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DIPOLE ANTENNA DESIGN LEVERAGING OPTIMIZATION TECHNIQUES

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Abstract

Dipole antennas are the commonest and simplest type of antennas in terms of design. Antenna Engineers and researchers have been looking for ways to design dipole antenna that can address specific needs of their clients, without incurring additional expenses on the available resources. Therefore, optimization techniques becomes necessary to be leveraged in order to design cost-effective antennas. This paper presents dipole antenna and its varieties as well as different optimization techniques that can be leveraged to design dipole Omni-directional antennas that can stand the test of time. Most dipole antenna designs carried out by some researchers did not include integrating optimization techniques in their approach. Clients are looking for cost effective

Keywords: Optimization, dipole Antenna, Omnidirectional, design, Radio.

INTRODUCTION

The fundamental principle in communication engineering involves a sender, a channel (medium), and a receiver. An antenna is responsible for transmitting signals to the intended destination [3]. In the field of communication engineering, dipole antennas are frequently employed due to their straightforward construction and fabrication.

Researchers and antenna engineers continually seek economical solutions to meet the diverse requirements of their clients. Therefore, the utilization of optimization techniques becomes essential, taking into account the existing resources [6].

Optimization is a process or technique of making maximum utilization of available resources, or in simple terms, it can be defined solutions, to this end; designing dipole Omni-directional antennas leveraging optimization is becoming increasingly popular among researchers and antenna design Engineers in the field of Telecommunications. This paper presents a technical review on the subject matter of dipole antenna design leveraging optimization techniques to design better dipole antennas.

as doing more with less [7]. Recently, optimization techniques are becoming increasingly popular in the field of antenna design. This is linked to the fact that clients are looking for solutions that is cost effective and timely to their problems. The following are some optimization techniques that can be leveraged in order to design robust antennas; particle swarm optimization, ant colony optimization, sine-cosine optimization, Grey-wolf optimization, Thompson sampling efficient multi-objective optimization, Optimization Defined Radio Approach, grasshopper optimization, differential evolution optimization among others.
This paper presents a review on some dipole antenna varieties and optimization techniques, in order to make the most of this paper, it is divided into sections such as: dipole antenna, Omni-directional antenna, optimization techniques, review of similar or related works, and conclusion.

Dipole Antennas

Dipole antennas are the simplest type of RF wire-antennas that uses two conducting metallic structures. at the center is an insulating material that separate the two melic structures called a section. At the center of this antenna, voltage is minimal while the current is maximum but at the two extremes, current is minimum and voltage is maximum [10].
Dipole antennas are grouped into dipole Hertzian, dipole half-wave, FM dipole etc. The dipole antenna is unarguably the preferred antenna choice because of its critical role in transmitting radio waves or signals in Omni directional nature; also it can be used alone as well as incorporated in many other antenna designs. [10]. Table 1 illustrates the comparison between the varieties of dipole antennas
When designing dipole antennas, it is crucial to take into account the omni-directional antenna feature. An omni-directional antenna radiates radio power uniformly in all directions perpendicular to the azimuthal directions. It adjusts power levels based on the angle of elevation, gradually decreasing from the initial position of zero on the axis [11[14]. As a result, many researchers opt for dipole omni-directional antenna designs that utilize optimization techniques to cater to specific requirements or meet the demands of their clients [15].

Table 1 illustrates the comparison between the varieties of dipole antennas

Dipole Antenna	Antenna Length	Applications
Half-wave dipole	$\frac{1}{2}\lambda$ of the frequency it is designed to transmit or receive	used in TV & Radio receivers
Short dipole	$< \frac{1}{2}\lambda$ in size	Low frequency receivers
Folded dipole	twice the wave length	High bandwidth

FM dipole	$\frac{150\ cm}{assigned\ frequency}$	FM broadcasting
Fan dipole	$\frac{1}{4}\lambda\ for\ each\ of\ the\ halves$	Radio communicating
	$many\ dipoles\ of\ diff.lengths$	

Omni-directional Antennas

An omni-directional antenna is characterized by its ability to radiate radio power uniformly in all directions perpendicular to the azimuthal directions. It adjusts power levels based on the angle of elevation. As it returns to the initial position of zero on the axis it diminishes gradually [11].

The radiation pattern associated with an omni-directional antenna can be described as doughnut-shaped. It's important to note that this pattern differs significantly from that of an isotropic antenna, which uniformly distributes power in all directions, resulting in a spherical radiation pattern.

