Optimisation of DTV coverage and broadcasting antennas

A thesis submitted for the degree of
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DECLARATION

I hereby declare that the contents of this thesis are original and solely the result of my own work and has not been submitted in whole or in part for any other degree or professional qualification, except where explicitly stated otherwise in the text. Parts of this work have been published in my own publications listed in the pages below.

Emmanouil N. Tziris

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ABSTRACT

The increased use of the available radio frequency spectrum by many existing as well as new technologies brings up the need of more advanced and specialised antennas, designed for very specific purposes. A very good example is the withdrawal of analogue TV from the radio spectrum, which has given space to be used by newer technologies such as 4G and 5G. Optimising the design of an antenna for a specific purpose is a goal that becomes more and more necessary. This suggests that an investigation of methods to optimise an electromagnetic design with the best possible results at the best possible time is also necessary. Evolutionary Algorithms (EA) are a very well know method which exhibits solid results within a smallest possible time for electromagnetic problems (e.g. antenna design optimisation). EA are nature inspired algorithms, and some very popular examples, which are widely used in antenna optimisation are the Differential Evolution (DE), Particle Swarm Optimisation (PSO) and Invasive Weed Optimisation (IWO).

This thesis researches a comparison between the aforementioned methods, while also proposing a novel method, which is a modified version of IWO and has proven to be very solid. To determine the efficacy of the proposed method, all the algorithms were compared on some of the most major test functions for such purposes. Some examples are Ackley's, De Jong's, Holder table, Rastrigin and Rosenbrock. By employing these test functions, it was possible to determine the optimum settings of the modified IWO version.

These methods are compared for different antenna design optimisation simulations using software such as MATLAB and CST Microwave Studio, to determine which method yields the best results and to output novel optimised antenna designs for different purposes. Some of the novel antenna designs that were applied to EAs for optimisation are a collinear dipole array with a specifically shaped radiation pattern and a log-periodic dipole antenna (LPDA) with flat gain response across its operating spectrum for Digital TV (DTV) broadcasting purposes. Other novel designs include a planar elliptical dipole antenna for Ultra-Wideband (UWB) Electromagnetic Compatibility (EMC) applications such as EMC measurements and a pin-fed notched circular patch antenna with circular polarisation for satellite communications, in which cases the small size of the generated geometries was also a goal so that portability is achieved. The geometrical parameters of the best possible antenna design were in some cases fabricated and compared to the simulated results so that the latter is compared to real world applications.

RESEARCH OUTPUT

Published journal papers

[1] **E. N. Tziris**, P. I. Lazaridis, Z. D. Zaharis, J. P. Cosmas, K. K. Mistry and I. A. Glover, "Optimised Planar Elliptical Dipole Antenna for UWB EMC Applications," *in IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 4, pp. 1377-1384, Aug. 2019, Available: 10.1109/TEMC.2019.2923781.

[2] P. I. Lazaridis, **E. N. Tziris**, Z. D. Zaharis, T. D. Xenos, J. P. Cosmas, P. B. Gallion, V. Holmes and I. A. Glover, "Comparison of evolutionary algorithms for LPDA antenna optimisation," *in Radio Science*, vol. 51, no. 8, pp. 1377-1384, Aug. 2016, Available: 10.1002/2015RS005913.

Published conference papers

[1] **E. N. Tziris**, P. I. Lazaridis, K. K. Mistry, Z. D. Zaharis, J. P. Cosmas, B. Liu and I. A. Glover, "1.62GHz Circularly Polarised Pin-Fed Notched Circular Patch Antenna," *2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC)*, Meloneras, 2018, pp. 1-3, Available: 10.23919/URSI-AT-RASC.2018.8471447.

[2] K. K. Mistry, P. I. Lazaridis, **E. N. Tziris**, Z. D. Zaharis, B. Liu, T. D. Xenos and I. A. Glover, "A Design of Elliptical Edge-Fed Circularly Polarised Patch Antenna for GPS and Iridium Applications," *2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Meloneras*, 2018, pp. 1-4, Available: 10.23919/URSI-AT-RASC.2018.8471443.

[3] K. K. Mistry, P. I. Lazaridis, Z. D. Zaharis, T. D. Xenos, **E. N. Tziris** and I. A. Glover, "An optimal design of printed log-periodic antenna for L-band EMC applications," *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, Singapore, 2018, pp. 1150-1155, Available: 10.1109/ISEMC.2018.8393968.

[4] **E. N. Tziris** et al., "Invasive weed optimised planar elliptical dipole antenna for ultra-wideband EMC applications," *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, 2018, pp. 233-236, Available: 10.1109/ISEMC.2018.8393772.

[5] P. I. Lazaridis, **E. N. Tziris**, Z. D. Zaharis, T. D. Xenos, V. Holmes, J. P. Cosmas and I. A. Glover, "Comparative study of broadcasting antenna array optimisation using evolutionary algorithms," *2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC),* Seoul, 2016, pp. 1299-1301, Available: 10.1109/URSIAP-RASC.2016.7601166.

[6] P. I. Lazaridis, **E. N. Tziris**, Z. D. Zaharis, T. D. Xenos, J. P. Cosmas, P. B. Gallion, V. Holmes and I. A. Glover. "Comparison of evolutionary algorithms for LPDA antenna optimisation*," 2015 1st URSI Atlantic Radio Science Conference (URSI AT-RASC)*, Las Palmas, 2015, pp. 1-1, Available: 10.1109/URSI-AT-RASC.2015.7302885.

[7] **E. N. Tziris**, P. I. Lazaridis, B. Mehrdadi, V. Holmes, I. A. Glover, Z. D. Zaharis, A. Bizopoulos and J. P. Cosmas, "Comparison of Evolutionary Optimisation Algorithms for FM-TV Broadcasting Antenna Array Null Filling," *19th International Conference on Circuits, Systems, Communications and Computers (CSCC'15)*, 2015.

[8] P. I. Lazaridis, Z. D. Zaharis, C. Skeberis, T. D. Xenos, **E. N. Tziris** and P. B. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimisation," *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, Aalborg, 2014, pp. 1-5, Available: 10.1109/VITAE.2014.6934491.

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LIST OF ABBREVIATIONS

ADIWO	-	Adaptive Invasive Weed Optimisation
AP-RASC	-	Asia-Pacific Radio Science Meeting
AR	-	Axial Ratio
AT-RASC	-	Atlantic Radio Science Meeting
DE	-	Differential Evolution
DVB-T	-	Digital Video Broadcasting-Terrestrial
EA	-	Evolutionary Algorithm
EMC	-	Electromagnetic Compatibility
F/R	-	Front to Rear Ratio
FCC	-	Federal Communications Commission
FM	-	Frequency Modulation
GPS	-	Global Positioning System
GSM	-	Global System for Mobile Communications
IWO	-	Invasive Weed Optimisation
IWPSO	-	Inertia Weight Particle Swarm Optimisation
LPDA	-	Log Periodic Dipole Array
LTE	-	Long Term Evolution
mIWO	-	modified Invasive Weed Optimisation
NEC	-	Numerical Electromagnetics Code
OA	-	Orthogonal Array
PSO	-	Particle Swarm Optimisation
RG	-	Realised Gain
SLL	-	Side Lobe Level
S/N	-	Signal to Noise Ratio
SNR	-	Signal to Noise Ratio
SWR	-	Standing Wave Ratio
TV	-	Television
URSI	-	International Union of Radio Science
UWB	-	Ultra Wide-Band

1 INTRODUCTION

Main focus of this research is the application of Evolutionary Algorithm (EA) optimisation method into pre-defined antenna design electromagnetic problems. According to [1] EAs are increasingly used into a wide range of engineering and the need for novel optimisation techniques is pointed out which is the case for electromagnetic applications as well and more specifically in antenna design as described in [2] and [3]. Research is actively being carried out with novel and state of the art optimisation techniques being applied on electromagnetic design problems along with method comparison research. In the current literature of the aforementioned publications, the reader can observe that there has been a lot of effort on optimising different antenna designs by using several different methodologies, many of them including the use of evolutionary methods. Such examples include the effort to optimise a Z-shaped antenna design using a simulation-based genetic algorithm in [4], or efforts to improve the efficiency of EAs in optimisation with newly proposed techniques such as the surrogate model assisted differential evolution for antenna synthesis (SADEA) [5]. Research output of this thesis also employed the Invasive Weed (IWO) method which was a novel approach to electromagnetic problems optimisation [6]-[9]. Research such as [10] and [11] has used more known EAs such as the Particle Swarm (PSO) or the Differential Evolution (DE) for optimisation problems such as designing an LPDA without the use of the standard Carrel's method, which is also the case for optimisations carried out in this thesis. Finally, it should be mentioned that there is also work considering more than one optimisation methods and comparing which method proves best for specific electromagnetic problems which can be found in [12] and [13]. The significance of the work presented in this thesis is to provide a comparison of six different EAs and discover which is the most appropriate in different electromagnetic problems, from simple ones such as the null filling a classical antenna array to more complex, such as the optimisation of an LPDA.

The EA optimisation methods that are applied in the antenna designs of this thesis are the 1) Differential Evolution (DE), 2) Particle Swarm (PSO), 3) Invasive Weed (IWO), 4) modified Invasive Weed (mIWO), 5) Adaptive Invasive Weed (ADIWO) and 6) Taguchi. All the aforementioned methods are applied in several different electromagnetic optimisation problems for the purpose of comparison as well as of optimal configuration per EA for consequently optimal output results.

The electromagnetic problems that the EA optimisation methods are tested on, include a computer simulation of an FM-TV broadcast antenna which is optimised for filling nulls that such antennas suffer from. Classical design methodologies for a FM-TV broadcasting antenna are easily susceptible to output a radiation pattern similar to the one depicted in Figure 1. Normalizing -20dB gain value as a null, the problem of nulls (gain < -20 dB) within the area of interest between 92° and 120° can be tackled via the use of EAs for the optimisation of the design's geometry.

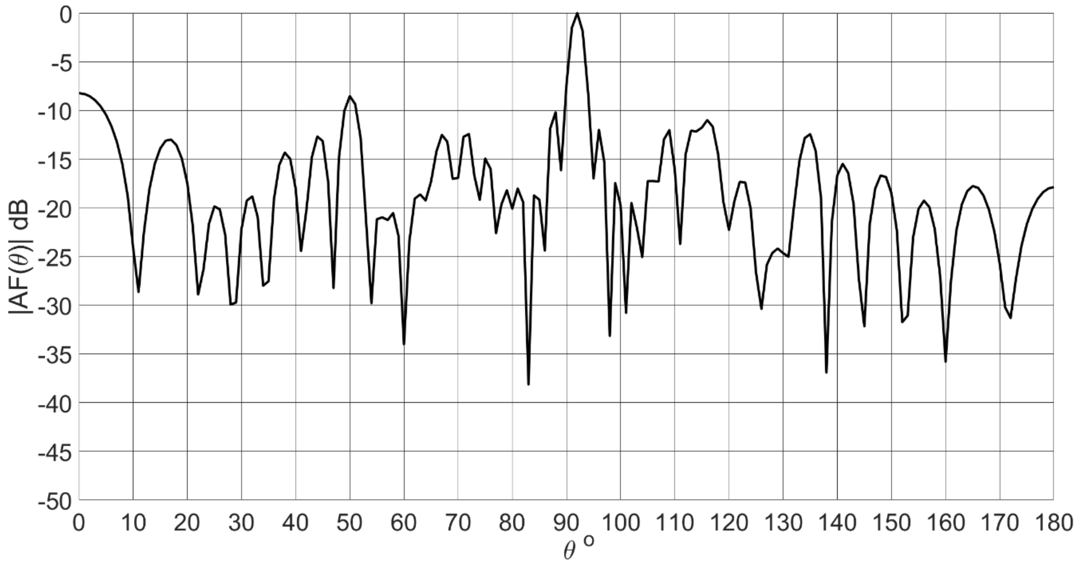


Figure 1. Radiation pattern of a classical antenna array design

With the best area coverage in mind, a collinear array antenna was optimised to acquire a most suitable antenna geometry for the coverage of a predefined levelled area which is a real world simulation to tackle the null filling problem of such antenna designs. The real-world problem application will be simulated for the purposes of this research.

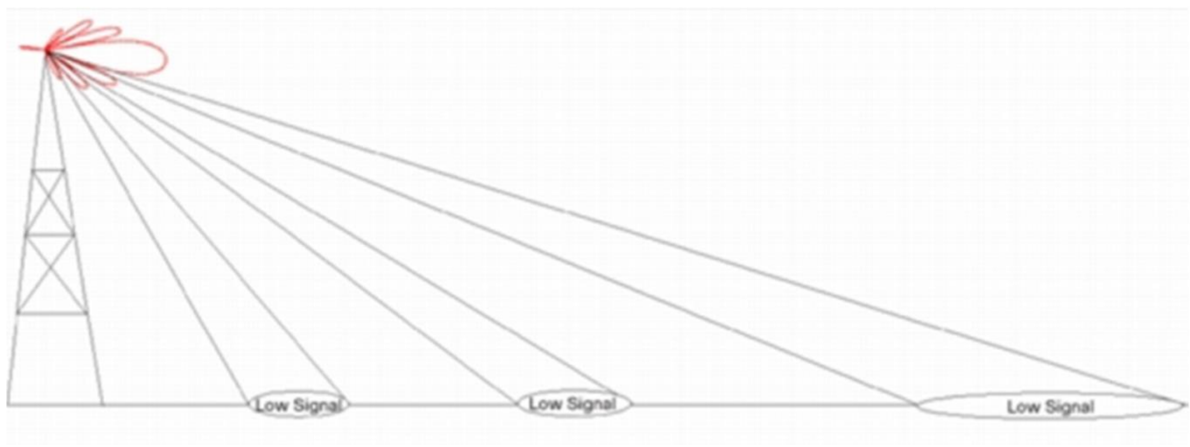


Figure 2. Real world null signal problem

Similarly, a LPDA's geometry is optimised using EA and output designs are compared to the well-established Carrel's classical method which employs the design constant τ and the relative spacing σ as on the diagram of Figure 3 to generate an LPDA geometry. This is executed to show that optimisation methods such as EA are powerful tools for optimal antenna design and are solid candidates to replace classical methodologies.

