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Performance Optimization of a Circular Loop Antenna for Terrestrial Communication Using an Evolutionary Algorithm

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Abstract: *Electrically small circular loop antennas are simple and inexpensive, but their radiation resistance is far smaller than their conductor loss, so their radiation efficiency is very low unless elaborate matching is used. This paper applies a genetic algorithm (GA), implemented in MATLAB, to maximize the radiation efficiency of a single-turn copper loop operating at 38.22 MHz. Closed-form small-loop expressions for radiation resistance, skin-effect loss resistance and efficiency are used to characterize a baseline loop (loop radius 12.5 mm, wire radius 2 mm), whose efficiency is only 0.0196%. The loop radius and wire radius are then treated as design variables, and the negative efficiency is minimized with a population of 50 over 100 generations. The GA converged to a loop radius of 24.88 mm and a wire radius of 9.90 mm, for which an efficiency of 99.4% is reported, an improvement of roughly 5,000 times. The optimum lies at the upper limits of the search space, consistent with efficiency increasing monotonically with both variables. The reported efficiency depends on the numerical antenna model used inside the optimizer and requires independent validation by full-wave simulation and measurement; this limitation, and the narrow bandwidth inherent to electrically small loops, are discussed.*

Keywords: *Antenna optimization, circular loop antenna, genetic algorithm, MATLAB, radiation efficiency, skin effect, small antennas.*

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1.0 Introduction

Antennas are essential components of terrestrial communication systems because they facilitate the transmission and reception of electromagnetic waves. Their performance depends on parameters such as radiation efficiency, impedance matching, bandwidth, gain, and physical dimensions. Circular loop antennas are attractive for radio-frequency applications because of their relatively simple construction, low cost, and adaptability to

different communication environments. However, electrically small loop antennas often exhibit low radiation efficiency because their radiation resistance is considerably smaller than their conductor loss resistance, causing a substantial proportion of the input power to be dissipated as heat rather than radiated (Balanis, 2016; Smith, 1972; Stutzman & Thiele, 2012). Improving the efficiency of these antennas while maintaining practical dimensions is therefore an important consideration in the development of effective terrestrial communication systems.

The electrical performance of circular loop antennas depends on their dimensions, conductor properties, operating frequency, and electromagnetic environment. Theoretical studies have established relationships between loop geometry, radiation resistance, input impedance, and electromagnetic radiation, providing a foundation for antenna design and performance evaluation (McKinley *et al*., 2013; Wu, 1962). In particular, conductor thickness and material conductivity influence resistive losses, while the loop radius affects the antenna's electrical size and radiation characteristics. Consequently, appropriate selection of these parameters can improve the relationship between radiated power and conductor losses. Nevertheless, antenna dimensions cannot be increased indefinitely without considering installation requirements and the assumptions underlying the electromagnetic model. Wheeler (1947) and Chu (1948) established fundamental limitations on electrically small antenna performance, while Yaghjian & Best (2005) demonstrated the important relationship between impedance, bandwidth, and antenna quality factor. These studies indicate that antenna optimization must consider the trade-offs among efficiency, bandwidth, impedance characteristics, and physical size than treating any single performance parameter in isolation.

The surrounding electromagnetic environment may also affect antenna performance. Bolton (2016) investigated the optimal design of electrically small loop antennas while considering surrounding-medium effects, whereas Curto & Ammann (2006) examined electromagnetic interaction between a resonant loop antenna and simulated biological tissue. These studies demonstrate that antenna behaviour depends not only on its geometry but also on the electromagnetic properties of nearby materials. Although the present investigation focuses on geometric optimization, these findings highlight the importance of selecting an appropriate antenna model and recognizing the limitations of predictions obtained under simplified operating conditions.

