

# DEA-based on optimization of inductive coupling for powering implantable biomedical devices

Brahim Ouacha, Hamid Bouyghf, Mohammed Nahid, Said Abenna

LSIB Laboratory, Faculty of Sciences and Techniques, Hassan II University of Casablanca, Mohammedia, Casablanca, Morocco

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## ABSTRACT

Inductive coupling wireless power transfer (WPT) is one of the best technologies for powering implantable microelectronic devices (IMD). A wireless power transfer system's important elements (indicators) are power transfer efficiency (PTE) and power delivered to load (PDL). The key characteristics of WPT are the size of the transmitting (Tx) and receiving (Rx) coils, the operating frequency, and the separation distance between the two parts of the system. The main goal of this research is to use the differential evolution algorithm (DEA) to optimize a wireless energy transfer system in order to maximize the PTE and PDL. By comparing the results acquired by the proposed technique to those obtained by other methodologies, we were able to validate the results obtained by the suggested method. With the aim of raising the PTE and PDL. Using this metaheuristic approach, we were able to improve WPT's critical parameters. For is, a PTE of 95% and 136 mW of power delivered to the load for a 13 cm separation distance.

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## Corresponding Author:

Brahim Ouacha

LSIB Laboratory, Faculty of Sciences and Techniques, Hassan II University of Casablanca

Mohammedia, Casablanca, Morocco

Email: brahim.ouacha-etu@etu.univh2c.ma

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## 1. INTRODUCTION

The power is required for electronic biomedical sensors to function [1], [2], and there are various instances where batteries cannot be used as the major source of energy. Implantable electronic devices for example [3], [4]. In long-term trials, due to the requirement of invasive surgery to change the battery. One of the issues of these systems is the implantable device's energy consumption. Most bio-implanted devices, such as cochlear implants, implanted retinal, and implanted microsystems that stimulate and monitor nerve activity and muscle, are now powered by induction [5], [6]. Wireless power transmission, which allows electrical energy to be transmitted over an exterior wall from a source of electricity to an electrical load without the requirement of connecting cables, will become mandatory to use soon. Because it removes the hazards of virus and attachment related with transcutaneous wires. To assist prevent these challenges, wireless power transfer (WPT) is utilized [7]-[10], inductive coupling transfer is one of the safest ways to power up implants, and magnetic coupling between transceiver coils (Tx) and (Rx) is used in this method. E.g. Ac current in a transmitter coil generates a time-varying magnetic field, which is used to activate the physical motion of a field in the receiver during an electrodynamic WPT (EWPT) system [11], [12]. The size of the system, as well as the separation distance between transceiver, have an impact on power efficiency, for example, a larger receiver can receive more power, but miniaturization limits receiver size [13]-[15]. Optimizing the geometric characteristics entails reducing the surface area occupied by implanted devices (miniaturization of implants). This research

focused on the development of a wireless energy transmission system for powering biomedical implants. To increase and improve the PTE and PDL of the system, the differential evolution algorithm (DEA) is used to identify the ideal values of the geometric properties of the two coils, separation distance, and operating frequency.

The rest of the paper is structured as: section 1 depicts the WPT's introduction and the inductive coupling transfer technique, section 2 summarizes some similar works that served as inspiration for the development of the suggested technique, the theoretical background about inductive coupling is presented in section 3. Section 4 describes the proposed differential evolution algorithm (DEA) method, while section 5 examines the outcomes in comparison to some existing methods, and section 6 concludes the paper.

## 2. RELATED WORKS

In previous decades, power transfer efficiency (PTE) and power delivered to load (PDL) were once considered the most difficult problems in wireless power transfer (WPT). To deal with those problems, a lot of study was done. To have a maximum power transfer efficiency, it is necessary to optimize the parameters which depend on this efficiency. RamRakhyani *et al.* [16], proposed a WPT depending on resonance type, such as using four coils instead of two inductive linkages. At 20 mm separation the power transfer efficiency was 82%, while at 32 mm separation, it was 72%. The inclusion of repeating coils, on the other hand, enhanced the surface area of the biomedical implant, despite this the separation distance is still small. Also, Kiani *et al.* [17], creates a WPT system that includes two transmitting and receiving coils as well as a repeater. i.e., a three-coil system. Although the separation distance was improved to  $d=120$  mm with a resonance frequency of  $f=13.56$  MHz, the transfer efficiency remained low at 55% and 83 mW of PDL. Kiani and Ghovanloo [18] presented a multi-coil wireless power transfer system, as they compared the two, three, and four-coils system. They notes that the system of four coils gives higher results of PTE such as 66.7% for a distance of 200 mm. However, the usage of repeater coils adds to the disadvantages, such as parasites and the implant's surface area. Using a multicoil inductively coupled array is also a method to achieve a high PTE and PDL such in [19], the authors can upgrade PTE and PDL to 76% and 115mW respectively.

