Wearable 5-Gigahertz Wi-Fi Antenna Design Using Whale Optimization Algorithm

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***Abstract*—In this paper, we design an antenna for wearable wireless applications. The proposed antenna is a planar inverted-F antenna (PIFA) for operation at 5 GHz. The antenna design procedure is accomplished using a new nature inspired algorithm, the Whale Optimization Algorithm. Numerical results exhibit the applicability and validity of the proposed design framework.**

***Index Terms*—wearable antennas, whale optimization algorithm, nature-inspired algorithms, printed inverted-F antenna.**

I. INTRODUCTION

Wearable devices have drawn a lot of attention during the last years, as they can potentially improve wireless communications in a wide range of applications related to health, athletics, public and emergency rescue services, and social care services of young and elderly people. One of the most important antenna features in these devices is that they support wireless transmission from or towards the body. Therefore, these antennas are designed under different requirements as compared as to their counterparts in free space. The main design challenge in this case is securing stable performance on the human body [1] - [3].

The design of wearable antennas includes several factors to consider. Above all is the realized gain achieved and their radiation pattern. Human body is a large non-homogeneous lossy dielectric object that can affect antenna input impedance behavior and radiation. In addition it tends to decrease gain by absorbing the power. A homogeneous pattern is thus preferred to cover several possible base-station positions while a separating layer between the antenna and the body can possibly alleviate gain decrease. Additional parameters to take into account include, planar design, feeding type etc.

Nature-inspired algorithms are global optimizers suitable for any kind of engineering problem. In this paper, we apply a recently proposed nature-inspired algorithm, the so-called Whale Optimization Algorithm (WOA) [4]. This algorithm is inspired by the social and hunting behavior of whales. We apply the WOA to a wearable antenna design case for operation in the Wi-Fi 5 GHz frequency band. The proposed antenna is a planar inverted-F antenna (PIFA), which was initially designed to support data telemetry and wireless harvesting inside the human body [5].

The rest of this paper is structured as follows. Section II briefly describes the algorithm details, Section III demonstrates the antenna design and numerical results. Finally, we conclude our paper in Section IV.

II. WHALE OPTIMIZATION ALGORITHM DESCRIPTION

The Whale Optimization Algorithm (WOA) is a nature-inspired metaheuristic algorithm, which was recently proposed in [4]. It is based on the social and the hunting behavior of humpback whales. In the natural environment, whales can identify the prey location and perform specific movements to encircle them. WOA models the prey as the best solution found in each iteration. All the population members (whales) try to reach close to that best solution and they update their positions accordingly. The whale behavior (prey encirclement in optimization process) in WOA can be mathematically expressed by the following equations:

$$D_j = \left|C_j \times x_{j,G}^{best} - x_{j,G}^i\right| \tag{1}$$

$$x_{j,G+1}^i = x_{j,G}^{best} - A_j D_j \tag{2}$$

where G indicates the current iteration, $x_{j,G}^i$ is the $i-th$ population member in the $j-th$ dimension, $x_{j,G}^{best}$ is the best solution found in the $j-th$ dimension, D_j is the distance vector of the current whale to the prey, and C_j, A_j are the coefficient vectors in the $j-th$ dimension ($j-th$ dimension refers to the vector of the decision variables in an optimization problem). The latter vectors are computed as follows:

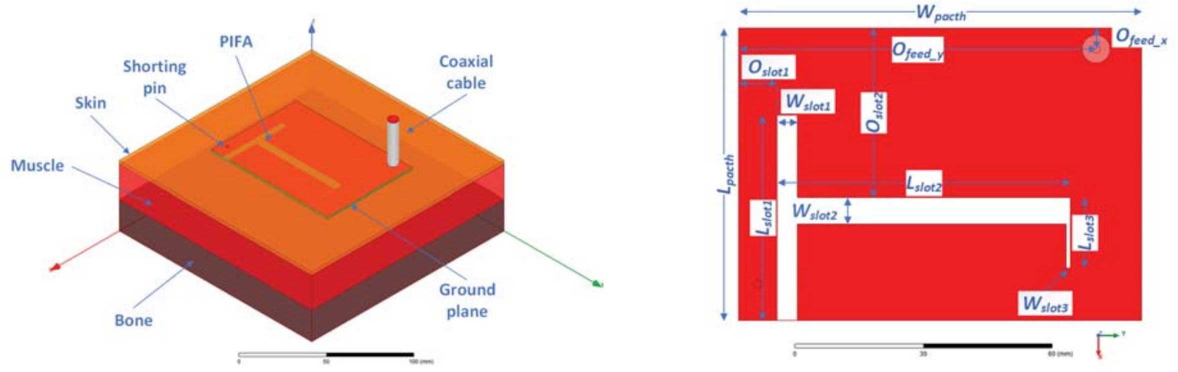
$$A_j = 2a_j rand_j - a_j \tag{3}$$

$$C_j = 2rand_j \tag{4}$$

where a_j is a number $\in [2, 0]$, which is linearly decreased during the iteration process (in both exploration and exploitation phases), and $rand_j$ is a uniformly distributed random number $\in [0, 1]$.

