Low-Cost Dual-Band E-shaped Patch Antenna for Energy Harvesting Applications Using Grey Wolf Optimizer

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***Abstract*—Radio frequency energy harvesting is a well promising technique for proactive energy replenishment in next-generation wireless networks. To meet the challenging requirements of power consumption in future wireless networks, new antennas must be designed. In this paper, we refer to the antenna design problem for energy harvesting applications, by introducing a low-cost dual-band E-shaped patch antenna that operates at LoRaWAN and mobile communication frequency bands. The designed antenna is tuned at two different frequencies (866 MHz, 937 MHz) with a satisfactory bandwidth for both frequency bands.**

***Index Terms*—Energy harvesting, LoRaWAN, mobile communications, patch antenna, E-shaped antenna, Grey Wolf Optimizer (GWO) algorithm.**

I. Introduction

Radio frequency (RF) energy harvesting techniques have become interesting methods to engage the next generation wireless networks in proactive energy replenishment [1]. Therefore, antenna design for energy harvesting applications in various frequency bands seems to be a challenging task. The use of microstrip patch antennas can provide a possible solution for energy harvesting systems. The main advantages of such antennas are small size, low fabrication cost, light in weight and support multiple frequency bands.

In the literature, several design efforts obtain E-shaped patch antennas in various frequency bands for energy harvesting applications. In [2], the authors designed a half and full E-shaped patch antenna operating at 2.4 GHz Wi-Fi frequency band. A slightly different design approach has been presented in [3]. The authors designed an E-shaped patch antenna which is fed by a folded L-shaped probe. In [4], the authors presented a modified E-shaped patch antenna operating at 5 GHz WLAN frequency band. A new design approach has been implemented in [5]. The authors presented a multiband patch antenna using E-shaped fractal geometry, suitable for mobile communication applications.

In this paper, we design a dual E-shaped patch antenna as an energy harvester for operation at 866 MHz and 937 MHz on a single layer. The antenna is fabricated on FR4 substrate that offers a low-cost advantage. We use a single microstrip feed, that offers additional design simplicity. The antenna is designed via the optimization of 10 different geometrical parameters. It is clear that such a design can be accomplished by using an optimization method.

Population-based algorithms like Particle Swarm Optimization (PSO) [6], Differential Evolution (DE) [7], and Teaching-Learning-Optimization (TLBO) [8] have been used in the literature for patch antenna optimization. In this paper, we propose the use of Grey Wolf Optimizer (GWO) algorithm [9], a recently introduced simple algorithm with low complexity, fewer parameters to adjust, and suitable for antenna design and optimization.

The rest of the paper is organized as follows: Section II describes the GWO algorithm. In Section III, we provide the antenna design procedure. The numerical results are depicted in Section IV. Finally, conclusions are outlined in Section V.

II. Algorithm description

The Grey Wolf Optimizer was introduced recently in [9]. It is a meta-heuristic optimization technique that has been stimulated by grey wolves (Canis lupus). The GWO algorithm imitates the basic mechanisms (hierarchy and hunting) of grey wolves in nature. It belongs to the Swarm Intelligence (SI) family algorithms. Its main characteristics are the preservation information about the search space over the course of iteration and the use of a smaller number of parameters to adjust. GWO algorithm has also fewer operators compared to evolutionary techniques.

A pack of grey wolves manifests two noteworthy social behaviors; social hierarchy and group hunting. In social hierarchy, grey wolves are ranked in four categories: alpha (α), beta (β), delta (δ), and omega (ω) (wolves categories are referred in descending order). The mathematical description of these two social behaviors are outlined in the following sections.

A. Social Hierarchy

In GWO algorithm, the first three best solutions are considered the alpha (α), beta (β) and delta (δ) categories. All the remaining solutions are counted as omega (ω). Therefore, the group hunting social behavior (optimization process) is directed by the previously mentioned categories.

