Journal of Engineering and Sustainable Development
Vol. 29, No. 06, November 2025
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.2618

Design of Microstrip Inter-Digital Capacitor Using Particle Swarm Optimization

Noora Mohammad Sadiq[1*], Sadiq K. Ahmed[2]

[1,2]Electrical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

[*]Email: noora.m.sadiq@uomustansiriyah.edu.iq

Article Info

Received dd/mm/yyyy
Revised dd/mm/yyyy
Accepted dd/mm/yyyy

Abstract

In this work, an inter-change capacitor design is developed using the particle swarm optimization technique. The PSO improves the inter-digital capacitor filter characteristics by varying capacitance geometry parameters. The capacitance value will vary greatly depending on the intended scale (in mm) for physical characteristics such as the number of fingers, finger width, and finger length. After executing the PSO algorithm for a predetermined number of iterations, the maximum capacitance value closest to the intended value is obtained. The optimization process was implemented in MATLAB and validated via full-wave simulations in HFSS at 1 GHz. The PSO algorithm achieved convergence within 50 iterations and produced capacitance values ranging from 0.48 pF to 0.92 pF, closely matching the desired targets with an average error of less than 2%. Results demonstrated that increasing the number and length of the fingers while reducing the gap between them significantly improved capacitance density. Compared with traditional trial-and-error and ANN-based approaches, the proposed PSO method reduced the design time by approximately 40% while maintaining high computational efficiency. The developed algorithm offers a simple mathematical formulation, fast convergence, and practical accuracy, making it a reliable optimization tool for high-frequency and RF/microwave circuit applications.

Keywords: Inter-Digital Capacitor, Microstrip Line, Optimization, Particle Swarm Optimization.

1. Introduction

PSO is an efficient stochastic evolutionary search strategy suggested by Eberhart and Colleagues [1]. The PSO algorithm is based on the nature of social behavior, the intelligence of the swarm, and the dynamic movements and communication of bird flocks, insect swarms, bee swarms, and fish schools [1]-[4]. PSO produces the best solution from a group of specific solutions, where each participating particle represents a solution [5]. Particle swarm optimization has several advantages, such as simplicity of conception, flexibility, ease of implementation, and computational efficiency compared to other deterministic techniques (e.g., GA). This allows for improvement in the abilities of local and global exploration [6]. Similar to other evolutionary algorithms, the PSO technique searches through a population of particles, forming a swarm that moves through the search space to find the optimal solution [7]. The Population of particles is randomly generated initially. Each particle has a position represented by a position vector X_i. The positions of particles change across a multidimensional search space until a relatively stable position is observed or a maximum number of iterations is reached, as constrained by computational limitations [8].

In the last two decades, Particle swarm optimization has been presented to antenna design and electromagnetic problems [1], [9], such as it used for the design of microstrip patch antenna [10], [11], the design of UWB antennas [12], [13], the synthesizing of phase antenna arrays [14], the optimized microstrip antenna with metamaterials [15], and the log-periodic dipole design [16]. Another application of PSO in electromagnetics is the design of a corrugated horn antenna, as reported in [1]. Syntheses of interdigital-capacitor IDC are introduced by [17]. The multi-finger periodic structure known as the (IDC) is used in RF-microwave circuits with lumped circuit parts. Compared to gap and MIM capacitors, IDC capacitors have a higher quality factor. IDC makes use of the capacitance that develops in the little space between inter-digital fingers. In essence, these slits are extremely long and fold to occupy a small space [18].

Many works have investigated the Optimization technique; more specifically, Chen [19] (2003) focuses on the modeling and design of interdigital capacitors using a neural network and a genetic algorithm. Using a complex mathematical model with Duroid substrate material, the resulting solution maximizes capacitance.

In 2006, Ababneh et al. [17] conducted research on the Synthesis of interdigital capacitors using particle swarm optimization and Artificial Neural Networks. They used complex mathematical models with different substrate materials and obtained the maximum capacitance. Beeresha et al. [18] used a sophisticated mathematical model based on RT/Duroid substrate material to address the Design and Optimization of Interdigital capacitors. The findings are intended to improve quality.

