch antenna, moth flame optimization.

I. INTRODUCTION

Microstrip antenna is made up of a metallic patch printed at upper surface of a substrate having a ground plane incorporated on its lower surface. These antennas are inexpensive, low profile, simple, compact, conformal and easy to fabricate [1]. Microstrip antennas have a number of applications in the field of modern wireless communication including radar systems, satellite communication, telemetry, telemedicine, consumer and military applications [2]. In today's world of wireless communication, the most elementary constraint is to have wideband as well as compact antenna systems. Size of a microstrip antenna can be further reduced by using fractal geometry [3-4] in its design. Also, introduction of fractal geometry leads to multiband behavior [4-7]. Further, the concept of soft computing possesses its own position to optimize the parameters of antenna for enhancing its performance [8]. A variety of optimization techniques can be applied on the patch antenna to get better performance [9-10]. Basically, two antennas are required for cognitive radios, i.e., spectrum sensing antenna which searches the spectrum holes and communicating antenna which communicate in these holes [11-12]. Wideband antenna with omnidirectional radiation pattern is mandatory for spectrum sensing [13]. An antenna with very large bandwidth (1.35 - 30 GHz) is designed for spectrum sensing [14], but non-omni-directionality in H-plane is observed in the same. In [15], an ultrawideband slotted disc antenna for 0.7 - 11.23 GHz is presented but quasi-omnidirectional radiation pattern is observed. A multiband fractal antenna for spectrum sensing in cognitive radios is presented [16], but in this case, S_{11} is not improved significantly and only simulated results are presented. Again in [17] a multiband Sierpinski triangular antenna for cognitive radios is reported but with simulated results only. In [18], Sierpinski gasket antenna is presented for cognitive radios which resonates at 1.89 GHz, 4.01 GHz 7.89 GHz, 15.3 GHz frequency but the value of S_{11} is not much improved. In order to address these issues, in the present work, a novel fractal antenna is designed for spectrum sensing which is further miniaturized and optimized by a recently introduced heuristic nature inspired optimization technique, Moth Flame optimization proposed in [19]. This algorithm was applied on unimodal, multi-modal and composite functions, and observed that this algorithm explore and exploit the search space properly. In this paper, MFO algorithm is applied to optimize the dimensions of patch and ground plane to optimize S_{11}. In order to achieve this, polynomial curve fitting method in the MATLAB environment is applied to model input-output response of the proposed antenna. The performance of the Moth Flame optimization is further examined by optimizing the geometrical dimensions of the proposed fractal antenna and its comparison is done with other two highly explored and universally accepted optimization techniques including Genetic algorithm (GA) and Powell optimization.

II. PROPOSED FRACTAL ANTENNA DESIGN

A. Geometrical description of the proposed antenna

The proposed fractal antenna is designed on the architecture of having repeated geometry of isosceles

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triangle. Scaling is applied on the angle. In 1st iteration, isosceles triangles are cut on the opposite sides of the rectangle of basic iteration. For next iteration, these sides of triangle are taken as base to make other isosceles triangles. In 2nd iteration, isosceles triangles with 0.5 scaling factor is introduced on each side of the triangle of 1st iteration. This course of action is repeated up to 3rd iteration. The geometrical description of the proposed architecture used to arrive at final geometrical shape of the proposed fractal antenna is illustrated in Fig. 1. Here, ABDC is a rectangle having AB = CD and AC = BD as well as ΔBOD is an isosceles triangle with angle ∠OBD = α, whereas, ΔOEB is also an isosceles triangle with ∠OBE=β. Again, using the same criteria, ΔOFE is drawn with ∠OEF = γ, where:

$$\gamma = \beta / 2 = \alpha / 4. \tag{1}$$

Same process of mathematical modelling is applied in all the quadrants. Figure 1 and Table 1 represent various dimensions of the proposed antenna geometry. The basic iteration is a CPW fed rectangle of 10 mm x 20 mm. Feed width is 2.6 mm and length is 15 mm. The gap, g, between patch and ground plane is 6 mm and that between feed & ground is 0.9 mm. Width of the ground plane is 4.8 mm and length is 9 mm. Overall dimensions are 25 mm x 20 mm. Various iterations of the proposed antenna is presented in Fig. 2. Basic geometry is fabricated with RT Duroid material having ε_r = 2.2, h = 1.6 and δ = 0.02. Antenna is fed by a 50 Ω CPW feed. Copper conductor with thickness of 35 µm is used. The proposed antenna geometry is mathematically presented by an Iterative Function System (IFS). An IFS is a method to create fractals. A series of affine transformations W is applied on the basic shape, defined by [3,20]:

