Modified Printed Bow-Tie Antenna for RF Energy Harvesting Applications

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***Abstract*—As the power requirements of electronic systems in wireless sensor networks are progressively reducing, radio frequency (RF) energy harvesting (EH) technique is becoming increasingly interesting during the last years. In this paper, we design and optimize a modified printed bow-tie antenna, operating in the frequency band of 5G NR mobile communication networks. For the optimization process, we have selected the Monarch Butterfly Algorithm that combines swarm intelligence and evolutionary characteristics. Computed results exhibit a quite acceptable performance of the optimized antenna as an RF energy harvester in the desired frequency band.**

***Index Terms*—radio frequency energy harvesting, bow-tie antenna, monarch butterfly optimization, evolutionary algorithm, swarm intelligence algorithm**

I. Introduction

Energy harvesting (EH) is a well-known and popular technique to deliver power in electronic circuits that require small amounts of energy to sustain their operation [1]. Radio frequency (RF) is one of the main sources of energy harvesting in the urban environment [2]. Compared to other sources of energy harvesting (e.g. solar, thermal, wind, etc.), RF EH is provided on a 24-hour basis from ambient sources in the environment. Thus, it represents a well-promising technique in the area of low-power networks, such as wireless sensor networks [3]. Typical ambient sources in an urban environment include FM/TV broadcasting and mobile communication networks.

Fifth Generation (5G) communication networks have been started to deploy in several areas around the world. According to the Global Mobile Suppliers Association (GSA) [4], by the end of May 2020, 386 operators all over the world have announced that they were investing in 5G. Moreover, a total of 81 operators in 42 countries have launched commercial 5G services to end-users. During the last year, the counted operators with commercial 5G services are increased by 10 at least every quarter. Based on the same report, the dominant frequency band of the 5G spectrum, according to the operators' investments, is the overlapping 5G New Radio (NR) n77 (3300 MHz - 4200 MHz) and n78 (3300 MHz - 3800 MHz).

Monarch Butterfly Optimization (MBO) is a recently introduced optimization technique [5] that imitates the migration process of monarch butterflies in nature. It is a nature-inspired metaheuristic algorithm that combines characteristics of swarm-intelligence [6] and evolutionary [7] algorithms to obtain optimal solutions in complex optimization problems.

Bow-tie antenna is one of the widely-known radiators in antenna design. It exhibits several advantages when compared to a linear wire or a printed dipole, such as broadband characteristics, improved directivity, and smaller size occupation in size-constrained applications [8]. The printed bow-tie antenna has been utilized in various applications of electromagnetism, including RF energy harvesting. The authors in [9] presented a printed bow-tie antenna on an FR-4 substrate, operating in the frequency band of EGSM-1800 mobile communication systems (1800 MHz). The maximum obtained reflection coefficient of the proposed antenna in the desired frequency band was about -23 dB (simulated result) and -17 dB (measured result). Based on the same substrate (FR-4), the authors in [10] introduced a broadband UHF (Ultra High Frequency) antenna of a biconical radiating dipole. The presented bow-tie antenna was operating in the frequency band of EGSM-900 mobile communication systems (900 MHz). They reported that the introduced antenna achieved a -3 dB power transmission bandwidth of 135 MHz (840 MHz - 975 MHz) that covers the whole frequency band of interest. In [11], the authors utilized a bow-tie antenna as a radiating element to propose a bow-tie array antenna of 4 $\times$ 1 for rectenna application. The antenna array was designed on an FR-4 substrate and achieved a maximum reflection coefficient of about -20 dB. Finally, the authors in [12] used a bow-tie antenna as a starting point to design a Sierpinski fractal asymmetrical bow-tie slot

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antenna operating in the frequency bands of EGSM-1800 (1800 MHz) and UMTS (2100 MHz) mobile communication systems. They reported that the maximum reflection coefficient of the proposed antenna was about -33 dB.

In this paper, we design and optimize a modified printed bow-tie antenna that operates as an electromagnetic radiation harvester in outdoor environments. The proposed bow-tie antenna is optimized using the MBO algorithm. It resonates in the frequency band of 5G mobile communication systems (5G NR n78: 3300 MHz - 3800 MHz). To the best of the authors' knowledge, this is the first time that a nature-inspired optimization algorithm has been utilizing to design and optimize a printed modified bow-tie antenna as an RF harvester that operates in the frequency band of 5G mobile communication networks. However, it is noteworthy that this topic has started to be of interest to the research community. A couple of publications for RF EH applications in the 5G frequency communication band that present less complex structures, such as a printed monopole antenna [13] or a microstrip antenna array [14], have been introduced in the literature. The usefulness of designing an antenna that operates in the 5G NR frequency communication band for RF EH applications lies to the fact that the sub-6GHz band of 5G systems will be the successor of 4G systems, providing coverage to a specific area (both outdoors and indoors) of interest. Although MIMO (Multiple Input Multiple Output) techniques will be also applied in the sub-6GHz band (5G NR1), their main application will be in the mm-Wave band (5G NR2) and mostly indoors, in order to deliver data rates to end-users in the order of Gbps.

