Dual-Band Frequency Selective Surface Design Using Harris Hawks Optimization

Achilles D. Boursianis
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
bachi@physics.auth.gr

Marco Salucci
ELEDIA Research Center
University of Trento
Trento, Italy
marco.salucci@eledia.org

Stavros Koulouridis
Dept. of Electrical and Computer Eng.
University of Patras
Patras, Greece
koulouridis@upatras.gr

Apostolos Georgiadis
Heriot-Watt University
Edinburgh, UK
apostolos.georgiadis@ieee.org

Manos Tentzeris
School of ECE
Georgia Institute of Technology
Atlanta, USA
etentze@ece.gatech.edu

Sotirios K. Goudos
ELEDIA@AUTH, School of Physics
Aristotle University of Thessaloniki
Thessaloniki, Greece
sgoudo@physics.auth.gr

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***Abstract*—Frequency Selective Surfaces (FSSs) are periodic structures that are designed to reflect, absorb or transmit electromagnetic fields in a variable frequency range. Their performance is strongly dependent on their fundamental structure, i.e. the unit cell. In this paper, we exploit the characteristic of absorption to design a dual-band FSS suitable for indoor RF energy harvesting systems. We combine an optimization technique by utilizing the Harris Hawk Optimization (HHO) algorithm and a high-frequency electromagnetic solver to optimize the geometry of the unit cell and the overall FSS. The proposed system operates in the frequency bands of Wi-Fi 2.4 GHz and Wi-Fi 5 GHz. Numerical results demonstrate that the optimized FSS exhibits quite satisfactory results and makes it a suitable candidate for RF energy harvesting applications.**

***Index Terms*—Frequency selective surface, RF energy harvesting, Harris Hawk Optimization, dual-slot, optimization method.**

I. Introduction

Next-Generation Wireless Networks (NGWN) will face several challenges in their deployment, including ultra-low power consumption. A well-promising technique to address this challenge is Radio Frequency (RF) Energy Harvesting (EH) [1]. Characteristics such as decoupling, isolation, and spatial filtering, will be paramount in these mobile communication networks since they will combine multiple diverse services that require different frequency ranges to operate. An electromagnetic device that combined the previously mentioned characteristics, among all, is a Frequency Selective Surface (FSS) [2].

FSSs have been extensively studied in the literature over the past four decades. Recently, they have attracted the interest of the researchers due to their combined characteristics and their wide range of applicability. FSSs are electromagnetic devices that are synthesized by a repetitive (periodic) structure [2]. They are designed to reflect [3], absorb [4] or transmit [5] electromagnetic energy based on the frequency or the frequency range of the incident field. The overall performance of the FSS strongly depends on the unit cell geometry (FSS-element), the substrate of the EM device and the inter-element spacing [2].

The key parameter to synthesize an FSS structure with the desired characteristics (reflectivity, transmissivity, absorptivity) is the unit cell geometry. In the literature, various designs of FSS-elements have been presented. The periodic structure of an FSS is also suitable for a receiving module of a rectenna system (antenna + rectifier). Therefore, FSSs can be applied in Radio Frequency (RF) Energy Harvesting (EH) systems by enabling absorptive characteristics.

The process of FSS design is complex and usually involves the tuning of several geometrical parameters. Such a design process is difficult to complete using a simple trial and error strategy. In many cases, an optimization method like an Evolutionary Algorithm (EA) is a suitable technique for addressing this type of problem.

Harris Hawk Optimization (HHO) is a recently proposed population-based EA [6]. In this paper, we apply the HHO algorithm to design FSS structures suitable for RF EH applications. To the best of the authors' knowledge, this is the first time that the HHO algorithm is utilized to address an antenna design problem.

The rest of this paper is organized as follows. Section II briefly describes the HHO algorithm. The details of the optimization procedure are presented in Sec. III. Moreover, in Sec. IV, the numerical results of the designed FSS are described. Finally, Sec. V denotes some concluding remarks of the paper.