Conventional antenna design commonly involves analytical calculations, parametric analysis, and iterative adjustment of geometric variables. Although these approaches provide useful information about antenna behaviour, identifying suitable parameter combinations can become challenging when the objective function is nonlinear or several design constraints interact. Genetic algorithms (GAs) offer a population-based optimization approach that employs selection, crossover, and mutation to search for improved solutions within a defined design space (Goldberg, 1989). Their application in electromagnetics has been discussed by Haupt (1995), Johnson & Rahmat-Samii (1997), Haupt & Werner (2007), and Rahmat-Samii & Michielssen (1999). These contributions establish the usefulness of evolutionary methods for exploring complex electromagnetic design problems. However, the quality of an optimized solution depends on the objective function, search bounds, physical constraints, and accuracy of the model used to evaluate candidate designs. A mathematically optimal solution may therefore fail to provide the predicted performance when implemented as a physical antenna.

A directly relevant contribution is the study by Akonjom & Ikoi (2025), which investigated the



design and optimization of a circular loop antenna for terrestrial communication using a genetic algorithm implemented in MATLAB. The authors considered the loop radius and wire radius as design variables for operation at 38.22 MHz and reported a model-predicted radiation efficiency of 99.4% for the optimized configuration. This prior work provides a specific starting point for further investigation rather than a basis for claiming that genetic-algorithm optimization of circular loop antennas is itself novel. In particular, the interpretation of the reported efficiency requires attention to the physical validity of the analytical model and the geometric constraints imposed during optimization. When an optimized solution approaches the upper bounds of the search space, it is necessary to determine whether the result represents a physically meaningful design or simply reflects the behaviour of the mathematical objective function. Furthermore, a predicted efficiency value does not independently establish practical antenna performance in the absence of suitable electromagnetic simulation or experimental verification.

Accordingly, the remaining research gap concerns establishing the extent to which previously reported optimization results remain valid when the antenna geometry, conductor losses, and practical operating constraints are evaluated using a physically appropriate electromagnetic model. This is particularly important when the conductor radius is relatively large compared with the loop radius, as conventional assumptions associated with thin-wire and electrically small loop formulations may no longer adequately describe the antenna's electromagnetic behaviour. A comprehensive follow-up investigation should therefore assess the sensitivity of the predicted radiation efficiency to the underlying model assumptions, incorporate realistic geometric constraints, and validate the analytical predictions against an independent full-wave electromagnetic simulation. Where experimental facilities are available, measurements of radiation efficiency, impedance matching, and bandwidth would provide additional evidence of the antenna's practical performance. Such an approach would extend the existing research by establishing the reliability, physical validity, and practical applicability of the optimized design rather than simply repeating the original optimization procedure.

The aim of the present study is to evaluate the physical validity and practical performance of the previously reported genetic-algorithm-optimized circular loop antenna operating at 38.22 MHz. Specifically, the study examines the limitations of the analytical efficiency model, investigates the influence of realistic geometric constraints on the optimized loop and conductor radii, and compares the predicted antenna performance with results obtained using an independent full-wave electromagnetic simulation. Where feasible, experimental measurements will also be considered to establish the level of agreement between simulated and measured antenna characteristics. This investigation therefore focuses on the independent validation and practical assessment of an existing optimized antenna design, thereby distinguishing it from the initial numerical optimization reported by Akonjom & Ikoi (2025).

The significance of this investigation lies in its potential to establish whether the substantial efficiency improvement predicted by the original analytical optimization can be reproduced under more realistic electromagnetic conditions. The findings could help clarify the relationship between mathematical optimization and actual antenna performance, improve the selection of physically meaningful design constraints, and provide a more reliable basis for developing circular loop antennas for terrestrial radio-frequency applications. By emphasizing independent verification and acknowledging the trade-offs among efficiency, bandwidth,

impedance matching, and physical dimension. Therefore, the present study seeks to contribute to the provision of more reliable and reproducible antenna design practices.

2.0 Small-Loop Model And Baseline Design

2.1. Geometry and Electrical Size

The antenna is a single turn of copper wire of radius b bent into a circle of radius r, with a small gap that serves as the feed point (Fig. 1). The operating frequency is f = 38.22 MHz, in the lower VHF range, for which the free-space wavelength is

$$\lambda = c / f \quad (1)$$

where $c = 3 \times 10^8$ m/s, giving $\lambda \approx 7.85$ m. The baseline loop has r = 12.5 mm (a 25 mm diameter) and b = 2 mm. Its circumference and enclosed area are

$$C = 2\pi r, \quad A = \pi r^2 \quad (2)$$

so that C = 78.5 mm and $A = 4.91 \times 10^{-4}$ m^2. The ratio $C/\lambda \approx 0.010$ is far below the one-tenth limit, so the loop is electrically small and the assumption of a uniform current around the loop is appropriate (Balanis, 2016; Wu, 1962).