The remainder of the paper is as follows. Section II outlines the main operations (migration operation, adjusting operation) of the MBO algorithm. In Section III, the optimal solution of the proposed antenna design obtained by the utilization of the MBO algorithm is described. Moreover, in the same section, its main results are presented. Finally, Section IV concludes the numerical results of the paper.

II. MBO Algorithm Description

Monarch Butterfly Optimization is a nature-inspired meta-heuristic algorithm that models the migration and the adjusting processes of monarch butterflies in nature, which is of the most known butterfly in Northern America territory [5]. To adjust the migration process of monarch butterflies in order to address various optimization problems, the following constraints should be considered.

- The population of the monarch butterflies is divided into two sub-populations, each one is assigned to a corresponding territory (e.g. territory A and territory B).
- Every offspring butterfly is generated either in territory A or in territory B.
- To maintain the population of the monarch butterflies immutable, each time an offspring is generated, a parent is passed away.
- Two different mechanisms model the optimization process of the monarch butterflies' behavior in nature; the migration and the adjusting processes.
- The members of the monarch butterfly population with the best fitness function are transferred to the next generation, thus staying untouched by the previously mentioned processes.

Considering the above constraints, let us define as pop_{MB} the population number of the monarch butterflies, pop_{MB}^{A} the sub-population in territory A, and pop_{MB}^{B} the sub-population in territory B, accordingly. We can easily derive that, if pop_{MB}^{ratio} is the ratio of the monarch butterflies in sub-population A, which is arbitrarily selected, then the sub-population in each territory is given by

$$\begin{aligned} pop_{MB}^{A} &= pop_{MB}^{ratio} \times pop_{MB} \\ pop_{MB}^{B} &= pop_{MB} - pop_{MB}^{A} \end{aligned} \tag{1}$$

During the migration process (a process in which a butterfly migrates from the sub-population in territory A to the sub-population in territory B), the position of the monarch butterflies in territory A is expressed by

$$MBA_{j,l}^{i+1} = \begin{cases} MBA_{c_1,l}^{i}, & \text{if } pop_{MB}^{rand} <= pop_{MB}^{ratio} \\ MBA_{c_2,l}^{i}, & \text{if } pop_{MB}^{rand} > pop_{MB}^{ratio} \end{cases} \tag{2}$$

where

- $MBA_{j,l}^{i+1}$ is the position of the j^{th} monarch butterfly in territory A at the l^{th} dimension of the $i+1$ iteration ($i = 1...MaxIt$, $j = 1...pop_{MB}^{A}$, $l = 1...MaxVar$),
- $MBA_{c_1,l}^{i}$ is the position of the $c_1 = pop_{MB}^{A} \times rnd + 0.5$ randomly selected butterfly from pop_{MB}^{A} in territory A at the l^{th} dimension of the i^{th} iteration,
- $MBA_{c_2,l}^{i}$ is the position of the $c_2 = pop_{MB}^{B} \times rnd + 0.5$ randomly selected butterfly from pop_{MB}^{B} in territory A at the l^{th} dimension of the i^{th} iteration, and
- $pop_{MB}^{rand} = rnd \times pop_{period}$ is a computed number, where $rnd \in (0,1)$ is a random number and pop_{period} is the migration period of the monarch butterflies.

During the adjusting process (a process in which the butterflies are ranked based on their score at each iteration), the position of the monarch butterflies in territory B is expressed by

$$MBB_{k,l}^{i+1} = \begin{cases} MBB_{best,l}^{i}, \\ \text{if } rnd \in (0,1) >= pop_{MB}^{ratio} \\ MBB_{c_3,l}^{i}, \\ \text{if } rnd \in (0,1) < pop_{MB}^{ratio} \end{cases} \tag{3}$$

where

- $MBB_{k,l}^{i+1}$ is the position of the k^{th} monarch butterfly in territory B at the l^{th} dimension of the $i+1$ iteration ($k = 1...pop_{MB}^{B}$),
- $MBB_{best,l}^{i}$ is the best position of monarch butterflies in pop_{MB}, and
- $MBB_{c_3,l}^{i}$ is the position of the $c_3 = pop_{MB}^{B} \times rnd + 0.5$ randomly selected butterfly from pop_{MB}^{B} in territory B at the l^{th} dimension of the i^{th} iteration.