In WPT system coil's geometric parameters are optimized using a variety of approaches. Mehri *et al.* [1], presented a new approach. In order to optimize the parameters influencing the efficiency of wireless energy transfer. GA-FEM is the proposed approach such that it manages improve the operational efficiency of PTE to 78% at a frequency of 13.56 MHz. But the problem of the distance between the two system coils still remains low  $d=30$  mm, so the dimensions of the implanted coil are still large.

Thus, a variety of methods have been proposed to handle this issue. Between those solution we find the metaheuristic algorithms, in order to optimize the geometric parameters of the two transceiver coils TX and RX. Such as genetic algorithm (GA), like in [20], to be capable to optimize the geometric parameters of WPT, the authors use a GA approach to the theoretical investigation. The improvement is seen in the energy transfer efficiency and output power, which is up to 84.18%, 109 mW respectively at  $d=120$  mm, but with this method the implanted coil's size are still rather enormous. This necessitates a larger surface. On the other hand, the transmission distance is quite short.

## 3. THEORETICAL BACKGROUND

### 3.1. Inductive link modeling

Inductive coupling is a technology that allows electrical energy to be distributed without the use of any material support. This method is developed for use in difficult-to-reach areas. Implantable devices, for example. The wireless energy transfer system consists of the Tx transmitter coil, located outside the human body, and the Rx receiver coil attached to the electronic implant placed inside the body, separated by air and skin. A simplified representation of two-coils inductive link is shown in Figure 1 where L1 and L2 are respectively the primary and secondary coils, coil windings are identified by their parasitic resistance (R1,R2).

Both portions of the system should be adjusted with the same resonance frequency to increase power transfer efficiency (PTE) [14], [21]. Place two capacitors C1 and C2 in the primary and secondary circuits, respectively to construct LC resonant circuits [21], [22]. All feasible combinations of inlet and outlet are available through four double tuned link options [23].

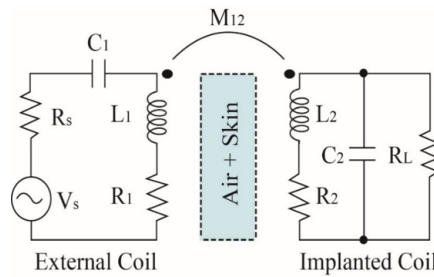


Figure 1. Equivalent diagram of inductive coupling with two-coils

### 3.2. Self and mutual inductances

When an electric current flows through a conductor, it creates a magnetic field in the area around it. The induced field is proportional to the primary and secondary coil's inductors  $L_1$  and  $L_2$  [21]. In the case of a square coil, as shown in Figure 2, (1) is used to calculate auto-inductance.

$$L = \frac{1.27 \cdot \mu_0 \cdot n^2 \cdot d_{avg}}{2} \cdot \left[ l \left( \frac{2.07}{\phi} \right) + 0.18\phi + 0.13\phi^2 \right] \quad (1)$$

Such as;  $\phi = \frac{(d_{out} - d_{in})}{(d_{out} + d_{in})}$ ;  $d_{avg} = \frac{(d_{out} + d_{in})}{2}$ ,  $n$  represent a total amount of turns,  $l$  is the length of conductor,  $d_{out}$  the outer diameter,  $d_{in}$  is the inner diameter, and  $\phi$  is a form factor.