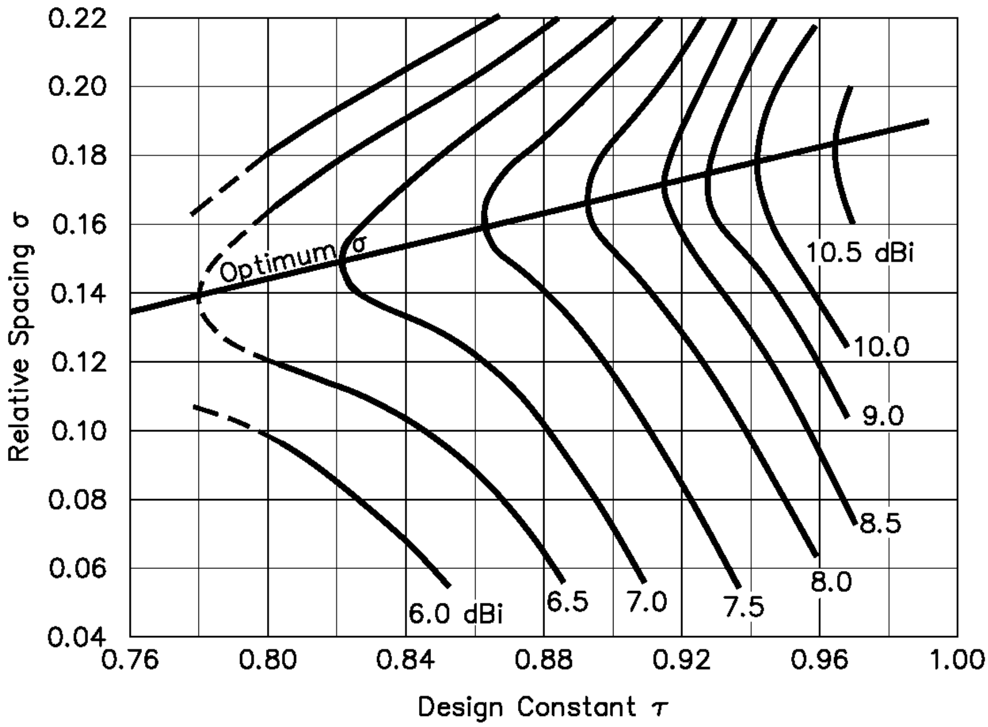


Figure 3. LPDA gain as a function of τ and σ

Apart from the existing EA, a novel modified version of IWO called mIWO is introduced in this thesis which is modification on the number of produced seeds per fitness value with the use of a non-linear seed production index α which is proposed. The best possible configuration for index α is investigated and results suggest that α should be configured with computational and time availability in mind. mIWO is compared with the conventional IWO as well as other optimisation methods on real-world antenna design for Electro-Magnetic Compatibility (EMC) as well as GPS and Iridium applications.

A discussion regarding how algorithms can improve antenna design methodology is carried out while all the results and conclusions of this research are presented.

1.1 Aims and objectives

The purpose of this research is to demonstrate that EAs are capable of generating antenna geometries which exhibit sufficient radiation characteristics for different applications and discover which method is most appropriate for any given electromagnetic optimisation problem by comparing them in the same optimisation problems. An additional objective is to make evident that a very strong optimisation method i.e. the IWO method, with fine tuning modifications can exhibit enhanced results in comparison with the conventional method.

1.2 Methodology and contribution to knowledge

The research methodology of this research is described as follows:

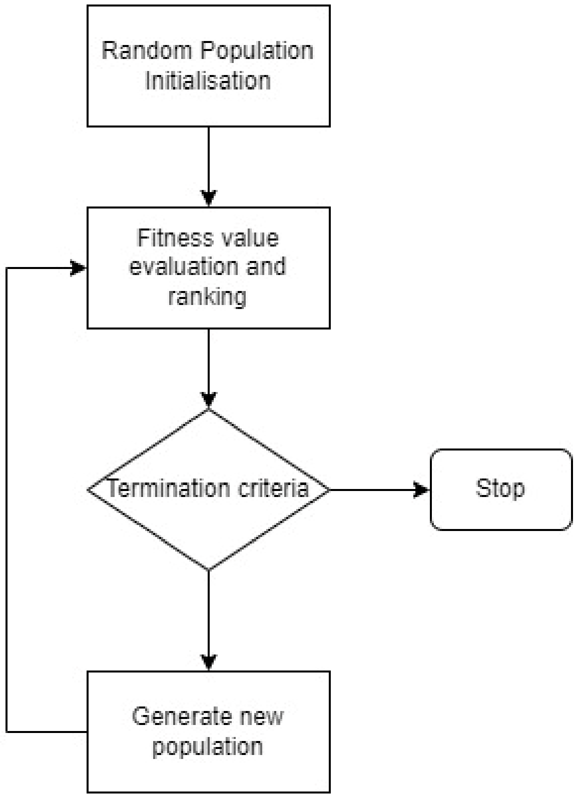
- In-depth investigation of the state of the art in electromagnetics and more specifically in antenna designs for FM-TV broadcasting such as collinear arrays and LPDAs.
- Analysis of the current optimisation methods based on evolutionary algorithms and the prospect of being used in electromagnetic applications.
- Development of the mathematical models of the different optimisation methods that will be used in computer software and design of antenna designs in simulation software. Via the employment of powerful computer software, the application of EA based optimisation methods on different antenna designs is simulated and thus, many different scenarios are tested with minimal cost and effort. The fabrication of the best designs is also carried out, so that the comparison of simulated results is validated.

1.3 Evolutionary Algorithms (EA)

EAs are powerful tools, which are utilised in many scientific fields, primarily for the purposes of optimisation and design. As previous research indicates, EAs have been proven to be very effective for optimising the geometry of antenna structures for specific applications. EAs are heuristic-based approaches for solving problems and, in most cases, yield near-global optimum results for a predetermined multi-target problem. Before starting to use an EA, the parameters (input independent variables or equivalently the input vector) that need optimisation must be determined. The dependent variable (scalar output) which needs to be maximised or minimised is the fitness function which is a multi-variable scalar function of the input parameters (input vector). The fitness function, which is scalar, is constructed in a way that includes all the performance indicators that need to be optimised (some will be maximised while others will be minimised). Moreover, the more input variables (the longer the input vector), the more difficult and time consuming the optimisation problem. Initially, a 'population' of input vectors is produced using a uniform random number generator within the search space. The size of the population is usually pre-defined and fixed. Normally, the more input variables, the bigger the size of the population required. Fitness values are evaluated for the whole population, and they are used in order to generate the next set of input vectors (next population). The phases of execution of an EA are:

1. **Initialisation** of a population of particles. The size of the population is determined by the size of the search space (i.e., the number of parameters to be optimised)
2. **Evaluation** of the population's particles, where the fitness of each individual in a certain population is calculated,
3. **Evolution** by selection, where individuals are evolved according to a certain mechanism in order to improve their fitness and thus become members of the next population, and
4. **Termination**, where the process comes to an end by recording the positions of the individuals in the search space together with their fitness values, and is then repeated from the second phase until a fixed amount of iterations is reached.

The following chart depicts the operation of an optimisation method based on an EA.



For the purposes of the research carried out in this thesis, the function files "de.m", "pso.m", "taguchi.m", "iwo.m" and "ADIWO" were developed in Mathwork's MATLAB software, one per algorithm used in this research. These functions were designed to consider certain input variables as well as output variables and can exchange data with other functions as well as external interfaces connected via MATLAB such as the Numerical Electromagnetics Code (NEC) described in Chapter 4, and the CST Microwave Studio.

Input variables are:

1. $\mathbf{X_{MAX}}$ – Upper limit of the search space.
2. $\mathbf{X_{min}}$ – Lower limit of the search space.
3. **Wx** – Population size calculated as the sum of particles inside a population.
4. $\mathbf{E_{MAX}}$ – Maximum number of fitness evaluations before function terminates. All of the researched methods but Taguchi, as a non-stochastic method terminates after a predetermined number of iterations, and so, it does not consider this input variable.

Output variables are:

1. **V_{best}** – Value of the particle with the best fitness which naturally is within the search space limits.
2. **F_{best}** – Fitness value of the particle with the best fitness.
3. **E_x** – Total number of evaluations concluded upon termination of the function.

These functions are coded in such way to exchange data with fitness function files which are also developed in MATLAB and contain a certain optimisation problem. As already stated in the introduction, the algorithms on which the designed functions were developed were the Differential Evolution, Particle Swarm Optimisation, Invasive Weed Optimisation, Adaptive Invasive Weed Optimisation and Taguchi Optimisation which are individually described below. The best outputs generated by intensive repetitive tests of every function will be compared to determine the optimal solution per optimisation problem.

1.3.1 The Differential Evolution optimisation method (DE)

DE is a global optimisation method for many real-valued problems and is a very simple, yet exceptionally powerful method. DE is a floating-point encoding evolutionary algorithm for global optimisation over continuous spaces but can also work with discrete variables. It creates new candidate solutions by combining the parent individual and several other individuals of the same population. A candidate replaces the parent only if it has better fitness value. Nonetheless, DE requires preliminary work by the user, such as control parameter tuning, which is a difficult task. Self-adaptation of control parameters is an important feature for DE, because it serves as a very practical solution to the control parameter tuning problem by configuring itself accordingly.

DE as described by Rainer Storn and Kenneth Price requires few control variables, is robust, easy to use, and lends itself very well to parallel computation [11]. DE can be applied with several different strategies, where some of the most popular are DE/rand/1/bin, DE/rand/2/bin, DE/best/1/bin and DE/best/2/bin. In order to classify the different variants, the notation DE/x/y/z is introduced where,

x specifies the vector to be mutated which currently can be either “rand” (a randomly chosen population vector) or “best” (the vector of lowest cost from the current population).

y is the number of difference vectors used.

z denotes the crossover scheme. The current variant is “bin” (Crossover due to independent binomial experiments)

Prior-art has shown that those which use a randomly chosen vector such as DE/rand/1/bin and DE/rand/2/bin are the most effective strategies [14]. The strategy that was picked to be used for the purposes of this thesis, is the DE/rand/1/bin strategy.

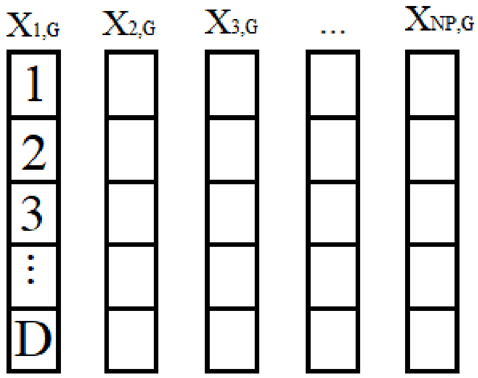


Figure 4. - NP D-dimensional vectors

According to this strategy, the initialisation is done by generating a total of NP D-dimensional parameter vectors $x_{i,G}$ as seen on Figure 4 above, with random values where G is the current generation and i is the i-th vector of that generation. The process that follows initialisation is mutation and for each $x_{i,G}$, DE creates a mutated vector $u_{i,G}$ calculated as

$$u_{i,G} = x_{r1,G} + F(x_{r2,G} - x_{r3,G}) \quad \textbf{(1)}$$

where $x_{r1,G}$, $x_{r2,G}$ and $x_{r3,G}$ are three random vectors (r_1, r_2 and r_3 are randomly chosen indices within the search space), F is a positive real number called mutation scaling factor and is used to scale the vector difference, and finally G is the population of the current iteration.

The operation that succeeds mutation is crossover, and it is a process that controls which and how many components are mutated in each element of the current population and has a strong impact on the algorithm's behaviour [15]. In crossover operation the trial vector $u_{i,G+1}$ is created and each of its indexed value is acquired either from the respective initial vector $x_{i,G}$ or from the respective mutated vector $u_{i,G}$ according to the following

$$u_{ji,G+1} = \begin{cases} u_{ji,G+1} & if\,(randb(j) \leq CR)\, or\ j = rnbr(i) \\ x_{ji,G} & if\,(randb(j) > CR)\, and\ j \neq rnbr(i) \end{cases} \quad \textbf{(2)}$$

$$j = 1,2,\ldots,D$$

Once trial vectors are generated, the algorithm picks either $u_{i,G+1}$ or $x_{i,G}$ as the member of the next generation G+1 according to their cost function value. If $u_{i,G+1}$ has a smaller cost function compared to $x_{i,G}$ then $x_{i,G+1} = u_{i,G+1}$, whereas if $u_{i,G+1}$ has a higher cost function compared to $x_{i,G}$ then $x_{i,G+1} = x_{i,G}$. This process is called mutation. Finally, the algorithm terminates once the maximum number of iterations is reached.

1.3.2 The Particle Swarm Optimisation method (PSO)

The PSO, as stated by its developers, has roots to both genetic algorithms and evolutionary strategies [16]. It is similar to genetic algorithms in that the initialisation consists of a random population of possible solutions called particles, yet it differs because each particle is assigned with a random velocity, which defines the movement of the particle towards the best solution.

In PSO terminology, every individual in a swarm is called "particle" or "agent". The number S of the particles that compose a swarm is the "population size" [17]-[19]. All the particles act in the same way as bees or birds, which means that they move in the search space and update their velocity according to the best positions already found by themselves and by their neighbours, trying to find an even better position. Each particle is treated as a point in the N-dimensional space. The position of the i-th particle (I = 1, …, S) is represented as ($x_i = x_{i1}, x_{i2}, \dots, x_{iN}$), where x_{in} (n = 1, …, N) are the position coordinates. Each coordinate x_{in} may be limited in the respective n-th dimension between an upper boundary U_n and a lower boundary L_n, so that $L_n \leq x_n \leq U_n$. The difference $R_n = U_n - L_n$ between the two boundaries is called "dynamic range" of the n-th dimension. The performance of each particle is measured according to a predefined fitness function, which is related to the problem to be solved. The value of the fitness function depends on the position coordinates, i.e.: $F = F(x_i) = F(x_{i1}, x_{i2}, \dots, \mathrm{x}_{iN})$. Actually, the particle position is considered to be improved as the value of the fitness function is increased or decreased (maximisation or minimisation problem). The best previous position of the i-th particle is recorded and represented as: $p_i = (\mathrm{p}_{i1}, p_{i2}, \dots, p_{iN})$. The change of x_i is: $\Delta x_i = u_i \Delta t$, where Δt is the time interval, $u_i = (u_{i1}, u_{i2}, \dots, u_{iN})$ is the velocity of the i-th particle. Thus, the new position of the i-th particle after a time step is given by:

$$x_i(t + \Delta t) = x_i(t) + u_i \Delta t \tag{3}$$

Particle swarms have been studied in two types of neighbourhoods, called global best (g-best) and local best (l-best). In the g-best neighbourhood, every particle is attracted to the best position found by the whole swarm. This position is called "g-best position". Due to its nature, the g-best model tends to converge rapidly to an optimum solution. However, this comes with the drawback that suffers from a tendency to get stuck in one near optimum solutions. For this reason, many studies have been carried out to improve its accuracy by employing mixed methodologies [19], [20]. In the l-best neighbourhood, each individual is affected by the best performance of its immediate neighbours, and it is attracted to the best position found by these neighbours. These neighbours are not necessarily particles who are near the individual in the parameter space, but rather ones that are near it in a topological space. This position is called l-best position”. The l-best neighbourhood is considered to be more effective and thus it is employed in this study [17], [18].

According to the l-best model, the velocity of the i-th particle after a time step is given by

$$\vec{u}_i(t+1) = w\vec{u}_i(t) + c_1\, rand(t)\left[\vec{p}_i(t) - \vec{x}_i(t)\right] + c_2\, rand(t)\left[\vec{l}_i(t) - \vec{x}_i(t)\right] \quad \textbf{(4)}$$

where w is the inertia weight, c1 and c2 are factors called “cognitive coefficient” and “social coefficient” respectively, $\vec{l}_i$ is the l-best position found by the neighbourhood of the i-th particle, $\vec{x}_i$ and $\vec{p}_i$ are respectively the current position of the i-th particle and the best position found by this particle until time step t, and lastly, rand(t) is a function that generates random numbers uniformly distributed between 0 and 1. Due to the use of inertia weight in (4), the above version of PSO is called inertia weight PSO (IWPSO).