When $rnd \in (0,1) < pop_{MB}^{ratio}$, the position of the monarch butterflies can be further updated if $rnd \in (0,1) > pop_{MB}^{rate}$, by applying the Lévy flight (a random trajectory in which the step-lengths follow the Lévy distribution). The expression of the updated position is given by

$$MBB_{k,l}^{i+1} = MBB_{k,l}^{i+1} + f \times \left(step_{Levy} - 0.5\right) \quad (4)$$

where

- f is a scale factor in the adjusting process that is defined as $f = step_{max}/i^2$,
- $step_{Levy}$ is the step of the k^{th} monarch butterfly that is computed by performing a Lévy flight, and
- pop_{MB}^{rate} is the monarch butterfly adjusting rate.

In Algorithm 1, the mathematical description in pseudo-code that models the migration and the adjusting processes of monarch butterflies in nature is outlined. A detailed description of the monarch butterfly algorithm and its processes can be found in [5].

Algorithm 1 Pseudo-code of MBO algorithm.

Define the population number of monarch butterflies pop_{MB} and the the ratio pop_{MB}^{ratio} of the monarch butterflies in territory A
Compute the sub-population numbers pop_{MB}^{A} and pop_{MB}^{B} in territories A and B, accordingly
Define the number of iterations $MaxIt$ and the number of decision variables $MaxVar$ in the optimization process
for $i = 1$ to $MaxIt$ **do**
  ——————Migration process——————
  for $j = 1$ to pop_{MB}^{A} **do**
    for $l = 1$ to $MaxVar$ **do**
      Compute pop_{MB}^{rand}
      if $pop_{MB}^{rand} <= pop_{MB}^{ratio}$ **then**
        Compute randomly selected coefficient c_1
        Compute monarch butterfly position using (2a)
      else
        Compute randomly selected coefficient c_2
        Compute monarch butterfly position using (2b)
      end if
    end for
  end for
  ——————Adjusting process——————
  for $k = 1$ to pop_{MB}^{B} **do**
    Define $step_{Levy}$ and MB adjusting rate pop_{MB}^{rate}
    Compute scale factor f
    for $l = 1$ to $MaxVar$ **do**
      if $rnd \in (0,1) >= pop_{MB}^{ratio}$ **then**
        Compute monarch butterfly position using (3a)
      else
        Compute randomly selected coefficient c_3
        Compute monarch butterfly position using (3b)
        if $rnd \in (0,1) > pop_{MB}^{rate}$ **then**
          Compute monarch butterfly position using (4)
        end if
      end if
    end for
  end for
  Compute the fitness function for the position of each monarch butterfly
end for

III. Numerical Results

Within the context of this paper, we design and propose an optimal solution geometry of a modified printed bow-tie antenna, which is suitable for RF energy harvesting applications. The proposed antenna operates in the 5G mobile communication systems frequency band (5G NR n78: 3300 MHz - 3800 MHz). The optimization process is carried out using the MBO algorithm. We set the dimensionality $MaxVar$ of the problem equal to 16, the population size pop_{MB} equal to 50, and the maximum number of function evaluations $MaxFES$ equal to 10000.

The objective of the design problem is to obtain an antenna geometry that satisfies certain criteria that lead to the optimization (minimization) of the reflection coefficient (S_{11} magnitude) within the previously mentioned operating frequency band. These criteria include the selection of the center frequency of the desired frequency band and the acceptance of a monarch butterfly solution reflection coefficient that is less than or equal to -10 dB. Taking into consideration the above criteria, the objective (fitness) function can be expressed as