The most commonly used category of omni-directional antennas are Vertically oriented omni-directional antennas due to their ability to distribute power evenly in all directions than their horizontally oriented counterparts [17]. These antennas are widely used for radio broadcasting applications. The pattern of radiation associated with a dipole is similar to the shape of a ring doughnut as illustrated in Figure 1. Therefore, the dipole is Omni-directional only in its orientation i.e., a vertical dipole is Omni-directional horizontally [18]

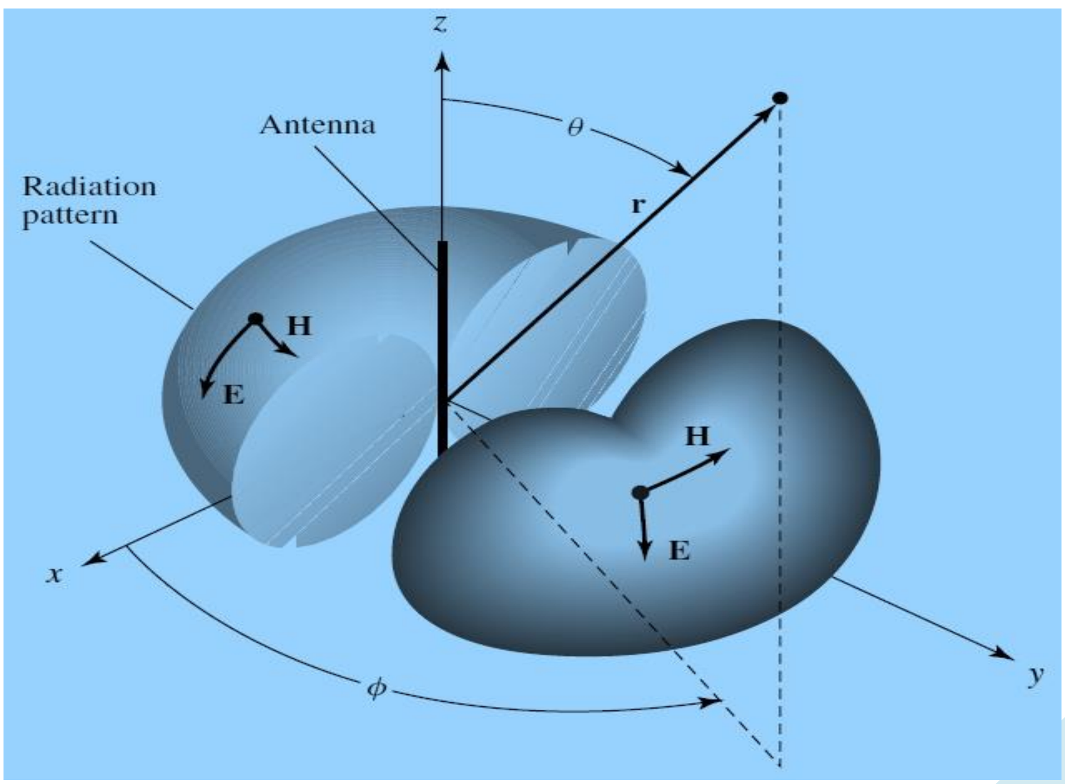

Figure 1: Omni-directional antenna pattern [11]

Optimization Techniques

In this subsection some trending optimization algorithms developed by some researchers for optimizing antenna design parameters are presented. These optimization algorithms include; Genetic Algorithms (GA), Grey Wolf Optimization (GWO), Ant Colony Optimization (ACO), Sine-Cosine Optimization (SCO), Simulated Annealing Algorithm (SAA), Particle Swarm Optimization, Differential Evolution (DE), Optimization Defined Radio Approach (ODRA) among others.

Grey Wolf Optimization (GWO)

This optimization technique is inspired by social hierarchies and intelligent searching, specifically modeled after the behavior of grey wolves to solve complex Problems. In this hierarchy, grey wolves are positioned at the highest level of the food chain, organized into individual packs typically consisting of 5 to 12 members. Figure 2 shows the social pyramid of Grey wolf optimization, In this hierarchy, the leadership role at the top is assumed by the male and female wolves, who act as the decision-makers. The remaining wolves in the pack function as followers, adhering to the decisions and guidance of the alpha pair at the apex of the social structure. At the next hierarchy is the beta that takes and enforces orders directly from alpha, while the last in the hierarchy is the omega which can be described as a scapegoat because, this level is the last pack to be allowed by other wolves to eat in the food chain. This social hierarchy and searching technique are applied in the design of smart antennas. The social behavior of wolves, particularly their approach to attacking and searching for prey. as illustrated in Figure 3, can be mathematically modeled to enhance the efficiency of smart antenna systems [10].

