Dual-Band Single-Layered Modified E-shaped Patch Antenna for RF Energy Harvesting Systems

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***Abstract*—Radio Frequency Energy Harvesting (RF EH) is an alternative, yet well-promising technique to deliver power in electronic circuits of wireless sensor networks that require small amounts of energy. The design of the receiving module (antenna) in RF EH systems is a demanding and, in most cases, a complex task. As a result, an optimization method is often required. In this paper, we apply The Salp Swarm Algorithm to design and optimize a receiving module (dual-band modified E-shaped antenna) for RF EH systems. The proposed antenna operates in the frequency bands of LTE-2600 and 5G NR mobile communication networks. Numerical results exhibit a satisfactory operation of the optimized antenna as a receiving module in an RF EH system.**

***Index Terms*—radio frequency, energy harvesting, salp swarm algorithm, E-shaped patch antenna, optimization method**

I. INTRODUCTION

Radio Frequency (RF) Energy Harvesting (EH) systems have become increasingly popular during the last years, as they provide an alternative, yet sustainable, way of delivering power to electronic systems that require small amounts of energy [1]. Typical examples of such systems include wireless sensor networks, Internet of Things (IoT) devices, smart metering systems, etc. RF EH can also be an alternative, yet quite promising technique for delivering power to the next generation of wireless networks [2].

A typical RF EH system consists of a rectenna. A rectenna system combines the operations of harvesting energy from the environment (receiving module) and processing and storing energy for future use (rectifying sub-module). Thus, the term rectenna originates from the words antenna + rectifier.

Radio frequency signals in energy harvesting are the main ambient energy source in both outdoor and indoor environments [3]. Typical sources of RF signals are FM and TV broadcasting, as well as mobile communications networks. Although this energy source suffers from daily variation depending on the source type (e.g mobile communication networks vary their transmitting power based on their subscribers' density within the coverage area of each base station), it is provided on a 24-hour basis with considerable amounts of power in urban environments.

Fifth Generation (5G) networks are just around the corner and their deployment will bring a revolution in applied technologies and services for the end-users [4]. Like their predecessors (1G to 4G), they are expected to be the dominant ambient power source in urban environments.

In the literature, there is an extensive research effort on designing RF EH systems for both outdoor and indoor environments. Most of these systems operate in a single [5]–[7] or a dual [8]–[10] frequency band. The choice of a compact antenna design (such as patch antenna) offers various comparative advantages including ease of fabrication, low cost, and, in most cases, medium complexity.

The design of an RF EH antenna with a compact structure that will operate at two different frequency bands of mobile communication networks is a challenging task. This task can be properly addressed by utilizing optimization algorithms in artificial intelligence. In this context, we apply the Salp Swarm Algorithm (SSA) [11] to optimize the geometry of a modified E-shaped patch antenna for RF energy harvesting applications. The SSA algorithm imitates salps behavior in deep oceans. It belongs to meta-heuristics and it is designed to obtain feasible and optimal solutions in a given optimization problem. The algorithm has been introduced recently to the literature and it can be utilized to the antenna design problem.

In this paper, we apply the SSA algorithm to address the challenging task of designing a dual-band and single-layered modified E-shaped patch antenna for RF EH applications. The proposed antenna operates in the frequency bands (downlink) of the fourth and fifth generation of mobile communication systems. To the best of the authors' knowledge, this is the first paper in the literature that addresses the issue of energy harvesting in fifth-generation communication systems.

The remainder of the paper is as follows. In Section II, we outline the mathematical formulation of the SSA that models the swarming behavior of salps to form chains in oceanic environment. Section III presents in detail the numerical results of the SSA application to the design and optimization of a modified E-shaped patch antenna for RF EH systems. Finally, Section IV concludes the results of the paper.

II. SSA Algorithm Description

SSA is a recently introduced Swarm Intelligence (SI) algorithm that is belonged to one of the three categories of meta-heuristics. Swarm intelligence algorithms imitate the social behavior of various swarms or herds of creatures in their natural environment.

The SSA algorithm mathematically models the swarming behavior of salps (barrel-shaped, planktic tunicate that moves by pumping seawater through its body) to form chains in their natural environment. Any salp chain is comprised of the leader salp (the first salp in the chain) and the followers' salps.