However, most of these studies relied on complex mathematical models and multi-parameter optimization, which resulted in high computational costs and long convergence times. In addition, the achieved capacitance accuracy in earlier works was often limited, with errors exceeding 5–10%, and the models were not readily adaptable to different substrate materials or fabrication tolerances. This study addresses these limitations by developing a simplified PSO-based optimization framework that directly links the geometric parameters (L and W) of the IDC to its capacitance using a concise mathematical model.

Due to increased resistance and reactive inductance, the IDC's dimensions are altered, increasing capacitance and decreasing the quality factor. Smaller sizes can be more flexible for higher-frequency applications, as shown by the intended configuration. There are two main dimensions to be adjusted for IDC: (L) and (W). Suppose tuning of IDC is to be done by trial and error. Hence, design time is very high, the results are not accurate, and the number of design iterations is large. Therefore, the PSO technique is used to synthesize the IDC in this paper. In other words, the IDC dimensions and the substrate specifications will be specified for a given capacitance value. Full-wave high-frequency structure simulation (HFSS) is used to support the proposed work for some of the IDC structures.

The novelty of this work lies in its simplified formulation, reduced iteration count, and improved accuracy, providing a practical and reliable optimization tool for high-frequency and RF/microwave applications.

2. IDC Design Equations

(IDCs) can function as lumped circuit elements in microwave circuits, particularly at higher frequencies, due to their larger size and higher quality factor. However, their maximum capacitance is significantly lower than 1% that of overlay capacitors, making them unsuitable for chip form. IDCs operate by utilizing the capacitance across a narrow gap between thin-film conductors, and this capacitance can be increased by adding more fingers, incorporating a thin layer of a high-dielectric-constant material, or using an overlay high-K dielectric layer [20]. For IDCs to be considered as lumped elements, their size must be relatively small compared to the wavelength. These capacitors can be fabricated utilizing either hybrid technology found in traditional ICs or MMIC technology [19].

The inter-digital capacitor (IDC) is composed of multiple components. The (N) makes the coupling between the input and output ports across the meander gaps. To reduce the parasitic capacitance, the (G) and (G_e) of the fingers are usually similar. The (ε_r) and (h) are the two most crucial design parameters. The capacitance per unit length along its breadth was calculated using the(L) and (W). IDC is printed on an Epoxy-FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.57mm, with a ground. Fig. 1 shows the IDC configuration.

The substrate's properties will also affect performance. Microstrip planar transmission lines are widely used in interdigital capacitors due to their ease of design and production. (1) introduces the total capacitance calculation for the inter-digital capacitor (IDC) [20]:

$$C = (\varepsilon_r + 1)\mathrm{L}[(N-3)A1 + A2] \quad (1)$$

The influence of h needs to be taken into account in A_1 and A_2 for a finite substrate [20]. The following are approximate expressions for A_1 and A_2:

$$A1 = 4.409\, tanh\left[0.55\left(\frac{h}{w}\right)^{-0.45}\right] \times 10^{-6} \quad (2)$$

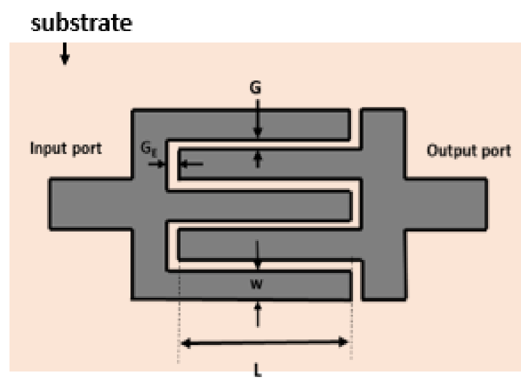


Figure 1. Inter-Digital Capacitor Structure.

$$A2 = 9.92\, tanh\left[0.52\left(\frac{h}{w}\right)^{-0.5}\right] \times 10^{-6} \quad (3)$$