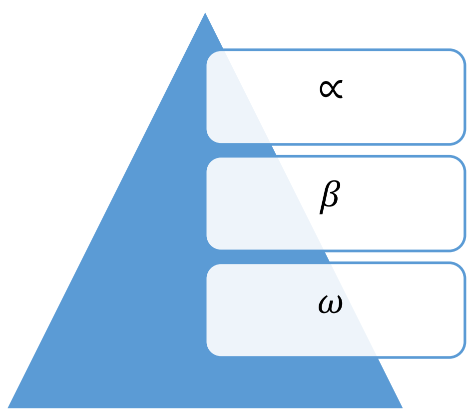

Figure 2: Social pyramid of Grey Wolf Optimization [10]

$$\overline{D} = \left|\overline{C} \times \overline{X}_p(t) - \overline{X}\,(t)\right| \quad (1)$$

$$\overline{X}(t+1) = \left|\overline{X}_p(t) - \overline{A}\, \times \overline{D}\right| \quad (2)$$

Where

t = iteration number

$\overline{A}$ & $\overline{C}$ represent vector coefficients

$\overline{X}_p$ is the prey's vector position

$\overline{X}$ represent the grey wolf's vector positions

$\overline{D}$ is the calculated new positions of the grey wolf

The vector coefficients $\overline{A}$ & $\overline{C}$can be calculated using equation 3 and 4