To model the swarming behavior of salps, let us consider as $u_{i,j}^{salp}$, the position of each salp to the position of the desired solution of the given optimization problem that can be defined as u_j^{best}. In the position expression of each salp, i is defined as the dimension of the salps population (swarm population) ($i = 1, 2, ..., M$) and j as the dimension of the decision variables for the given optimization problem ($j = 1, 2, ..., N$). At each iteration, the position of each salp is updated as

$$u_{i,j}^{salp} = \begin{cases} u_j^{best} - k_1 \cdot (bu_j - bl_j) \cdot k_2 + bl_j, \\ \text{if } i \leq M/2 \text{ and } k_3 \geq 0.5 \quad \text{(a)} \\ \\ u_j^{best} + k_1 \cdot (bu_j - bl_j) \cdot k_2 + bl_j, \\ \text{if } i \leq M/2 \text{ and } k_3 < 0.5 \quad \text{(b)} \\ \\ \frac{u_{i,j}^{salp} + u_{i-1,j}^{salp}}{2}, \quad \text{otherwise} \quad \text{(c)} \end{cases} \tag{1}$$

where $k_1 = 2 \cdot e^{-\left(\frac{4 \cdot It}{MaxIt}\right)^2}$ $\big(It = 1, 2, ..., MaxIt\big)$, k_2 and k_3 are randomly selected numbers ($k_2,\ k_3 = rnd \in [0, 1]$), bu_j and bl_j are the upper and lower boundary limits of the optimization problem, and $u_{i-1,j}^{salp}$ is the position of the $i-1$ follower salp in the $j-th$ dimension. Algorithm 1 summarizes the pseudo-code of the mathematical description of the Salp Swarm Algorithm.

Algorithm 1 Pseudo-code of the mathematical formulation that models SSA algorithm.

Define the number of iterations $MaxIt$
Define the number of salp swarm population M
Define the number of decision variables N
Define the upper bu_j and lower bl_j boundary limit for each decision variable
Initialize positions of the leader u_j^{best} and the followers salps $u_{i,j}^{salp}$
for $i = 1$ to M **do**
  Initialize the objective function OF^{salp} of each salp
end for
while $It < MaxIt$ **do**
  Compute k_1
  for $i = 1$ to M **do**
    if $i \leq M/2$ **then**
      for $j = 1$ to N **do**
        Select random numbers k_2 and k_3
        if $k_3 \geq 0.5$ **then**
          Compute salp position using eq. 1(a)
        else
          Compute salp position using eq. 1(b)
        end if
      end for
    else
      Compute salp position using eq. 1(c)
    end if
  end for
  for $i = 1$ to M **do**
    Compute the objective function OF^{salp} of each salp
  end for
  $It = It + 1$
end while

III. Numerical Results

In this paper, we design and optimize a dual-band single-layered modified E-shaped patch antenna for RF energy harvesting systems operating in urban environments. The proposed antenna is tuned in the frequency bands of LTE-2600 (Long Term Evolution, Frequency band 7 (Downlink frequencies: 2620 MHz - 2690 MHz)) and 5G NR (n78 frequency band (Downlink/Uplink frequencies: 3300 MHz - 3800 MHz)) mobile communication networks. The optimization of the antenna is carried out by utilizing the SSA algorithm.

The objective of the given optimization problem is to find a geometry solution of the proposed antenna that obtains the minimization of the reflection coefficient (S_{11} magnitude) within the desired frequency bands. To quantify the minimization constraint of the objective, we have selected the center frequencies (i.e. 2.655 GHz and 3.550 GHz) of the desired frequency bands (LTE-2600 and 5G NR). To this end, we apply the following objective function to the SSA optimization algorithm

$$\begin{aligned} F\big(\vec{u_i}\big) = & \\ & max\big(S_{11}^{2.655GHz}\big(\vec{u_i}\big), S_{11}^{3.55GHz}\big(\vec{u_i}\big)\big) \\ & + \Xi \times max\big(0, S_{11}^{2.655GHz}\big(\vec{u_i}\big) - T_{dB}\big) \\ & + \Xi \times max\big(0, S_{11}^{3.550GHz}\big(\vec{u_i}\big) - T_{dB}\big) \end{aligned} \tag{2}$$

where $F\big(\vec{u_i}\big)$ is the objective function of the position vector $\vec{u_i}$ (the elements of the position vector are the decision variables of the optimization problem), S_{11}^k $\big(k = \{2.655$ GHz, 3.550 GHz$\}\big)$ is the reflection coefficient of the patch antenna at the given frequency, T_{dB} is the reflection coefficient threshold (in dB) that is applied in the SSA algorithm, and Ξ is a very large number (e.g. 1E+10).