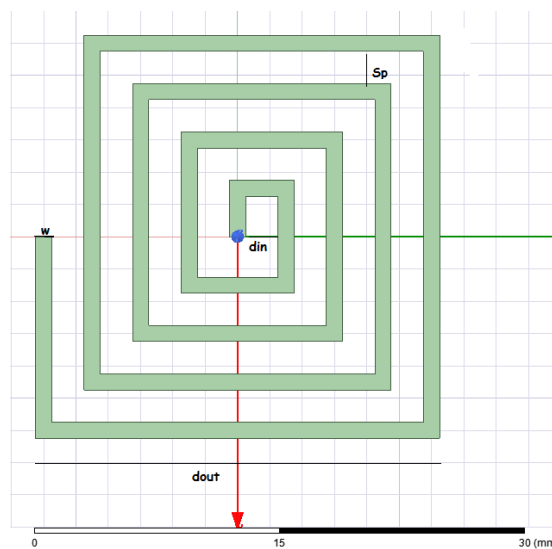


Figure 2. Geometry of a square shaped coil

The number of turns ( $n$ ), track width ( $w$ ), track spacing ( $S_p$ ), and the outside diameter ( $d_{out}$ ) are the geometric factors that characterize the inductance in a square spiral. ( $d_{in}$ ) The inductor's inner diameter. They are also linked by (2) and (3).

$$d_{out} = d_{in} + 2 \cdot n \cdot w + 2 \cdot (n - 1) \cdot S_p \quad (2)$$

$$l = 4 \cdot n \cdot (d_{out} - (n - 1) \cdot S_p - n \cdot w) - S_p \quad (3)$$

Mutual inductance is also a factor that cannot be eliminated. as it is criterion to have a perfect magnetic induction. The mutual inductance, is a function of the inductances of the two-coupled coils and the coupling factor, as shown in (4).

$$M_{12} = k_{12} \sqrt{L_1 L_2} \quad (4)$$

### 3.3. Quality factor

The link power efficiency is influenced by the inductor quality factor [1]. It's something to do with the inductor's parasitic resistance and capacitance. The overall parasite resistance can be computed using (5), which accounts for the skin effect [18].

$$R_s = R_{dc} \left( \frac{t_c}{\delta(1 - \exp(-\frac{t_c}{\delta}))} \right) \quad (5)$$

With  $\delta$  being the metal depth of the skin and  $R_{dc}$  the resistance, which can be stated as (6).

$$R_{dc} = \rho_c \frac{l_c}{w.t_c} \quad (6)$$

Where  $\delta = \sqrt{\frac{\rho_c}{\pi \cdot \mu \cdot f}}$  and  $\mu = \mu_0 \cdot \mu_r$ .  $l_c$ : conductor total length;  $t_c$ : conductor thickness;  $\rho_c$ : conductor resistivity;  $\delta$ : depth of skin;  $\mu$ : permeability constant;  $\mu_r$ : Relative permeability of the conductor. Thus, if the circuit's parasitic capacitance is ignored and for a low frequency [24], [25], the quality factor can be found by [7].

$$Q_i = \frac{wL_i}{R_i} \quad (7)$$

### 3.4. Power transfer efficiency

Enhancing the efficiency of electricity transfer is the main goal of implanted device developers. To maximize this coefficient, it is sufficient to maximize the quality and coupling factors. And also, the resonance frequency for both elements of the system should be the same  $w_0 = w_{01} = w_{02}$ . Thus, the PTE can be found by substituting (1) and (7) in (8).

$$PTE = \frac{k_{12}^2 Q_1 Q_{2L} Q_{2L}}{1 + k_{12}^2 Q_1 Q_{2L} Q_L} \quad (8)$$

Such as:  $Q_{2L} = \frac{Q_L Q_2}{Q_L + Q_2}$ ,  $Q_L = \frac{R_L}{wL_2}$ ;  $k_{12} = \frac{M_{12}}{\sqrt{L_1 L_2}}$ .

### 3.5. Power delivered to load

To increase the PDL, you need maximize the PTE and choose the best source resistance. As they are related by (9).

$$PDL = \frac{V_s^2}{R_s} PTE \quad (9)$$

Where  $V_s$ : driving voltage and  $R_s$ : source resistance.

## 4. PROPOSED METHOD

An adaption of a new optimization approach is presented in this research. Predicated on having the best values for the geometric characteristics of the WPT's key element. Differential evolution (DE), is a stochastic optimization method-based evolutionary approach for solving continuous space functions. DEA is a vector-based metaheuristic algorithm that, because to its use of crossover and mutation, resembles pattern search and genetic algorithms [24], [26]. We can also say that differential evolution algorithm is a development of genetic algorithm.