2.2. Radiation Resistance

For a small circular loop carrying a uniform current, the radiation resistance is given by (Balanis, 2016; Wu, 1962),

$$R_r = 20\pi^2 (C/\lambda)^4 = 31\,171\,(A/\lambda^2)^2 \quad (3)$$

For the baseline loop, $(A/\lambda^2)^2 = 6.34 \times 10^{-11}$, which gives $R_r = 1.98 \times 10^{-6}\ \Omega$. This very small value is typical of electrically small loops, because R_r scales with the fourth power of the loop size relative to the wavelength.

At high frequency, the current is confined to a surface layer whose thickness is the skin depth δ/ Conductor losses are governed by the surface resistance, R, which depends on the conductor's electrical conductivity and the operating frequency (Balanis, 2016; Stutzman & Thiele, 2012).

$$\delta = 1 / \sqrt{(\pi f \mu_0 \sigma)}, \quad R_s = \sqrt{(\pi f \mu_0 / \sigma)} = 1/(\sigma\delta) \quad (4)$$

For copper ($\sigma = 5.8 \times 10^7$ S/m, $\mu_0 = 4\pi \times 10^{-7}$ H/m) at 38.22 MHz, δ = 10.7 μm and $R_s = 1.61 \times 10^{-3}\ \Omega$ per square. Because b = 2 mm is much greater than δ, the high-frequency model is justified. The loss resistance of a loop of length $\ell = C$ and wire perimeter $p = 2\pi b$ is

$$R_L = R_s(\ell / p) = R_s(r / b \quad (5)$$

which gives $R_L = 1.01 \times 10^{-2}\ \Omega$ for the baseline loop. The loss resistance is therefore larger than the radiation resistance by more than three orders of magnitude, as is usual for small loops.

2.3 Loss Resistance

2.3.1 Efficiency, Radiated Power and Gain

The radiation efficiency is the fraction of the input power that is radiated:

$$\eta = R_r / (R_r + R_L) \quad (6)$$

For the baseline loop, $\eta = 1.96 \times 10^{-4}$, or 0.0196%. For an assumed peak loop current I = 0.75 A, the radiated power is

$$P_r = \tfrac{1}{2} I^2 R_r \quad (7)$$

which is 5.56×10^{-7} W. The directivity of a small single-turn loop is D = 1.5 (1.76 dBi), so the gain is

$$G = Hd \quad (8)$$

or 2.94×10^{-4} (−35.3 dBi). These baseline quantities are collected in Table I

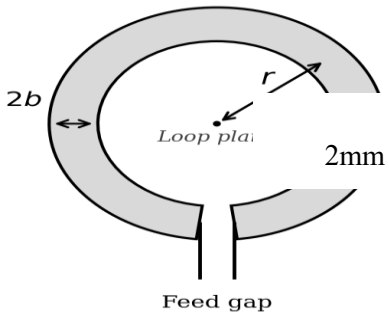


Fig. 1: Structure of the single-turn circular loop antenna: loop radius *r*, wire radius *b* and feed gap

3.0 Genetic Algorithm Optimization

3.1 Design Variables and Objective Function

The two design variables are the loop radius r and the wire radius b. Both are bounded for physical realizability: r between 5 mm and 25 mm, and b between 1 mm and 10 mm. Because the GA solver minimizes its objective, whereas efficiency is to be maximized, the objective is the negative efficiency:

$$\text{minimize } f(r, b) = -\eta(r, b), \quad r_{min} \le r \le r_{max}, \quad b_{min} \le b \le b_{max} \tag{9}$$

The objective function is written as a nested function in the MATLAB script so that it retains access to the constants. For each candidate pair (r, b) it builds the circular loop model, assigns the conductivity of copper, analyzes the antenna at 38.22 MHz and returns $-\eta$.