B. Group Hunting

The mathematical description of prey encirclement is given by (1) and (2):

$$\vec{V} = |\vec{C}^2 \cdot \vec{P}(t) - \vec{W}(t)| \tag{1}$$

$$\vec{W}(t+1) = \vec{P}(t) - \vec{C}^1 \cdot \vec{V} \tag{2}$$

where $\vec{C}^1$ and $\vec{C}^2$ are coefficient vectors, $\vec{P}$ is the position vector of the prey, $\vec{W}$ is the position vector of the grey wolf, and t indicates the current iteration. The vectors $\vec{C}^1$ and $\vec{C}^2$ are given by (3) and (4):

$$\vec{C}^1 = 2\vec{u} \cdot \vec{v}_1 - \vec{u} \tag{3}$$

$$\vec{C}^2 = 2 \cdot \vec{v}_2 \tag{4}$$

where $\vec{u} \in [2, 0]$ and $\vec{v}_1, \vec{v}_2 \in [0, 1]$ (random vectors).

Consequently, the mathematical description of hunting behavior in grey wolves assumes that the first three best solutions are obtained by α, β and δ categories. Therefore, the rest of the pack members have to update their positions according to the position of the first three best solutions. Equations (5) - (7) describe the hunting process of GWO algorithm.

$$\begin{aligned} \vec{V}_\alpha &= |\vec{C}_1^2 \cdot \vec{W}_\alpha - \vec{W}| \\ \vec{V}_\beta &= |\vec{C}_2^2 \cdot \vec{W}_\beta - \vec{W}| \\ \vec{V}_\delta &= |\vec{C}_3^2 \cdot \vec{W}_\delta - \vec{W}| \end{aligned} \tag{5}$$

$$\begin{aligned} \vec{W}_1 &= \vec{W}_\alpha - \vec{C}_1^1 \cdot (\vec{V}_\alpha) \\ \vec{W}_2 &= \vec{W}_\beta - \vec{C}_2^1 \cdot (\vec{V}_\beta) \\ \vec{W}_3 &= \vec{W}_\delta - \vec{C}_3^1 \cdot (\vec{V}_\delta) \end{aligned} \tag{6}$$

$$\vec{W}(t+1) = \frac{\vec{W}_1 + \vec{W}_2 + \vec{W}_3}{3} \tag{7}$$

The pseudo code of GWO algorithm is outlined in algorithm 1.

Algorithm 1 GWO algorithm

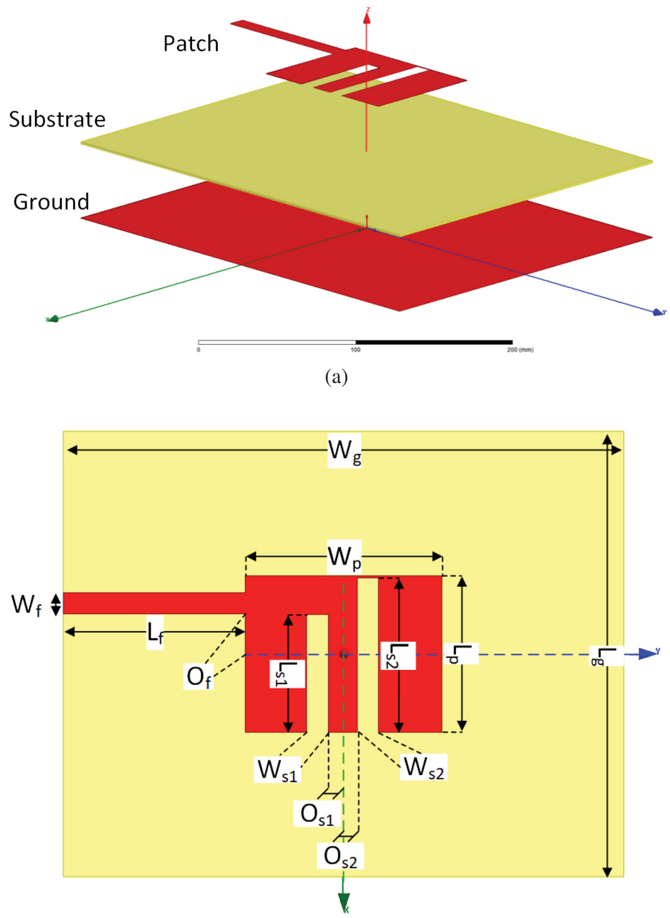
```
Initialize grey wolf population W_i (i = 1, 2, ..., n)
Initialize u, C^1, and C^2
Calculate the category position vectors: W_α, W_β, and W_δ
while (t < max no. of iterations) do
    for each member of the pack do
        Update the position vector of the current member by
        (7)
    end for
    Update u, C^1, and C^2
    Calculate the position vectors of all members
    Update W_α, W_β, and W_δ
    Set: t = t + 1
end while
```