DE is a portion of the metaheuristic search algorithm, which is stochastic and has a tendency to self-organize. No encoding or decoding is required because DE uses actual integers as solution strings. Because of its simplicity and efficiency, it is used to solve a wide range of technical challenges. Within the initial parameter bounds, the population of a DE algorithm is random initialized. Mutation, crossover, and selection are the three basic processes that are used in the optimization process [27].

The differential evolution algorithm's mathematical formulation is presented here. An optimization problem can be phrased as follows if the issue to be solved is to maximize a fitness function (power transfer efficiency).

$$PTE_{max} = \max f(X) \quad (10)$$

With  $X = [d_{in1}, d_{in2}, n_1, n_2, S_{p1}, S_{p2}, w_1, w_2, t_1, t_2, d_{12}, f]^T$  the decision vector and  $X(i) \in [X_{min}(i), X_{max}(i)]$ ;  $i=1, 2, \dots, 12$ . The lower and upper bounds for each choice variable are  $X_{min}(i)$  and  $X_{max}(i)$  respectively.

#### 4.1. Initialization

At generation  $G$ , a solution or an individual  $i$  is a multidimensional vector  $X_i^G = (X_{(i,1)}, \dots, X_{(i,D)})$ . Individuals are generated at random to start the population.

$$X_{(i,k)}^G = X_{kmin} + rand[0, 1] \cdot (X_{kmax} - X_{kmin}) \quad (11)$$

$i \in [1, N_p], k \in [1, D]$  With  $D$  is dimension and  $N_p$  is population size.

#### 4.2. Mutation

The mutation operator can improve the DE algorithm's solution space exploration capability as well as increase the diversity of solution vectors. For each target vector at generation  $G$ ,  $X_i^{(G+1)}$ , a mutant vector  $v_i^{(G+1)}$ ,  $i=1, 2, \dots, N_p=12$  is produced by the process of (12) [28].

$$v_i^{(G+1)} = X_{r1}^G + F \cdot (X_{r2}^G - X_{r3}^G) \quad (12)$$

Where, the indexes  $r_1, r_2$ , and  $r_3$  are all different numbers between 1 and  $N_p$ , and  $F \in [0, 1]$  is a user-supplied real constant that controls the difference vector's amplification  $(X_{r2}^G - X_{r3}^G)$ .

#### 4.3. Crossover

The uniform crossover is the most prevalent crossover in DE, and it is defined as (13).

$$u_{ij}^{(G+1)} = \begin{cases} v_{ij}^{(G+1)} & \text{if } rand(i) > C_r \text{ or } j = r(i) \\ x_{ij}^{(G+1)} & \text{if } rand(i) \leq C_r \text{ or } j \neq r(i) \end{cases} \quad (13)$$

Where,  $j=1, \dots, D$ ,  $rand(j) \in [0, 1]$ , is the  $j$ th evaluation of a uniform random generator number. And also  $C_r \in [0, 1]$  our case  $C_r=0.5$ .  $r(i) \in [1, 2, \dots, D]$ , is a random integer.

#### 4.4. Selection

The target vector  $X_i^G$  is compared against the trial vector  $v_i^{(G+1)}$ , and the one with the higher fitness value is promoted to the next generation. The following equation can be used to represent the DE selection scheme (for a maximizing issue) [25].

$$X_i^{(G+1)} = \begin{cases} u_i^{(G+1)} & \text{if } f(u_i^{(G+1)}) > f(X_i^G) \\ X_i^G & \text{otherwise.} \end{cases} \quad (14)$$

With,  $f(u_i^{(G+1)})$  and  $f(X_i^G)$  are the aim of  $u_i^{(G+1)}$  and  $X_i^G$  such,  $i=1, 2, \dots, N_p$ . The goal or objective function in our situation is to maximize the PTE between two linked coils, in order to transfer a necessary amount of energy to the implant.

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#### Algorithm 1 Differential Evolutionary pseudo-Algorithm

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1: Begin
2: G=0
3: Create a population  $X_i$  containing N people who are chosen at random
4: Evaluate  $f(X_i^G)$ 
5: for G=1 to maximum of iteration do
6:   for i=1 to population size do
7:     Select random integers  $r_1 \neq r_2 \neq r_3 \neq i$ 
8:      $v_i^{(G+1)} = X_{r1}^G + F \cdot (X_{r2}^G - X_{r3}^G)$ 
9:     for j=1 to dimension do
10:      if  $((rand(j) > C_r) \text{ or } (j = r(i)))$  then
11:         $u_{ij}^{(G+1)} = v_{ij}^{(G+1)}$ 
12:      else
13:         $u_{ij}^{(G+1)} = X_{ij}^{(G+1)}$ 
14:      endif
15:    endfor
16:    if  $(f(u_i^{(G+1)}) \geq f(X_i^G))$  then
17:       $X_i^{(G+1)} = u_i^{(G+1)}$ 
18:    else
19:       $X_i^{(G+1)} = X_i^G$ 
20:    endif
21:  endfor
22:  G=(G+1)
23: endfor
24: End