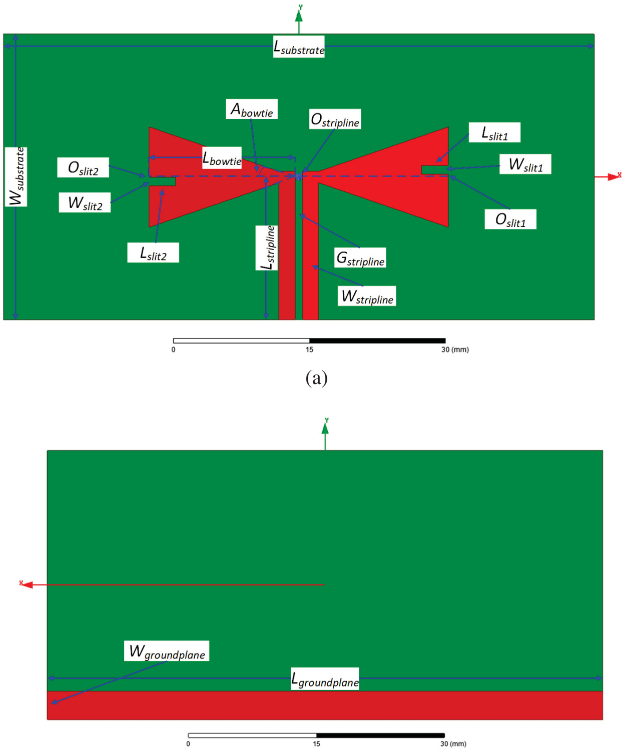
$$\begin{aligned} F\left(\vec{MB}_i\right) = {} & max\left(S_{11}^{3.550GHz}\left(\vec{MB}_i\right)\right) \\ & + \Psi \times max\left(0, S_{11}^{3.550GHz}\left(\vec{MB}_i\right) - L_{dB}\right) \end{aligned} \quad (5)$$

where

- $F\left(\vec{MB}_i\right)$ is the objective function of the position vector $\vec{MB}_i$ for the entire population number pop_{MB} of monarch butterflies,
- S_{11} is the reflection coefficient of the printed bow-tie antenna at the center frequency of the desired band,
- L_{dB} is the limit in dB for a solution of a monarch butterfly to be considered in the optimization process, and
- Ψ is a number (1E+10) that is assigned to the result of the objective function when the solution is less than the corresponding limit.

Fig. 1 illustrates the design of the proposed antenna. It comprises of a modified printed bow-tie antenna, along with two slits, that is attached to an FR-4 substrate (relative permittivity ϵ_r = 4.4, thickness = 1.6 mm). The antenna is fed using a series of parallel printed microstrip lines. Beneath the substrate layer, a metal strip foil is attached at the edge of the microstrip lines as a partial ground plane. Finally, boundary conditions of finite conductivity (conductivity = 5.80E+07 Siemens/m, relative permeability = 1) are applied in the radiator, the microstrip lines, and the partial ground plane.

Table I lists the values of the decision variables, as they indicated in Fig. 1a, which are obtained by utilizing the MBO algorithm. The optimization process in the given problem is carried out as follows. At each iteration i, the MBO algorithm



(a)

(b)

Fig. 1. (a) Top and (b) bottom view of the proposed modified printed bow-tie antenna geometry (the decision variables of the optimization problem are indicated; red color: bow-tie antenna with a series of microstrip lines, partial ground plane, green color: FR-4 dielectric substrate).

is applied to derive an antenna design solution for every monarch butterfly in the population. These design solutions are used as an input to a high-frequency electromagnetic solver (HFSS, © 2020 ANSYS, Inc.) to compute the antenna reflection coefficient at the desired frequency band. The extracted results are compared to the predefined limit and the final result is parsed to the MBO algorithm to form the fitness function vector for the monarch butterflies population.

Fig. 2 depicts the reflection coefficient (S_{11} magnitude) versus frequency of the proposed modified planar bow-tie antenna with and without the existence of the slits. From the presented results we can easily conclude that the existence of the two slits in the bow-tie antenna enhances its performance in terms of its reflection coefficient. The modified bow-tie antenna achieves a quite satisfactory tuning operation at 3.524 GHz (-59.27 dB) and its -10 dB bandwidth resides between 3.171 GHz and 3.864 GHz, covering the whole n78 frequency band of 5G NR communication systems. It is noteworthy that the lack of the two slits in the bow-tie antenna deteriorates the tuning operation of the reflection coefficient of more than 26 dB.

TABLE I
OPTIMAL ANTENNA GEOMETRY (BEST POSITION VECTOR - SOLUTION OF THE OPTIMIZATION PROBLEM) OBTAINED BY THE MBO ALGORITHM.

