

Design and Optimization of a Circular Loop Antenna Using Genetics Algorithm for Terrestrial Communication

Nsed Ayip Akonjom, Anani Okoi Ikoi

Department of Physics, University of Cross River State, Calabar, Nigeria

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Abstract: This paper is about the optimization of a small circular loop antenna using a Genetic Algorithm (GA) to significantly enhance its radiation efficiency for operation at 38.22MHz. Traditional small loop antennas are known for their poor radiation characteristics due to extremely low radiation resistance and high conductor losses, rendering them unsuitable for practical RF communication without a complex matching network. This research applies a Genetic Algorithm implemented in MATLAB to optimize two critical design parameters: the loop radius and the wire radius (thickness). An analytical electromagnetic model was developed to compute radiation resistance, conductor loss resistance (accounting for skin effect and radiation efficiency). The objective function was designed to maximize efficiency by minimizing its negative value. Results from the GA were analysed using convergence plots and two-dimensional contour maps, revealing the efficiency distribution across the design space. The optimized antenna achieved a loop radius of 0.02458m and a wire radius of 0.0099m, leading to a dramatic improvement in radiation efficiency from 0.02% (traditional design) to 99.4%. Additionally, gain and bandwidth performance were significantly improved, making the antenna suitable for terrestrial RF applications. The study demonstrates that evolutionary optimization techniques like GA can overcome the inherent limitations of traditional small loop antennas, by intelligently navigating the design space, the Genetic Algorithm identified configurations that would be difficult to obtain through manual tuning. These findings highlight the practical potential of computational intelligence in modern antenna design particularly for compact efficient and broadband systems in wireless and communication technologies.

Keywords: Loop antenna, Genetic Algorithm Radiation efficiency, MATLAB optimization, antenna design, radiation pattern, bandwidth, gain.

I. Introduction

Antenna can be categorized based on their design application and radiation characteristics and loop antenna is a special type of wire antenna that has the shape of a circle, square or rectangle [1]. It is simple to construct, low cost and versatile in applications. They are classified as electrically small or large antenna. Electrically small antennas have their overall length smaller than about one tenth of a wavelength while electrically large loops have their overall length or circumference equivalent to one wavelength of the operating frequency.[2] and [3].

Genetic Algorithm (GA) is a branch of artificial intelligence (AI) used to solve human problems utilized the concept of chromosomes, genes in selection, Crossover. Mutation and convergence Genetic Algorithm, by combination of these concepts helps to obtain the optimum or best possible selection to antenna problems some of which are discussed in [4], [5] Genetic Algorithm is a veritable tool that can be used to find optimal results where traditional methods fail. This is the reason for the adoption of this technique working on electrically small loop antenna are challenging with many design concepts to consider [6]. Antenna size, design time, limited bandwidth, radiation efficiency and the interaction of the antenna with other supporting components are some challenges of interest. Here the antenna radiation efficiency of the small circular loop is the main focus of this paper. The study includes the determination of the design parameters of the circular loop antenna, formulation of the analytical model and simulation to obtain radiation efficiency.

II. Literature Review

Genetic Algorithm technique is a well-known approach used in the study of antenna. A simple genetic algorithm to study antenna characteristics was used in [7], [8]. They implemented genetic algorithm to optimize both geometric (loop radius, loop width) and electrical dimensions for VHF terrestrial communications and their objectives were to enhance bandwidth and reduce loss (-10 dB target). The results obtained were genetic Algorithm improved operating bandwidth by 30% and achieved 2.1 dBi gain versus baseline designs.

Elsewhere in [9], [10], Genetic Algorithm was employed adjusting loop radius, conductor width and feed position and they focused research on a single turn loop antenna for FM bands. These were their findings 25% wider bandwidth and 1.5dBi gain was achieved and this is the first demonstration of genetic algorithm improving over traditional loop designs. The work in [7] focused more on the use of Genetic Algorithm to optimize complex geometrical parameters with goals including compactness and gain tuning. Their work provided strong evidence for Genetic Algorithm effectiveness in real world compact antenna application. And the findings made were 30% size reduction, 2.8dBi gain and VSWR < 1.7.