1.3.3 The Invasive Weed Optimisation method (IWO)

The IWO method, originally proposed by Mehrabian and Lucas in 2006 [21], is a numerical stochastic optimisation methodology which in short simulates the colonising behaviour of weeds in nature. The general idea behind this algorithm is the robustness and adaptation ability of weeds and thus, by capturing their properties, the result is a powerful algorithm, which can be utilised in electromagnetic optimisation problems [22]-[24]. IWO, as all algorithms that fall under the EA category, is an iterative process and consists in creating subsequent generations of random search solutions that are going to be better than the previous ones. Only the best solutions are going to “survive”, while all other ones are going to be eliminated. Usually, the algorithm is terminated after a fixed pre-determined number of iterations, by considering CPU and time limitations.

This colonising behaviour is simulated by the following phases:

1. Initially, a population of weeds is dispersed at random positions inside an N-dimensional search space, where N is the number of parameters to be optimised by the IWO algorithm for a given problem. Thus, a first generation of random search positions is produced. These positions are produced by a Gaussian random number generator within higher and lower limit values for each parameter.

2. Fitness calculation and reproduction of every grown weed (plant) into new seeds depending on its individual calculated fitness value and according to the following linear formula:

$$X_s = \text{int}\left(\frac{F_w - F_s}{F_w - F_b}\right) X_{MAX} \quad \textbf{(5)}$$

where X_s is the number of seeds produced by the s-th weed, X_{max} is the maximum number of seeds produced by a weed, F_w and F_b are respectively the worst (maximum) and the best (minimum) fitness value of the population, and finally F_s is the fitness value of the s-th weed. In equation (5), it is considered that the worst performing weed X_w is not permitted to produce any seeds at all ($X_w = 0$).

3. Spatial dispersion of the newly produced seeds according to a Gaussian distribution with standard deviation expressed as:

$$SD = \left(\frac{\mathrm{I}_{\mathrm{MAX}} - \mathrm{I}}{\mathrm{I}_{\mathrm{MAX}}}\right)^n \left(SD_{\max} - SD_{\min}\right) + SD_{\min} \quad \textbf{(6)}$$

where I and I_{MAX} are respectively the current and the maximum number of iterations, SD_{max} and SD_{min} are the maximum and minimum standard deviation limits respectively, and n is the nonlinear modulation index used to define the reduction rate of SD.

4. Competitive exclusion, where all the weeds are sorted according to their fitness values and then, the weeds with the highest fitness are eliminated until a predefined number of them is left.

The above process is repeated from the second step until a user predefined number of iterations I_{MAX} is reached and the optimisation process is terminated.

Current research findings suggest that IWO is a very effective optimisation method for electromagnetic applications, and it can outperform many of its competitors in many different instances, and more specifically in electromagnetic applications designs. [25].

1.3.4 Adaptive Dispersion Invasive Weed Optimisation (ADIWO)

The ADIWO algorithm is based on the conventional IWO and was introduced in 2012 in [26]. The main difference between the conventional IWO and the ADIWO lies in the way the seeds produced by a weed are dispersed in the search space. In the conventional IWO, the standard deviation for seed dispersion decreases as a function of the number of iterations and is the same for all the seeds at a given iteration. However, in the ADIWO, the standard deviation of the dispersion of the seeds produced by a given weed is a function of the fitness value of that given weed. This adaptive seed dispersion results in faster convergence rate.

In conventional IWO and most of its variants, the standard deviation of the seed dispersion σ decreases as a function of the number of iterations. Obviously, the value of σ defines the exploration ability of the weeds. Therefore, as the number iterations increases, the exploration ability of all the weeds is gradually reduced. At the end of the optimisation process, the exploration ability has diminished enough that every weed can only fine tune its position. Hence, if the optimal position has not been found at that stage, it will never be found. In the ADIWO, the standard deviation σ of the dispersion of the seeds produced by a given weed is a linear function of the fitness value of that given weed. Considering that the goal is the minimisation of the fitness function, σ can be estimated according to the following expression:

$$SD = \frac{SD_{\max} - SD_{\min}}{f_{\max} - f_{\min}} + \frac{SD_{\min} f_{\max} - SD_{\max} f_{\min}}{f_{\max} - f_{\min}} \quad \textbf{(7)}$$

where SD_{max} and $SD_{\min}$ are the standard deviation limits defined in the same way as in the original IWO algorithm, while $f_{\max}$ and $f_{\min}$ represent respectively the maximum and minimum fitness values of the population at a certain iteration. From the above it is understandable that a weed with a fitness value close to $f_{\min}$ has reduced exploration ability, while a weed with a fitness value close to $f_{\max}$ can disperse in a wider search space to find better positions.

This variation of IWO has proven to be a very solid method which exhibits much faster convergence rate compared to the conventional IWO. This comes with the drawback that even though ADIWO converges faster to its optimum solution, it is not as effective as its conventional counterpart on reducing the overall fitness of a given problem as iterations progress. [27]

1.3.5 The Taguchi optimisation method

The Taguchi method was initially developed as a strategy to provide a solution to the extensive time and money resources required for Full Factorial Experiments. It is a method which can be more effective than the Trial and Error approach in many experiments according to [28] where Taguchi method is introduced in the EM community. The development of Taguchi method is based on orthogonal arrays (OAs). Orthogonal arrays were introduced during the 1940s and have been a go to solution for designing experiments.

They provide an efficient and systematic way to determine control parameters so that the optimal result can be found with only a few experimental runs by ensuring a balanced and fair selection of parameters in all possible combinations. The Taguchi method utilises OAs for input parameter selection. An orthogonal array, more specifically a fixed element orthogonal array of s elements, denoted by $OA_N(s^m)$, is an N*m matrix whose columns have the property that in every pair of columns each of the possible ordered pairs of elements appears the same number of times. Orthogonal arrays can be viewed as plans of multifactor experiments where the columns correspond to the factors, the entries in the columns correspond to the test levels of the factors and the rows correspond to the test runs. The OAs that were used in this research are $OA_9(3^4)$ for experiments with 4 or less parameters, $OA_{27}(3^{13})$ for experiments between 5 and 13 parameters and $OA_{81}(3^{40})$ for experiments between 14 and 40 parameters. $OA_9(3^4)$ is shown below as example.

Table 1. Orthogonal Array $OA_9(3^4)$

0	0	0	0
0	1	1	1
0	2	2	2
1	0	1	2
1	1	2	0
1	2	0	1
2	0	2	1
2	1	0	2
2	2	1	0

The Taguchi method which was put to use in this research is the modified Taguchi optimisation algorithm proposed in [29]. It is a valid utilisation of the Taguchi method for electromagnetic experiments and has been used in research.

The process description of Taguchi algorithm used in this research can be described in the following steps.

1. Problem Initialisation: The optimisation procedure starts with the problem initialisation, which includes the selection of a proper OA and the design of a suitable fitness function. The selection of an OA (E, P, L, t) mainly depends on the number of optimisation parameters. Where E is the number of Experiments, P is the number of Parameters, L is the number of Levels, and t is the strength.

2. Input Parameters Designation: Once the appropriate OA is found, the input parameters need to be selected to conduct the experiments. When the OA is used, the corresponding numerical values for the levels of each input parameter should be determined. For each i-th iteration and each p-th parameter, the level difference LD_{pi} is calculated by the following formula:

$$LD_{pi} = rr^{(i-1)} \cdot LD_{p1}, \quad p = 1, \ldots, P \qquad \textbf{(8)}$$

where,

$$LD_{p1} = \frac{(\max_p - \min_p)}{L+1}, \quad p = 1, \ldots, P \qquad \textbf{(9)}$$

is the initial level difference and *rr* is the reduced rate. Also, $\max_p$ and $\min_p$ are respectively the upper and the lower bound of the p-th parameter. Using this, the initial OA is transformed to a corresponding level value of the input parameter $x_n |_1^m$, where n is the nth element, m is the level and 1 represents the first iteration of the algorithm.

3. Experiments Conduction and Response Table Building: Following the parameter designation, the calculation of the fitness function for each experiment (e) is carried out and for each of the calculated fitness values, a dB conversion to signal-to-noise (S/N) ratio (η) using the following formula is performed:

$$\eta = -20 \log(Fitness) \qquad \textbf{(10)}$$

The values acquired from (10) are then averaged for each parameter n and each level m to build the response table with the following equation:

$$\bar{\eta}(m,n) = \frac{s}{N} \sum_{i, OA(i,n)=m} \eta_i \qquad \textbf{(11)}$$

4. Optimal Level Values Identification and Confirmation Experiment Conduction: To identify the optimal level values, all that is needed is to locate the largest η ratio in the response table for each parameter. When the optimal levels are identified, a single confirmation experiment is performed using the combination of the optimal levels identified in the response table.

5. Optimisation Range Reduction and Termination: If the termination criteria are not met, the algorithm moves on to reduce the optimisation range by multiplying LD_i with the reduced rate rr to find LD_{i+1}. Beyond some point, the level difference between previous and current elements converge to a similar fitness value and continuing the

process is futile, thus termination of the algorithm should take place if either termination criteria are met or if the following expression is true:

$\frac{LD_i}{LD_1} < desired\,accuracy$, where a proper value for the desired accuracy would be equal to 0.001 for most experiments.

1.4 References

[1] Slowik and H. Kwasnicka, "Evolutionary algorithms and their applications to engineering problems", *Neural Computing and Applications*, vol. 32, no. 16, pp. 12363-12379, 2020. Available: 10.1007/s00521-020-04832-8.

[2] S. Goudos, C. Kalialakis and R. Mittra, "Evolutionary Algorithms Applied to Antennas and Propagation: A Review of State of the Art", *International Journal of Antennas and Propagation*, vol. 2016, pp. 1-12, 2016. Available: 10.1155/2016/1010459.

[3] E. Michielssen and Y. Rahmat-Samii, *Electromagnetic optimisation by genetic algorithms*. New York: Wiley, 1999.

[4] Y. Li, "Simulation-based evolutionary method in antenna design optimisation", *Mathematical and Computer Modelling*, vol. 51, no. 7-8, pp. 944-955, 2010. Available: 10.1016/j.mcm.2009.08.017.

[5] Liu, H. Aliakbarian, Z. Ma, G. Vandenbosch, G. Gielen and P. Excell, "An Efficient Method for Antenna Design Optimisation Based on Evolutionary Computation and Machine Learning Techniques", *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 1, pp. 7-18, 2014. Available: 10.1109/tap.2013.2283605.

[6] E. N. Tziris, P. I. Lazaridis, Z. D. Zaharis, J. P. Cosmas, K. K. Mistry and I. A. Glover, "Optimised Planar Elliptical Dipole Antenna for UWB EMC Applications," *in IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 4, pp. 1377-1384, Aug. 2019, Available: 10.1109/TEMC.2019.2923781.

[7] P. I. Lazaridis, Z. D. Zaharis, C. Skeberis, T. Xenos, E. Tziris and P. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimisation," *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, 2014, pp. 1-5, Available: 10.1109/VITAE.2014.6934491.

[8] P. I. Lazaridis et al., "Comparative study of broadcasting antenna array optimisation using evolutionary algorithms," *2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC)*, 2016, pp. 1299-1301, Available: 10.1109/URSIAP-RASC.2016.7601166.

[9] Z. Zaharis, C. Skeberis, T. Xenos, P. Lazaridis and J. Cosmas, "Design of a Novel Antenna Array Beamformer Using Neural Networks Trained by Modified Adaptive Dispersion Invasive Weed Optimisation Based Data", *IEEE Transactions on Broadcasting*, vol. 59, no. 3, pp. 455-460, 2013. Available: 10.1109/tbc.2013.2244793.

[10] M. Pantoja, A. Bretones, F. Ruiz, S. Garcia and R. Martin, "Particle-Swarm Optimisation in Antenna Design: Optimisation of Log-Periodic Dipole Arrays", *IEEE Antennas and Propagation Magazine*, vol. 49, no. 4, pp. 34-47, 2007. Available: 10.1109/map.2007.4385594.

[11] R. Storn and K. Price, "Differential Evolution – A Simple and Efficient Heuristic for global Optimisation over Continuous Spaces", *Journal of Global Optimisation*, vol. 11, no. 4, pp. 341-359, 1997. Available: 10.1023/a:1008202821328.

[12] Basak and J. D. Lohn, "A comparison of evolutionary algorithms on a set of antenna design benchmarks," *2013 IEEE Congress on Evolutionary Computation*, 2013, pp. 598-604, Available: 10.1109/CEC.2013.6557623.

[13] P. Civicioglu, "Circular antenna array design by using evolutionary search algorithms", *Progress In Electromagnetics Research B*, vol. 54, pp. 265-284, 2013. Available: 10.2528/pierb13050112.

[14] Y. Ao and H. Chi, "Experimental Study on Differential Evolution Strategies," *2009 WRI Global Congress on Intelligent Systems*, 2009, pp. 19-24, Available: 10.1109/GCIS.2009.31.

[15] D. Zaharie, "Influence of crossover on the behavior of Differential Evolution Algorithms", *Applied Soft Computing*, vol. 9, no. 3, pp. 1126-1138, 2009. Available: 10.1016/j.asoc.2009.02.012.

[16] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, 1995, pp. 39-43, Available: 10.1109/MHS.1995.494215.

[17] Zaharis Z., Kampitaki D., Papastergiou A., Hatzigaidas A., Lazaridis P., Spasos M., "Optimal design of a linear antenna array under the restriction of uniform excitation distribution using a particle swarm based optimisation method," *WSEAS Trans. on Communications*, 2007, vol. 6, No.1, pp. 52-59.

[18] Z. Zaharis, D. Kampitaki, P. Lazaridis, A. Papastergiou and P. Gallion, "On the design of multifrequency dividers suitable for GSM/DCS/PCS/UMTS applications by using a particle swarm optimisation-based technique", *Microwave and Optical Technology Letters*, vol. 49, no. 9, pp. 2138-2144, 2007. Available: 10.1002/mop.22658.

[19] S. Jun and L. Jian, "A Hybrid of Differential Evolution and Particle Swarm Optimisation for Global Optimisation," *2009 Third International Symposium on Intelligent Information Technology Application*, 2009, pp. 138-141, Available: 10.1109/IITA.2009.36.

[20] W. Lin, Z. Lian, X. Gu and B. Jiao, "A Local and Global Search Combined Particle Swarm Optimisation Algorithm and Its Convergence Analysis", *Mathematical Problems in Engineering*, vol. 2014, pp. 1-11, 2014. Available: 10.1155/2014/905712.

[21] A. Mehrabian and C. Lucas, "A novel numerical optimisation algorithm inspired from weed colonisation", *Ecological Informatics*, vol. 1, no. 4, pp. 355-366, 2006. Available: 10.1016/j.ecoinf.2006.07.003.