III. Antenna Design Procedure

The dual-band E-shaped patch antenna geometry is given in Fig. 1. The proposed antenna design consists of three layers (ground plane, substrate, patch antenna - see Fig. 1a). The dimensions of the substrate (and the ground plane) are proportional to the dimensions of the patch antenna by a factor of 2.85. The dual E-shaped patch antenna is designed on a single layer of FR4 substrate ($\epsilon_r = 4.4$) with a thickness of $1.6mm$. The source point is located at the edge of the substrate. Moreover, a microstrip line is used to feed the antenna. Its length is given by:

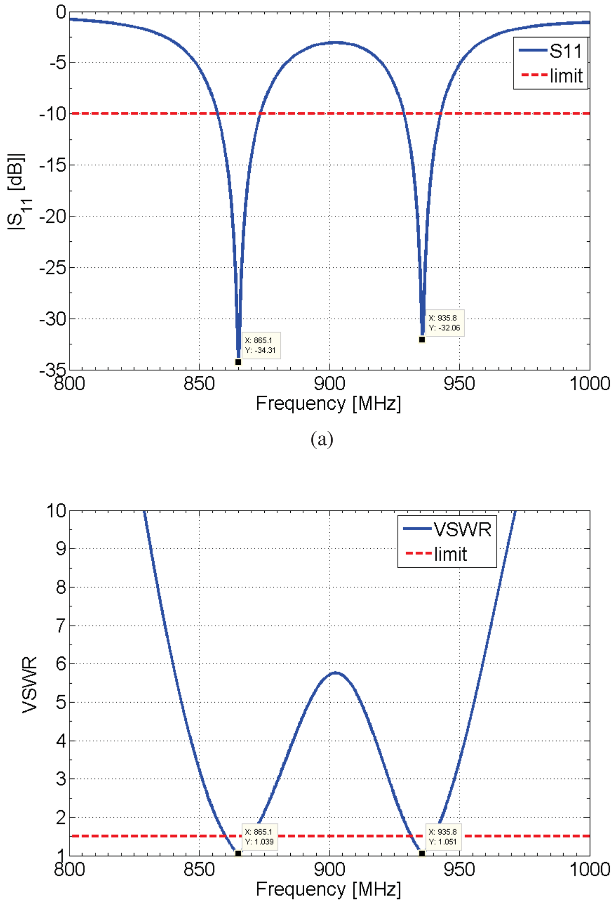
$$L_f = \frac{W_g}{2} - \frac{W_p}{2} \tag{8}$$

The rest of the design parameters which are presented in Fig. 1b are subject to modification in order to achieve the optimal design of the patch antenna. One may notice that the antenna geometry is rather complex. It consists of 10 different design parameters. Therefore, it is quite difficult to assess the effect of each parameter, in order to attain the desired antenna characteristics. As a result, an optimization technique is an



(b)

Fig. 1. Geometry of the proposed dual-band E-shaped patch antenna: (a) expanded view, (b) top view.



(a)

(b)

Fig. 2. S11 and VSWR vesrus frequency of the best antenna geometry found with GWO algorithm: (a) S11, (b) VSWR.

evident solution to the design problem previously described and, for this purpose, the GWO algorithm is selected.

The objective is to minimize the S_{11} magnitude in two different frequencies at Narrowband Internet of Things (NB-IoT) downlink bands (866 MHz and 937 MHz) below $-10dB$. The above frequencies are also used in mobile communication systems. The design problem can be defined by the following objective function:

$$F(\bar{z}) = S_{11}^{866MHz}(\bar{z}) + \Xi \times ||S_{11}^{866MHz}(\bar{z})| - |L_{dB}|| + S_{11}^{937Hz}(\bar{z}) + \Xi \times ||S_{11}^{937Hz}(\bar{z})| - |L_{dB}|| \quad (9)$$

where $\bar{z}$ is the vector of the antenna geometry variables (10 parameters), S_{11}^{866MHz} and S_{11}^{937MHz} are the desired S_{11} magnitudes, L_{dB} is the S_{11} dB limit, and Ξ is a very large number. In our case, we have set $L_{dB} = -10dB$.