WOA also mathematically models the bubble-net behavior of humpback whales, which corresponds to the exploitation phase of the optimization process. This is accomplished by combining two different movement mechanisms: (a) an encircling mechanism with a shrinking radius and (b) an updating position mechanism with a spiral trajectory. The latter is modeled using a spiral equation that mimics the helix-shaped motion of humpback whales. It is expressed as:

$$x_{j,G+1}^i = B_j e^{ks} cos(2\pi s) + x_{j,G}^{best} \tag{5}$$



(a) (b)

Fig. 1. Geometry of the proposed wearable antenna operating in the Wi-Fi 5 GHz frequency band obtained by WOA: (a) 3D model view, (b) plane view of the proposed PIFA (optimization geometry parameters are indicated).

where B_j is the $j-th$ coordinate of the distance vector of the $i-th$ solution to the best solution, k is a constant number that defines the shape of the logarithmic spiral, and s is a uniformly distributed random number $\in [-1, 1]$.

The humpback whales perform two different mechanism movements at the same time; they swim towards the prey in a circle with a shrinking radius and along a spiral-shaped trajectory. The authors in [4] chose to model this behavior based on 50% probability, which can be expressed as:

$$x^i_{j,G+1} = \begin{cases} x^{best}_{j,G} - A_j D_j, & if \;\; b < 0.5 \\ B_j e^{ks} cos(2\pi s) + x^{best}_{j,G}, & otherwise \end{cases} \tag{6}$$

where b is a random number $\in [0, 1]$.

Moreover, the humpback whales search for prey on a random pattern. This is the exploration phase of WOA in the optimization process, and it is given by:

$$D_j = \left| C_j \times x^r_{j,G} - x^i_{j,G} \right| \tag{7}$$

$$x^i_{j,G+1} = x^r_{j,G} - A_j D_j \tag{8}$$

where r, with $r \neq i$ is a randomly selected member of the population that the $i-th$ member will follow.

To better comprehend the functionality of the WOA, the pseudo-code is summarized in Algorithm 1. During the initialization, the Whale optimization algorithm applies a set of random solutions to each of the population member. Then, at each iteration, the position vectors, as well as the distance vectors to the prey are computed with respect to either a random search pattern or the best fitness values obtained so far. The a_j parameter controls the exploitation and the exploration phases of the algorithm. Finally, the b parameter provides a switching between the encircling mechanism with a shrinking radius and an updating position mechanism with a spiral trajectory.

III. NUMERICAL RESULTS

In this paper, we apply the Whale Optimization algorithm to obtain an optimal solution in the design of a wearable antenna tuned at the Wi-Fi 5 GHz operating band. Fig. 1 illustrates the proposed wearable antenna model. It is a planar inverted-F antenna (PIFA) [5] above a three-layer phantom that emulates the main tissues of a human arm (skin, muscle, bone). The PIFA is designed between a double substrate (substrate, superstrate) of Rogers RO3210 material (thickness = 1.6 mm) with relative permittivity ϵ_r = 10.2. The antenna is fed by the use of a coaxial cable. A ground plane is adjacent to the superstrate (right on top), thus forming the final design of the PIFA (note that only the PIFA antenna has slots, thus forming the planar inverted-F structure. Ground plane and

