Modified Bow-Tie Antenna Design Using Artificial Hummingbird Algorithm for Wireless Power Transfer IoT Applications

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***Abstract*—The advent of the Internet of Things has allowed the re-usability of established techniques combined with emerging technologies. In the TERMINET project, several key-enabling technologies in an IoT ecosystem are explored. The smart farming paradigm is one of the realistic use cases of the project, in which Wireless Power Transfer, assisted by an Unmanned Aerial Vehicle, will be demonstrated as a proof-of-concept, to deliver energy in wireless sensor networks. In this work, we provide a feasible solution of a rectifying antenna module in a rectenna system, which operates in the Wi-Fi 2.4 GHz frequency band. The proposed antenna is optimized by utilizing the Artificial Hummingbird Algorithm. Numerical results demonstrate excellent performance of the proposed antenna, in terms of the key characteristics of reflection coefficient, input impedance, realized gain, and efficiency.**

***Index Terms*—wireless power transfer, radio frequency energy harvesting, bow-tie antenna, artificial hummingbird algorithm, swarm intelligence, optimization method, Internet of Things**

I. Introduction

Wireless Power Transfer (WPT) is an alternative technique to deliver energy in electrically-driven devices [1]. Based on its mechanism, it can transfer energy to a large number of low-power devices in a cordless manner. Thus, WPT is one of the emerging techniques in the Internet of Things (IoT) technology [2], whereas a variety of sensors can be spread over a large area. Considering the reception module of a WPT transceiver, Radio Frequency (RF) Energy Harvesting (EH) is gaining significant interest during the last years, since it can be easily applied to low-power systems, such as wireless sensor networks [3], [4]. The advent of the IoT era, in conjunction with Unmanned Aerial Vehicles (UAVs) or UAV swarms, gave a considerable boost to this technique, particularly in environments that are difficult to reach.

One of the main visions of the TERMINET project is to provide a novel next-generation reference architecture based on cutting-edge technologies while introducing intelligent IoT devices for market-oriented use cases [5]. Within the TERMINET project, several key-enabling technologies are investigated, such as Software Defined Networking (SDN), Multiple-access Edge Computing (MEC), and virtualization for next-generation IoT. At the same time, intelligent IoT devices will be introduced, focusing on the low-latency requirement, to deliver individual proof-of-concept validated demonstrations of realistic use cases. These use cases extend to several IoT domains, including energy, smart buildings, smart farming, healthcare, and manufacturing.

One of the use cases that will be validated and demonstrated within the TERMINET project is the smart farming paradigm. The TERMINET platform will be applied in an end-to-end way, to optimize the performance and the scalability of the previously mentioned use case in an IoT ecosystem. As a result, several emerging technologies will be tested within the use case, including RF energy harvesting technique. Although RF EH is an alternative technique to deliver energy in devices with low power requirements, it is expected to be one of the prevalent techniques in wireless sensor networks, especially with the vast deployment of IoT and Cyber-Physical Systems (CPS) [6]. In the specific use case, the RF EH scenario describes the demonstration of wireless power transfer in wireless sensors deployed in the field, by utilizing a UAV and an attached transmitter.

Based on this context, this work includes the design and optimization of a rectifying antenna module in a rectenna system, focusing on the IoT ecosystem and the smart farming paradigm of TERMINET project. The proposed antenna, which is a microstrip-modified bow-tie antenna, exhibits novel characteristics in its design and operates in the Industrial, Scientific, and Medicine (ISM) frequency band of Wi-Fi 2.4 GHz. It is designed and optimized by utilizing a recently introduced algorithm in the literature, i.e., the Artificial Hummingbird Algorithm (AHA) optimizer [7]. The modifications in its design, compared to the legacy microstrip bow-tie antenna, have been made to improve the antenna's characteristics for IoT applications. Finally, the proposed antenna is designed on a cheap substrate, allowing in this way the vast deployment of wireless sensors, which are equipped with the corresponding rectifying antenna module, in large areas, such as cultivation fields.

The remainder of this work is structured as follows. Section II presents the terminology and the mathematical formulation of the utilized AHA optimizer. Section III analyzes the numerical results of the proposed antenna, which are mainly focused on its operation as a rectifying antenna module of a rectenna system. Finally, Section IV infers this work, by quoting some concluding remarks.