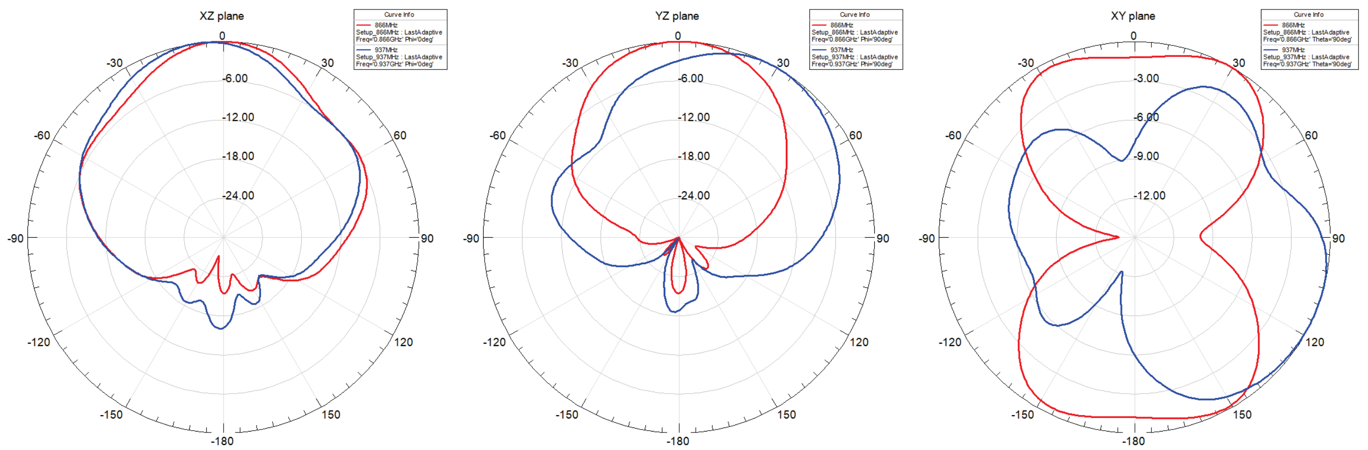
To optimize the antenna design in two different frequencies, a numerical technique for the simulation of the antenna operation is required. Therefore, the GWO algorithm is used in conjunction with a commercial 3D electromagnetic (EM) simulation software. The dual-band E-shaped patch antenna is designed in ANSYS HFSS [10]. In order to incorporate the source code of the GWO algorithm with HFSS, a wrapper batch script is created using HFSS MATLAB API [11]. The whole process can be described in algorithm 2.

Algorithm 2 Antenna design procedure

1: For each new geometry vector $\bar{y}$
2: Generate a HFSS Visual Basic script file using Matlab API
3: Execute HFSS software with the newly created script and generate antenna geometry
4: Calculate S_{11} at 866 MHz and 937 MHz and export results in an ascii file
5: Parse ASCII file and calculate objective function value
6: Return result to GWO algorithm

IV. Numerical Results

The GWO algorithm is applied for the dual-band E-shaped patch antenna using the fitness function given by (9). We



(a) (b) (c)

Fig. 3. Radiation patterns of the best antenna geometry at 866 MHz (red solid line) and 937 MHz (blue solid line): (a) $\phi = 0^0$, (b) $\phi = 90^0$, (c) $\theta = 90^0$.