II. Algorithm Description

Harris Hawks Optimization (HHO) is a recently swarm intelligence algorithm introduced in [6]. It models the cooperative behavior and chasing style of Harris' hawks in nature that is called "surprise pounce". HHO has a mechanism to keep a balance between exploration and exploitation, to find

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high-quality solutions at a high convergence rate. Thus, two basic phases can be found in HHO, the exploration, and the exploitation phase.

HHO evolves a population of NP vectors, whereas the Harris' hawks are the candidate solutions. The best candidate solution in each step of the process is considered as the intended "prey" or nearly the optimum. The Harris' hawks perch randomly on some locations and wait to detect a prey based on two strategies.

The HHO algorithm can switch from exploration to exploitation phase and then, change between different exploitative behaviors based on the escaping energy of the prey. This is modeled with the parameter E. This energy E of prey decreases significantly during the escaping behavior. The switching between the two phases occurs for different E values. If $|E| \geq 1$, then the exploration phase is active, whereas the exploitation phase starts at later iterations where $|E| < 1$. During the exploitation phase, the Harris' hawks perform the "surprise pounce" and attack the intended prey found in the exploration phase. Preys, on the other hand, often attempt to flee from risky circumstances. As a result, various chasing types appear in real-life scenarios. To model the attacking stage, the HHO proposes four possible strategies based on prey escaping behaviors and Harris' hawk chasing strategies.

HHO utilizes the parameter r as the probability that models the condition if a prey escapes ($r < 0.5$) or not ($r \geq 0.5$). Regardless of the prey's actions, the hawks will perform a hard or soft besiege to catch the prey. This means that they will encircle the prey in many ways depending on how much energy the prey has stored. In real life, the hawks get closer and closer to their intended prey, to maximize their chances of killing it cooperatively by executing a "surprise pounce". As time goes by, the fleeing prey will lose more and more energy, and the hawks will intensify the besiege to capture the tired prey easily. This kind of strategy is modeled in HHO using the E parameter that allows the switching between soft and hard besiege. Thus, if $|E| \geq 0.5$, then the soft besiege occurs. More details and the complete mathematical formulation is given in [6].

III. FSS Design

We consider the unit cell of the geometry given in Fig. 1. It consists of 13 different geometrical parameters. It is designed on an FR-4 substrate with ϵ_r = 4.4 and thickness 1.6 mm. The objective of this optimization problem is to achieve a dual band operation for the FSS structure in both 2.45 GHz and 5.8 GHz Wi-Fi frequency bands. This objective can be expressed by the reduce of the reflection coefficient (S_{11} magnitude) at both previously mentioned frequency bands. Thus, the formulation of the above objective is given by

$$\begin{aligned} F(\vec{z}) =& max\left(S_{11}^{2.45GHz}(\vec{z}), S_{11}^{5.8GHz}(\vec{z})\right) \\ &+ \Xi \times max\left(0, S_{11}^{2.45GHz}(\vec{z}) - T_{dB}\right) \\ &+ \Xi \times max\left(0, S_{11}^{5.8GHz}(\vec{z}) - T_{dB}\right) \end{aligned} \tag{1}$$

where $F(\vec{z})$ is the objective function, $\vec{z}$ a vector, whose its elements are assigned to the decision variables of the

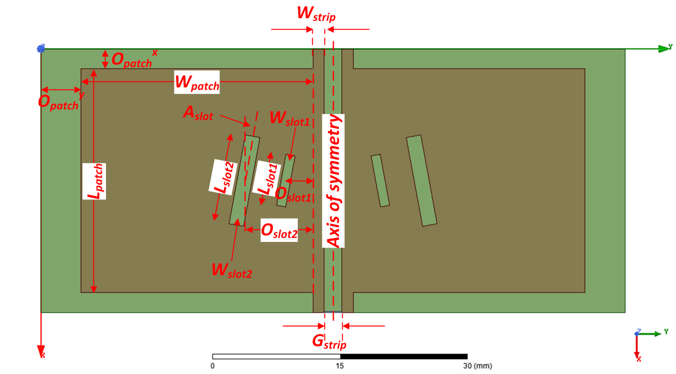

Fig. 1. Unit Cell geometry. The lighter color (shade of green) denotes the dielectric substrate. The parameters that have been included in the optimization process are remarked.