$$W\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} e \\ f \end{bmatrix}, \tag{2}$$

where matrix,

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} (1/s)\cos\theta & -(1/s)\sin\theta \\ (1/s)\sin\theta & (1/s)\cos\theta \end{bmatrix}, \tag{3}$$

and a, b, c, d, e & f are real numbers in which rotation and scaling is controlled by a, b, c & d, whereas linear translation is controlled by e & f. IFS generator equations for the proposed geometry are given as:

$$w_1(x,y) = \left(\frac{1}{s}\cos\theta.x - \frac{1}{s}\sin\theta.y, \frac{1}{s}\sin\theta.x + \frac{1}{s}\cos\theta.y\right). \tag{4}$$

$$\begin{aligned} w_2(x,y) = {} & \left(\frac{1}{s}\cos\theta.x + \frac{1}{s}\sin\theta.y + \frac{1}{2},\right. \\ & \left. -\frac{1}{s}\sin\theta.x + \frac{1}{s}\cos\theta.y + \frac{1}{2}\tan\theta\right), \end{aligned} \tag{5}$$

where, $\theta = \frac{44^0}{2^n}$, $s = \frac{1}{2\cos\theta}$, $n = \begin{bmatrix} 0 \text{ for } 1^{st} \text{ iteration} \\ 1 \text{ for } 2^{nd} \text{ iteration} \\ 2 \text{ for } 3^{rd} \text{ iteration} \end{bmatrix}$.

IE3D software which is based on method of moment (MOM) is used for the design and simulation of the proposed fractal antenna. It is an integrated full-wave electromagnetic simulation and optimization package used for the design and analysis of 3D and planar microwave circuits, MMIC, RFIC, RFID and antennas. Present results demonstrated in Fig. 3, illustrates that as the number of iterations goes on increasing, the lower cut off frequency of band I goes on reducing up to 2nd iteration. The lower cut off frequency in basic shape is at 6.884 GHz with S_{11} at –10.2 dB. In 1st iteration it has been shifted to 6.206 GHz with -10.35 dB S_{11}. In the 2nd iteration, it is further shifted to 6.055 GHz with S_{11} at -10.11 dB. In the 3rd iteration the lower cut off is 6.055 GHz with -10.29 dB.

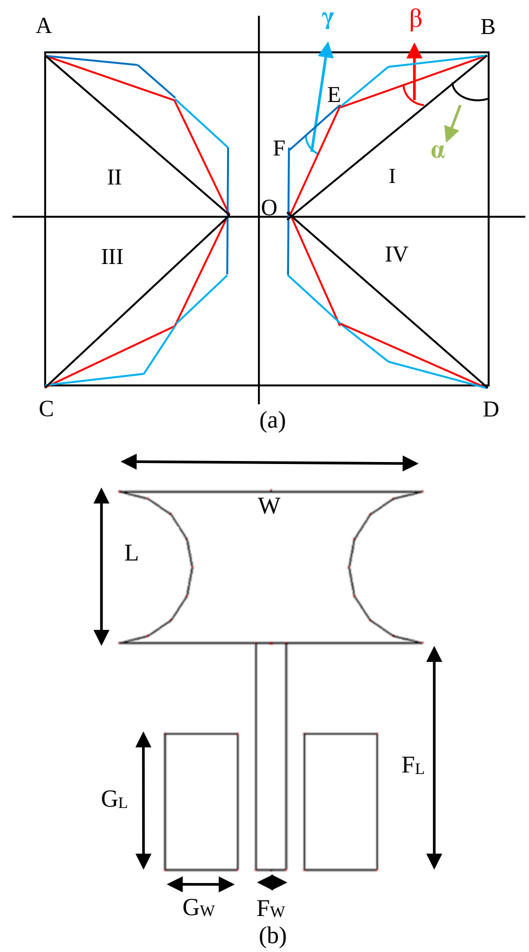


Fig. 1. Geometrical description of the proposed design.