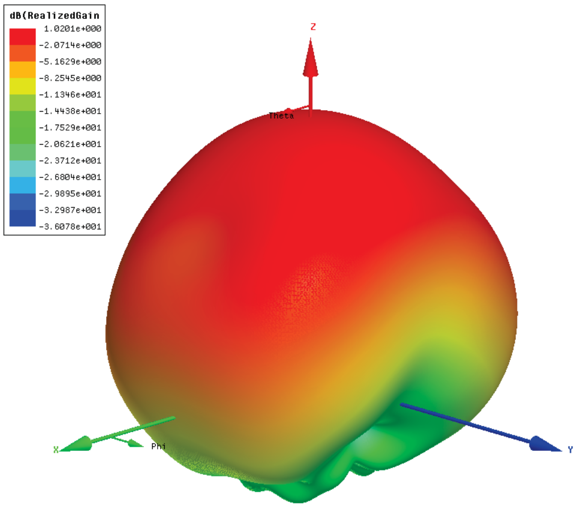
set the population size to 20 and the maximum number of iterations to 2000. The GWO algorithm is executed 10 times and the final (best) results are shown in Table I.

Figs. 2 to 5 illustrate a general view of the performance of the final dual-band E-shaped patch antenna geometry obtained by GWO algorithm. Fig. 2a depicts the S_{11} magnitude at the feeding port of the patch antenna versus frequency. The S_{11} variation shows a dual frequency tuning (865.1 MHz and 935.8 MHz) with operation $(S_{11} < -10dB)$ within the European LoRaWAN frequency band (863-870 MHz) and the EGSM-900 cellular communications frequency band (Downlink: 925-960 MHz) designated by the ITU. From the variation of the VSWR graph (Fig. 2b), it is clear that the operational frequencies of the best antenna design provided by GWO algorithm that meets the acceptable level $(VSWR < 1.5)$, is within the aforementioned frequency bands.

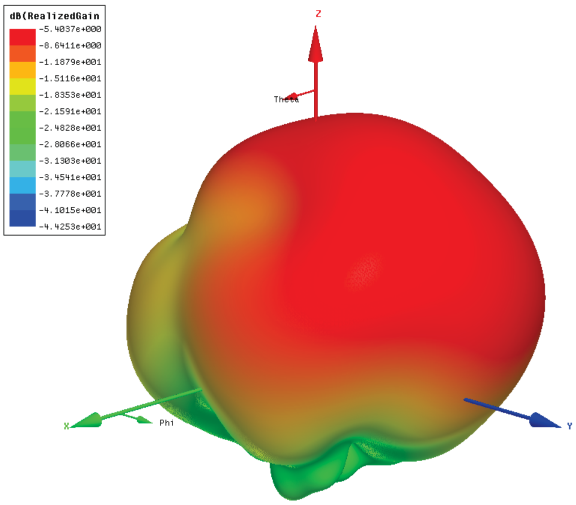
Fig. 3 presents the normalized radiation patterns (realized gain) of the best antenna geometry at 866 MHz and 937 MHz in three main planes (XY, XZ, YZ). Additionally, Fig. 4 illustrates the 3D pattern of the antenna gain obtained with GWO algorithm at both desired frequencies. Finally, Fig. 5 depicts the surface current distribution of the best antenna geometry. From the above results, it is clear that the proposed antenna can be utilized as an energy harvester in LoRaWAN and EGSM-900 mobile communication systems.

TABLE I
FINAL PARAMETER VALUES OF THE ANTENNA GEOMETRY (BEST SOLUTION) OBTAINED BY GWO ALGORITHM.

Parameter	Value (mm)	Parameter	Value (mm)
W_g	102	W_{s2}	11
L_g	81	L_{s2}	80
W_{s1}	11	O_{s2}	7
L_{s1}	61	W_f	11
O_{s1}	8	O_f	-32

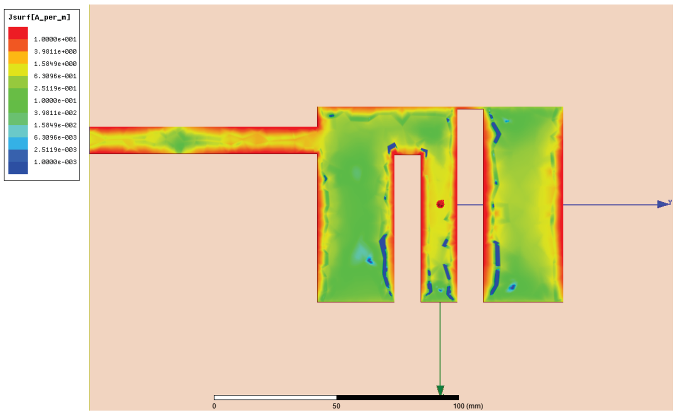


(a)