[22] Z. Zaharis, C. Skeberis, T. Xenos, P. Lazaridis, and D. Stratakis, “IWO-based synthesis of log-periodic dipole array,” *in Proc. International Conference on Telecommunications and Multimedia sTEMU)*, Crete, Greece, 2014, pp. 150-154.

[23] A. Mallahzadeh, H. Oraizi and Z. Davoodi-Rad, "Application of the invasive weed optimisation technique for antenna configurations", *Progress In Electromagnetics Research*, vol. 79, pp. 137-150, 2008. Available: 10.2528/pier07092503.

[24] P. I. Lazaridis, Z. D. Zaharis, C. Skeberis, T. Xenos, E. Tziris and P. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimisation," *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, 2014, pp. 1-5, Available: 10.1109/VITAE.2014.6934491.

[25] S. Karimkashi and A. Kishk, "Invasive Weed Optimisation and its Features in Electromagnetics", *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 4, pp. 1269-1278, 2010. Available: 10.1109/tap.2010.2041163.

[26] Z. D. Zaharis, C. Skeberis, T. D. Xenos, P. I. Lazaridis and J. Cosmas, "Design of a Novel Antenna Array Beamformer Using Neural Networks Trained by Modified Adaptive Dispersion Invasive Weed Optimisation Based Data," *in IEEE Transactions on Broadcasting*, vol. 59, no. 3, pp. 455-460, Sept. 2013, Available: 10.1109/TBC.2013.2244793.

[27] P. I. Lazaridis et al., "Comparison of evolutionary algorithms for LPDA antenna optimisation," *2015 1st URSI Atlantic Radio Science Conference (URSI AT-RASC)*, 2015, pp. 1-1, Available: 10.1109/URSI-AT-RASC.2015.7302885.

[28] W. Weng, F. Yang and A. Elsherbeni, "Electromagnetics and Antenna Optimisation Using Taguchi's Method", *Synthesis Lectures on Computational Electromagnetics*, vol. 2, no. 1, pp. 1-94, 2007. Available: 10.2200/s00083ed1v01y200710cem018.

[29] Z. Zaharis, "A Modified Taguchi's Optimisation Algorithm for Beamforming Applications", *Progress In Electromagnetics Research*, vol. 127, pp. 553-569, 2012. Available: 10.2528/pier12040108.

2 NULL FILLING OPTIMISATION FOR FM-TV BROADCASTING ANTENNA ARRAY

2.1 Introduction

The work shown in this chapter is based on published papers [1]-[3]. Research on antennas has become very challenging, especially in the area of broadcasting [4], [5]. Plenty techniques have been proposed to design base station antenna arrays so that essential requirements for broadcasting applications, are satisfied [6], [7]. The requirements that are most considered for a broadcasting antenna array are described below:

1. As a result of the large distance between the transmitting base station and the service area, the antenna array is required to generate a very narrow main lobe which, combined with the need for reducing the spatial spread of the radiated power, leads to the requirement of maximum gain.
2. Given that a broadcasting base station is usually located at places of high altitude relative to the service area, the main lobe must be tilted on the horizontal plane. Because of its long distance from the service area, the tilting angle is usually very slight (between 2° to 4°).
3. For the adequate reception of a transmitted signal inside an angular sector under the main lobe, the directional gain should maintain a certain value in relation to the maximum gain value, which naturally would facilitate the filling of radiation pattern nulls inside the aforementioned angular sector. The null filling level depends on the service type (e.g., FM radio, TV DVB-T) and the signal-to-noise ratio (SNR).
4. In order to reduce the power reflection along the feeding lines, and thus, increase the efficiency of the whole feeding network, the impedance matching condition is required for each element of the antenna array, which means that the standing wave ratio (SWR) of each element must be close to unity.

Considering all of the above, it is evident that designing such antenna arrays is a multi-objective problem, due to the fact that all of the above requirements must be satisfied all together. Hence, the use of an optimisation method is a valuable tool to determine the best solution to this problem. As for many other electromagnetic optimisation problems, EAs are a suitable solution [8]-[11].

In the following study, linear arrays of 8 and 16 elements are excited by a uniform-amplitude distribution since that would be a straightforward implementation in practice. Such arrays are described in Figure 5. In these two cases, the linear arrays of 8 and 16 isotropic sources, are optimised to exhibit maximum gain, main lobe tilting and null filling, while the impedance matching condition is not required due to the use of isotropic sources.

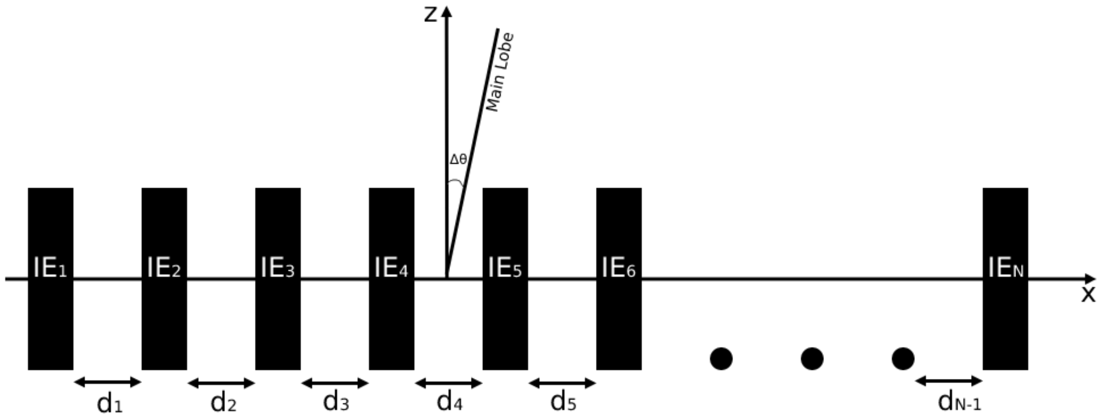


Figure 5. Linear antenna array with N Isotropic Elements (IE_x) and their respective distances (d_x)

For the purpose of this study, a fitness function which facilitates all of the above is created, and the goal is to minimise this function by applying the optimisation methods on it. The optimisation results exhibit the relative effectiveness of the proposed methods. The goal in antenna array geometry synthesis is to determine the physical layout of the array that produces a radiation pattern that is closest to the desired pattern. The shape of the desired pattern can vary widely depending on the application.

2.2 Implementation

The studied cases are with regards to a theoretical aspect of linear array design meant for wavelengths of VHF-UHF frequencies and therefore the arrays are considered to be composed respectively of 8 (case 1) and 16 (case 2) isotropic sources. For these, the performed optimisation is set for 1) maximum gain $G_{des}>14$, 2) $\Delta\theta_{des} = 2°$ (downward main lobe electrical tilting), and 3) g_{des} = -20dB (null-filling) for a service area between 90° and 120°, which are attained with the minimisation of the fitness function designed for this purpose. Given that G_p maximisation does not have a specified target value, two reference directional gain values are calculated to be compared with G_p. These values are: 1) the maximum directional gain G_{bp} of a broadside linear array (i.e., array without main lobe tilting, $\Delta\theta_{des} = 0°$) composed of 8 and 16 isotropic sources respectively per case with equal distances between elements *d* and equal excitation phases, and 2) the maximum directional gain G_{tp} of a linear array composed of 8 and 16 isotropic sources respectively per case with equal distances *d* and equal excitation phase differences between adjacent sources given by the expression

$$\Delta\phi = \frac{2\pi}{\lambda} d \sin(\Delta\theta_{des}) \qquad \textbf{(12)}$$

where $\Delta\theta_{des} = 2°$, and lastly with no null filling requirement.

Hence, the fitness function shall be expressed as below:

$$Fitness = [G_{des} - \min(G_{des}, G_{act})] + |(\Delta\theta_{des} - \Delta\theta_{act})| + [g_{des} - \min(g_{des}, g_{act})] \qquad \textbf{(13)}$$

where G_{des} and G_{act} are the desired and actual simulated values of Gain, $\Delta\theta_{des}$ and $\Delta\theta_{act}$ are the desired and actual angles where main lobe (maximum gain) is found, and lastly, g_{des} and g_{act} are the desired and actual values of the nulls within the service area of the radiation pattern.

All the optimisation algorithms were applied for the two cases. The parameters that are set to undergo optimisation are the excitation phases of the elements along with the distances between each element. Naturally, this equals to a sum of 14 optimised parameters for the 8 element array and 30 optimised parameters for the 16 element array. Hence, the selected total number of iterations for the 8 element array is set for 5,000 evaluations in total, whereas for the 16 element array is set for 10,000 evaluations in total so that the algorithms will be able to pick the best possible final outcome for each case. Evidently, the more parameters, the more evaluations are needed. Each case was run 20 times per algorithm, which is enough for an average fitness comparison of the algorithms, except for the Taguchi algorithm which automatically picks the total number of iterations. The population size (experiments, particles, or weeds) is 82 for both cases and all algorithms.

2.3 Simulated results

As pointed out, the target of the simulations is gain maximisation for the derived antenna and the gain to exhibit no less than -20dB from the peak value between the 92º and 120º azimuth angle. The fitness values per iteration for both the 8 element and 16 element antenna arrays of all the algorithms are shown and a final comparison can be obtained concerning the behaviour of each algorithm. The convergence graphs depict the average convergence of the algorithms in 20 executions. In both scenarios all of the algorithms produced a radiation pattern which satisfies an antenna design with broadcasting capabilities for VHF-UHF frequencies because the relative gain is higher than -20dB between 92º and 120º, revealing that there are no deep nulls within the service area. Even though, the performance of all the algorithms is satisfactory, IWO's performance stands out, since it demonstrates the lowest average fitness value compared to the other methodologies in exchange for a slower convergence rate which equals to a larger computational time and thus, resources. On the other hand, the ADIWO method exhibits the poorest results, since the best average fitness value is a much larger value, and in spite of its fairly quick convergence rate, Taguchi, PSO and DE demonstrate a faster convergence rate. In Figures 8 to 17, the normalised radiation patterns of the IWO optimised arrays are depicted, to display the successful null filling optimisation.

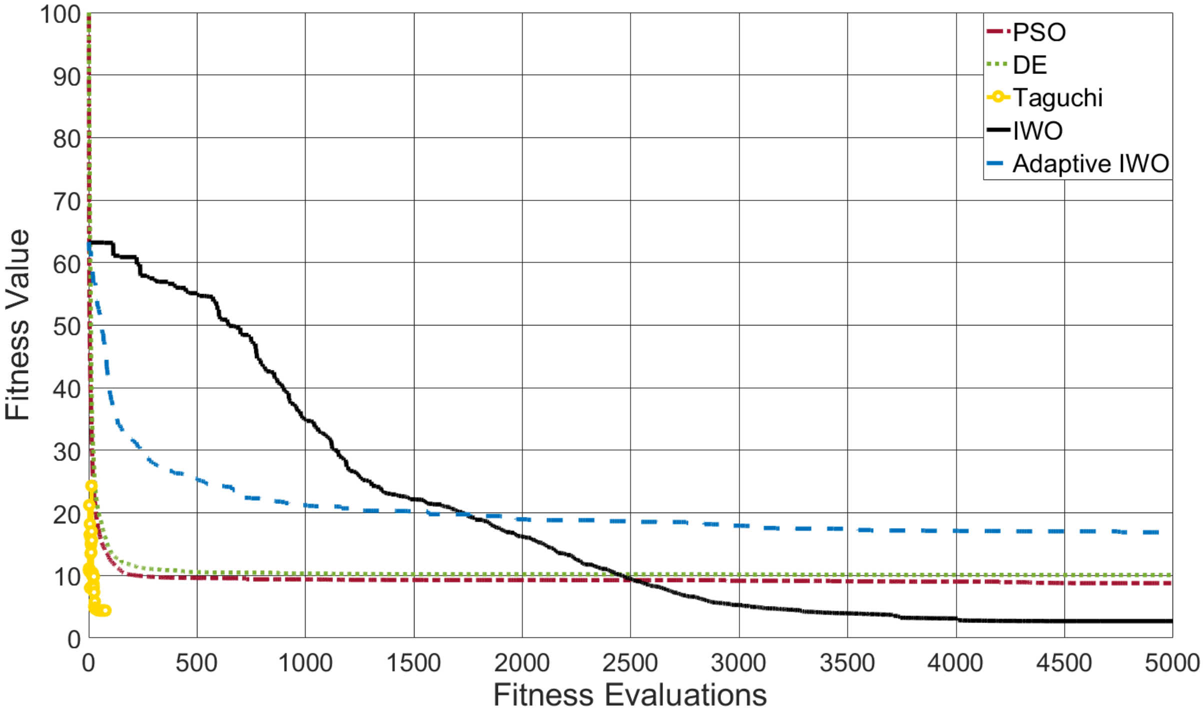


Figure 6. Fitness convergence diagram of all the optimisation methods for an array consisting of 8 elements

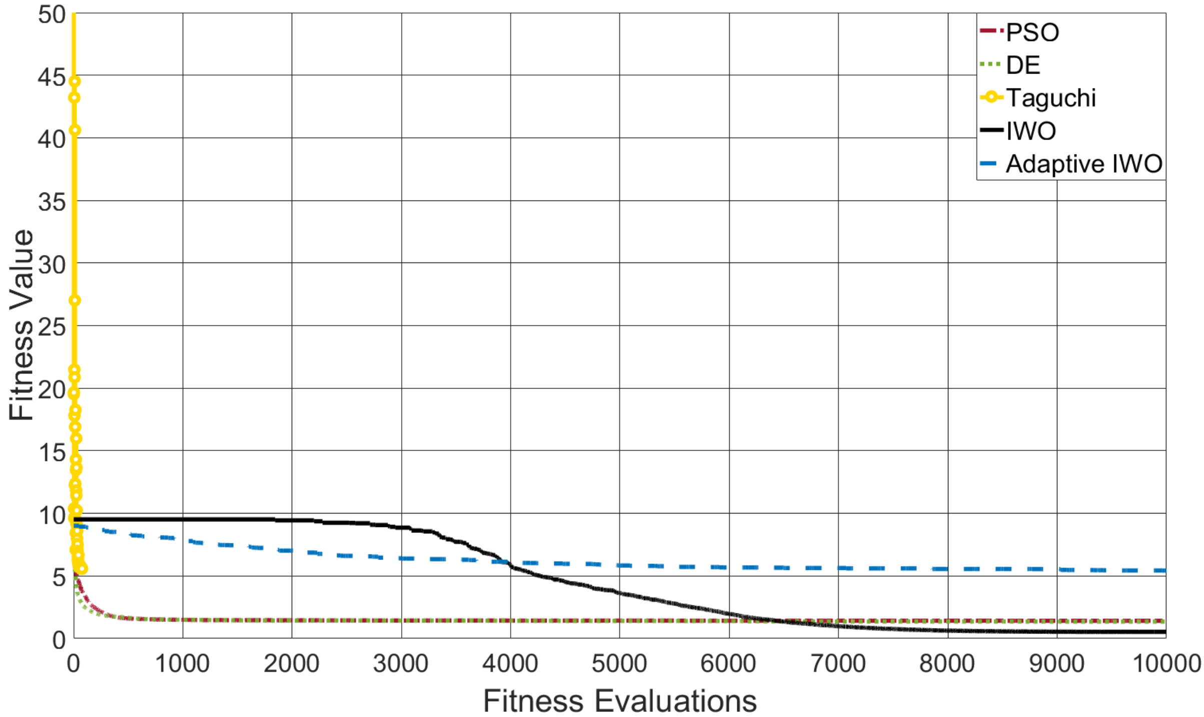


Figure 7. Fitness convergence diagram of all the optimisation methods for an array consisting of 16 elements