Table 1: Dimensional parameters of proposed shape

Dimension	Value (in mm)
W	20
L	10
G_L	9
G_W	4.8
F_W	2.6
F_L	15

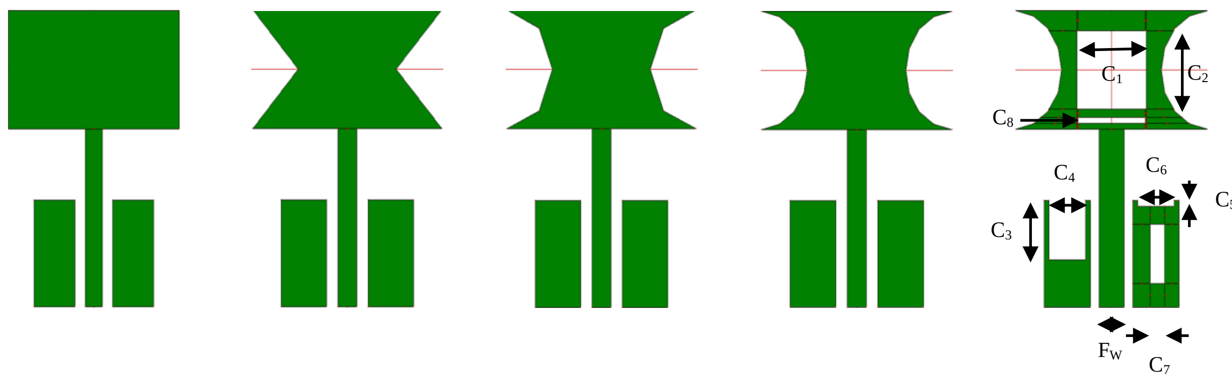


Fig. 2. Multiple iterations of the proposed design.

B. Optimization of proposed fractal antenna

Three optimization methods namely Powell, Genetic and Moth Flame optimization are applied on the proposed design in the present work to achieve best results in terms of S_{11}. Comparative evaluation of these three techniques established the effectiveness of the proposed Moth Flame optimization method. Powell Optimization method is used to find out local minima of a function when derivative is not available. A set of directions is iteratively updated to reach at the desired direction [21]. The method is used to find out local minima of a continuous but simple functions but it is really very difficult to find optimal solutions for complex multi-objective problems with desired accuracy. Moreover, the function should be real-valued with a fixed number of real-valued inputs. Genetic algorithm is a heuristic search and optimization algorithm, based on the process of natural selection. These are computational models inspired by process of evolution [22]. The method is used extensively for the optimization of microstrip patch antennas. Hence, the same has been included in the present work so as to establish the effectiveness of the MFO. In MFO, the moths are actual search managers that travel around the search space and flames are their best positions [19]. Each moth search around a flame and bring up to date itself to find a best solution intended for the proposed design as defined in Table 2, with search agents, 1000 and iterations, 200. MFO is executed in MATLAB environment in which first of all, a random matrix (M) of moths is created. Then, an array of moth fitness (OM) is computed. In the next step, a matrix of flames is calculated. Ultimately, the location of the moth (M) with respect to flame is updated using following expression:

$$M_i = S\,(M_i, F_j),$$

where S is logarithmic spiral function and is given by the following expressions:

$$S\,(M_i, F_j) = D_i.\, e^{bt}.\cos(2\pi t) + F_j,$$

$D_i = |\, F_j - M_i \,|$, i.e., distance of i^{th} moth for j^{th} flame.

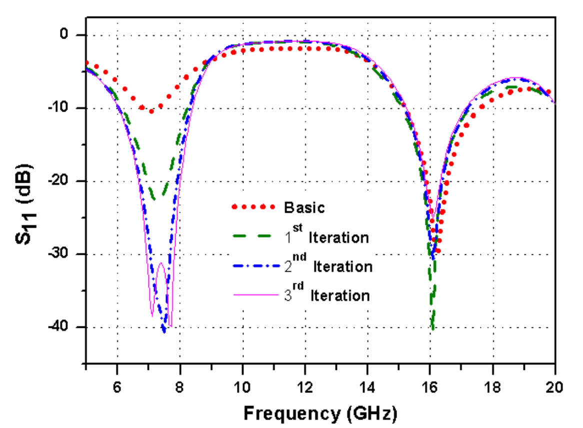


Fig. 3. Simulated S_{11} of proposed antenna in various iterations.