Fig. 1 illustrates the geometry of the proposed antenna. It consists of a modified E-shaped patch radiator with a proper

TABLE I

BEST POSITION VECTOR (OPTIMAL SOLUTION OF THE DECISION VARIABLES DESCRIBING THE GEOMETRY OF THE ANTENNA) OBTAINED BY THE SSA ALGORITHM.

Variable	**Value (mm)**	**Variable**	**Value (mm)**
W_{sub}	58.01	L_{sub}	53.00
W_{ant}	23.92	L_{ant}	26.50
W_{slot1}	1.70	L_{slot1}	8.40
W_{slot2}	2.65	L_{slot2}	14.51
W_{feed}	3.35	L_{feed}	22.13
O_{slot1}	3.40	O_{slot2}	14.59
O_{feed}	4.55		

feeding line (a source port is attached at the edge of the feeding line), a dielectric material of FR-4 substrate (relative permittivity $\epsilon_r = 4.4$, thickness $= 1.6$ mm), and a foil of ground plane (the ground plane is omitted in Fig. 1; it is placed beneath the FR-4 substrate). For the given optimization problem, we apply boundary conditions of finite conductivity (conductivity $=$ 5.80E+07 Siemens/m, relative permeability $=$ 1) in both the modified E-shaped patch antenna and the ground plane.

Table I lists the elements (a set of 13 decision variables as they indicated in Fig. 1) of the best position vector (optimal solution) obtained by applying the SSA algorithm for modified E-shaped patch antenna optimization. To achieve the optimal solution, a commercial high-frequency electromagnetic solver is combined at each iteration with the SSA algorithm.

Fig. 2 presents the reflection coefficient (S_{11} magnitude) of the modified E-shaped patch antenna versus frequency. The proposed antenna exhibits a quite satisfactory tuning operation

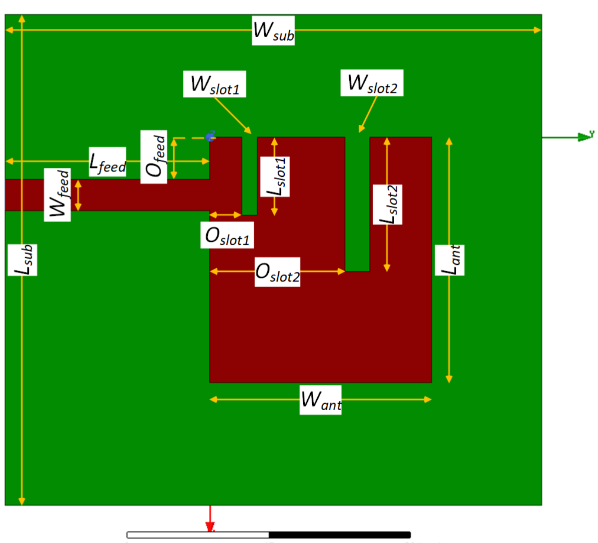


Fig. 1. Plane view of the proposed modified E-shaped antenna geometry (the decision variables of the optimization process are displayed; brown color: patch antenna with stripline, green color: dielectric material of FR-4 substrate; ground plane is omitted).

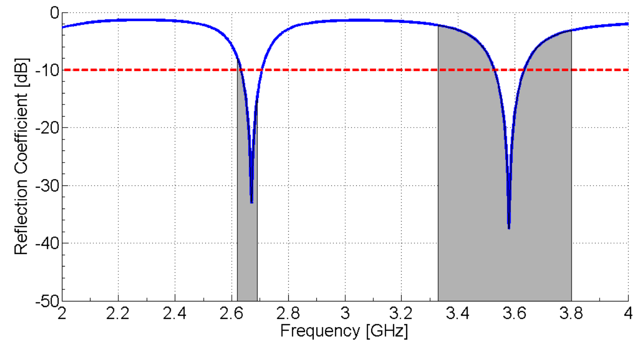


Fig. 2. Reflection coefficient (S_{11} magnitude) versus frequency of the optimal solution (best position vector) obtained by SSA algorithm (blue solid line: Reflection Coefficient (S_{11}), red dash line: -10 dB threshold, and grey shaded areas: LTE-2600 (frequency band 7) and 5G NR (n78 frequency band) mobile communication frequency bands).

within the mobile communication frequency bands of LTE-2600 and 5G NR (grey color in Fig. 2). In detail, the dual-band tuning operation resides at the frequencies of 2.670 GHz (-33.03 dB) and 3.579 GHz (-37.48 dB).