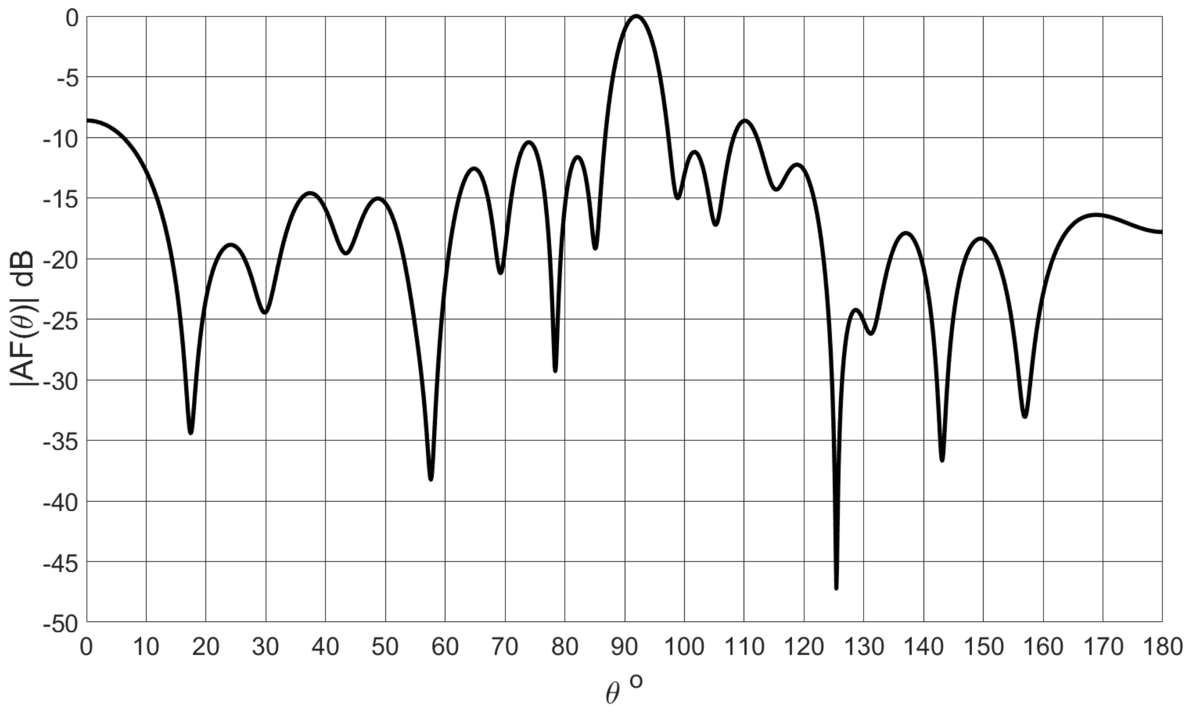


Figure 8. Radiation Pattern of IWO optimised array with 8 elements

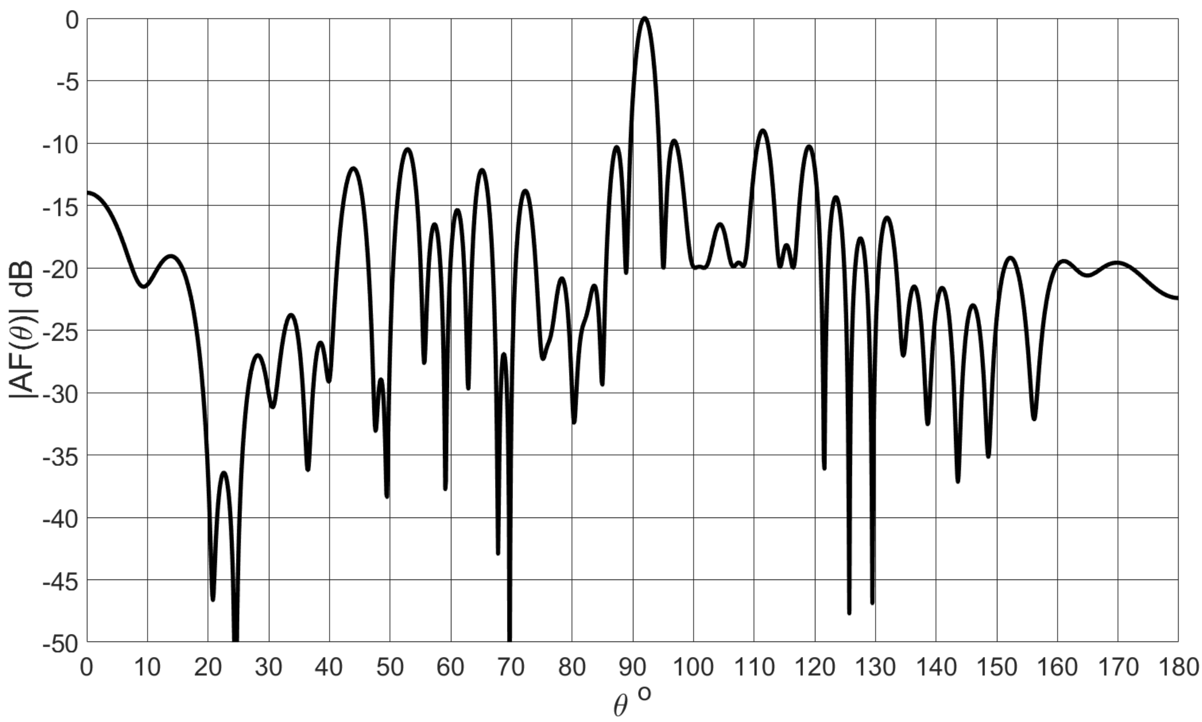


Figure 9. Radiation Pattern of IWO optimised array with 16 elements

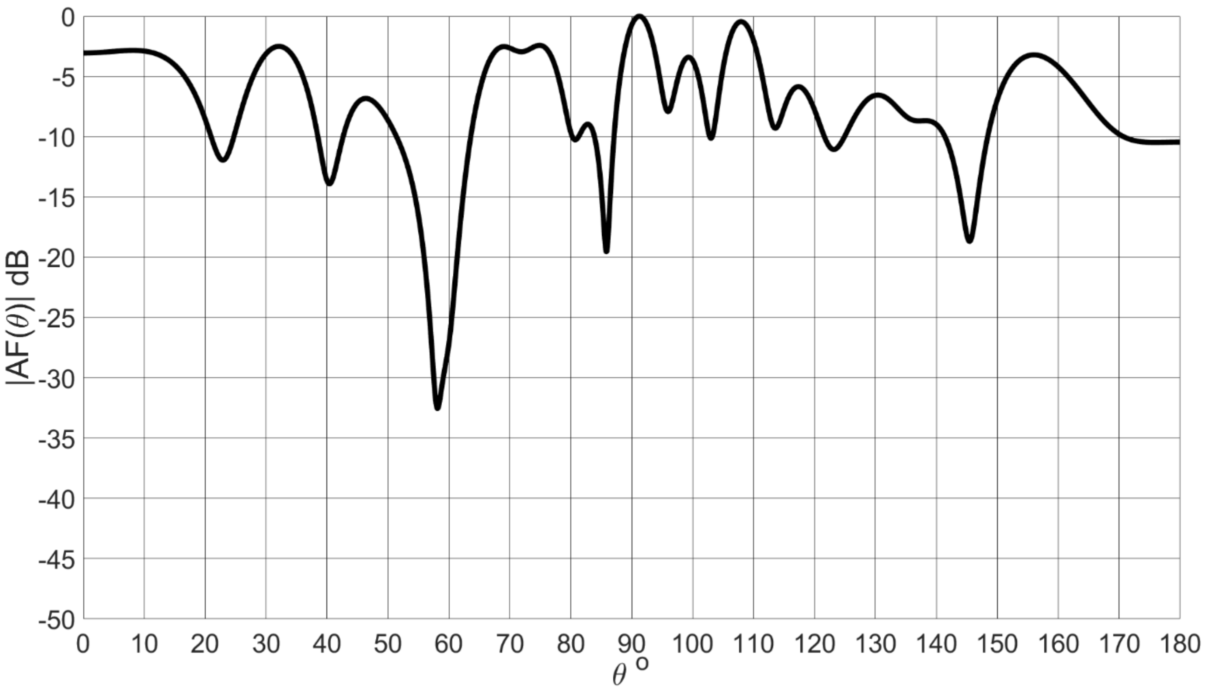


Figure 10. Radiation Pattern of DE optimised array with 8 elements

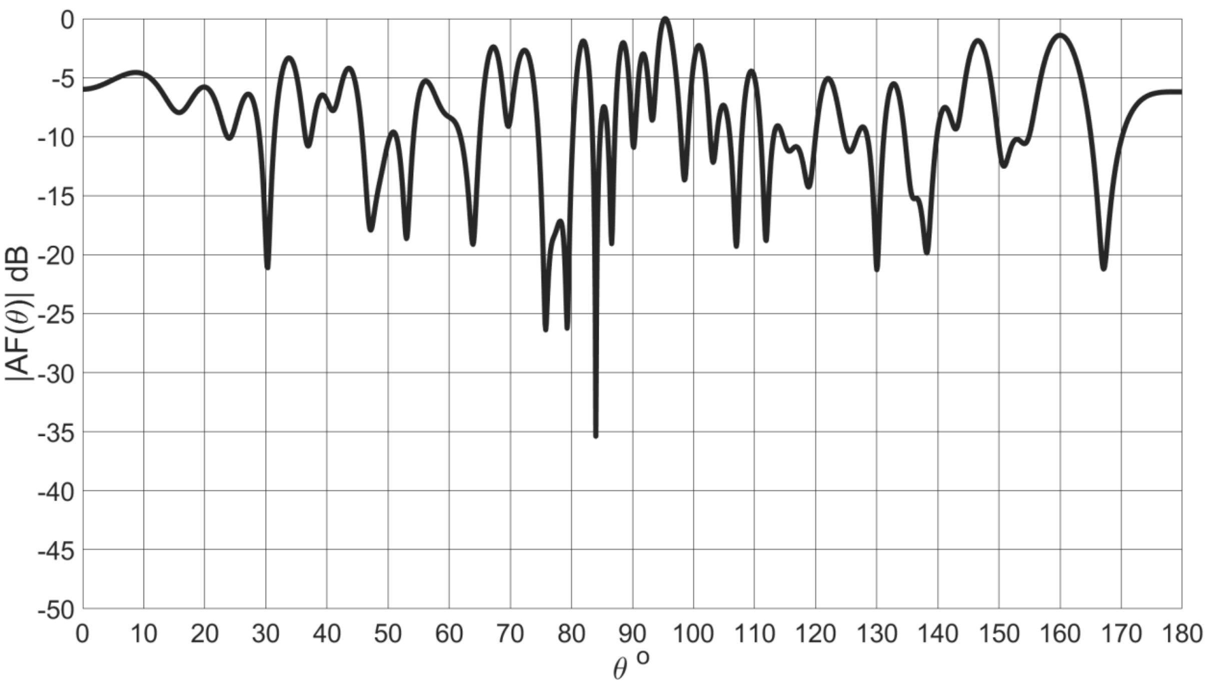


Figure 11. Radiation Pattern of DE optimised array with 16 elements

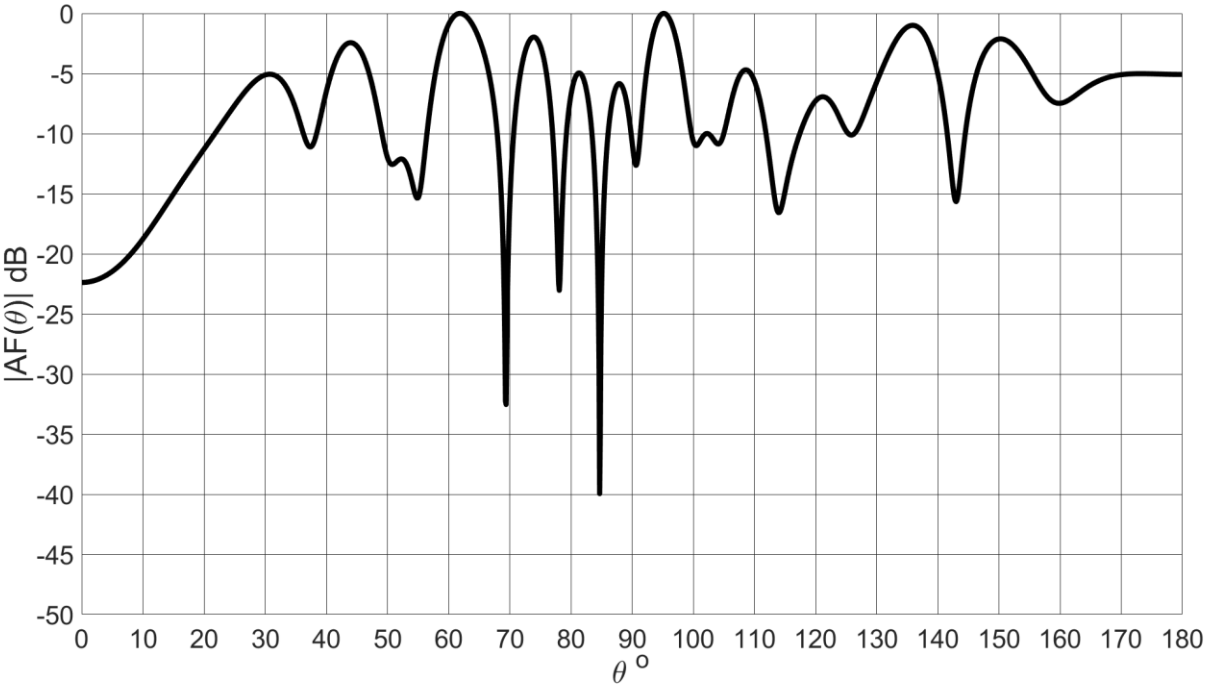


Figure 12. Radiation Pattern of PSO optimised array with 8 elements

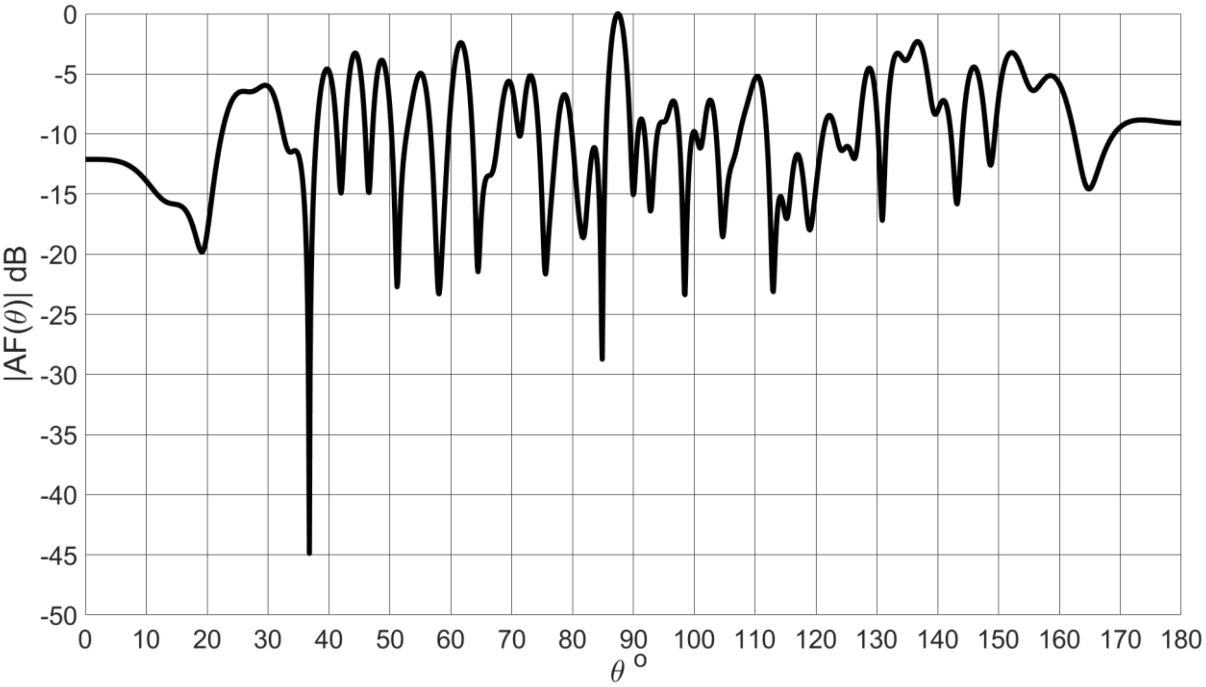


Figure 13. Radiation Pattern of PSO optimised array with 16 elements

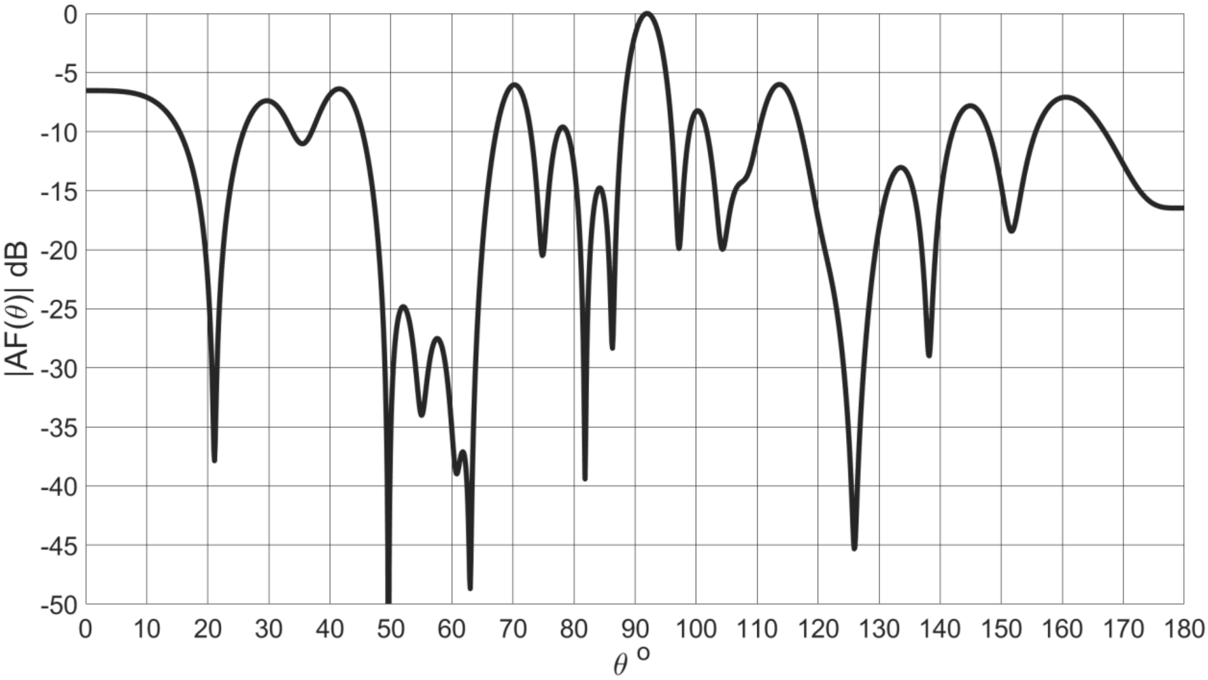


Figure 14. Radiation Pattern of Taguchi optimised array with 8 elements

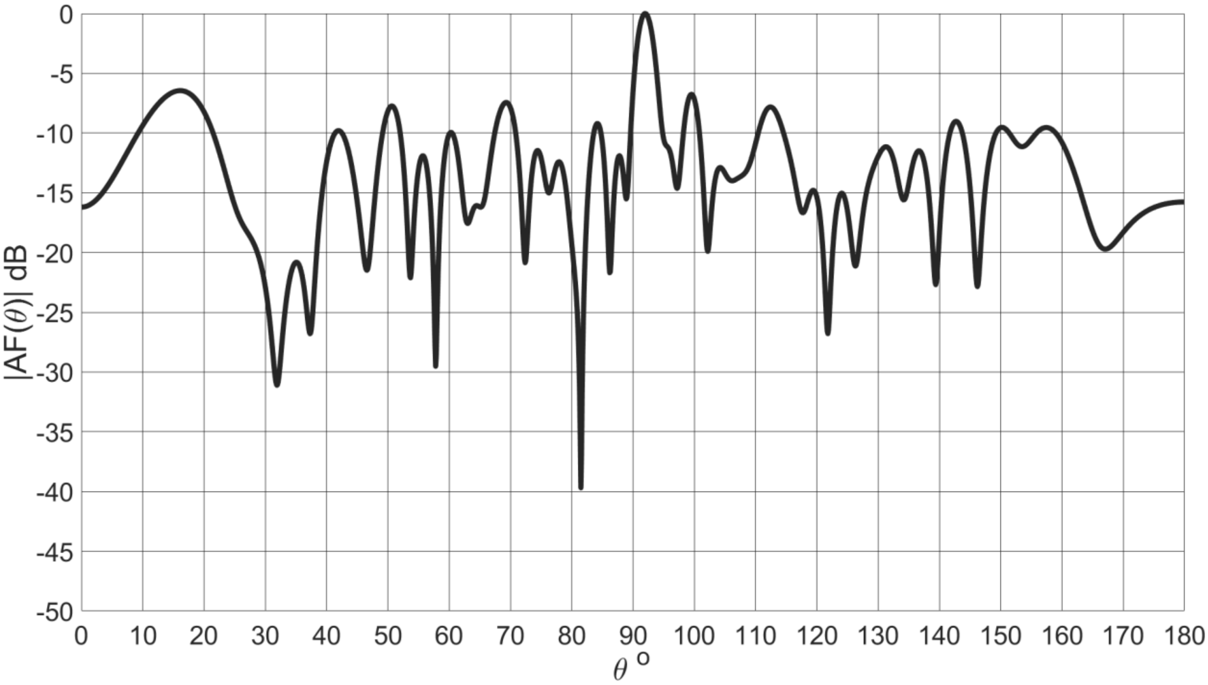


Figure 15. Radiation Pattern of Taguchi optimised array with 16 elements

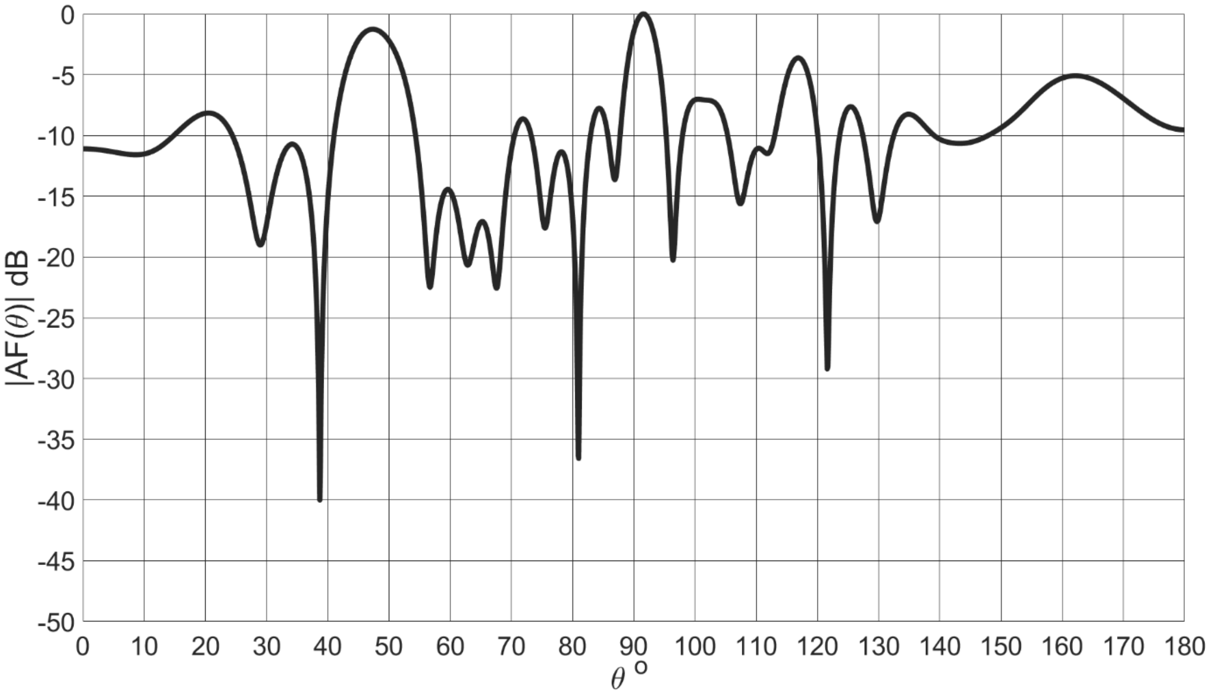


Figure 16. Radiation Pattern of ADIWO optimised array with 8 elements

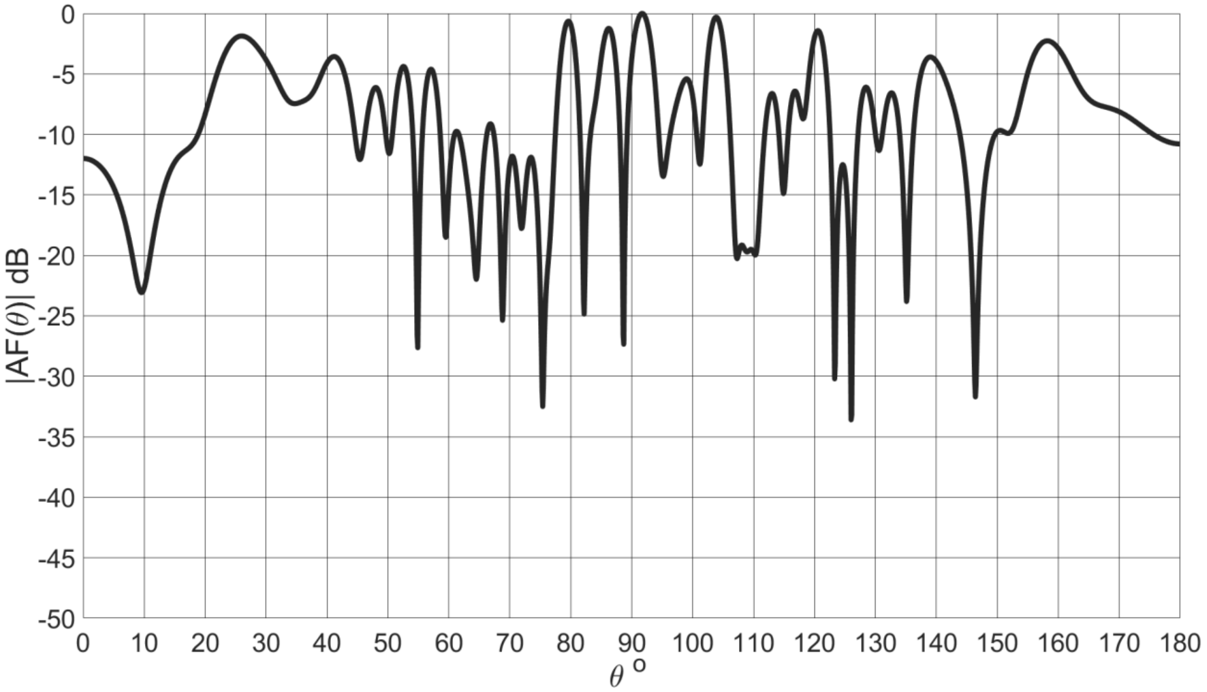


Figure 17. Radiation Pattern of ADIWO optimised array with 16 elements

2.4 Conclusions

Studying a theoretical aspect of linear arrays was a suitable introduction for testing EAs on electromagnetic applications. The optimisation's requirements are close to none with regards to time and money. The optimisation methods that are exercised in this research demonstrate that utilising them in electromagnetic applications is essential to generate antenna geometries with enhanced radiation characteristics compared to the classical methodologies.