The letters h and W stand for the substrate material's height and the conductor's width, respectively. In the inter-digital capacitor construction, the inside and outer fingers are represented by (2) and (3), respectively. The equivalent circuit shown in (4) can be used to compute the series resistance, which is provided by Bahl [20]

$$R = 1.33\frac{l}{WN} R_s \quad (4)$$

Where Rs is the conductors' surface resistance for the capacitors, the microstrip transmission theory is utilized to compute the values of capacitance C_s and inductance L_i shown in (5) and (6) (see Fig.2).

$$C_s = 0.5 \times \frac{\sqrt{\varepsilon_{re}}}{Z_0 C} \times L \quad (5)$$

$$Li = \frac{Z_0\sqrt{\varepsilon re}}{c} \times L \qquad (6)$$

Where the velocity of light in space is given by c = 3×10^{10} cm/s, and Z_o and ε_{re} are computed using W and h microstrip parameters [21]-[22]. Fig. 2 shows the equivalent circuit of the inter-digital capacitor with a lumped element [19].

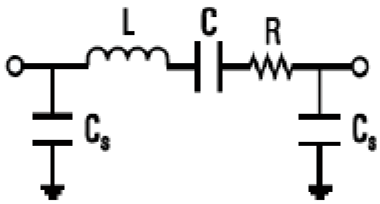


Figure 2. Equivalent Circuit of Inter-Digital Capacitor.

3. Method of the Research

In this paper, the PSO technique is introduced to determine optimal dimensions (L and W) for the IDC to maximize capacitance. The simplicity and versatility of the PSO algorithm make it a compelling choice for a wide range of applications, surpassing traditional and evolutionary optimization methods. The physical dimensions of the IDC are controlled by two main parameters: L and W, in addition to other parameters such as (N), (ε_r), and (h).

The objective of this work is to find the values for these two parameters (L and W) that give the maximum value of capacitance. Adjusting L and W alters other parameters, such as G and G_e. Thus, optimizing two parameters (L and W) will automatically optimize G and G_e. Fig.3 shows the flowchart diagram. Outlines the primary stages of the PSO algorithm described in the following section. The algorithm starts by defining the solution space (W and L) and then randomly assigning the particle's velocity and position in the PSO. In an N-dimensional problem with M particles, every particle has its position and velocity in each dimension.