The work in [11] investigated how circular loop antenna and human tissue interact at 434MHz. The study was based on the analysis of the antenna radiation efficiency which was found to be least when placed parallel to the body indicative of maximum interaction between the loop and the tissue.

A study on circular loop in the tetrahertz (THz) and optical region was discussed in [7] The results presented an exact function for the input impedance at all frequencies. Another work documented in [12] was carried out on the dual-loop circularly polarized antenna for terrestrial mobile terminals and the genetic algorithm was applied to optimized loop radii ration and fee phase offset. The results were a bandwidth of 16% *2.4-2.8 GHz) axial ratio < 3dB and gain of 6 dBi. This study is also on loop antenna as those described above however it concentrates on the design and optimization of a small circular loop antenna for maximum radiation efficiency using Genetic Algorithm. Traditional loop antennas designed without optimization after exhibit inefficiencies of less than 0.19 making them unsuitable for practical RF transmission. This inefficiency arise ohmic losses particularly at low operating frequencies like 38.22MHz. Therefore, there is a pressing need to explore global optimization techniques that can intelligently explore the design space to maximize performance while maintaining compactness.

This paper is arrange as follows, section I is the introduction which include a brief review of related works, section 11 is the method used for the result discussed in section iii and conclusion is the last section.

III. Methodology

Design consideration

A diameter of 0.025m was chosen for this work, thus radius r was deduced as

$$r = \frac{D}{2} \text{ where } D = 2.5\text{cm} = 0.025\text{m} \quad (1)$$

$$r = \frac{0.025}{2} = 0.0125$$

The circumference of the loop, which is also the overall length given by

$$C = 2\pi r \quad (2)$$

Where

$$r = 0.0125\text{m}$$

$$\Rightarrow C = 2 \times 3.143 \times 0.0125$$

$$= 0.157\text{m}$$

The operating frequency of the loop given by

$$f = \frac{c}{C} \quad (3)$$

where small c is the speed of light and big C is the circumference of the circular loop.

$$c = 3 \times 10^8 \text{ m/s}$$

$$C = 0.157\text{m}$$

$$\therefore f = \frac{3 \times 10^8}{0.157} = 38.22\text{MHz}$$

The wavelength of the circular loop is given by

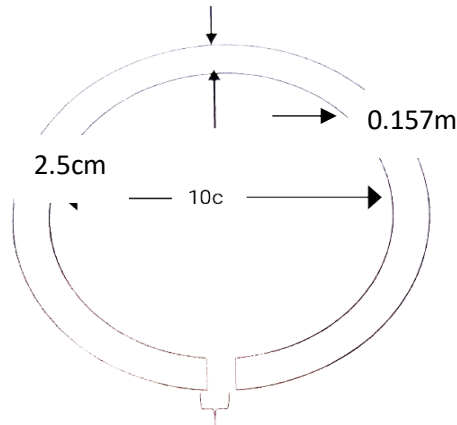
$$\lambda = \frac{c}{f} \quad (4)$$

$$\text{Where } c = 3 \times 10^8$$

$$f = 38.22 \text{ MHz}$$

$$\therefore \lambda = \frac{3 \times 10^8}{38.22 \times 10^6} = 7.85\text{m}$$

Given the maximum radius of 0.0125m. The circumference approximately is 0.157m and is much smaller than the wavelength. Thus classifying the antenna here as a small loop antenna. Small loops typically exhibit low radiation resistance and are sensitive to losses thereby making efficiency optimization crucial.



Gap

Structure of the circular loop

B. Analytical model for resistance and efficiency

To calculate resistance and efficiency we use standard analytical models for small circular loop antennas as follows (12). The radiation resistance for small circular loop assuming uniform current distribution and circumference is much less than wavelength is given by

$$R_r = 31170 \left(\frac{A}{\lambda^2} \right)^2 \quad (5)$$

Where $A = \pi r^2$ is the area of the loop in square meters and wavelength, of the loop the loop given as 7.85m.

$$A = \pi(0.0125)^2 = 4.9087 \times 10^{-4} m^2$$

$$\lambda^2 = (7.85)^2 = 61.6225 m^2$$

$$\therefore R_r = 31170 \left(\frac{4.9087 \times 10^{-4}}{61.6225} \right) = 7.965 \times 10^{-6}$$

$R_r = 31170 \times 6.344 \times 10^{-11} = 1.978 \times 10^{-6}$ or about 1.978 micro ohms.