By utilising the optimisation methods which are demonstrated in this chapter, it is observable that no method is inadequate for electromagnetic optimisation. Some methods exhibit faster convergence rate, such as Taguchi, DE and PSO, whereas IWO exhibits better convergence overall. Considering this, each method would be most appropriate depending on the application.

2.5 References

[1] P. I. Lazaridis, E. N. Tziris, Z. D. Zaharis, T. D. Xenos, V. Holmes, J. P. Cosmas and I. A. Glover, "Comparative study of broadcasting antenna array optimisation using evolutionary algorithms," *2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC)*, Seoul, 2016, pp. 1299-1301, Available: 10.1109/URSIAP-RASC.2016.7601166.

[2] E. N. Tziris, P. I. Lazaridis, B. Mehrdadi, V. Holmes, I. A. Glover, Z. D. Zaharis, A. Bizopoulos and J. P. Cosmas, "Comparison of Evolutionary Optimisation Algorithms for FM-TV Broadcasting Antenna Array Null Filling," *19th International Conference on Circuits, Systems, Communications and Computers (CSCC'15)*, 2015.

[3] P. I. Lazaridis, Z. D. Zaharis, C. Skeberis, T. D. Xenos, E. N. Tziris and P. B. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimisation," *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, Aalborg, 2014, pp. 1-5, Available: 10.1109/VITAE.2014.6934491.