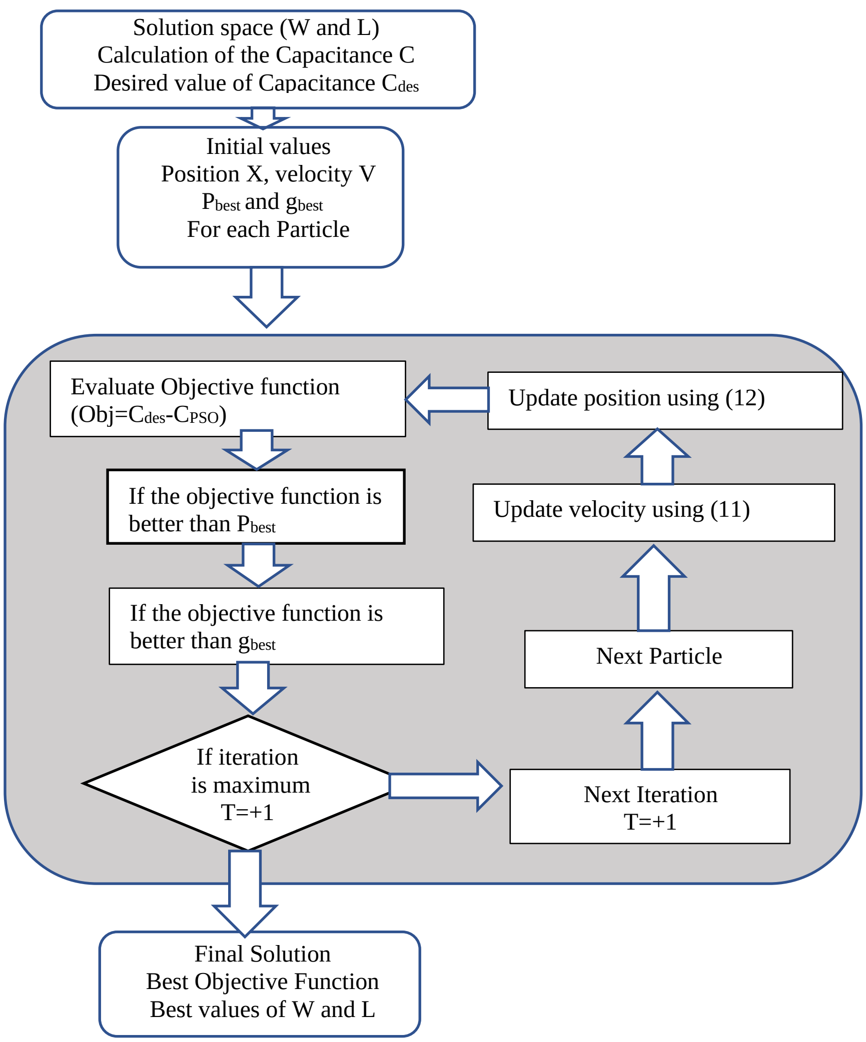


Figure 3. Flow Chart of PSO Algorithm

Thus, the positions and velocities of the particles can be repre sented by the subsequent M-N matrices shown in (7) and (8):

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1N} \\ x_{21} & x_{22} & \cdots & x_{2N} \\ & & \ddots & \\ x_{M1} & x_{M2} & \cdots & x_{MN} \end{bmatrix} \quad (7)$$

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1N} \\ v_{21} & v_{22} & \cdots & v_{2N} \\ & & \ddots & \\ v_{M1} & v_{M2} & \cdots & v_{MN} \end{bmatrix} \quad (8)$$

A possible solution can be represented by any row of the position matrix, as illustrated in (7). The velocity of each particle can be determined by the distance between its current position and the best position with the best objective value. To obtain the updated velocity vector, every particle must know its personal best and the global position vectors. The position of each particle that obtained its best objective function up to the current iteration is defined as the personal–best position. (9) gives the following matrix, which can be used to specify the personal best position Xp:

$$X_p = \begin{bmatrix} x_{p11} & x_{p12} & \cdots & x_{p1N} \\ x_{p21} & x_{p22} & \cdots & x_{p2N} \\ & & \ddots & \\ x_{pM1} & x_{pM2} & \cdots & x_{pMN} \end{bmatrix} \quad (9)$$

The global-best position vector X_g is attained from the row of the position matrix that yields the best objective function. The global best position vector is determined by (10):

$$X_G = [X_{G1}\ X_{G2}\ \dots\ X_{GN}] \quad (10)$$

Now, all the information (X, V, X_P, and X_G) is provided to the PSO algorithm. The basic operation of the PSO algorithm is to adjust these parameters (X, V, X_P, and X_G) at each iteration. The updated velocity matrix is given by (11):

$$V_{mn}^{t} = \theta V_{mn}^{t-1} + C_1 \eta_{n1}^{t}(p_{mn}^{t} - X_{mn}^{t-1}) + C_2 \eta_{n2}^{t}(g_n^{t} - X_{mn}^{t-1}) \quad (11)$$

Where η_{n1} and η_{n2} are represented as two distinct random integers within the interval [0,1]. The proportional weight of the personal-best position X_{Pmn} about the global-best position X_{Gmn} is indicated by the two parameters (c_1 and c_2). The choice of 2.0 for both values has become standard practice. The "inertial weight" parameter, denoted by θ, is a number between 0 and 1 that indicates the weight by which the current velocity of the particle is dependent upon its prior velocity as well as the separation between the position of a particle and its global best and personal-best positions. The updated position matrix depends on the previous value of the position matrix and the current update velocity and is given as (12):