$$\overline{A} = 2\overline{a} \times \overline{r_1} - \overline{a} \quad (3)$$

$$\overline{C} = 2 \times \overline{r_2} \quad (4)$$

Where $\overline{a}$ *is a vector set that decreases linearly from* 2 *to* 0

$\overline{r_1}$ & $\overline{r_2}$ *takes random values between* 0 & 1

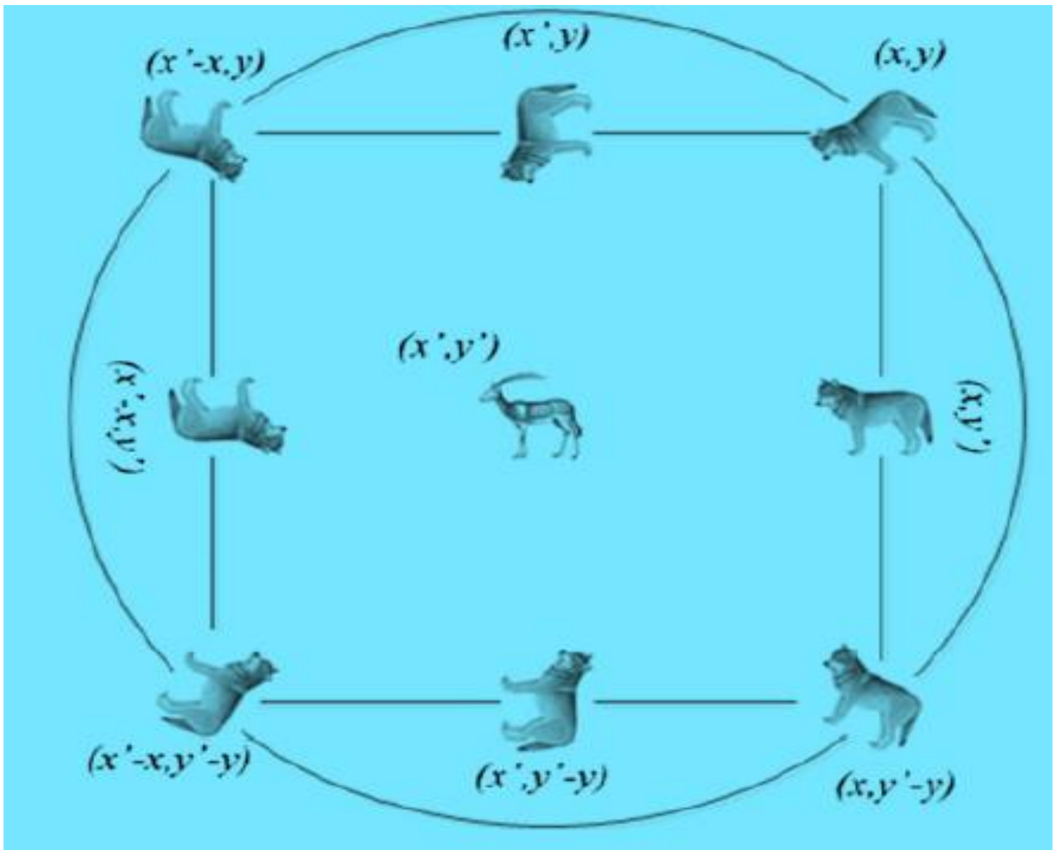

Figure 3: Attacking and searching for prey using GWO [10]

Advantages of Grey Wolf Optimization

(i) Implementation simplicity

(ii) The parameters can be easily controlled and precise.

(iii) Ease of training the model

(iv) Training process is fast and consume less time

(v) Few parameters are required in carrying out optimization designs

Drawbacks of Grey Wolf Optimization

(i) The convergence rate is very slow and most times leads to wrong solutions
(ii) It has limited solution searching abilities
(iii) The accuracy level for solving problems using this optimization technique is notably low
(iv) The difficulty in achieving an optimal solution

Ant Colony Optimization (ACO)

Ant colony optimization employs searching and probabilistic strategies in a bid to achieve optimal solutions to problems. The concept is based on the analogy of ants' behaviors in searching for food. The ant colony employs a process of repeated trials to devise the shortest optimal path to the source of food, see Figure 4. The shortest path discovered by the colony of ants is the third path as illustrated in Figure 4. This meta-heuristic optimization technique was developed in 1997 by Gambardella Dorigo.

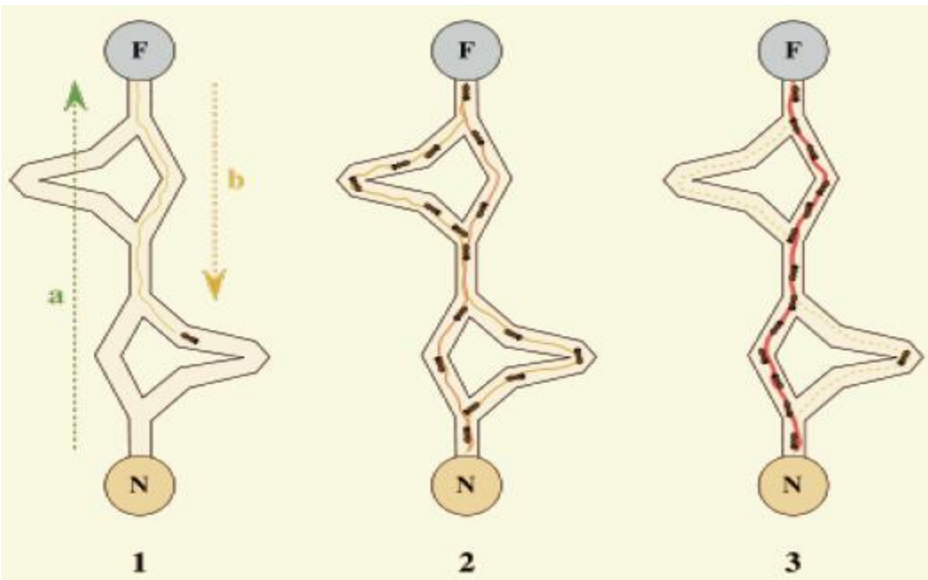

Figure 4: Ant colony optimization analogy [16]

Researchers have applied this technique to design antennas for various applications, drawing inspiration from nature-inspired behaviors such as those observed in ants.

The optimization technique is governed by equation:

$$p_{i,j} = \frac{\left(\tau_{i,j}^{\alpha}\right)\left(\eta_{i,j}^{\beta}\right)}{\sum\left(\tau_{i,j}^{\alpha}\right)\left(\eta_{i,j}^{\beta}\right)} \quad (5)$$

Where

α & β *respectively* represent parameter used to control $\eta_{i,j}$ & $\tau_{i,j}$

$\tau_{i,j}$ & $\eta_{i,j}$ represent the amount of secretions on the edge and attraction towards to the edge respectively

Advantages of Ant Colony Optimization

(i) Adaptive to different features
(ii) Dynamism and flexibility in terms of application usage
(iii) It provides high efficiency in providing optimal solutions to complex problems
(iv) It provides a feedback path for assessment of progress
(v) The optimization has ability to carry out multidimensional processing at the same time

Disadvantages of Ant Colony Optimization

(i) It is time consuming and high uncertainty of when the process will end or converge.
(ii) It lacks theoretical basis but rather rooted in experimental approach
(iii) The probability distribution of the technique tend to change with iterations
(iv) It is a random decision making optimization technique
(v) Difficulty in analyzing the theoretical concept of the optimization technique.