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#### 4.5. Parameters configuration

The selection of the algorithm's parameters is a delicate and crucial process. According to both empirical and parametric investigations, the parameter values should be fine-tuned [25]. Table 1 represents the various parameters of the algorithm with their considered values.

Table 1. Parameter's values

Parameters	Value
Maximum number of generations ( $G_{max}$ )	1000
Population size ( $N_p$ )	30
Scaling factor (F)	0.6
Crossover rate ( $C_r$ )	0.5
Dimension(D)	12

#### 5. SIMULATION RESULTS

This section discusses the results of the proposed implementation of our objective function using the DEA. The MATLAB software was used to examine our proposition. Likewise, after configuring the algorithm's parameters, we display the objective function against the number of iterations or generations, in order to demonstrate our approach's convergence towards the greatest value of PTE from the DEA's optimal values. Figure 3 shows this:

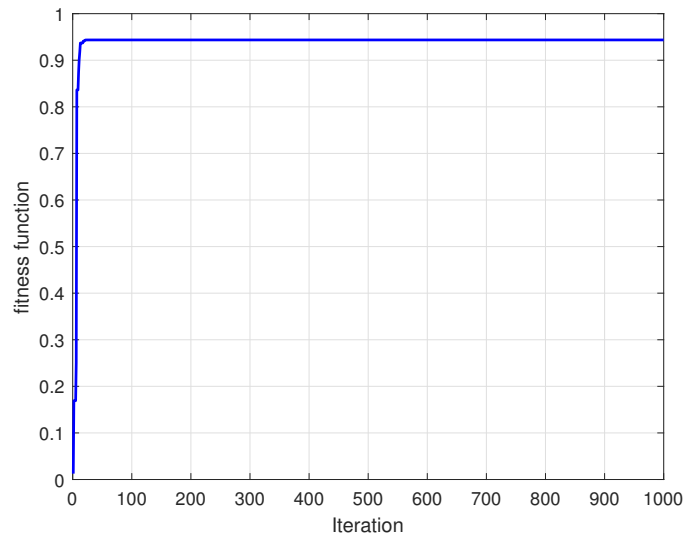
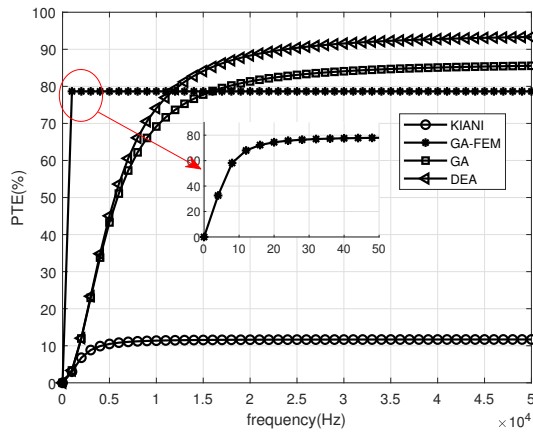


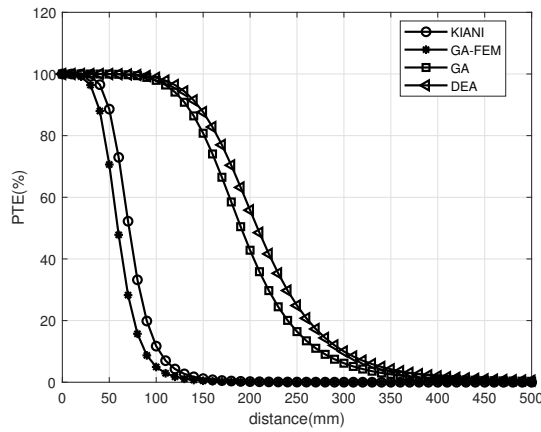
Figure 3. Cost function (PTE) versus number of iterations

The differential evolution method clearly converges to the best solution quickly, since the objective function reaches its maximum value of 95% after only 50 iteration. Power transfer efficiency varies with the operating frequency and the separation distance of the two connected parts, as shown in Figures 4(a) and 4(b) respectively. A comparison between our proposed method and some other methods existed in the literature, such as the DE algorithm reaches the highest value of PTE is 95%, on the other hand 90%, 78%, and 15% are reached by GA, GA-FEM, and the KIANI procedure. Also, for the variation according to the separation distance of the transceiver coils. Always our method succeeds in securing the transmission distance more than 13 cm, compared to the other methods.