$$X^{t} = X^{t-1} + V^{t} \quad (12)$$

The disp uses the concept of objective values to evaluate the quality of the particle position matrix, similar to GA. During each iteration of the PSO technique, the particle vector that yielded the best objective function is selected as the global best position vector $X_{Gmn.}$ This work's objective is to design the IDC's geometry to maximize its capacitance. To fulfill this objective, the following (13) is utilized for determining the objective function as follows:

$$Obj = |C_{des} - C_{PSO}| \quad (13)$$

Where C_{des} represents the intended capacitance, and C_{pso} repr esents the capacitance calculated from the previously mention ed PSO model. From equation (13), it is evident that for the present problem, the particle wit h the optimal objective value is the one whose position vector minimizes the objective function outlined in (13).

4. Results and Discussion

Once the algorithm PSO has been run for a designated number of iterations (50 iterations), maximum capacitance values are obtained, which are close to the desired value. The range of the input parameters is given in Table 1. The substrate material (ε_r) and the substrate thickness (h) are considered constant.

Table 1. Input parameters range in (mm)

ε_r	h	N	L	W	G	G_e
4.4	1.57	6	2-8	0.5-2	2-0.5	6.5-2

In synthesizing the IDC, the aim is to determine its geometric dimensions. It is supposed to find the parameters that yield the maximum capacity. Table 2 shows the dimensions of the IDC calculated using the PSO algorithm for different specific desired capacitance values. Some of the design parameters are constant values, such as the substrate dielectric, the thickness of the substrate material, and the number of fingers (N=6), which are assumed to be manufacturing standards, and the other parameters (L and W) are to be searched for. Parameters that yield the desired capacitance with an acceptable level of error are being identified. The results of IDC utilizing the parameters obtained by the PSO algorithm are very close to the desired values. As shown in Table 2, the smallest error (0.4%) was obtained for Cdes = 0.6 pF, while the maximum deviation (2.3%) occurred at Cdes = 1.0 pF. These results confirm the robustness and reliability of the proposed PSO model in achieving precise capacitance values across a wide range of geometric parameters.

In Table 3, the number of fingers determines the desired value of capacitance, and the other parameters (W, L, G, and G_e) are obtained using the PSO model. It demonstrates the influence of the number of fingers (N) on the capacitance performance. Increasing the number of fingers from 4 to 10 resulted in an average capacitance increase of 35%, while the optimized finger width (W) and spacing (G) ensured impedance matching at 1 GHz.

Table 4 shows the Synthesis of IDC by adjusting the h values. It explores the impact of substrate height (h) variations, showing that thinner substrates yield higher capacitance density due to increased finger coupling.

Table 5 compares this study with other references on various aspects, including the optimization technique, mathematical model, and objective function.

Table 2. Inter-digital capacitors result in different values of $C_{des.}$

C_{des}(pF)	h(mm)	ε_r	N	L(mm)	G_e(mm)	W(mm)	G(mm)	C(pF)
0.5	1.57	4.4	6	5.11	1.4	1.46	1.04	0.512
0.6	1.57	4.4	6	4.85	1.15	1.45	0.95	0.55
0.75	1.57	4.4	6	4.5	2	2.1	0.4	0.582
1	1.57	4.4	6	6.35	0.15	1.5	1	0.915

Table 3. Inter-digital capacitors result in different values of N.

C_{des}(pF)	h(mm)	ε_r	N	L(mm)	G_e(mm)	W(mm)	G(mm)	C[pF]
0.5	1.57	4.4	4	3.95	2.55	0.4	3.6	0.35
0.5	1.57	4.4	6	4.35	1	1.5	2.15	0.489
0.5	1.57	4.4	8	4.15	2.35	0.5	0.5	0.511
0.5	1.57	4.4	10	4.27	2.23	0.76	0.84	0.49

Table 4. Inter-digital capacitors result in different values of h.