Particle Swarm Optimization (PSO)

The optimization technique is inherently stochastic, and over the years, it has been employed to optimize antenna parameters for improved design. To manage its stochastic nature, researchers adopt carefully crafted strategies to constrain it toward a specific target. This algorithm is coined from a typical scene of biological behavior observed among the swarm bees, it was deduced that without any initial position, each bee (also known as particle) from the particle swarm optimization begins with a random velocity and accelerates with a target of getting to a flower in the field with the highest concentration of floral density. In their journey to reach the destination, each bee tends to periodically update its location and velocity based on two critical pieces of information. Firstly, its ability to remember the location of the flower it personally found (particle best). Secondly, by incorporating the ability to remember the location found by other bees, often referred to as the global best position. As the updating process continues, eventually one of the bees will locate a point on the flower with the highest density. This behavior is harnessed to optimize antenna design parameters, aiming to enhance the target results. The optimization process involves specifying the solution space, defining a fitness function, and randomly initializing the positions and velocities of the swarm. By utilizing these principles inspired by bee behavior, researchers seek to achieve improved antenna designs. Figure 5 illustrates the concept of this PSO technique [3].

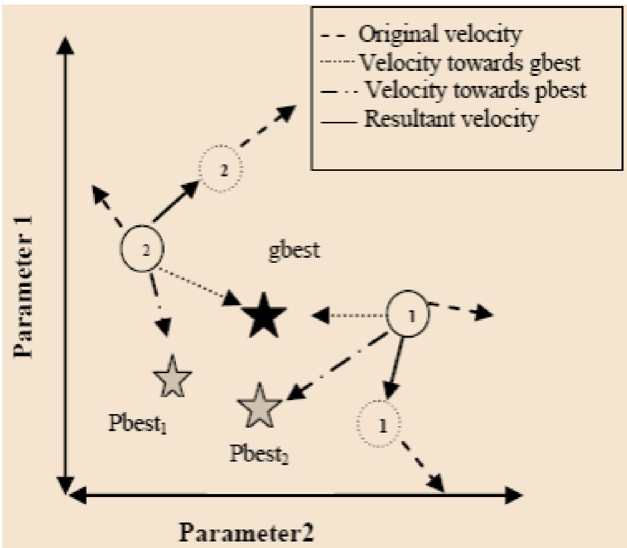

Figure 5: Particle Swarm Optimization [3]

Strengths of Particle Swarm Optimization (PSO)

(i) Implementation of this optimization technique is easy and simple
(ii) The parameters involved in this type of optimization are relatively few
(iii) It has the ability to self-organize tasks
(iv) The optimization technique is highly flexible
(v) The scalability property or feature of this optimization technique makes it effective and particularly noteworthy
(vi) It is a robust optimization technique

Drawbacks of Particle Swarm Optimization (PSO)

(i) The convergence rate is very slow
(ii) Computationally expensive and complex
(iii) It cannot solve multi-objective problems
(iv) Behavioral rule prediction is difficult to achieve

Sine-Cosine Optimization (SCO)

This meta-heuristic optimization algorithm is a based on trial and error discovery (probabilistic search) approach in solving problems by updating the positions of the agents using trigonometric functions known as cosine and sine. It can be best described as being predicated on sine and cosine periodicity property with a period of 2π *and range* $[-1, 1]$ [4].

The technique initiates a set of search agents randomly across the entire space of interest. This comprehensive set, known as the population, has its search space initialized using equation 6.