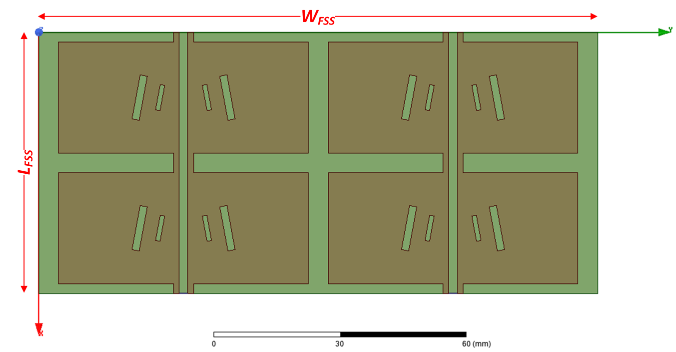

Fig. 2. FSS with 2 × 2 Unit Cells geometry (The overall length and width of the obtained FSS are L_{FSS} = 63.32 mm and W_{FSS} = 135.68mm, accordingly).

optimization problem, S_{11}^{k} $\left(k = \{2.45GHz, 5.8GHz\}\right)$ is the magnitude of the reflection coefficient for the FSS structure at the given frequencies, T_{dB} a reflection coefficient threshold (in dB), and Ξ is a very large number (e.g. 10^{20}). The HHO algorithm performs a set of searches for solutions that satisfy (1). This is carried out in conjunction with a commercial high-frequency electromagnetic solver (HFSS) and the MATLAB HFSS API environment.

IV. Numerical Results

We apply the HHO algorithm for 10 repetitions. The population size is set to 100 and the maximum number of iterations is 1000. The T_{dB} threshold is set to -10 dB. The design parameters of the best obtained result are listed in Table I. Fig. 3 illustrates the frequency response of S_{11} magnitude (reflection coefficient). The first resonance occurs at 2.45 GHz with a value of -34.2 dB, whereas the resonance at 5.815 GHz is about -25.7 dB. An additional resonance occurs at 3.975 GHz with a value of about -20.9 dB. From the presented results, we can easily conclude that the obtained design meets the design constraints and satisfies the objective of the optimization problem.

Fig. 4 displays the Smith chart of the FSS structure. From the given graph, we can notice that the impedance matching

TABLE I
BEST DESIGN PARAMETERS FOR THE UNIT CELL GEOMETRY OBTAINED BY THE HHO ALGORITHM.

Variable	Value (mm)	Variable	Value (mm)
W_{patch}	27.88	L_{patch}	26.94
O_{patch}	2.36	O_{patch}	4.82
W_{slot1}	1.11	L_{slot1}	6.23
W_{slot2}	1.77	L_{slot2}	10.85
W_{strip}	1.36	G_{strip}	2.13
O_{slot1}	1.92	O_{slot2}	3.53
A_{slot}	10.46 (deg)		

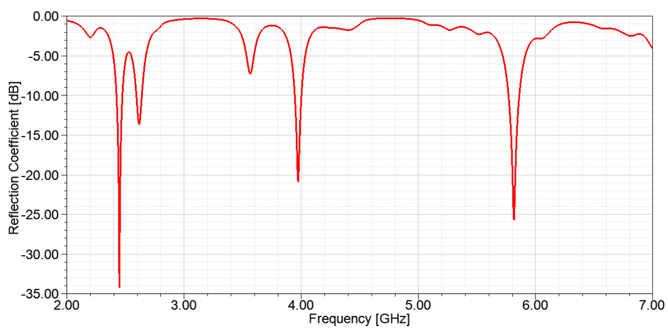

Fig. 3. S_{11} frequency response of FSS with 2×2 Unit Cells.