C_{des}(pF)	h(mm)	ε_r	N	L(mm)	G_e(mm)	W(mm)	G(mm)	C(pF)
0.5	1	4.4	6	4.244	1.766	1.024	0.97	0.4789
0.5	1.57	4.4	6	3.125	2.875	0.507	1.5	0.5047
0.5	1.65	4.4	6	3.013	2.987	0.708	1.292	0.4760
0.5	1.85	4.4	6	3.398	2.602	1.476	0.524	0.5201

Table 5. Comparison with other references concerning different aspects.

Ref.	Optimization technique	Mathematical model	Substrate material	Obtained results
The proposed work	PSO	simple	FR4-epoxy	Maximize the capacitance
[17]	PSO+ANN	complex	Different materials	Maximize the capacitance
[18]	Using classical equations	complex	RT/Duroid	better quality
[19]	NN+GA	complex	Duroid	Maximize the capacitance

Fig. 4 shows the performance of the PSO algorithm over 50 iterations. The value of the objective function decreases as the number of iterations increases (it approaches zero). The objective function rapidly decreases and stabilizes after approximately 25 iterations, confirming fast convergence and strong optimization stability.

Fig. 5 presents the 2D and 3D structures of the IDC implemented in HFSS, with N=6, L=6 mm, and W=2 mm. The PSO algorithm is described and implemented in MATLAB. To verify the proposed work, the full-wave high-frequency simulation software is used to obtain the reflection and transfer parameters (S_{11} and S_{21}) for several IDC design examples, as shown in Tables 2 and 3. The simulation was conducted at a center frequency of 1 GHz, with a finite-element mesh of a minimum edge length of 0.2 mm and perfect electric conductor (PEC) boundary conditions. The simulation results for some examples are shown in Fig. 6. It is observed that the transmission coefficient S_{21} is -0.6 dB at the center frequency of 1 GHz. The return loss (S_{11}) was below −15 dB, and the transmission coefficient (S_{21}) reached −0.6 dB at 1 GHz, indicating good impedance matching and low signal attenuation.

These results collectively confirm that the proposed PSO-based approach achieves higher capacitance precision, faster convergence, and lower computational complexity than conventional analytical and hybrid ANN–PSO optimization techniques.

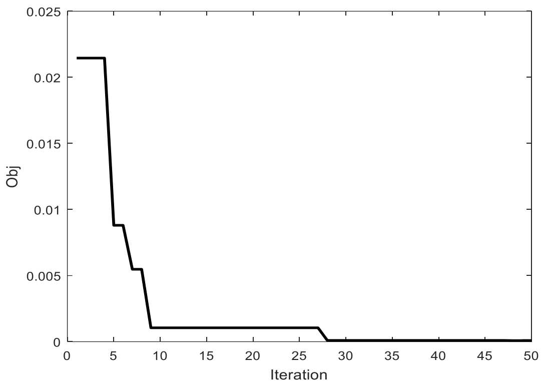
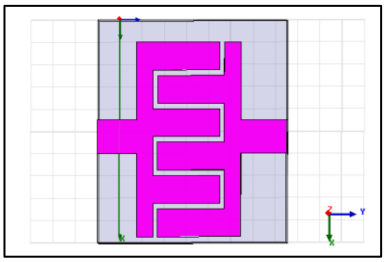
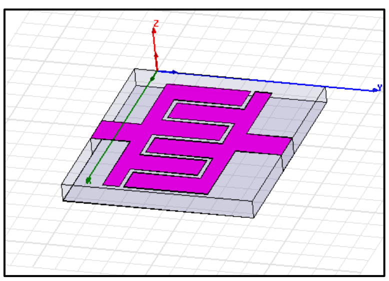


Figure 4. Objective function with 50 iterations



(a)



(b)

Figure 5. 2D and 3D structure of IDC implemented using HFSS with N=6, L=6 mm, W=2 mm

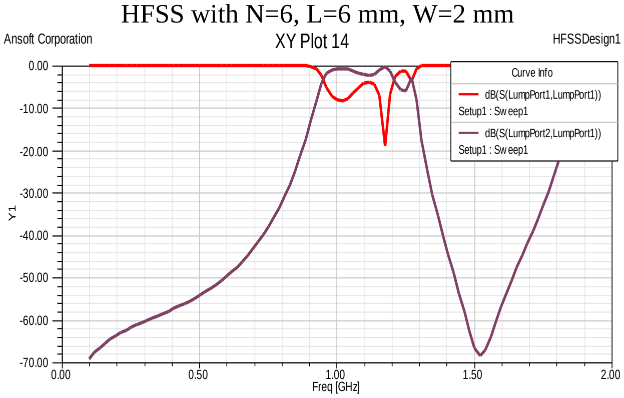


Figure 6. S-parameters for IDC (S_{11} and S_{21}).