The search agent with the $ith\ value$ $X_{ij} = (X_{i1}, X_{i2} \dots X_{id})$ can also be initialized using equation 6

$$X_{ij} = X_{ij}^{lb} + rand\,() * \left(X_{ij}^{ub} - X_{ij}^{lb}\right) \quad (6)$$

$$j = 1{:}\,d, \qquad i = 1{:}\,Np$$

Where

X_{ij} is the jth dimension of the ith solution

X_{ij}^{ub} & X_{ij}^{lb} represent upper and lower boundaries respectively of the ith solution in the jth dimension of the given search space

$rand$ (()) is responsible for generating random numbers between 0 & 1

Np represent the population size

The next step is to update the initialized positions using equations 7 & 8

$$X_{IJ}^{t+1} = X_{ij}^{t} + r_1 \times sin(r_2) \times \left| r_3 \times P_g^t - X_{ij}^t \right| \quad (7)$$

$$X_{IJ}^{t+1} = X_{ij}^{t} + r_1 \times cos(r_2) \times \left| r_3 \times P_g^t - X_{ij}^t \right| \quad (8)$$

Where

$X_i^t = \left(X_{i1}^t + X_{i2}^t \ldots X_{id}^t\right)$ is the ith search agent's position in the tth iteration

$P_g^t = \left(P_{g1}^t + P_{g2}^t \ldots P_{gd}^t\right)$ denotes the gth search agent with the best fitness

$$j = 1{:}\,d, \qquad i = 1{:}\,Np$$

$|.|$ is the modulus operator

$$r_1 = b - b \times \left(\frac{t}{T}\right)$$

$$r_2 = 2 \times \pi \times rand()$$

$$r_3 = 2 \times rand()$$

By plotting the range against the iterations as illustrated in figure 6. The trajectory of sine cosine optimization is presented.

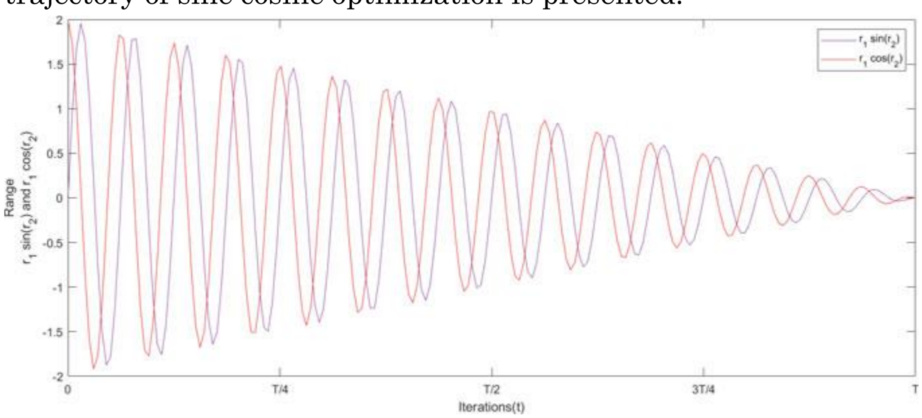

Figure 6 SCO plot [4]

Researchers in the field of antenna design have also utilized this optimization approach to design antennas to meet specific needs based on the evolving trends in Telecommunications engineering.

Strengths of Sine Cosine Optimization (SCO)

(i) It is user friendly algorithm and easy to implement

(ii) The search strategy is targeted towards optimal or best solution based on the position updating feature
(iii) This optimization technique exhibits higher explorative abilities, attributed to the incorporation of four random parameters in its process.
(iv) Higher processing speed
(v) There is seamless transition from explorative phase to exploitative phase

Drawbacks of Sine Cosine Optimization (SCO

(i) It can only solve continuous optimization tasks
(ii) It is a memoryless algorithm because previous optimal solutions cannot be tracked.
(iii) It is weak in terms of preserving previous processed solution
(iv) An optimal solution cannot be guaranteed.
(v) It shows slow convergence abilities to complex problems

Thompson sampling efficient multi-objective optimization (TSEMO)

The goal of this optimization technique is to model the antenna structure and size with a view to increasing the antenna gain and reducing the side lobe level. In order to achieve this, a bottom-up approach is use to optimize the shape of the antenna and point of feed while multi-layer neural network is used to optimize the antenna parameters. Figure 7 illustrates how the algorithm works [6]. The first step required in this optimization process is dataset collection, followed by antenna parameters and size optimization using deep neural networks. In order to achieve the intended gain, the lengths of the antenna- and widths are optimized within the available bandwidth. This optimization employs the regression mode of deep neural networks to achieve high gain through training, validation and testing phases. It is worth noting that the Long Short Term Memory (LSTM) facilitates in the prediction of the optimal lengths and widths of the antenna and other parameters in order to achieve optimum results.