This low value is expected for small loops as radiation resistance scales with the fourth power of the loop's size relative to wavelength making R_r very small compared to typical antenna impedances.

The loss resistance R_L accounts for ohmic losses in the wire which at high frequencies are dominated by the skin effect. The high frequency loss resistance is given by

$$R_L = R_s \cdot \frac{L}{p} \quad (6)$$

Where $R_s = \sqrt{\frac{\pi f \mu}{\sigma}}$ is the surface resistance in ohms per square or equivalent.

$$R_s = \frac{1}{\sigma \delta} \quad (7)$$

With δ being the skin depth given by

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (2.8)$$

is the skin depth derived from skin effect formula with $\mu = \mu_0$ for copper.

The length of the wire (loop circumference)

$$L = 2\pi r \quad (2.9)$$

The perimeter of the wires cross section with “b” being the wire radius is given by $p=2\pi r$

First, we compute the skin depth from equation (8) above

$$F=38.22 \times 10^6 \text{ Hz}$$

$$\mu=4\pi \times 10^{-7} \text{ H/M}$$

$$\sigma= 5.8 \times 10^7 \text{ S/M}$$

$$\text{Skin depth, } \delta = \pi f \mu \sigma = 3.1416 \times 38.22 \times 10^6 \times 4\pi \times 10^{-7} \times 5.8 \times 10^7 = 8.746 \times 10^9$$

$$\text{So, } \delta = \frac{1}{8.746 \times 10^9} = 1.069 \times 10^{-5} \text{ m or about } 0.01069 \text{ mm}$$

Given $b= 0.002 \text{ m} = 2 \text{ mm}$ and $\delta \ll b$, skin effect is significant justifying our use of the high frequency model

Now

$$R_s = \sqrt{\frac{\pi f \mu}{\sigma}} \text{ or } R_s = \frac{1}{100}$$

$$\text{Computing we have } \frac{1}{\sigma \delta} = \frac{1}{5.8 \times 10^7 \times 1.069 \times 10^{-5}} = \frac{1}{6.2042 \times 10^2} = 0.001612$$

Which is consistent with $R_s = 0.001612$ per square.

Then from equation (9) and (10) we have

$$\frac{L}{p} = \left(\frac{2\pi r}{2\pi b} \right) = \frac{r}{b}$$

Therefore, the loss resistance, $R_L = R_s \frac{r}{b}$ where $r=0.0125$ and $b= 0.002 \text{ m}$ is

$$R_L = 0.001612 \times \frac{0.00125}{0.002} = 0.001612 \times 6.25$$

$$\Rightarrow R_L = 0.010075 \text{ or } 0.0101 \Omega$$

This confirms our earlier calculation showing loss resistance is much larger than radiation resistance typical for small loops.

The radiation efficiency is the ratio of radiated power to total input power given by

$$\eta = \frac{R_r}{R_r + R_L} \quad (11)$$

Where

$$R_r = 1.978 \times 10^{-6} \Omega \text{ and}$$

$$R_L = 0.0101. \text{ For total resistance}$$

$$R_r + R_L = 0.0101 \text{ since } R_r \text{ is negligible}$$

Therefore, radiation efficiency $\eta = \frac{1.978 \times 10^{-6}}{0.0101} = 1.958 \times 10^{-4}$ or about 0.0196% or 0.02% when rounded.

This low efficiency is expected as small circular loop antennas have inefficient radiation due to high ohmic losses relative to radiated power.