Table 2: Input/Output parameters for MFO with fixed C_8 (0.5 mm x 7 mm)

Parameter (in mm)	Lower Limit	Upper Limit	Optimized Value
Width, C_1	0.25	4.5	3.6
Length, C_2	0.25	4.75	3.3
Length, C_3	2	6.5	5
Width, C_4	0.8	3.8	3.8
Length, C_5	0.5	8.5	0.5
Width, C_6	0.5	3.8	3.8
Feed width, F_W	1	3.4	2.6
Width, C_7	0.5	3.5	1.5

Curve fitting tool in MATLAB is used to calculate the objective functions which are several order equations. Optimum value of the S_{11} is realized by optimizing a range of dimensions of the design. Various curve fitting equations to accomplish the task are shown in Table 3 with objective function described by:

Objective function = min $f(z)$,

$$\text{where } z = \begin{Bmatrix} z_1 \\ z_2 \\ . \\ . \\ z_8 \end{Bmatrix}.$$

Genetic, Powell and MFO have been applied on the design. From Fig. 4, it reveals that the end result obtained from moth flame optimization is best in terms of S_{11}, which must be least.

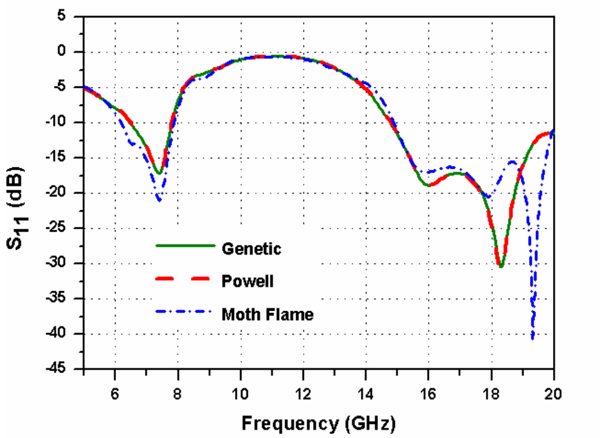


Fig. 4. Simulated S_{11} of proposed antenna with different optimization algorithms.

C. Proposed fabricated fractal antenna

In order to validate the performance of the proposed fractal antenna, the same is fabricated using printed circuit technology by making the use of single side RT Duroid copper clad board material as shown in Fig. 5. The measurements on the fabricated antenna were carried out by coupling it to the Vector Network Analyzer (ANRITSU MS46322A) through 50 ohm SMA connector. The simulated results are compared with measured results. The S_{11} is measured at different frequencies of its operation covering specified bands completely. The results are presented in next section.

III. RESULTS & DISCUSSION

A. Simulated and measured S_{11}

Experimental validation of the proposed fractal antenna is carried out by having a comparison of simulated and measured S_{11} from fabricated antenna. The graph obtained in Fig. 6 reveals that there is a good matching in simulated and measured results pertaining to S_{11}. A slight discrepancy is observed in band II which is due to fabrication tolerances as well as experimental errors. Such type of small deviation is always expected in the experimental investigations of the fabricated antenna in real time measurements.

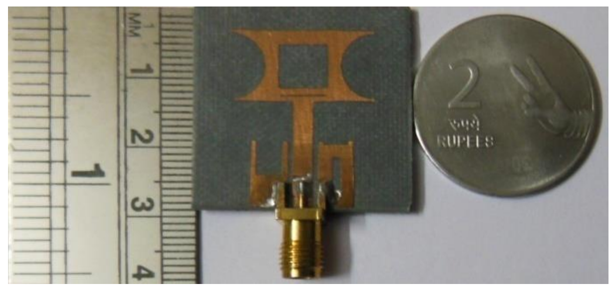


Fig. 5. Proposed fabricated fractal antenna.

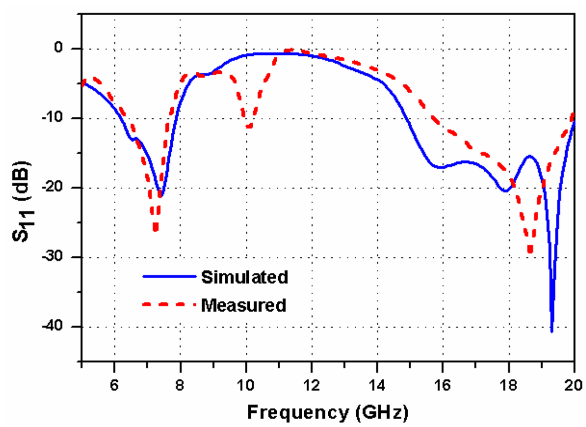


Fig. 6. Simulated and measured S_{11} of the proposed design.