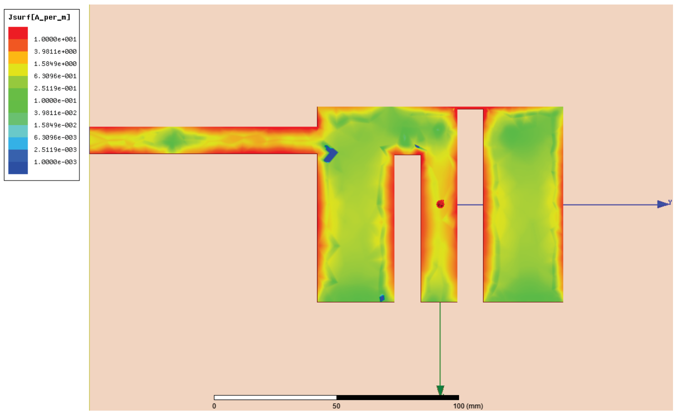


(b)

Fig. 4. 3D pattern of the antenna gain (realized gain) obtained with GWO algorithm at: (a) 866 MHz, (b) 937 MHz.



(a)



(b)

Fig. 5. Surface current distribution of the best antenna geometry derived with GWO algorithm at: (a) 866 MHz, (b) 937 MHz.

V. Conclusion

In this paper, we have presented a dual-band E-shaped patch antenna operating in LoRaWAN and EGSM-900 mobile communication networks as an energy harvester. For the design approach, a new and simple optimization technique using the GWO algorithm has been applied. From the obtained results (S_{11}, $VSWR$), it is evident that the patch antenna is tuned at two different frequency bands, covering the European LoRaWAN frequency band, as well as the EGSM-900 cellular communications frequency band. The applicability of the method described in this paper is proven by the above results. Future work includes the design of a multi-band E-shaped patch antenna, as well as fabrication and experimental validation of the system.

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References

[1] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with rf energy harvesting: A contemporary survey," *IEEE Communications Surveys Tutorials*, vol. 17, no. 2, pp. 757–789, Secondquarter 2015.

[2] R. Chair, C. . Mak, K.-F. Lee, K.-M. Luk, and A. A. Kishk, "Miniature wide-band half u-slot and half e-shaped patch antennas," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2645–2652, Aug 2005.

[3] J. Xiong, Z. Ying, and S. He, "A broadband e-shaped patch antenna of compact size and low profile," in *2008 IEEE Antennas and Propagation Society International Symposium*, July 2008, pp. 1–4.

[4] Z. Ali, V. K. Singh, A. K. Singh, and S. Ayub, "E-shaped microstrip antenna on rogers substrate for wlan applications," in *2011 International Conference on Computational Intelligence and Communication Networks*, Oct 2011, pp. 342–345.

[5] N. Bayatmaku, P. Lotfi, M. Azarmanesh, and S. Soltani, "Design of simple multiband patch antenna for mobile communication applications using new e-shape fractal," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 873–875, 2011.

[6] N. Jin and Y. Rahmat-Samii, "Parallel particle swarm optimization and finite-difference time-domain (PSO/FDTD) algorithm for multiband and wide-band patch antenna designs," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 11, pp. 3459–3468, 2005.

[7] L. Zhang, Z. Cui, Y.-C. Jiao, and F.-S. Zhang, "Broadband patch antenna design using differential evolution algorithm," *Microwave and Optical Technology Letters*, vol. 51, no. 7, pp. 1692–1695, 2009.

[8] R. Rao, V. Savsani, and D. Vakharia, "Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems," *Computer-Aided Design*, vol. 43, no. 3, pp. 303 – 315, 2011.

[9] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey wolf optimizer," *Advances in Engineering Software*, vol. 69, pp. 46 – 61, 2014.

[10] ANSYS, *Electomagnetics Suite, ANSYS: User's Guide, Version 18.0.0*, 2016.

[11] V. Ramasami, 2017. [Online]. Available: https://github.com/yuip/hfss-api/