[4] Kosalay, "Estimation of RF Electromagnetic Levels Around TV Broadcast Antennas Using Fuzzy Logic", *IEEE Transactions on Broadcasting*, vol. 56, no. 1, pp. 36-43, 2010. Available: 10.1109/tbc.2009.2035944.

[5] P. Mousavi, M. Fakharzadeh and S. Safavi-Naeini, "1K Element Antenna System for Mobile Direct Broadcasting Satellite Reception", *IEEE Transactions on Broadcasting*, vol. 56, no. 3, pp. 340-349, 2010. Available: 10.1109/tbc.2010.2049611.

[6] F. Ares-Pena, J. Rodriguez-Gonzalez, E. Villanueva-Lopez and S. Rengarajan, "Genetic algorithms in the design and optimisation of antenna array patterns", *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 3, pp. 506-510, 1999. Available: 10.1109/8.768786.

[7] W. Shen and W. Zhang, "Pattern synthesis of non-symmetric tapered slotline antenna", *Electronics Letters*, vol. 42, no. 8, p. 443, 2006. Available: 10.1049/el:20064482.

[8] N. Nemri, A. Smida, R. Ghayoula, H. Trabelsi and A. Gharsallah, "Phase-only array beam control using a Taguchi optimisation method," *2011 11th Mediterranean Microwave Symposium (MMS)*, 2011, pp. 97-100, Available: 10.1109/MMS.2011.6068537.

[9] D. Liu, Q. Feng, W. Wang and X. Yu, "Synthesis of unequally spaced antenna arrays by using inheritance learning particle swarm optimisation", *Progress In Electromagnetics Research*, vol. 118, pp. 205-221, 2011. Available: 10.2528/pier11050502.

[10] Z. D. Zaharis, C. Skeberis, T. D. Xenos, P. I. Lazaridis and J. Cosmas, "Design of a Novel Antenna Array Beamformer Using Neural Networks Trained by Modified Adaptive Dispersion Invasive Weed Optimisation Based Data," *in IEEE Transactions on Broadcasting*, vol. 59, no. 3, pp. 455-460, Sept. 2013, Available: 10.1109/TBC.2013.2244793.

[11] Z. D. Zaharis, C. Skeberis, T. D. Xenos, P. I. Lazaridis and D. I. Stratakis, "IWO-based synthesis of log-periodic dipole array," 2*014 International Conference on Telecommunications and Multimedia (TEMU)*, 2014, pp. 150-154, Available: 10.1109/TEMU.2014.6917752.

3 LPDA ANTENNA OPTIMISATION

3.1 Introduction

Broadband log-periodic antenna optimisation is a very challenging problem for antenna design. However, up to now, the universal method for log-periodic antenna design is Carrel's method dating from the 1960s, [1], [2]. In this chapter, the optimisation algorithms, are put to use as solutions to the broadband antenna design problem. Log-periodic Dipole Arrays (LPDA) are a preferred solution for broadband applications because of their solid directivity characteristics and their flat gain curve. In this chapter, the accurate modelling of the log-periodic type of antennas, the detailed calculation of the important characteristics of the antennas under test (gain, gain flatness, SWR, and Front-to-Rear ratio that is equivalent to the ratio of the gain of the main lobe to the gain of the side lobe with opposite direction) and the comparison with accurate measurement results are compared.

Minimizing the designed fitness function which includes all the above requirements, leads to the optimum dipole lengths, spacing between the dipoles, and dipole wire diameters. In some optimisation cases, a constant dipole wire radius could be adopted in order to simplify the construction of the antenna. The work shown in this chapter is based on published papers [3] and [4].

3.2 Classical LPDA design

The most complete and practical design procedure for an LPDA is the one proposed by Carrel, [1], [2]. The configuration of the LPDA antenna is described in terms of the design parameters: τ (design constant), α, and σ (relative spacing), related by:

$$\alpha = \tan^{-1}\left[\frac{1-\tau}{4\sigma}\right] \quad \textbf{(14)}$$

Once two of the design parameters are specified, the other one can be found. The proportionality factors that relate lengths, diameters, and spacings between dipoles are:

$$\tau = \frac{L_{m+1}}{L_m} = \frac{d_{m+1}}{d_m} \quad \textbf{(15)}$$

$$\sigma = \frac{S_m}{2L_m} \quad \textbf{(16)}$$

where, L_m and $d_m = 2r_m$ are respectively the length and the diameter of the m-th dipole, while S_m is the spacing between the m-th and (m+1)-th dipoles as depicted in Figure 18. However, for many practical LPDA antenna designs, wire dipoles of equal diameters d_m are used, or for some advanced designs, three or four groups of equal diameter dipoles are used to cover the whole frequency range. In order to reduce some anomalous resonances of the antenna, a short-circuited stub is usually placed at the end of the feeding line at some distance behind the longest dipole. Directivity (in dB) contour curves as a function of τ for various values of σ are shown in [2], as they have been corrected by [5]. A set of design equations and graphs are used, but in practice it is much easier to use a software incorporating all the necessary design procedure, such as LPCAD, [6]. Moreover, LPCAD produces a file that can be used for the detailed simulation of the antenna using the Numerical Electromagnetics Code (NEC) software. NEC employs the Method of Moments for wire antennas and is well documented, [7]-[9]. The NEC model of the log-periodic antenna employs an ideal transmission line for feeding the antenna dipoles characterised only by its characteristic impedance Z_0. Furthermore, the thin-wire approximation is monitored during the execution of the NEC algorithm, and it is confirmed that it is not violated.

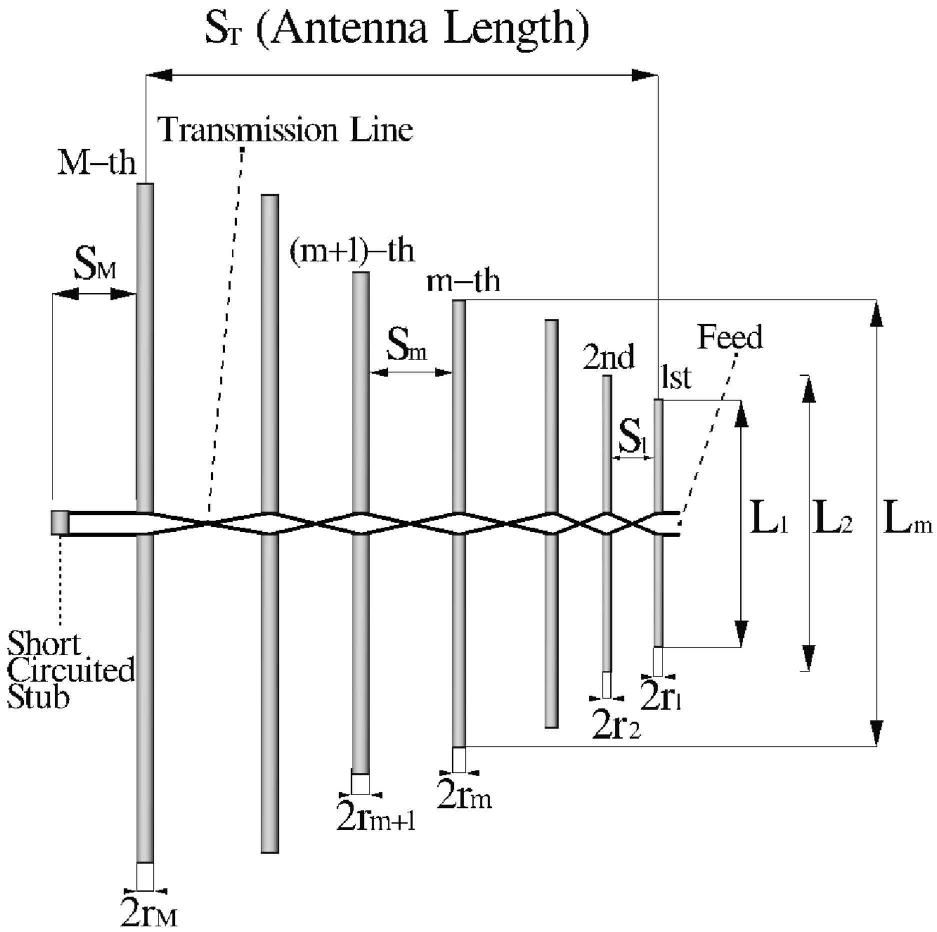


Figure 18. Construction details of a broadband LPDA antenna

3.3 Implementation

For the comparison of the optimisation methods under study, the algorithms were applied on an LPDA antenna for the UHF-TV band between 470MHz to 790MHz with a total of 10 dipoles and a rear shorting stub. The frequency band that was used for the optimisation is marginally larger between 450MHz to 800MHz with respect to maximum gain, gain flatness, Front to Rear ratio (F/R) and matching to 50 Ohms, or, equivalently Standing Wave Ratio (SWR). Therefore, a fitness function which is a linear combination of the above four performance indicators is created:

$$\begin{aligned} f(L_1,...,L_M,S_1,...S_{M-1},d_1,...,d_M,Z_0,S_M) &= w_1[\max(GF,2)-2]-w_2(G_{min}-10) \\ &+w_3[\max(SWR_{max},1.5)-1.5]-w_4[\max(FR_{min},20)-20] \end{aligned} \quad \textbf{(17)}$$

where, Z_0 is the characteristic impedance of the antenna boom. The dimensions of the geometrical characteristics of the LPDA are defined in Figure 18. The composition of the fitness function is done in such a way to satisfy the following requirements:

1. $SWR_{max} \leq 1.5$
2. G_{min} (the minimum gain) close to or higher than a target gain of 10dBi
3. GF ≤ 2 dB (Gain Flatness, the difference between the maximum and minimum gain values throughout the optimised band)
4. $FR_{min} \geq 20$ dB (Front to Rear ratio).

In the fitness expression, the positive terms GF and SWR_{max} are minimised whereas the negative terms G_{min} and FR_{min} are maximised. The values that were used as the weights of each fitness term are: w_1 = 8, w_2 = 6, w_3 =12, w_4 = 20 which denotes that emphasis is mostly given to the impedance matching and the Front to Rear ratio. These values were chosen after trial and error, meaning that several different sets of values were tested on the simulations until the combination which yielded the best possible output was found. The performance of the optimised antenna that results from the optimisation, depends substantially on the weights used in the fitness function formula. Hence, the careful assignment of the relative weights to each performance indicator is important for the emphasis given to particular properties, e.g. F/R performance over gain. The antenna performance indicators are calculated by applying the NEC engine in the 4NEC2 software. The aforementioned is an implementation of the NEC algorithm. For every possible solution, i.e. for each set of design parameters, the antenna performance is calculated for all frequencies by steps of 10MHz, i.e. for 35 discrete frequencies. The antenna parameters which undergo optimisation are the lengths of the dipole, the diameters of the dipoles, along with the spacings between the dipoles and the characteristic impedance of the transmission line that feeds the dipoles, i.e. in this case 31 variables. The optimisation methods are set to be executed for a total of 44,000 fitness evaluations, i.e. 44,000 NEC calculations or until all requirements are met, where the algorithm will be terminated. At the end of the execution of each algorithm the best fitness and the geometry of the optimised antenna are produced. The geometry of the optimised antenna is then extracted to a 'nec' file. The 4NEC2 software was used to run the NEC file produced by MATLAB, to derive the SWR, Gain, F/R Ratio, while the convergence diagram figures were derived directly from the optimisation algorithms. For the calculation of the convergence diagram, the highest Gain value (main lobe) recorded for a specific frequency is considered as the Gain of that frequency and the Gain of the opposite direction is used to calculate the F/R ratio for that frequency.

3.4 Simulated results

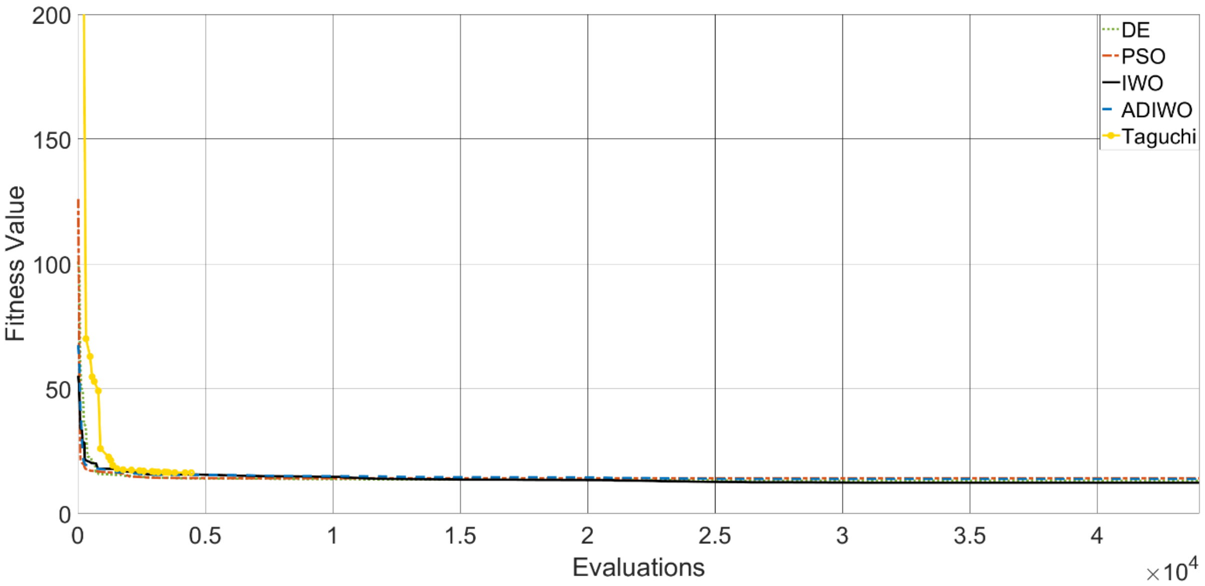


Figure 19. Convergence diagram of optimised LPDA per optimisation method.

Figure 19 depicts the convergence diagram of all of the algorithms for a total of 44,000 fitness evaluations except for the Taguchi method which terminates automatically at approximately 4,400 fitness evaluations and it shows that all the optimisation methods had similar success at the design of the LPDA geometry. Although, by considering Table 2 and the rest of the figures, IWO is the best performer since it shows a relatively flat gain of approximately 8dBi as seen in Figure 21 and it is higher compared to the rest of the algorithms across the whole of the UHF-TV band. The Differential Evolution optimised antenna performs similarly but with somewhat fluctuating gain values throughout the frequency range, which is considered worse than the flat frequency response of the IWO based optimisation. On the other extreme, the Taguchi-optimised antenna exhibits the poorest performance with relatively low gain.

Likewise, Figure 22 demonstrates that the best Front to Rear ratio results are the ones generated from the IWO and Differential Evolution algorithms which exhibited increased F/R ratio values in comparison with the remaining algorithms. However, the performance of PSO is not poor and can be considered minorly inferior to those of IWO and DE, while the results shown by the Taguchi method (lowest F/R ratio across the desired frequency range) and the Adaptive IWO (poor low frequency F/R ratio values) are less satisfactory.