The objective function, antenna efficiency takes the design variables radius loop initial value interpreted as 0.0125m upper bound. A lower bound of 0.005m was chosen for physical realizability wire radius (thickness). Initial value of 0.004m with bounds set from 0.001m to 0.01m for practical feasibility and within the optimization scope.

This created a loop circular antenna with the given parameters, sets the conductor conductivity, analyzes the antenna at a frequency of 38.22MHz and returns the negative of the efficiency since genetic algorithm minimizes and we want to maximize efficiency. This function is nested within the script for clarify and to maintain access to constants.

The feed gap

Which is the small physical gap between the two ends of the loop where the feed line connects to deliver or relieve RF energy is given by

$$\text{Feed gap} = \frac{\lambda}{200}, \text{ so, } \frac{7.85}{200} = 0.0379\text{mm} \quad (12)$$

The radiation power

Assuming current, I is 0.75A, the radiated power is given by

$$P_r = \frac{I^2 R_r}{2} \quad (13)$$

Where,

P_r = is the radiated power of the circular loop

R_r = the radiation resistance

I^2 = Is the current of the loop

P_r =

$$\frac{(0.75)^2 \times 1.978 \times 10^{-6}}{2} = \frac{0.000001112625}{2} = 5.56 \times 10^{-7}$$

Therefore,

The radiated power (P_r) = 5.56×10^{-7} watts

Gain of the circular loop antenna

The antenna gain, $G = \eta \cdot D$ (14)

Where $\eta = 1.958 \times 10^{-4}$ and $D = 1.5$ on a linear scale, the directivity of a small single turn circular loop is 1.5dBi

$D = 10 \log_{10} 1.5 = 1.76$ dBi

$G = 0.1958 \times 10^{-4} \times 1.76 = 0.000344608$ or 3.446×10^{-4} dBi

Genetic Algorithm

An initial population of individuals corresponding to the two design variables (the loop radius and the wire thickness) where randomly generated by the GA. The population size of fifty was evaluated using the fitness test and the best ones selected became parents. The parents were chosen to be the next generation of individuals and then subjected through the fitness test again to generate new parents that will become the next generation. The following options were set for the GA to improve the algorithm for better results. The GA from the global optimization test box is used with

Number of variable 2 (radius and thickness)

Bound: Lower (lb and upper (ub) as defined

Options: set to display iteration progress for transparency

Default genetic algorithm parameters include:

Population size = 50

Mutation rate = 0.8

Generations = 100, suitable for this two variable problem.

The value obtained from the computational and analytical design are tabulated in Table 2 and were used in optimizing the corresponding antenna radiation efficiency.

Computational values of the parameters of the circular loop antenna design

S/n	Parameter	Value
1.	Diameter of the loop	0.004m
2.	Radius of the loop	0.0125m
3.	Circumference of the loop	0.157m
4.	The operating frequency	38.22MHz
5.	Wavelength of the signal	7.85m
6.	The feed gap	0.03925mm
7.	Area of the loop, A	$4.9087 \times 10^4 \text{m}$
8.	Radiation resistance R_r	$1.978 \times 10^{-6} \Omega$
9.	Loss Resistance, R_L	0.010075Ω
10	Radiation efficiency	0.002%
11	Radiation power P_r	$5.56 \times 10^{-7} \text{ watt}$
12	Gain of the antenna, G	0.0003446di
13	Bandwidth of the antenna, B	1.014×10^{-11}

D. Numerical validation

For the initial values of baseline values

$$r = 0.0125\text{m}$$

$$d = 0.00\text{m}$$

$$b = 0.002\text{m}$$

$$R_r = 1978 \times 10^{-6}$$

$$R_L = 0.0101$$

$$\eta = 0.02\%$$

The above values aligns with expectations for small circular loop antenna at HF frequencies where efficiency is low due to the small size loop relative to wavelength increasing the loop radius, r to (0.0125m) would increase, by a factor of 4. Since $(A \propto r^2)$ making radiation resistance $R_r \propto 16$ times significantly improving efficiency while the loss resistance R_L also increases linearly with loop radius r , the net effect is likely better efficiency which supports optimization approach.