II. AHA Description

Artificial Hummingbird Algorithm is a bio-inspired metaheuristic algorithm that models the intelligent behavior of hummingbirds in nature. Hummingbirds are the smallest birds in nature, which can be found in the continent of America. AHA optimizer incorporates the following terminology:

- **Food source:** It is the source in nature where the hummingbirds seek to feed. Generally speaking, each hummingbird assesses the properties of each source, including the content of flowers, the quality of the nectar, the nectar-refilling rate, and the last time a flower was visited by a hummingbird. The food sources with the highest properties are the best positions in the optimization process.
- **Hummingbird:** It is the member of the population that is assigned to a specific source. Based on this assignment, source, and hummingbird, as a pair of elements in the optimization process, have the same position. Moreover, each hummingbird can recall the characteristics of the source (position, nectar-refilling rate, elapsed time from the last visit) and share them with the rest of the population.
- **Visit table:** It is a matrix where the information regarding the visiting level of each source for different members (hummingbirds) of the population is recorded. Based on the visit table, a source that has a high visiting level for a specific hummingbird will also have the maximum priority to visit. Generally speaking, the visit table in AHA ranks the sources based on the members of the population and computes the corresponding priorities for each of the available sources. At each iteration of the optimization process, the visit table is updated.

Taking into consideration the above terminology, let us define the population of hummingbirds as $NPop$, the maximum number of decision variables as $MaxVar$, the position of each member (hummingbird) of the optimization problem as u_j ($j = 1...NPop$), and the maximum number of iterations as $MaxIt$ (($i = 1...MaxIt$)). During the algorithm's initialization, the position of each of the hummingbirds is computed as

$$u_j = LB + rand \times \big(UB - LB\big) \tag{1}$$

where LB and UB are the lower and upper boundaries of the optimization problem that correspond to its decision variables, and $rand$ is a random vector $\in [0,1]$. Furthermore, the visit table can be expressed as

$$MT_{j,k} = \begin{cases} 0, & \text{if } j \neq k \\ null, & \text{if } j = k \end{cases} \tag{2}$$

The value of $MT_{j,k} = 0$ when $j \neq k$ indicates the immediate visit of the $j-th$ hummingbird in the $k-th$ source at the current iteration, whereas the value of $MT_{j,k} = null$ when $j = k$ indicates that the $j-th$ hummingbird is harvesting food from the $k-th$ source at the current iteration.

During the foraging process of hummingbirds, three distinguished flight categories are defined, i.e., omnidirectional, diagonal, and axial flight. These categories are combined to form a direction switch vector, which is utilized to determine the type of category that will be applied for each of the hummingbirds in the optimization process. They can be expressed as

- **Omnidirectional flight:**

$$FL_m = 1, \quad m = 1...MaxVar \tag{3}$$

- **Diagonal flight:**

$$FL_m = \begin{cases} 1, & \text{if } m = IND_n, \quad n \in [1, s] \\ 0, & \text{elsewhere} \end{cases} \tag{4}$$

where the parameter IND is computed as

$$IND_n = rndperm(s), s \in [2, (r_1 \times (m-2)) + 1] \tag{5}$$

where $rndperm(s)$ creates a set of randomly permuted integers, and r_1 is a random number $\in [0,1]$.

- **Axial flight:**

$$FL_m = \begin{cases} 1, & \text{if } m = rand\big([1, MaxVar]\big) \\ 0, & \text{elsewhere} \end{cases} \tag{6}$$

where $rand$ is a random function that computes a random integer from 1 to $MaxVar$.

The next steps of the AHA in the optimization process include three foraging mechanisms of hummingbirds, i.e., the guided, the territorial, and the migration foraging.

- **Guided foraging:** This mechanism is used by the hummingbirds to visit a food source with the best characteristics (closest position relative to the member's position, best nectar-refilling rate, longest elapsed time from the last visit). It can be referred to as a 'greedy' mechanism in the optimization process. The position of each hummingbird can be expressed as

$$u_{j+1} = food_k^{best}(j) + g \times MaxVar \times \Big(food_k(j) - food_k^{best}(j) \Big) \quad (7)$$

where $food_k^{best}(j)$ is the food position of the $j-th$ hummingbird that is about to visit for harvesting food, $food_k(j)$ is the position of the $k-th$ food for the $j-th$ member of the population, g is a normally distributed factor (related to guided foraging mechanism) with $N[0,1]$, having an average value equal to 0 ($mean = 0$) and standard deviation equal to 1 ($std = 1$). Based on the guided foraging mechanism, the update of the food position can be computed as

$$food_{k+1} = \begin{cases} food_k, & \text{if } OF(food_k) \leq OF(u_{j+1}) \\ u_{j+1}, & \text{if } OF(food_k) > OF(u_{j+1}) \end{cases} \quad (8)$$

where $OF()$ is the objective (cost) function of the optimization problem.