Table 3: Curve fitting equations for MFO

Implemented Cut in Patch, Ground Plane	Subsequent Equation for Input-Output Response of Various Cut in Proposed Antenna
Width, C_1	$z_1 = -0.69x^6 + 10.56x^5 - 61.36x^4 + 172.2x^3 - 243.46x^2 + 160.58x - 53.58$
Length, C_2	$z_2 = 0.006x^6 - 0.08x^5 + 0.51x^4 - 1.428x^3 + 2.06x^2 - 2.57x - 9.37$
Length, C_3	$z_3 = -0.44x^6 + 10.006x^5 - 90.20x^4 + 413.97x^3 - 1021.2x^2 + 1285.1x - 664.82$
Width, C_4	$z_4 = -1.5x^3 + 9.5x^2 - 23x - 9.8$
Length, C_5	$z_5 = 0.02x^5 - 0.53x^4 + 4.406x^3 - 15.78x^2 + 27.33x - 47.26$
Width, C_6	$z_6 = 0.08x^3 - 0.64x^2 + 0.42x - 19.27$
Feed width, F_W	$z_7 = -5.65x^5 + 60.67x^4 - 246x^3 + 470.77x^2 - 432.92x + 147.07$
Width, C_7	$z_8 = -0.34x^3 + 2.93x^2 - 6.91x - 14.27$

B. Current distribution

Current distribution of the optimized geometry for two resonating frequencies is presented in Fig. 7. At lower resonant frequency, the current density is mainly due to the edges of the patch and feed, but at higher resonating frequency it is strongly confined at the edges of the cut because cylindrical cut is having more curvature than planar surface.

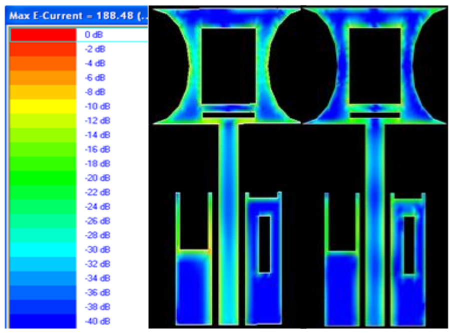


Fig. 7. Simulated current distribution at: (a) 7.412 GHz and (b) 19.32 GHz.

C. Gain versus frequency

Figure 8 reveals that gain of the proposed optimized design is positive for all frequencies of band I and band II. A significant value of gain 7.26 dBi at 18.04 GHz in band II has been achieved. Gain of the antenna is a factor which illustrates the capability of antenna to focus energy in a given direction, which is revealed by radiation pattern. Gain of the antenna should be positive.

D. Efficiency versus frequency

Figure 9 depicts the efficiency of the proposed design is more than 80% for numerous frequencies in both bands. High value of radiating efficiency is a sign of power delivered by the antenna is more and conduction-dielectric losses are less.

E. Radiation pattern

Figures 10 & 11 depict the radiation pattern of the proposed antenna for 7.03 GHz, 7.18 GHz, 7.26 GHz frequencies of band I and 18.04 GHz of band II. It may be noticed that radiation pattern is directional in elevation plane and non-directional in azimuth plane which means its radiation pattern is omnidirectional, which is the fundamental requirement of cognitive radio.

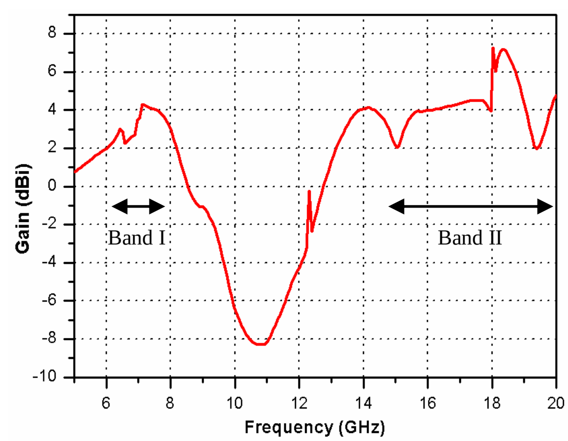


Fig. 8. Simulated peak gain vs. frequency of the proposed design.