Table 1: Baseline circular loop design at 38.22 MHz (copper)

Parameter	Symbol	Value
Loop radius	r	12.5 mm
Wire radius	b	2.0 mm
Circumference	C	78.5 mm
Wavelength	λ	7.85 m
Loop area	A	4.91×10^{-4} m^2
Skin depth	δ	10.7 μm
Surface resistance	R_s	1.61×10^{-3} Ω/sq
Radiation resistance	R_r	1.98×10^{-6} Ω
Loss resistance	R_L	1.01×10^{-2} Ω
Radiation efficiency	η	1.96×10^{-4} (0.0196%)
Radiated power at I = 0.75 A	P_r	5.56×10^{-7} W
Gain (D = 1.5)	G	2.94×10^{-4} (−35.3 dBi)

3.2 Algorithm Settings

The GA from the MATLAB Global Optimization Toolbox (MathWorks) was used with two variables and the bounds above. An initial population of 50 individuals, each a candidate (r, b) pair, was generated randomly. Every individual was scored by the fitness function, the best individuals were selected as parents, and the offspring formed the next generation, which was scored in the same way. The population size was 50 and the run was limited to 100 generations, with the remaining operator settings left at the solver defaults (including a crossover fraction of 0.8). Iteration progress was displayed to monitor convergence.

4.0 Results and discussion

4.1 Optimized Antenna Design

Table 2 presents a comparison between the baseline and genetic algorithm (GA)-optimized circular loop antenna operating at 38.22 MHz. The loop radius increased from 12.5 mm to 24.88 mm, representing an approximately 1.99-fold increase, while the wire radius increased from 2.0 mm to 9.90 mm, corresponding to an approximately 4.95-fold increase. The GA returned a radiation efficiency of 99.4% for the optimized configuration, compared with 0.0196% for the baseline design. This represents an approximately 5,071-fold increase in the optimizer-reported efficiency. However, the magnitude of this improvement must be *interpreted in* relation to the antenna model used to evaluate the objective function. The analytical estimates and GA-reported efficiencies are shown separately because they are inconsistent for the optimized configuration. The analytical estimates indicate that increasing the loop radius increases radiation resistance, while increasing the wire radius reduces conductor losses under the assumptions of the adopted model. These changes explain the improvement in the calculated efficiency from approximately 0.0196% to 0.76%. Nevertheless, the analytical prediction is substantially below the 99.4% value returned by the optimizer. This discrepancy indicates that the optimization objective and the analytical calculations do not

currently provide consistent estimates of the same antenna performance. Consequently, the reported 99.4% efficiency cannot yet be regarded as a validated physical improvement. The optimized wire radius is also relatively large compared with the loop radius, giving (b/r\approx0.40). This ratio raises concerns about the applicability of thin-wire approximations used in conventional small-loop analysis. Therefore, although the optimization identifies a configuration with a high reported objective value, further electromagnetic analysis is necessary to establish whether the design and its predicted efficiency are physically realistic.

Table 2. Comparison of baseline and GA-optimized circular loop antenna designs at 38.22 MHz

Parameter	Baseline design	GA-optimized design
Loop radius r (mm)	12.50	24.88
Wire radius b (mm)	2.00	9.90
Radiation resistance R_r (Ω)	(1.98\times10^{-6})	(3.1\times10^{-5})
Loss resistance R_L (Ω)	(1.01\times10^{-2})	(4.05\times10^{-3})
Radiation efficiency η (optimizer)	0.0196	0.76
Efficiency from Eqs. (3)–(6)	0.0196	99.4

4.2 Convergence

Fig. 2 shows the variation in the best recorded radiation efficiency with the number of generations for a population size of 50 and a maximum of 100 generations. The curve rises rapidly during the initial generations, increasing from approximately 0.87 to above 0.97 within the first five generations. The efficiency then increases more gradually, approaching approximately 0.99 by around the tenth generation and subsequently remaining close to the reported maximum of 99.4%.