- **Territorial foraging:** This mechanism is used by hummingbirds to search for a new source instead of visiting existing known sources. The position displacements of the hummingbirds are taking place within the same territory. It can be referred to as the 'exploitation' mechanism in the optimization process. The position of each hummingbird can be expressed as

$$u_{j+1} = food_k(j) + t \times MaxVar \times food_k(j) \quad (9)$$

where $food_k(j)$ is the position of the $k-th$ food for the $j-th$ member of the population and t is a normally distributed factor (related to territorial foraging mechanism) with $N[0,1]$, having an average value equal to 0 ($mean = 0$) and standard deviation equal to 1 ($std = 1$).

- **Migration foraging:** This mechanism is used by each of the hummingbirds when its territory lacks food sources. In this case, the migration foraging mechanism is taking place and the hummingbirds seek food sources in different territories. It can be referred to as the 'exploration' mechanism in the optimization process. The position of the food source with the worst nectar-refilling rate related to the randomly produced one can be expressed as

$$food_{j+1}^{worst} = LB + rand\big(UB - LB\big) \quad (10)$$

where $food_{j+1}^{worst}$ is the position of the food source with the worst nectar-refilling rate.

A detailed description of the artificial hummingbird algorithm and its distinguished mechanisms can be found in [7].

III. Numerical Results

In this work, a feasible geometry solution of a modified microstrip bow-tie antenna is designed by utilizing the AHA optimizer. The proposed antenna's characteristics are optimized to operate as a receiving module in a rectenna system. It resonates in the Wi-Fi 2.4 GHz frequency band (2.4-2.47 GHz). Based on the brief description of the AHA optimizer in Section II, the following parameters are set:

- Maximum number of iterations $MaxIt$: 5000
- Number of decision variables $MaxVar$: 11
- Population of hummingbirds $NPop$: 50

The objective of the given optimization problem is to obtain a feasible solution for the proposed microstrip-modified bow-tie antenna by minimizing its reflection coefficient at the frequency band of interest. At the same time, and for each value of the reflection coefficient that is computed by each member of the hummingbird population, the corresponding values of gain, input impedance, and efficiency are also temporarily stored. Thus, a set of specific key performance numbers is monitored to obtain an optimal geometry of the feasible antenna. In the optimization process, the value of -10 dB is also set as a threshold, whether to store the current value of the reflection coefficient to the specific member of the population or not. Moreover, the frequency of 2.45 GHz is selected as the center frequency of the desired band to solve the optimization problem. Taking into account the above criteria, the objective (cost) function of the optimization problem can be computed as

$$OF\big(\vec{u_i}\big) = max\big(S_{11}^{2.45GHz}\big(\vec{u_i}\big)\big) + \Xi \times max\big(0, S_{11}^{2.45GHz}\big(\vec{u_i}\big) - TH_{dB}\big) \quad (11)$$

where

- $OF\big(\vec{u_i}\big)$ is the objective (cost) function of the position vector $\vec{u_i}$, which is constructed from the positions of the entire population of hummingbirds,
- S_{11} is the reflection coefficient of the microstrip modified bow-tie antenna that is computed at the frequency of 2.45 GHz,
- TH_{dB} is the reflection coefficient threshold in dB, and
- Ξ is an arbitrarily selected number (in our case is equal to 10^4) to differentiate the output value of the reflection coefficient when its computed value by the algorithm is less than -10 dB.

Fig 1 presents the proposed microstrip modified bow-tie antenna design. It comprises a printed-on-a-substrate bow-tie

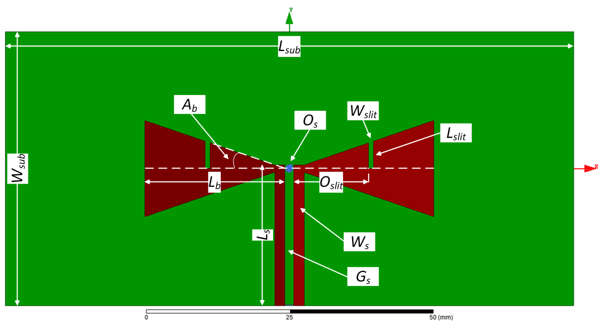

Fig. 1. Top view of the proposed microstrip modified printed bow-tie antenna (the parameters (decision variables) of the antenna design are indicated; brown color: bow-tie antenna with a series of microstrip lines, green color: FR-4 epoxy dielectric substrate).

TABLE I
PARAMETERS OF THE PROPOSED ANTENNA'S FEASIBLE SOLUTION (BEST POSITION VECTOR) OBTAINED BY THE AHA OPTIMIZER.