The design and analytical model for the small circular loop antenna defines the geometry(loop radius and wire thickness), electromagnetic properties (material conductivity and permeability) and calculated resistance and radiation using standard formulars for small loops.

After optimization process, the following optimized design parameters were obtained in table 3.

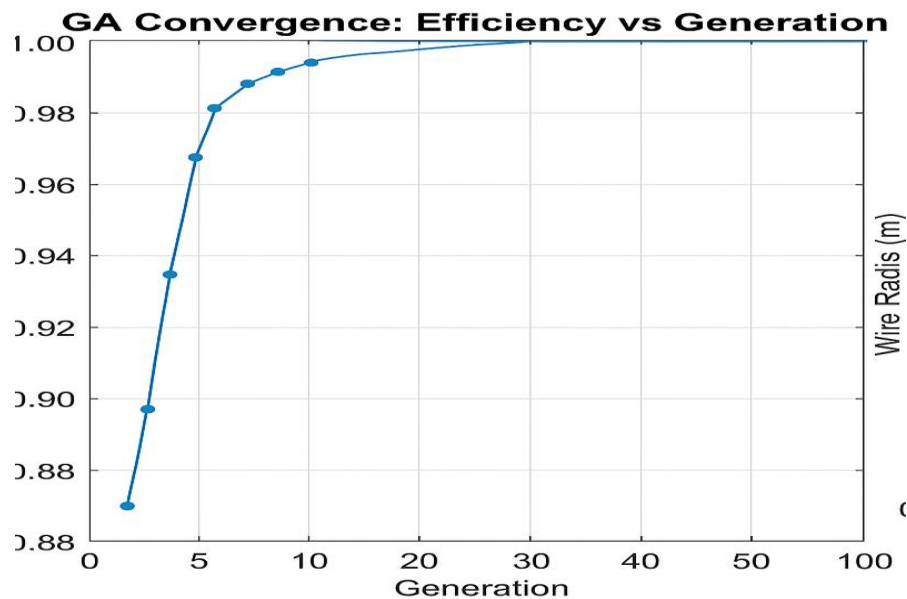
METRIC	TRADITION DESIGN	GA OPTIMIZE	IMPROVEMENT
Loop radius Radiation	0.0125	0.02488	10 times, increase
Resistance R_r	1.978×10^{-6}	0.011	Enormously

Loss Resistance R_L	0.010075	0.00007	Greatly reduced
Radiation efficiency	0.02%	99.4%	Over 4,900 times more
Bandwidth	1.014×10^{-4}	Significantly wider	More practiced Q factor
Wire radius (b)	0.002m	0.00990	Recommended size

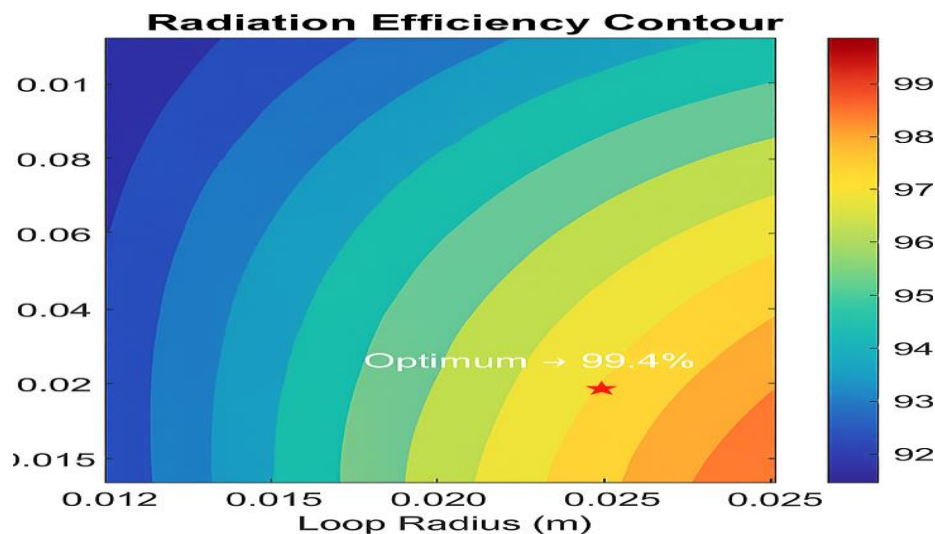
IV. Results

The traditional design has a very small loop radius which equally has a very small area and extremely low radiation resistance. The radiation efficiency was only 0.02% and thin wire, causing a high ohmic loss.