Fig. 3 portrays the input impedance of the proposed modified E-shaped patch antenna versus frequency. From the presented graph, we can conclude that the proposed antenna achieves satisfactory values of the input impedance at the frequencies of tuning operation ($48.13 - j1.14\ \Omega$ at 2.670 GHz and $48.71 - j0.30\ \Omega$ at 3.579 GHz), which are all a close approximation of the source input impedance ($50 + j0$ Ω).

Fig. 4 illustrates the realized gain (3D plot of the gain including mismatches) of the modified E-shaped patch antenna. From the presented 3D plots, we can deduce that the proposed antenna radiates (and consequently receives energy from the environment in the case of an RF energy harvester) satisfactorily at the broadside direction in both the two cases of the tuning operation frequencies. The maximum gain value achieved is 4.26 dBi at 2.670 GHz, and 2.58 dBi at 3.579 GHz.

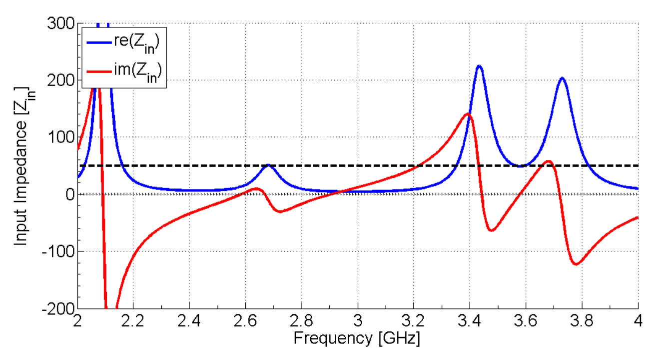
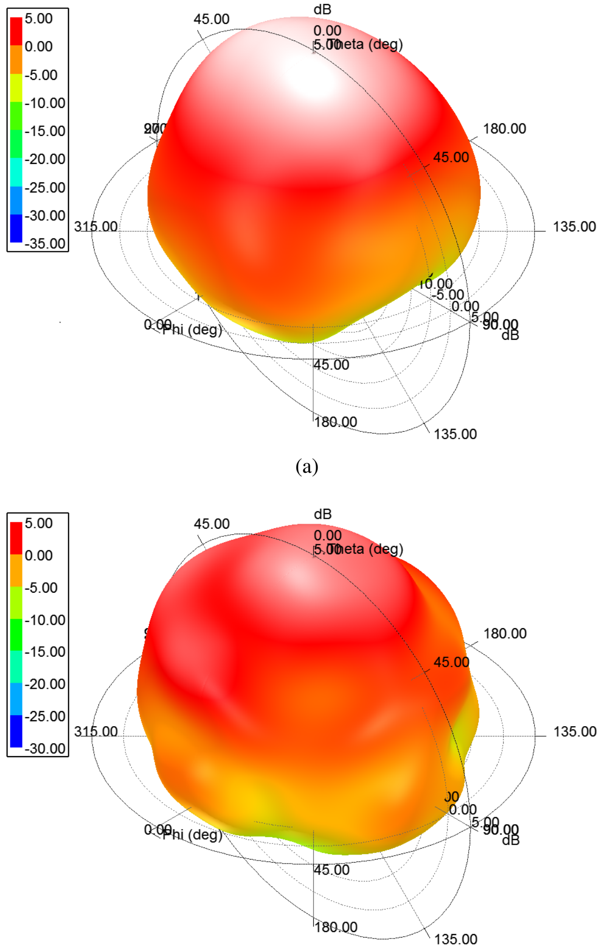


Fig. 3. Input Impedance (Z_{in}) versus frequency of the optimal solution (best position vector) obtained by SSA algorithm (blue solid line: Real part $(Re(Z_{in}))$ of input impedance, red solid line: Imaginary part $(Im(Z_{in}))$ of input impedance, black dot line: $Z_{in} = 0\,\Omega$, and black dash line: $Z_{in} = 50\,\Omega$.



(a)

(b)

Fig. 4. Realized gain of the optimal solution (best position vector) obtained by SSA algorithm: (a) 2.670 GHz and (b) 3.579 GHz (color scale in dB).

IV. Conclusion

In this paper, we have presented the design and optimization of a modified E-shaped patch antenna, as the receiving module of an RF energy harvesting system (rectenna). The proposed antenna is optimized using the Salp Swarm Algorithm. From the demonstrated results, we can derive that the patch antenna operates at two different frequency bands of LTE-2600 (frequency band 7) and 5G NR (n78) mobile communication networks, and exhibits satisfactory gain values at the desired frequencies. Future work comprises the proposed antenna prototype fabrication and experimental assessment in urban environments.

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