Variable	Value	Variable	Value
L_{sub}	100.94 mm	W_{sub}	48.52 mm
L_b	24.85 mm	A_b	0.33 rad
L_{slit}	4.86 mm	W_{slit}	0.88 mm
O_{slit}	13.32 mm	L_s	24.74 mm
W_s	1.84 mm	G_s	1.54 mm
O_s	0.77 mm		

antenna that has two symmetrical slits in its ties (the plane of symmetry is perpendicular to the antenna plane). The proposed antenna is fed by a series of microstrip lines. The whole system is designed to have an input impedance of 50 Ω. The antenna is designed on an FR-4 epoxy dielectric substrate, having the following characteristics: relative permittivity $\epsilon_r = 4.4$, thickness $= 1.6$ mm, $tan\delta = 0.02$. The partial ground technique is applied to the proposed antenna design at the edge of the microstrip lines (beneath the substrate) with a length equal to the substrate's length and a width equal to 4.978 mm. Finally, the metal foils of the proposed antenna (modified bow-tie antenna, microstrip lines, partial ground plane) are designed by taking into account the boundary conditions of finite conductivity (conductivity $=$ 5.80E+07 Siemens/m, relative permeability $= 1$).

Table I lists the final values of the proposed antenna design, which were obtained by the AHA optimizer. These values are extracted by applying the following process. At each iteration, the parameters of the antenna geometry are selected, and the AHA optimizer computes the objective function of the optimization problem by parsing the decision variables vector to a high-frequency electromagnetic solver. The solution of the solver is parsed back to the AHA optimizer and the result is assigned to a member of the population. The above process is repeated iteratively until stopping criteria are met.

Fig. 2 displays the reflection coefficient (S_{11} magnitude) as a function of the frequency of the proposed antenna's feasible solution, which was obtained by the AHA optimizer. For comparison purposes, the legacy microstrip bow-tie antenna's (the slits are absent) reflection coefficient is also included. From the comparative results, we can conclude that the proposed antenna exhibits a quite satisfactory tuning performance, having a resonance of -45.99 dB at the frequency of 2.464 GHz. Moreover, the -10 dB bandwidth of the proposed antenna extends from 2.29 GHz to 2.66 GHz, which covers the whole Wi-Fi 2.4 GHz frequency band. Moreover, the minimum value of the reflection coefficient at the whole frequency band of interest does not exceed -18.80 dB. It is also worth noting that the introduction of the two slits in the bow-tie antenna (and the optimization of the derived geometry) improves its performance by about 10 dB in terms of its reflection coefficient.

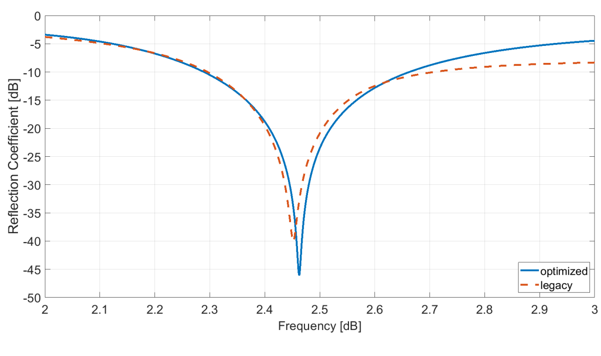

Fig. 2. Reflection coefficient (S_{11} magnitude) as a function of the frequency of the proposed antenna's feasible solution obtained by the AHA optimizer (blue solid line: reflection coefficient (S_{11}) of the microstrip modified bow-tie antenna, red dash line: reflection coefficient (S_{11}) of the legacy microstrip bow-tie (the slits are absent)).