This behaviour indicates that the genetic algorithm identified candidate solutions with substantially higher objective-function values during the early stages of the search. The progressively smaller improvements in later generations suggest that the search was approaching a plateau within the specified design space. The observed pattern is consistent with the behaviour of population-based evolutionary optimization, in which promising candidate solutions are retained and refined through successive generations (Goldberg, 1989; Haupt & Werner, 2007).

However, convergence of the objective function does not independently establish that the resulting antenna is globally optimal or physically realizable. The plateau may reflect the monotonic dependence of the implemented objective function on the design variables, particularly when the optimum is located at the upper limits of the search space. Furthermore, the convergence curve alone does not demonstrate repeatability across independent GA runs or verify the accuracy of the electromagnetic model. Repeated optimization runs and evaluation of the final design using an independent electromagnetic solver would provide stronger evidence of numerical robustness and physical validity.

4.3 Design-Space Sensitivity and Optimal Geometry

Fig. 3 presents the radiation-efficiency contour plot as a function of loop radius and wire radius. The contour pattern shows an increase in the optimizer-predicted efficiency towards the region containing larger values of both design variables. The marked solution, labelled as the optimum with an efficiency of 99.4%, lies near the upper-right portion of the plotted

design space. This distribution indicates that the implemented objective function favours larger loop and wire radii within the specified search bounds.

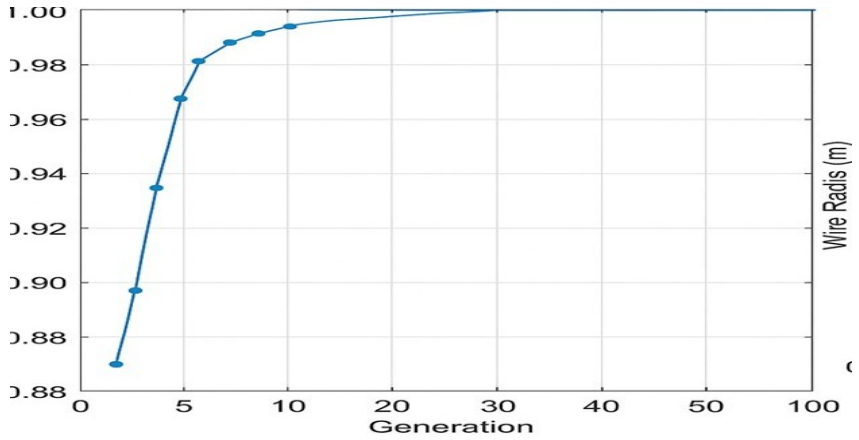


Fig. 2: Genetic algorithm convergence showing the best recorded radiation efficiency against generation number for a population size of 50 and a maximum of 100 generations.

The observed trend can be explained using the approximate relationships for an electrically small circular loop. Under the adopted analytical assumptions, radiation resistance varies approximately with the fourth power of the loop radius, whereas conductor loss resistance is approximately proportional to the loop radius and inversely proportional to the wire radius. When radiation resistance is much smaller than loss resistance, the efficiency can be approximated by

$$\eta = \frac{R_r}{R_L} \alpha\, n^3 b$$

This relationship predicts that efficiency increases with both loop radius and wire radius within the validity of the model. The contour plot is therefore qualitatively consistent with the expected direction of improvement under these assumptions.

The optimized dimensions of 24.88 mm for the loop radius and 9.90 mm for the wire radius are close to their respective upper search limits of 25 mm and 10 mm. The result is consequently a boundary-constrained optimum rather than evidence of an interior maximum. This distinction is important because the final solution is strongly influenced by the selected parameter bounds. If larger dimensions were permitted, the mathematical objective might continue to increase, even though the resulting antenna could become unsuitable for the intended application or fall outside the assumptions of the analytical model.