5. Conclusions

This work presents an IDC design based on the PSO algorithm. The particle swarm optimization technique was employed to optimize the dimensions of the IDC structure to achieve the maximum capacitance value. The PSO algorithm has several advantages, such as reduced design time and fewer iterations, and a simple mathematical model. Furthermore, several tables and figures show the behavior of PSO and its effects on the desired capacitance value. The observed outcomes of IDC indicate that an increase in the number of fingers, the length of the fingers, and a reduction in the gaps between the fingers will maximize the capacitance value. This proposed algorithm is considered a powerful and suitable optimization tool for many engineering applications, using the MATLAB package and the full-wave simulation (HFSS) software.

Acknowledgement

The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq), Baghdad, Iraq, for their support and scholarly guidance during the composition of this work.

Abbreviations

G	spacing between fingers
G_e	spacing between the tips of the fingers
h	substrate height
IDC	Inter-digital capacitor
L	Finger length
N	Number of fingers
PSO	Particle swarm optimization
W	Finger width
ε_r	dielectric constant ε_r

Conflict of interest

The authors affirm that they have no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Noora Mohammad Sadiq.: Implemented the PSO methods and investigated

Sadiq Ahmed.: Proposed and developed the methodology and reviewed and edited the work.

References

[1]. J. Robinson and Y. Rahmat-Samii, "Particle swarm optimization in electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 52, no. 2, pp. 397–407, Feb. 2004, doi: https://doi.org/10.1109/TAP.2004.823969.

[2]. J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. ICNN'95 - Int. Conf. Neural Netw.*, vol. 4, 1995, pp. 1942–1948, doi: https://doi.org/10.1109/ICNN.1995.488968.

[3]. A. G. Gad, "Particle swarm optimization algorithm and its applications: A systematic review," *Arch. Comput. Methods Eng.*, vol. 29, no. 5, pp. 2531–2561, Jul. 2022, doi: https://doi.org/10.1007/s11831-021-09659-7.

[4]. T. M. Shami et al., "Particle swarm optimization: A comprehensive survey," *IEEE Access*, vol. 10, pp. 10031–10061, 2022, doi: https://doi.org/10.1109/ACCESS.2022.3142859.

[5]. T. Tashan and A. K. Kadhim, "Particle swarm optimization-based multilevel MRI compression using compressive sensing," *Bull. Electr. Eng. Inform.*, vol. 11, no. 5, pp. 2621–2628, Oct. 2022, doi: https://doi.org/10.11591/eei.v11i5.3873.

[6]. M. Jain et al., "An overview of variants and advancements of PSO algorithm," *Appl. Sci.*, vol. 12, no. 17, p. 8392, Aug. 2022, doi: https://doi.org/10.3390/app12178392.

[7]. L. Zheng et al., "Particle swarm algorithm path-planning method for mobile robots based on artificial potential fields," *Sensors*, vol. 23, no. 13, p. 6082, Jun. 2023, doi: https://doi.org/10.3390/s23136082.

[8]. D. Wang, D. Tan, and L. Liu, "Particle swarm optimization algorithm: An overview," *Soft Comput.*, vol. 22, pp. 387–408, Feb. 2018, doi: https://doi.org/10.1007/s00500-016-2474-6.

[9]. R. A. Khan et al., "A modified particle swarm optimization with a smart particle for inverse problems in electromagnetic devices," *IEEE Access*, vol. 9, pp. 99932–99943, Jul. 2021, doi: https://doi.org/10.1109/ACCESS.2021.3095403.