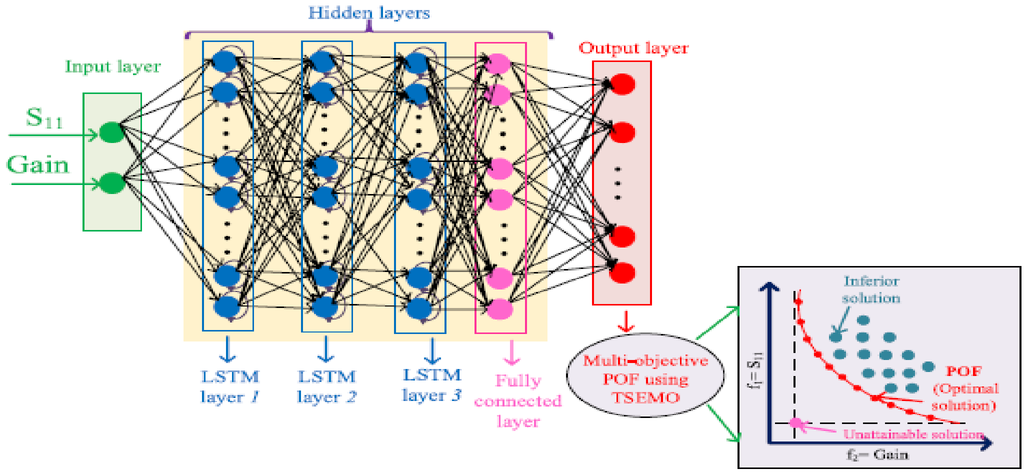

Figure 7: TSEMO Approach [6]

Strengths of Thompson sampling efficient multi-objective optimization (TSEMO

(i) Complex antenna designs can be modelled accurately.
(ii) It provides ready to fabricate layouts to help designers in carrying out antenna fabrication
(iii) Accurate prediction of antenna parameters for optimization.

Drawbacks of Thompson sampling efficient multi-objective optimization (TSEMO)

(i) Suitable for micro strip antenna designs
(ii) Algorithm performs optimally at the frequency range of 1-100 MHz, at higher frequencies the optimization technique is prone to errors.
(iii) Extreme and detailed training is required to achieve optimum results
(iv) The optimization technique is computationally expensive
(v) It is a data-driven optimization technique, hence incorrect input data will ultimately give rise to wrong output predictions by the Long SHORT Term Memory (LSTM)

Optimization Defined Radio Approach (ODRA)

This is a novel antenna optimization technique used for designing smart and intelligent antennas to meet the high demand of access to signals transmitted from radio broadcasting outlets or stations to different locations. The effectiveness and quality of signal reception coming from a radio station particularly an FM station depends largely on two factors among other factors. These two key factors are the transmitter power and the type of antenna, whether a conventional or students' radio, the transmitter is assigned a certain amount of power and the footprint by NBC. The assigned or approved transmission power cannot be altered as this will be seen as a breach in the level of agreement; to play by the rules and laws, optimization can be leveraged in designing antennas that can utilize the available resource (transmitter power) but achieve a greater efficiency or output. In other words, optimization can defined as doing more with little. Little in the sense that one is constrained by a particular resource and at the same time a better output is targeted.

There has been a paradigm shift from designing conventional antennas to smart and intelligent antennas recently by antenna design engineers. This paradigm shift has informed the choice of this novel optimization technique referred to as Optimization Defined Radio Approach (ODRA)

Optimization Defined Radio Approach (ODRA) is a deep search algorithm that seeks to optimize the available resources by engaging in a smart scanning process to get the optimal values for the antenna design parameters in order to reach a wider audience or target. In order to achieve this, the model searches for the optimal gain, lengths and breath in the design process and gives out the optimal values that when used in the antenna design process. When the values given out after the deep search has been completed are found not to be optimal, the algorithm quickly retracts the values and re-scan until the best values or results that will achieve the desired target location are obtained.

Strengths of Optimization Defined Radio Approach (ODRA)

(i) The model is flexible in terms of configurability, it can be reconfigured easily.
(ii) The optimization model can predict the desired output.
(iii) The ability to give out only optimal results
(iv) Computational less expensive
(v) .it is robust and scalable
(vi) User friendly

Review of Related Works

This sub-section presents similar or related works carried out by other authors, the strengths and weakness of their models at a glance.