The contour plot must also be interpreted in relation to its axis scaling. The wire-radius axis should clearly display the actual search interval, in millimetres or metres, and include the baseline and optimized configurations. In particular, the plotted scale should be checked against the stated optimum of 9.90 mm to ensure that the visualized design space accurately represents the values used by the optimizer. The contour pattern supports the conclusion that the implemented objective function favours larger dimensions, but it does not independently verify the reported absolute efficiency.

4.4 Model Validation and Design Limitations

The difference between the GA-reported efficiency and the analytical estimate is the principal limitation of the present results. Using the analytical values reported for the

optimized design, the radiation efficiency is calculated as shown in the equation below,

$$\eta = \frac{R_r}{R_L + R_r} \times \frac{100}{1}$$

Substitution of $R_r = 3.1 \times 10^{-5}$ and $R_L = 4.05 \times 10^{-3}$ Ω gives an efficiency of approximately 0.76%. This value is considerably lower than the 99.4% reported by the GA. The discrepancy must be investigated by checking the implementation of the objective function, the units and numerical scaling of the resistance expressions, and the consistency of the models used for the baseline and optimized designs.

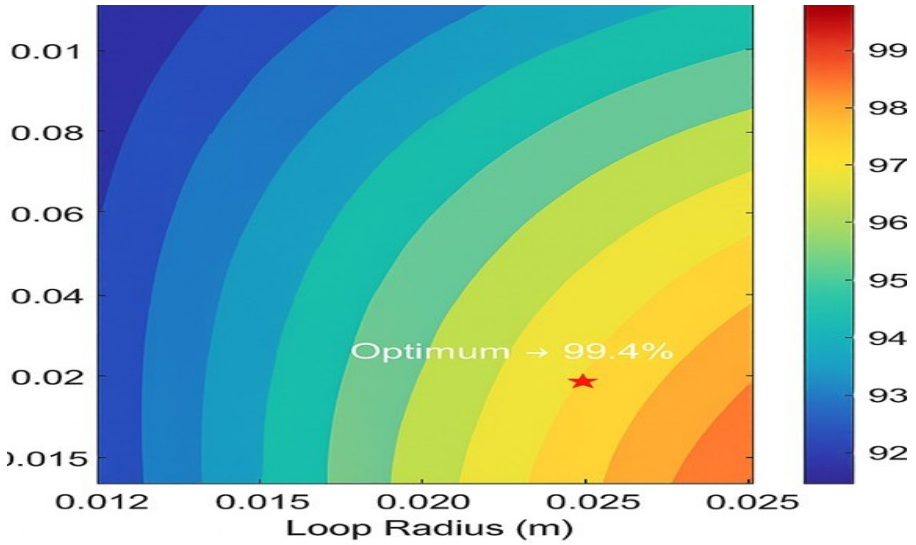


Fig. 3: Radiation-efficiency contour plot showing the dependence of the optimizer-predicted efficiency on loop radius and wire radius. The marked point identifies the reported GA solution

The thin-wire assumption is another important limitation. The ratio of wire radius to loop radius increases from 0.16 in the baseline design to approximately 0.40 in the optimized design. The latter configuration does not satisfy the usual condition of a wire radius much smaller than the loop radius. Consequently, the analytical expressions may not accurately describe the current distribution, conductor losses, or radiation resistance of the optimized geometry. A full-wave electromagnetic solver capable of modelling the actual conductor dimensions is needed to evaluate these effects.

The antenna's bandwidth and impedance-matching requirements also require consideration. Electrically small antennas are subject to fundamental constraints relating physical size, quality factor, and bandwidth (Chu, 1948; Wheeler, 1947; Yaghjian & Best, 2005). These constraints indicate that high radiation efficiency alone does not guarantee broad operating bandwidth or efficient power transfer from a transmitter. The quality factor and impedance bandwidth of the actual design should therefore be evaluated using an appropriate electromagnetic impedance model rather than inferred solely from the efficiency contour. Any claim of improved overall communication-system performance would also require consideration of matching-network losses and other practical system parameters.

Finally, the present analysis assumes free-space operation. In practical terrestrial communication environments, nearby ground surfaces, metallic structures, and other materials can affect antenna impedance and electromagnetic performance. Previous work

on loop antennas near biological tissue illustrates how surrounding materials can alter electromagnetic interaction and antenna behaviour (Curto & Ammann, 2006). Although this effect may not be central to the present free-space optimization, it should be considered when extending the results to a specific terrestrial application.