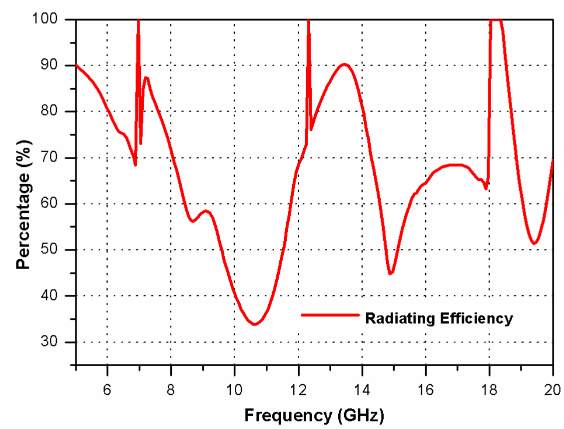
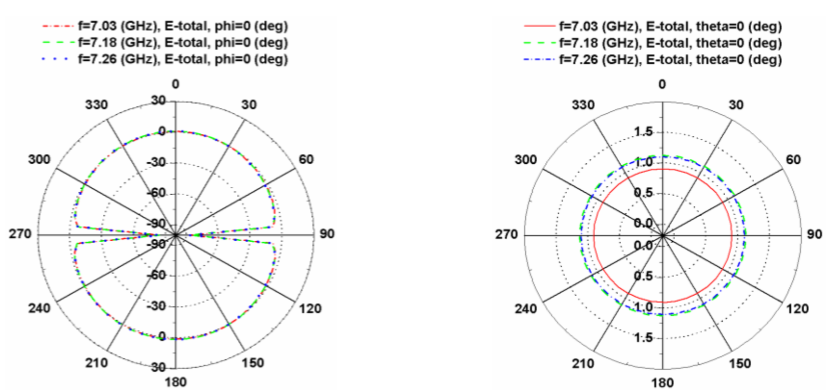
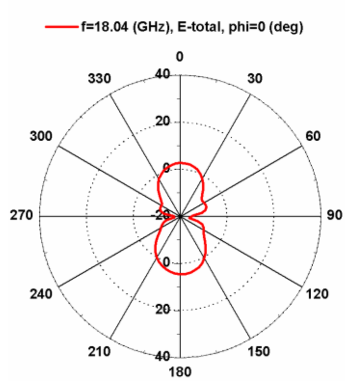


Fig. 9. Simulated efficiency of the proposed design.

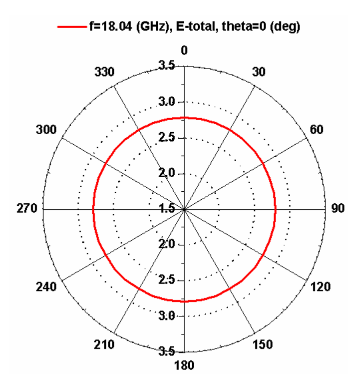


(a) (b)

Fig. 10. Radiation pattern for Band I in: (a) elevation plane and (b) azimuth plane.



(a)



(b)

Fig. 11. Radiation pattern for Band II in: (a) elevation plane and (b) azimuth plane.

IV. CONCLUSION

The results obtained illustrate that the antenna exhibits broadband characteristic within two bands (6.206 - 7.864 GHz, 23.56%) and (14.95 - 20 GHz, 28.89%) specified for IEEE C-band, Ku-band and K-band applications respectively by International telecommunication union and having very high peak gain (7.26 dBi at 18.04 GHz) and high radiation efficiency in these two bands. This antenna is also having omnidirectional radiation pattern and good impedance matching at all frequencies in both the bands thus making it a capable design for spectrum sensing in cognitive radios. From comparative evaluation, it is revealed that Moth Flame optimization technique outperforms in an attempt to achieve optimal S_{11} at most of the frequencies in the specified bands. Moreover, it is also found that very few parameters are required to be adjusted for the execution of this technique. The present study revealed that Moth flame optimization technique is an effective alternative for the optimization of microstrip fractal antennas.

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