Variable	Value	Variable	Value
L_{bowtie}	16.41 mm	A_{bowtie}	0.331 rad
L_{slit1}	3.00 mm	W_{slit1}	1.00 mm
O_{slit1}	0.30 mm	L_{slit2}	3.00 mm
W_{slit2}	1.00 mm	O_{slit2}	-1.00 mm
$L_{stripline}$	16.69 mm	$W_{stripline}$	1.80 mm
$G_{stripline}$	0.83 mm	$O_{stripline}$	0.62 mm
$L_{substrate}$	66.47 mm	$W_{substrate}$	32.14 mm
$L_{groundplane}$	66.47 mm	$W_{groundplane}$	3.34 mm

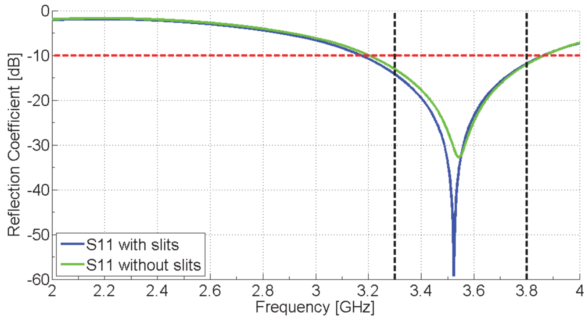


Fig. 2. Reflection coefficient (S_{11} magnitude) versus frequency of the optimal antenna geometry (best position vector - solution of the optimization problem) obtained by MBO algorithm (blue solid line: reflection coefficient (S_{11}) of the proposed modified printed bow-tie antenna with two slits, green solid line: reflection coefficient (S_{11}) of the proposed antenna without the two slits present, horizontal red dash line: -10 dB limit, and vertical black dash lines: 5G NR (n78 frequency band) mobile communication systems frequency band).

Fig. 3 presents the input impedance (real and imaginary part) versus frequency of the proposed modified printed bow-tie antenna. From the presented result we can derive that the optimized antenna exhibits a quite satisfactory performance in the desired frequency band. At the tuning operation of 3.524 GHz, the proposed antenna has an input impedance of $49.89 - j0.01\ \Omega$, which is close to the input impedance of the source port ($50 + j0\ \Omega$), thus maximizing the power transfer from the antenna to the rectifier in a rectenna system.

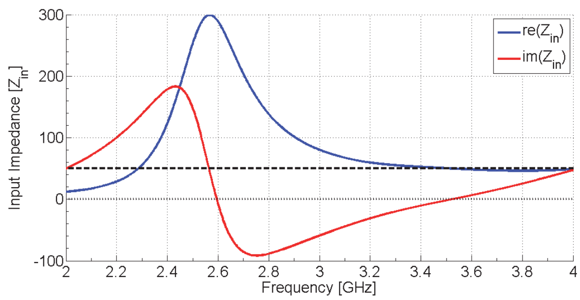


Fig. 3. Input Impedance (Z_{in}) versus frequency of the optimal antenna geometry (best position vector - solution of the optimization problem) obtained by MBO algorithm (blue solid line: Real part $(Re(Z_{in}))$ of input impedance, red solid line: Imaginary part $(Im(Z_{in}))$ of input impedance, black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

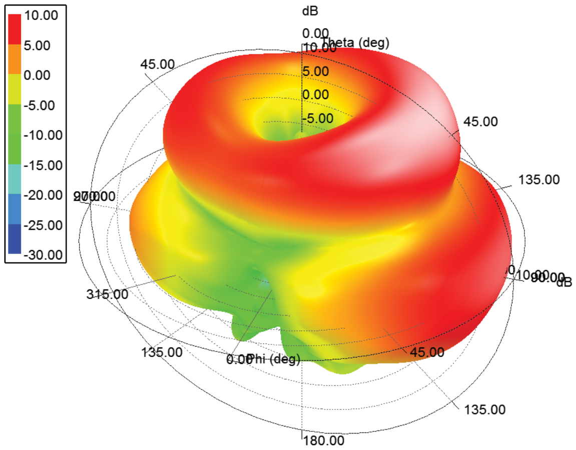


Fig. 4. Realized gain of the optimal antenna geometry (best position vector - solution of the optimization problem) obtained by MBO algorithm at 3.524 GHz (color scale in dB).

Fig. 4 portrays the realized gain of the modified printed bow-tie antenna in a 3D plot at the frequency of 3.524 GHz. From the presented graph we can conclude that the proposed antenna operates quite acceptably as an RF energy harvesting module in a rectenna system. The maximum gain value obtained is 8.63 dBi and the computed efficiency of the antenna is 96%.

IV. Conclusion

In this paper, we have demonstrated the optimization of a modified printed bow-tie antenna, operating in the 5G NR n78 mobile communication systems frequency band. For the optimization process of the antenna design, the Monarch Butterfly Optimization algorithm is applied. From the presented results we can conclude that the proposed optimized antenna operates acceptably in the desired frequency band, its -10 dB operating bandwidth covers the entire frequency band of interest, its input impedance is close to the source input impedance, and it delivers high gain values. Future work includes the comparison of the MBO algorithm performance against other popular optimization algorithms, as well as the fabrication and experimental validation of the proposed antenna.

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