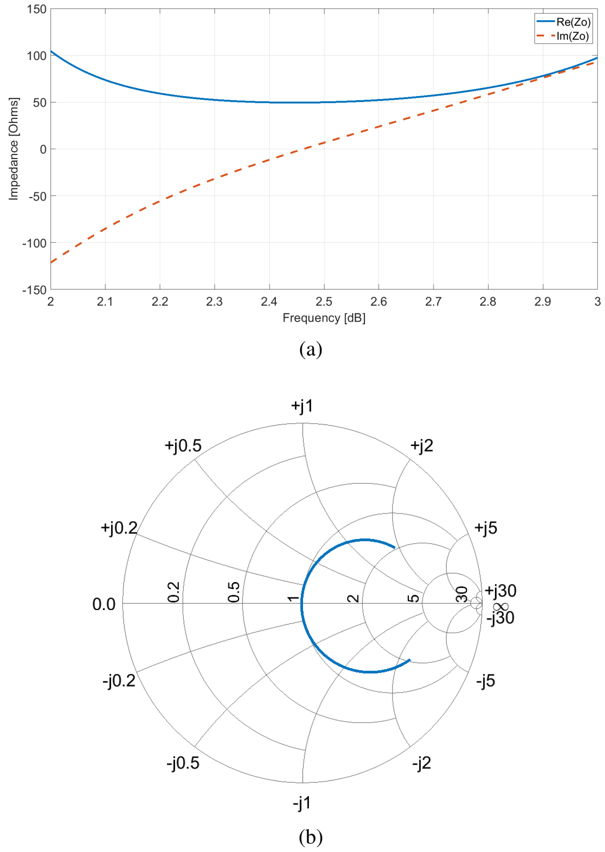

Fig. 3. (a) Input impedance (real and imaginary part) as a function of the frequency of the proposed antenna's feasible solution obtained by the AHA optimizer (blue solid line: real part, red dash line: imaginary part), (b) Smith chart of the proposed antenna's feasible solution obtained by the AHA optimizer.

Fig. 3 illustrates the input impedance (real, imaginary) as a function of frequency, as well as the corresponding Smith chart of the proposed antenna's feasible solution, which was obtained by the AHA optimizer. From the presented results we can conclude that the proposed antenna design exhibits remarkable performance in terms of its input impedance at the solution frequency, which falls into the desired frequency

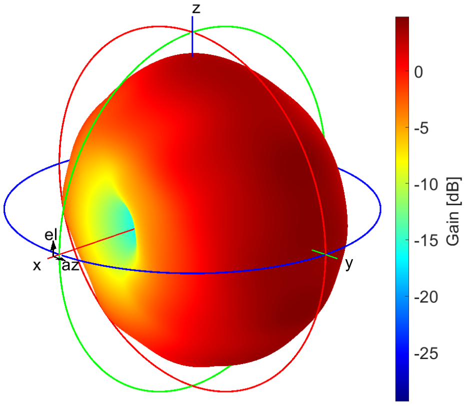

Fig. 4. Realized gain of the proposed antenna's feasible solution obtained by the AHA optimizer at the frequency of 2.45 GHz (color scale in dB).

band. The best-obtained input impedance value of the optimal design is $49.51 - j \times 0.08\ \Omega$ at the frequency of 2.462 GHz, which is quite close to the ideal value of $50 + j \times 0\ \Omega$. The input impedance of the antenna is one of the key performance numbers in RF energy harvesting systems [8], [9] since it determines the maximum transferred energy from the rectifying antenna module to the RF-to-DC rectifier module of a rectenna system. The same conclusion can be derived from the Smith chart of the proposed antenna design. It is also worth noting that the proposed antenna achieves normalized (to the input impedance of 50 Ω) input impedance values at the boundaries of the desired frequency equal to $0.9948 - j \times 0.2305\ \Omega$ and $0.9909 - j \times 0.0271\ \Omega$, for the frequencies of 2.40 GHz and 2.47 GHz, accordingly.

Fig. 4 portrays the realized gain (including any mismatches between the source port and the antenna) of the proposed antenna's feasible solution, which was obtained by the AHA optimizer. The antenna's gain is plotted in a 3D graph at the frequency of 2.45 GHz. From the presented graph we can conclude that the proposed antenna design exhibits a quite satisfactory performance in terms of its gain. The antenna radiates (and equivalently harvests) electromagnetic energy in a broad angle range at both main directions (z- and $-$z-direction, which are perpendicular to the antenna plane). Therefore, it can be considered as a quite promising candidate for a rectifying antenna module in a rectenna system. Moreover, from the same graph, we can compute that the maximum gain value is equal to 4.82 dBi, and the efficiency at the corresponding solution frequency is 97.56%.

IV. Conclusion

In this work, we demonstrate a feasible solution of a microstrip-modified bow-tie antenna that operates in the ISM Wi-Fi 2.4 GHz frequency band. The proposed antenna is a part of a rectenna system in a proof-of-concept realistic use case scenario of the TERMINET project. It is designed and optimized by utilizing the AHA optimizer. From the derived numerical results, we can conclude that the presented feasible solution exhibits excellent performance, focusing on the key characteristics of RF energy harvesting operation. The -10 dB bandwidth covers the entire frequency band of interest, and at the same time, the input impedance variations in the desired frequency band are small. Moreover, the maximum realized gain value reaches up to 4.82 dBi at the frequency of 2.45 GHz, whereas its efficiency is 97.56%. Future work includes the comparison between the proposed design and the completion of the rectenna design, the fabrication of the prototype, and its experimental demonstration in the field.

Acknowledgment

This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 957406 (TERMINET).

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