The aim of the graph presented in Figure 5 is see the influence of the transmission distance on the quantity of energy delivered to the load (implant). Similarly, as compared to other competitors, the DE algorithm is able to send a considerable amount of energy to the implant (GA, GA-FEM, and KIANI).



(a)



(b)

Figure 4. Power transfer efficiency (PTE) versus (a) frequency and (b) separation distance

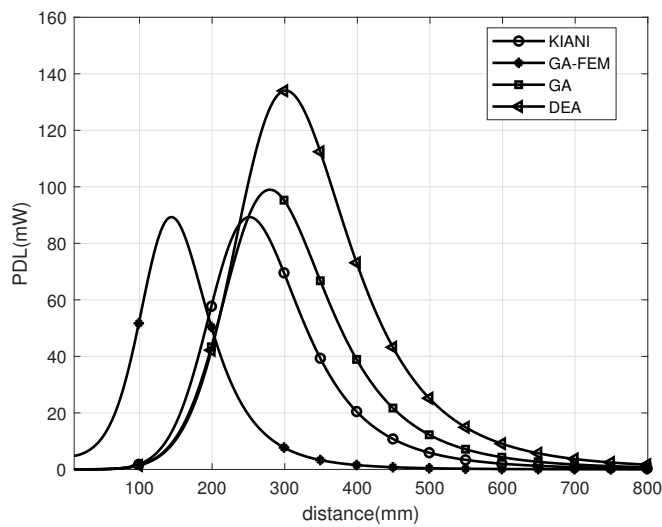


Figure 5. PDL (power delivered to load) versus transmission distance

### 5.1. Results discussion

When compared to GA, GA-FEM, and KIANI procedures, the differential evolutionary algorithm showed a significant improvement in power transmission reliability and electricity supplied to implant. This enhancement was achieved because our proposed method has the property of avoiding falling on local maximums when searching for an ideal value (maximum PTE). The following table represents a comparison of the proposed approach and the other methods of literature, at the level of the values of the optimized parameters.

The Figure 4(a) illustrates the overall efficiency values for the optimized coils using DEA, as well as efficiency outcomes for the GA, GA-FEM, and KIANI procedures. These efficiency values are provided as variable by frequency, with a frequency range of [0-18 MHz] simulated. DEA is capable of achieving 95 percent for 13.56 MHz in particular. In the same way always, our basic method is classified first, such as, 95% at 13 cm. As it showed in Figure 4(b). And also, it was shown by simulation in Figure 5, that at  $V_s=1V$  and a small source resistance ( $R_s$ ), the differential evolutionary approach is able to provide a huge amount of energy to the load. Compared to GA, the other approaches are less effective. From Table 2, it is clear that the optimal characteristics detected by differential evolutionary approach is more miniaturized compared to other approaches, external diameter of the implant as an example.

Table 2. Specifications results for all optimization approaches

Parameters	KIANI	GA-FEM	GA	This work
Outer diameter of external coil ( $d_{out1}$ )	36 mm	80 mm	51.60 mm	56.80 mm
Outer diameter of internal coil ( $d_{out2}$ )	10 mm	20 mm	5.22 mm	5.22 mm
Line width of external coil ( $w_1$ )	1.15 mm	1.9 mm	2 mm	2 mm
Line width of internal coil ( $w_2$ )	0.51 mm	0.7 mm	0.05 mm	0.05 mm
Line spacing of external coil ( $S_{p1}$ )	100 $\mu$ m	2.5 mm	0.6 mm	0.6 mm
Line spacing of internal coil ( $S_{p2}$ )	100 $\mu$ m	0.52 mm	10.3 $\mu$ m	10.3 $\mu$ m
Number of turns in external coil ( $n_1$ )	10	8	9	10
Number of turns in internal coil ( $n_2$ )	1	4	2	2
Separation distance (d)	10 cm	3 cm	13 cm	13 cm
Operating frequency ( $f_0$ )	13.56 MHz	13.56 MHz	13.56 MHz	13.56 MHz
Power delivered to load (PDL)	83 mW	89 mW	110 mW	134 mW
Power transfer efficiency (PTE)	15%	78%	90%	95%