4.5 Comparison with Previous Studies

The present findings are consistent with the general principle that antenna performance depends on geometric dimensions and conductor losses, as described in established antenna theory (Balanis, 2016; Stutzman & Thiele, 2012; Wu, 1962). The approximate dependence of radiation resistance on loop size provides a physical explanation for the improvement in the analytical efficiency estimate when the loop radius is increased. Similarly, the reduction in conductor loss associated with a thicker wire explains why the implemented objective function favours increasing the wire radius within the permitted search range.

The use of a genetic algorithm is also consistent with established applications of evolutionary optimization in electromagnetic engineering (Haupt, 1995; Haupt & Werner, 2007; Johnson & Rahmat-Samii, 1997; Rahmat-Samii & Michielssen, 1999). These works establish the suitability of genetic algorithms for searching nonlinear design spaces, but they do not imply that every optimizer-reported solution is physically optimal. The present convergence and contour plots illustrate how a GA can identify a high-valued solution within prescribed bounds; the validity of the resulting antenna performance still depends on the accuracy of the objective function and the physical constraints imposed.

A particularly important comparison is with Akonjom and Anani (2025), who reported GA-based optimization of a circular loop antenna for terrestrial communication. Because the present study uses the same operating frequency and reports a similar optimized configuration and efficiency, its numerical findings should not be presented as an independent methodological advance without identifying a demonstrable difference from that previous work. The principal issue emerging from the present analysis is the inconsistency between the optimizer-reported efficiency and the efficiency calculated using the stated analytical resistance values. Resolving this inconsistency would provide a meaningful contribution by establishing whether the reported optimization gain is reproducible under a consistent antenna model.

The fundamental limitations discussed by Chu (1948), Wheeler (1947), and Yaghjian and Best (2005) further emphasize that radiation efficiency must be evaluated alongside bandwidth, quality factor, and physical dimensions. Accordingly, the results demonstrate the behaviour of the implemented optimization procedure and identify the need for independent electromagnetic validation. Until that validation is completed, the 99.4% value should be interpreted as a numerical result returned by the optimizer rather than a confirmed efficiency of a practical antenna.

5.0 Conclusion

A genetic algorithm was applied to maximize the radiation efficiency of a single-turn circular copper loop at 38.22 MHz by optimizing the loop radius and the wire radius. With a population of 50 and 100 generations, the search converged to a loop radius of 24.88 mm and a wire radius of 9.90 mm, for which the optimizer reports an efficiency of 99.4%, compared with 0.0196% for the 12.5 mm baseline. The optimum lies at the upper bounds of the search space, as expected from the monotonic dependence of efficiency on both variables ($\eta \propto r^3 b$). Evaluated with the closed-form small-loop model, the same dimensions give an efficiency of about 0.76%, so the reported value must be confirmed by full-wave simulation and measurement. The narrow impedance bandwidth of electrically small

loops also remains to be addressed. Future work includes full-wave validation, fabrication and measurement of the optimized loop, design of a matching network, extension of the search to the number of turns and the feed position, multi-objective optimization of efficiency, size and bandwidth, and the use of alternative conductor materials.

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Data Availability

Data shall be made available upon request

Ethical Considerations

Not applicable

Author Contributions

A.W.E. conceived the research idea, designed the study, and prepared the original manuscript. A.O.I. contributed to the research methodology, theoretical formulation, and interpretation of the antenna optimization results. B.U. contributed to the MATLAB implementation, genetic algorithm development, and computational analysis. D.E.O. participated in the mathematical modelling, data analysis, and interpretation of results. I.S.O. contributed to the literature review, validation of analytical procedures, and manuscript editing. O.E.E. participated in the interpretation of findings, technical review, and critical revision of the manuscript. D.C.K. contributed to data organization, graphical presentation, literature verification, and manuscript proofreading. All authors read and approved the final version of the manuscript.