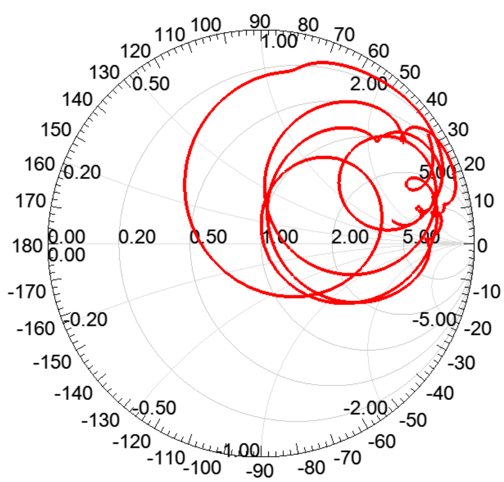

Fig. 4. Smith Chart plot of FSS with 2×2 Unit Cells.

of the designed FSS achieves quite satisfactory values at 3 frequencies, which are identical to the frequencies derived by the plot of Fig. 3. Moreover, Fig. 5 portrays the 3D pattern of the realized gain for both of the desired frequencies of operation. The maximum gain is 4.4 dBi and 5.3 dBi for the frequencies of 2.45 GHz and 5.8 GHz, accordingly. Overall, the FSS structure exhibits satisfactory results in terms of the reflection coefficient and the realized gain for both of the desired frequencies.

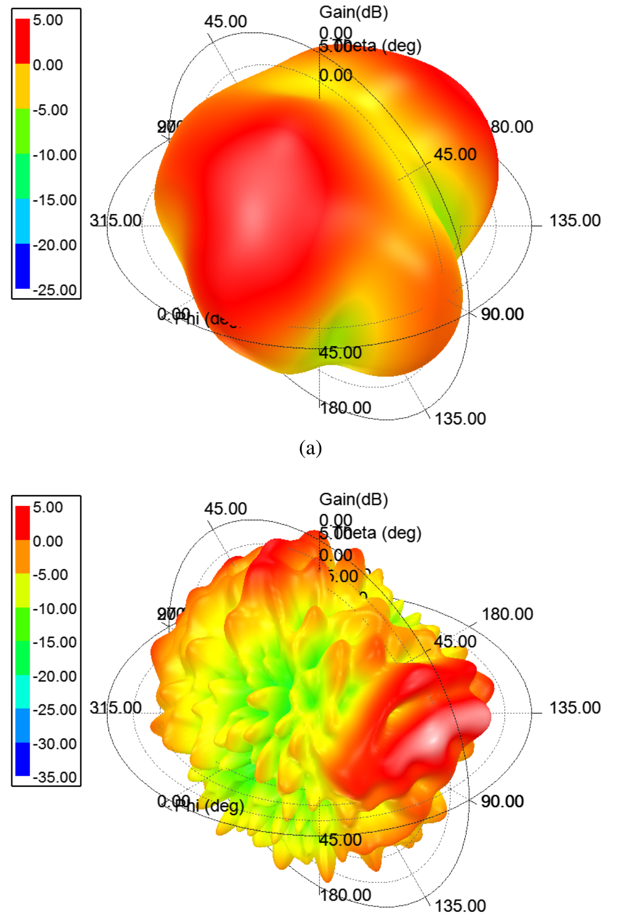

Fig. 5. Realized gain of the best FSS with 2×2 Unit Cells obtained by HHO: (a) 2.45 GHz, (b) 5.8 GHz (color scale in dB).

V. CONCLUSION

We have presented a new design framework for FSS structures based on the HHO algorithm. The presented results indicate that the HHO is a powerful optimizer that can be applied to antenna design problems. The feasible solution of the FSS structure presents satisfactory performance and fully complies with the design requirements. Future work includes the theoretical analysis of the proposed structure in terms of its equivalent circuit to highlight its properties, the application of the HHO algorithm to other antenna design problems, and the fabrication, as well as the experimental validation, of the designed FSS structure.

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