## 6. CONCLUSION

In this work, we presented a novel method to design a system of wireless power transfer and optimized (maximizing) the two principles factors, the power transfer efficiency and the power delivered to load. This approach is among the family of metaheuristic algorithms. These are iterative stochastic algorithms that proceed towards a global optimum, or the global extremum of a goal function. They operate similarly to search algorithms, attempting to learn the attributes of a problem in order to obtain a good estimate to the optimal solution.

To assess the performance of the inductive coupling system for wireless power transmission, simulations were carried out. The results demonstrated that, At the same search intervals, applying DEA increased the PTE by 80% compared to KIANI, 17% compared to GA-FEM, and more than 5% evaluated to GA. The presented method has heightened the transmission distance. Also, for the PDL our approach achieved 134 mW. The metaheuristic algorithms were used to find the best solutions to a variety of issues in several domains, such as automatic control. In perspective of this work, it is planned to adopt a neutrals networks method in order to have a significant PTE and a high PDL value at large transmission distance for a more miniaturized implant.





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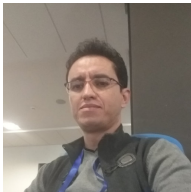
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**BIOGRAPHIES OF AUTHORS**

**Brahim Ouacha**     he received his license degree in physical sciences for engineers from the University Moulay Ismail Errachidia-Morocco (FSTE) in 2018, and then a Master's degree in Electronic and Embedded System from the same faculty in 2020. He is currently a Ph.D. student at Hassan II University in Mohammedia-Casablanca, Morocco, in the Laboratory of Engineering Sciences and Biosciences (LSIB). Under the direction of Pr. M. NAHID, Professor in the Electrical Engineering Department at the same University, his research and interests are centered on the design and optimization of wireless energy transfer and microelectronic systems, embedded systems, and biomedical systems. Brahim.ouacha-etu@etu.univh2c.ma is his email address.







**Hamid Bouyghf**     he was born in Errachidia, Morocco, in 1982. He got his B.S. and M.S. degrees in Electrical Engineering and Telecom from the University of Science and Technology in Fez, Morocco, in 2007, and his Ph.D. in Electrical Engineering & Telecom from Hassan II University of Casablanca, Morocco, in 2019. From 2015 until 2019, he worked as a Research Assistant at the Princeton Plasma Physics Laboratory. Since 2019, he has worked as an Assistant Professor at the Electrical Engineering Department of Hassan II University's FST Mohammedia in Casablanca, Morocco. In the topic of IC optimization, he has written numerous articles. His research interests include biomedical electronics, analog IC design, electromagnetic fields, low power design, and BLE applications.



**Mohammed Nahid**     studied electronics at ENSET Institute of Mohammedia, Morocco in 1994, received the Aggregation diploma of electronics and electrical engineering, from ENSET institute of Rabat, Morocco in 2000. He received the DESA diploma in computer engineering, telecoms and multimedia in 2004. He conducted doctoral research at images, videos coding and quality assessment under psychovisual quality criteria since 2004 at Mohamed V university of Rabat, Morocco, where he received his Ph.D. in 2010. Dr. Nahid, which is research professor in the Faculty of Science and Technology of Mohammedia since 2011, conducts research on visual perception and its application to coding, understanding, and display of visual information and to human vision, image quality, and digital imaging. Research and projects are also focused on artificial intelligency, embedded systems, biomedical systems, smart grids.



**Said Abenna**     received the M.Sc. degree in intelligence systems from the Sidi Mohammed Ben Abdellah National School of Applied Sciences Fes, Morocco, in 2018. He is currently pursuing a Ph.D. degree with the laboratory of Engineering Sciences and Biosciences, Hassan II Faculty of Sciences and Technology, Mohammedia, Morocco. His current research includes a brain-computer interface, electroencephalography, rehabilitation engineering, neuroscience, and the application of machine learning and deep learning (DL) and optimization algorithms for the development of biomedical control and diagnostics systems.