[10]. Y. Yulindon, N. A. Samsudin, and R. Efendi, "Optimization of E-shaped microstrip patch antenna using particle swarm optimization (PSO) for wideband application," *Int. J. Intell. Eng. Syst.*, vol. 13, no. 4, pp. 343–351, Aug. 2020, doi: https://doi.org/10.22266/ijies2020.0831.27.

[11]. E. Karpat and F. Imamoglu, "Optimization and comparative analysis of quarter-circular slotted microstrip patch antenna using particle swarm and fruit fly algorithms," *Int. Arab J. Inf. Technol.*, vol. 20, no. 4, pp. 624–631, Jul. 2023, doi: https://doi.org/10.34028/iajit/20/4/9.

[12]. M. Trimukhe and B. Hogade, "Design of the compact ultra-wideband (UWB) antenna bandwidth optimization using particle swarm optimization algorithm," *Iran. J. Electr. Electron. Eng.*, vol. 15, no. 2, pp. 236–245, Jun. 2019, doi: https://doi.org/10.22068/IJEEE.15.2.236.

[13]. S. Salma et al., "Particle swarm optimization of a multi-band MIMO antenna for ultra-wide band characteristics," in *Proc. 1st Int. Conf. Electr., Electron., Inf. Commun. Technol. (ICEEICT)*, 2022, pp. 1–4, doi: https://doi.org/10.1109/ICEEICT53079.2022.9768597.

[14]. W.-T. Li, X.-W. Shi, and Y.-Q. Hei, "An improved particle swarm optimization algorithm for pattern synthesis of phased arrays," *Prog. Electromagn. Res.*, vol. 82, pp. 319–332, 2008, doi: https://doi.org/10.2528/PIER08030904.

[15]. N. Feiz, F. Mohajeri, and A. Ghaznavi, "Optimized microstrip antennas with metamaterial superstrates using particle swarm optimization," *Bull. Electr. Eng. Inform.*, vol. 2, no. 2, pp. 123–131, Jun. 2013, doi: https://doi.org/10.11591/eei.v2i2.215.

[16]. M. Aziz-ul-Haq et al., "Log periodic dipole antenna design using particle swarm optimization," *Int. J. Electromagn. Appl.*, vol. 2, no. 4, pp. 65–69, 2012, doi: https://doi.org/10.5923/j.ijea.20120204.03.

[17]. J. Ababneh, M. Khodier, and N. Dib, "Synthesis of interdigital capacitors based on particle swarm optimization and artificial neural networks," *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 16, no. 4, pp. 322–330, Jul. 2006, doi: https://doi.org/10.1002/mmce.20141.

[18]. R. Beeresha, A. Khan, and H. Manjunath-Reddy, "Design and optimization of interdigital capacitor," *Int. J. Res. Eng. Technol.*, vol. 5, no. 21, pp. 73–78, Nov. 2016, doi: https://doi.org/10.15623/ijret.2016.0533016.

[19]. R. Chen, X. Zhang, K. Tsang, and K. Yung, "Modeling and design of interdigital capacitor based on neural networks and genetic algorithm," *Microw. Opt. Technol. Lett.*, vol. 38, no. 3, pp. 231–235, Aug. 2003, doi: https://doi.org/10.1002/mop.11023.

[20]. I. J. Bahl, *Lumped Elements for RF and Microwave Circuits*. Norwood, MA, USA: Artech House, 2003.

[21]. D. Caratelli and R. Cicchetti, "A full-wave analysis of interdigital capacitors for planar integrated circuits," *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1598–1601, May 2003, doi: https://doi.org/10.1109/TMAG.2003.810410.

[22]. R. H. Mahdi, H. A. Abdulnabi, and A. Alsudani, "Plasmonic high-gain graphene-based antenna array design for ultra-wide band terahertz applications," *Bull. Electr. Eng. Inform.*, vol. 11, no. 6, pp. 3322–3328, Dec. 2022, doi: https://doi.org/10.11591/eei.v11i6.3673.