Algorithm 1 Pseudo-code of the WOA.

```
Define the number of decision variables in the optimization problem $(j = 1, 2, \cdots, m)$
Define the population number of whales $(i = 1, 2, \cdots, n)$
Compute the position vectors for each population member $x^i_j$
Find the population member with the best position vector $x^{best}_j$
while $(G < G_{max})$ do
    for $(j = 1 : m =)$ do
        Compute $a_j$, $rand_j$, $A_j$, $C_j$
        for $(i = 1 : n)$ do
            if $(b < 0.5)$ then
                if $(|A_j| \geq 1)$ then
                    Compute distance vector $D_j$ using (7)
                    Compute position vector $x^i_{j,G+1}$ using (8)
                else
                    Compute distance vector $D_j$ using (1)
                    Compute position vector $x^i_{j,G+1}$ using (2)
                end if
            else
                Compute position vector $x^i_{j,G+1}$ using (5)
            end if
        end for
    end for
    Set: $G = G + 1$
end while
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substrate/superstrate layers are solid). It is worth mention that the coaxial pin is probing the PIFA via the ground plane. In our proposed design, we apply boundary conditions of perfect electric conductor (PEC) in both the PIFA and the ground plane. Moreover, we set the dielectric properties values (relative permittivity or dielectric constant e_r, electric (bulk) conductivity in $siemens/m$) of the human tissues as follows: skin = (35.5, 3.29), muscle = (49.2, 4.37), and bone = (9.9, 1.03), which correspond to the tuning frequency of 5.29 GHz.

From Fig. 1 we can conclude that, in order to describe the geometry of the proposed wearable antenna, a considerable number of parameters (12) is required. To this end, we apply the WOA to find an optimal solution of the proposed PIFA. The Whale optimization algorithm is combined with a 3D electromagnetic field simulator by the use of a HFSS-MATLAB-API wrapper [6]. We set the population size of the WOA equal to 50 and the maximum number of iterations equal to 1000.

Fig. 2 presents the S_{11} parameter (reflection coefficient) of the best wearable antenna design achieved by WOA. From the presented graph we can derive that the proposed PIFA has a resonance of -34.74 dB at 5.286 GHz, which is within the Wi-Fi 5 GHz frequency band. Its operational bandwidth ($S_{11} < -10dB$) is 8.36% or 444 MHz.

Fig. 3 portrays the radiation pattern (Fig. 3a) and the 3D polar plot (Fig. 3b) of the realized gain of the best wearable antenna obtained by WOA. From the depicted graph, we can conclude that the proposed PIFA exhibits broadside beamwidth in both main planes (XZ, YZ) and achieves satisfactory gain values (maximum value of 6.05 dB).

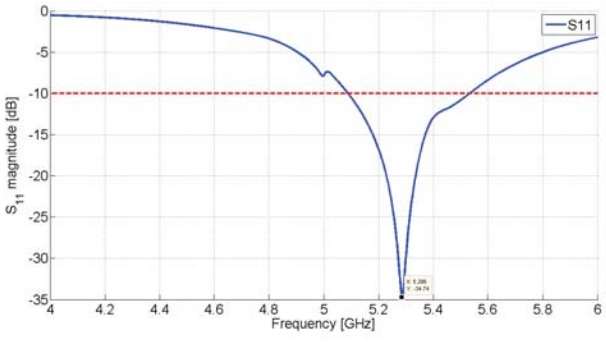
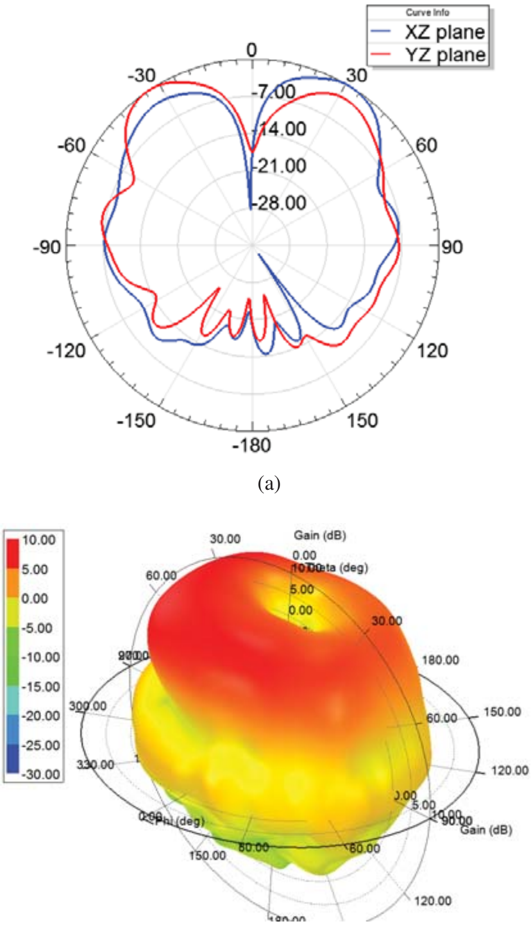


Fig. 2. S_{11} parameter (return loss) of the proposed wearable antenna operating in the Wi-Fi 5 GHz frequency band obtained by WOA (blue solid line: S_{11} parameter, red dash line: -10 dB limit).



(a)

(b)

Fig. 3. Realized gain of the proposed wearable antenna operating in the Wi-Fi 5 GHz frequency band achieved by WOA. (a) normalized radiation pattern (blue solid line: XZ plane, red solid line: YZ plane), (b) 3D polar plot (color scale in dB).

IV. CONCLUSION

In this paper, we have presented a PIFA operating in the Wi-Fi 5 GHz frequency band, suitable for wearable wireless applications. The proposed antenna is optimized based on a design framework using the Whale Optimization Algorithm. From the derived results, we can conclude that the PIFA is tuned at the desired frequency band, exhibits broadside beamwidth at both main planes, and achieves high gain values. Future work includes the fabrication and the experimental assessment of the proposed wearable antenna in textiles.

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