Authors	Title of Paper	Strength	Weakness
[3]	A review on the recent applications of particle swarm optimization & genetic algorithm during antenna design	The review paper emphasized the need for GA and PSO for improved efficiency in smart antenna designs. Furthermore, hybrid approaches were recommended.	However, tradeoffs of using hybrid approach was not elucidated.
[6]	Deep neural learning based optimization for automated high performance antenna designs	The model reduces the complexities involved in modelling complex antenna designs as well as set ready to fabricate layout by following the rules and constraints.	However, only gain and the S-parameters were optimized neglecting radiation efficiency
[7]	A Review on Optimization Techniques of Antennas Using AI and ML / DL Algorithms	The comparative review provides a systematic approach to reduce computational time and improve performance in AI-enabled models	However, the study was based on Machine Learning and Deep Learning
[8]	Smart Antenna Optimization Techniques for Wireless Applications	The Survey presented at a glance some smart –enabled optimization techniques for designing smart antennas	The survey was only tailored towards wireless applications
[12]	A smart optimization-enabled omnidirectional dipole antenna	The model achieved high gain and improved area of signal coverage	However, the antenna design was not fabricated

	design for campus and conventional fm radio: A case study of 92.3 MHz Campus radio FUT Minna		
[16]	On nature-inspired design optimization of antenna structures using variable-resolution EM models	The optimization model achieved high fidelity and accuracy	However, the model was computationally expensive by incurring additional cost on the CPU

Dipole Antenna Design Trends

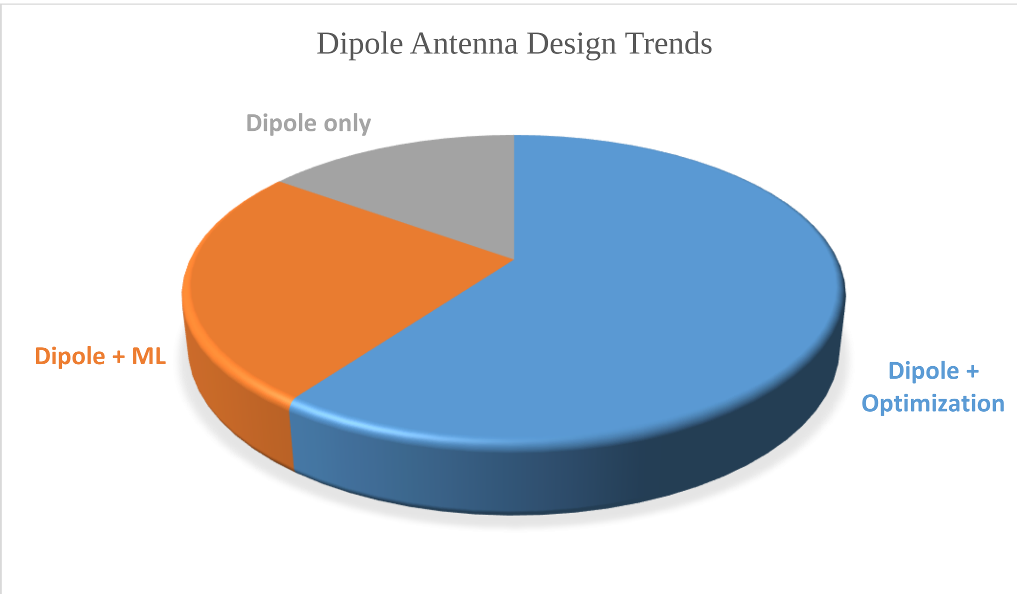

Figure 8: Dipole Antenna Design Trends

A chart illustrating the summary of recent advancement in dipole antenna design is shown in Figure 8. It can be observed from the pie chart that, optimization based dipole antenna designs are gradually taking over from the conventional dipole antenna designs, this could be as a result of a paradigm shift from depending on the abundant resources at one's disposal to making the most of the available resources.

Conclusion

This paper presents the fundamental knowledge required for designing smart antennas leveraging optimization techniques in an ever changing world of communication engineering where antennas are required to be designed to meet the needs of the end users. Individual optimization techniques are presented. In view of the drawbacks of the individual antenna design optimization techniques, a hybrid or combination of two or more of these optimization techniques to address all the drawbacks of the individual antenna optimization techniques is recommended. Dipole antenna and its varieties have also been reviewed.

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