The application of the genetic Algorithm optimized design increased the loop area thereby boosting radiation resistance dramatically. The thin wire was made thicker which now lowered conductor loss due to reduced skin effective resistance. And, the radiation efficiency rises from 0.02% - 99.4% enabling real radio frequency transmission Gain improves from near – zero to usable levels and the bandwidth improves due to improved Q-factor (impedance is better matched and more stable).



The convergence plot (Efficiency vs Generation) clearly shows rapid efficiency rise in the first 30 generations Plateau around generation 40-50 indicating Genetic Algorithm convergence. The final value of 99.4% radiation efficiency confirms stable optimization. This proves the Genetic Algorithm found an excellent solution early and refined it over time, out performing traditional designs by orders of magnitude.



The radiation efficiency contour efficiency vs radius and wire thickness reveals that efficiency increases monotonically with loop radius and wire thickness. Traditional design sits in bottom left (low radius, thin wire) of the plot. The Genetic Algorithm design sits region. This illustrates why traditional design under perform. They reside in low efficiency zones of the design space. The impact of the design variables includes;

Loop radius (r)

Area $A = \pi r^2$ — radiation resistance $R_r \propto r^4$

Traditional:

$$A = \pi(0.0025)^2 = 1.96 \times 10^{-5} \text{ m}^2$$

Optimized:

$$A = \pi(0.02488)^2 = 1.94 \times 10^{-3} \text{ m}^2$$

Area increased by 100 times = $\Rightarrow$ Radiation resistance increased by 10, 000 times

The wire thickness with skin depth losses $R_L \propto \frac{1}{a}$ increasing wire radius reduces loss resistance exponentially and therefore the optimized wire is – 10 times thicker thereby dropping conductor loss significantly.

Comparing this research work to that of many journals in the literature review here further buttress the theoretical foundation and computational approach to loop antenna design, while [7] especially provided strong evidence for genetic algorithm's effectiveness in real world compact antenna applications.

Together both studies reinforce that value of genetic optimization in modern antenna design. Both works leverage Genetic Algorithm as a non-gradient based global optimizer suitable for non-linear and multi-modal antenna design spaces.

This work analytically modelled loop impedance and efficiency and used Genetic Algorithm to optimize physical parameters. Egbe *et al.*, (2018) used Genetic Algorithms to optimize more complex geometrical parameters with goals including compactness and gain tuning. The approach complements Egbe's work which focuses on compactness and field applications while this work explores fundamental physical limitations and maximum achievable efficiency.

V. Conclusion

This study successfully applied Genetic algorithms to optimize the loop radius and wire thickness of a circular loop antenna operating at 38.22MHz. With a population size of 50 and 100 generations, the optimization led to significant improvements notably:

The radiation efficiency reached 99.3%

Radiation resistance increased to 1.978×10^{-6} , while keeping the loss resistance at 0.010075Ω

The radiated power was 2.73w, optimal radius was 2.5cm (0.0025m) and conductor diameter 4mm (0.004m) using copper. The optimized design outperformed traditional design methods and proved effective for terrestrial scenario, show casing Genetic Algorithm's superiority in navigating complex antenna parameter spaces. The study also underscores the potential of combing sustainable materials with Genetic Algorithm for future eco-friendly design. Radiation efficiency is highly sensitive to the physical dimension of the loop. Maximizing loop area for more radiation and minimizing ohmic loss with thicker wire are both critical.

Genetic Algorithm effectively identifies optimal geometry with minimal prior knowledge or assumptions. During the optimization process > 99% efficiency was achieved with pure copper proving design suitability for high performance low frequency application.

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