Table 2. Best total fitness per optimisation method and for each goal

Opt Method	DE	PSO	IWO	ADIWO	Taguchi
VSRW Fitness weights not considered	0	0	0	0.21	0
Gain Fitness weights not considered	2.19	2.36	2.07	2.45	2.73
GF Fitness weights not considered	0	0	0	0	0
F/R Fitness weights not considered	0	0	0	0	0
Best Fitness weights not considered	2.19	2.36	2.07	2.66	2.73
Best Fitness weights considered	13.08	13.80	12.36	14.10	16.32

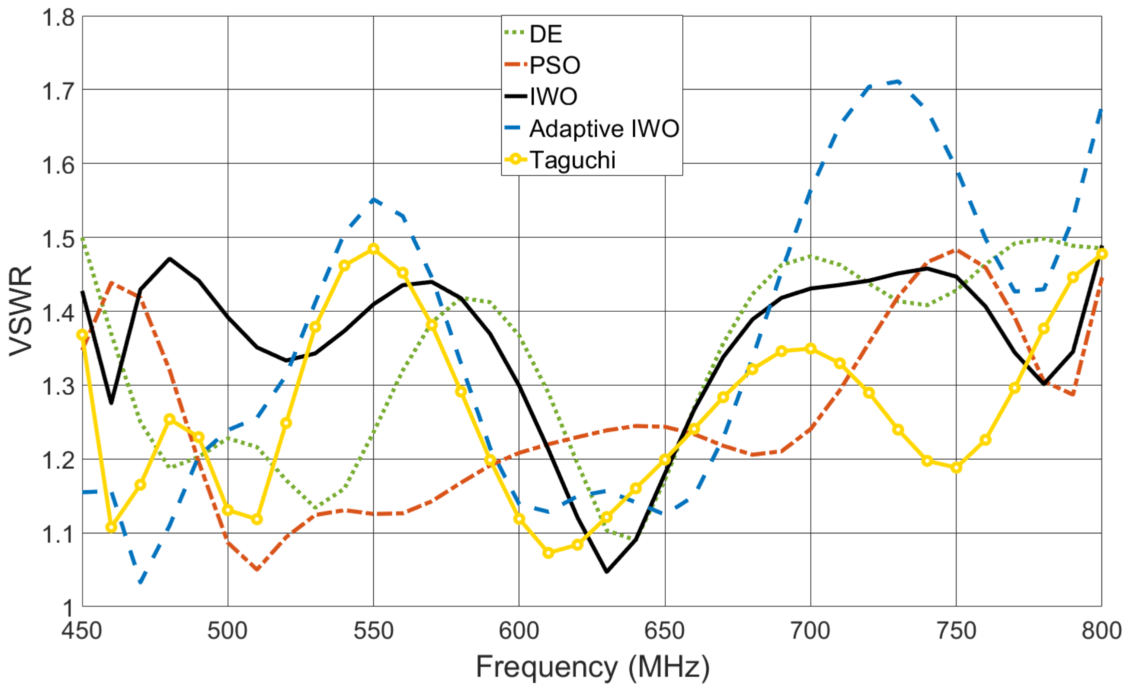


Figure 20. VSWR of optimised LPDAs

In Figure 20 the comparison of SWR between the evolutionary algorithms which are used to generate the geometries of five different LPDAs shows that the results are very satisfying for all of the algorithms, since the SWR values are all below 1.8. Naturally, some algorithms performed better than others, with PSO exhibiting the best possible VSWR throughout the frequency range whereas the Adaptive IWO is the only method which exceeded the limit of 1.5.

Another factor to be considered is the rate of convergence. A rather higher than lower convergence rate means that a lower fitness value will be achieved within a smaller time, which equals to faster acquisition of results with less computational resources. It is notable that PSO has a very fast average convergence rate compared to the rest of the algorithms (three times than that of IWO). Table 3 provides a comparison between the average convergence rate of each optimisation method.

Table 3. Average fitness convergence rate in percentage

Opt Method	**DE**	**PSO**	**IWO**	**ADIWO**
Convergence rate (%)	0.1997	0.2862	0.0971	0.1534

The convergence rate of each optimisation method is calculated using the following formula:

$$\frac{\sum_{n=1}^{N}(f_{n+1}-f_n)}{N} \qquad \textbf{(18)}$$

where, f_n is the fitness of the n−th evaluation, and N the total number of evaluations.

An observation that comes by examining the results is that the better the best fitness value is, the slower the average convergence rate is. PSO shows a 0.2862% average convergence rate and a best fitness of 14.1 for instance, while IWO shows a 0.0971% average convergence rate while its best fitness has the lowest value of 12.36.

Table 4 summarises the performance of the optimisation methods with regards to fitness requirements.

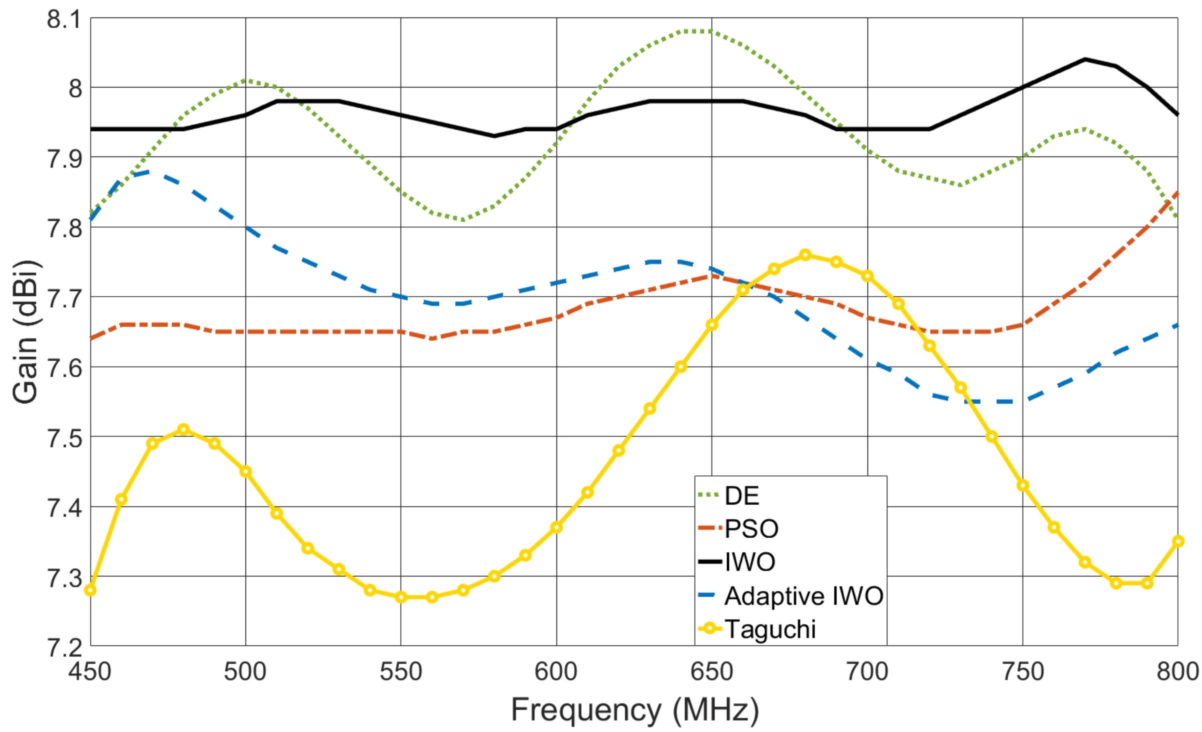


Figure 21. Gain of optimised LPDAs

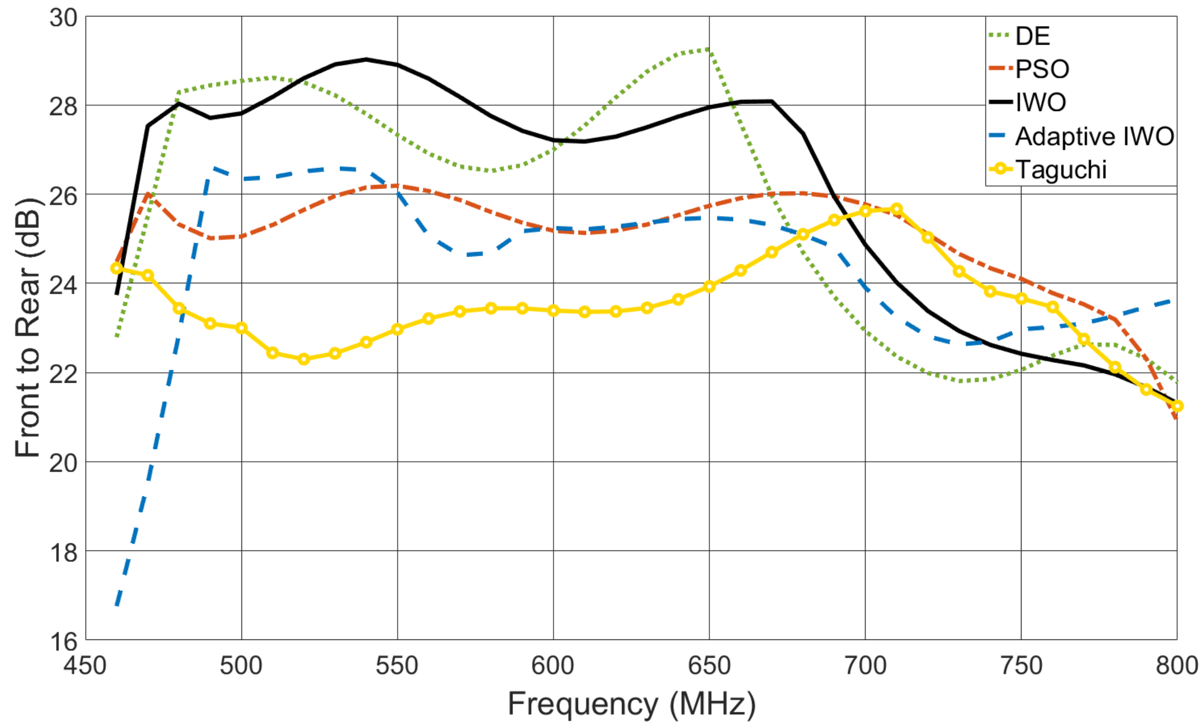


Figure 22. Front to rear ratio of optimised LPDAS

Table 4. Radiation characteristics of optimised LPDAs

Opt Method	MIN Gain	GF (MAX – MIN)	MAX VSWR	MAX F/R Ratio
DE	7.81	0.27	1.50	21.78
PSO	7.64	0.21	1.48	20.90
IWO	7.93	0.11	1.49	21.31
ADIWO	7.55	0.33	1.71	22.52
Taguchi	7.27	0.49	1.48	21.25

3.5 Conclusion

The evolutionary algorithms under study were employed to design a Log-Periodic Dipole Array each, so that their performance is compared, and consequently to find the algorithm that demonstrates the best performance. The LPDA geometries derived from the optimisations were with satisfying properties (SWR, Gain, gain flatness, and F/R Ratio). Other than the best fitness exhibitors which was IWO and DE, it was observed that the algorithms with faster average convergence rate compared to others are not the ones that show the best final results and lowest fitness values. Overall, the IWO algorithm would be considered the definitive best performer, while PSO the fastest average convergence rate performer.

3.6 References

[1] R. Carrel, "Analysis and design of the log-periodic dipole antenna.," 1961, Urbana: Electrical Engineering Research Laboratory, Engineering Experiment Station, University of Illinois.

[2] C. Balanis, *Antenna theory, Analysis and Desing*, 2nd ed. John Wiley & Sons, 1997, pp. 551-566.

[3] P. I. Lazaridis, E. N. Tziris, Z. D. Zaharis, T. D. Xenos, J. P. Cosmas, P. B. Gallion, V. Holmes and I. A. Glover, "Comparison of evolutionary algorithms for LPDA antenna optimisation," *in Radio Science*, vol. 51, no. 8, pp. 1377-1384, Aug. 2016, Available: 10.1002/2015RS005913.

[4] P. I. Lazaridis, E. N. Tziris, Z. D. Zaharis, T. D. Xenos, J. P. Cosmas, P. B. Gallion, V. Holmes and I. A. Glover. "Comparison of evolutionary algorithms for LPDA antenna

optimisation," *2015 1st URSI Atlantic Radio Science Conference (URSI AT-RASC)*, Las Palmas, 2015, pp. 1-1, Available: 10.1109/URSI-AT-RASC.2015.7302885.

[5] P. Butson and G. Thompson, "A note on the calculation of the gain of log-periodic dipole antennas", *IEEE Transactions on Antennas and Propagation*, vol. 24, no. 1, pp. 105-106, 1976. Available: 10.1109/tap.1976.1141278.

[6] LPCAD (2015), 'WB0DGF Antenna Site - LPCAD - Log Periodic Antenna Design'. [Online]. Available: http://wb0dgf.com/LPCAD.htm.

[7] G. Burke and A. Pogio, "Numerical electromagnetics code (NEC), " 1981, San Diego, Calif.: Naval Ocean Systems Center.

[8] L. Cebik, "A beginner's guide to modeling with NEC," 2000, *QST Magazine*, pp. 40-44.

[9] Qsl.net , "4nec2 antenna modeler and optimizer," 2015, [Online]. Available: http://www.qsl.net/4nec2/.

4 COLLINEAR ARRAY ANTENNA OPTIMISATION FOR SHAPED RADIATION PATTERN

4.1 Introduction

A lot of techniques have been proposed for the design of base station antenna arrays in order to satisfy requirements which are essential for broadcasting applications [1]-[3]. The requirements considered by a broadcasting antenna array are:

1. Uniform reception throughout the service area. Due to the various distances between the transmitting base station and a wide service area, the antenna array needs to emit its radiating power uniformly across the service area, which implies that different gain values are needed across the radiation pattern. In order to have uniform reception, the directive gain values at each angle within the service area, need to be specified.
2. Horizontal main lobe tilting provided that the broadcasting base station is normally located at higher places relative to the service area.
3. Minimum permitted gain value in relation to the maximum gain value, which results in the filling of radiation pattern nulls inside a specified service area as shown in Figure 23. The level of null filling depends on the service type (e.g. FM or DAB radio, TV DVB-T, or GSM-LTE) and the value of minimum required received signal level, and
4. The radiation pattern needs to exhibit low side lobes level, except naturally for the null-filling region in order to avoid radiation energy being wasted, e.g. upwards towards the sky, and thus avoid lowering of the main lobe gain.

The IWO optimisation method is applied to optimise a linear array according to the specified requirements. Antenna arrays play an important role in broadcasting and the goal in this antenna array geometry synthesis is to determine the physical layout of the array that produces a radiation pattern that is closest to the desired pattern.

In order to acquire equal reception at any given point inside the service area (equal power distribution) of Figure 23, the radiation of the antenna needs to exhibit specific Gain values across the angles of its radiation pattern that serve the service area. For that purpose, a suitable formula is needed. A suitable formula which specifies the desired normalised gain as a function of the elevation angle in dB is the following:

$$G(\theta) = 20\log_{10}\frac{\cos(\theta_\alpha)}{\cos(\theta)} \tag{19}$$

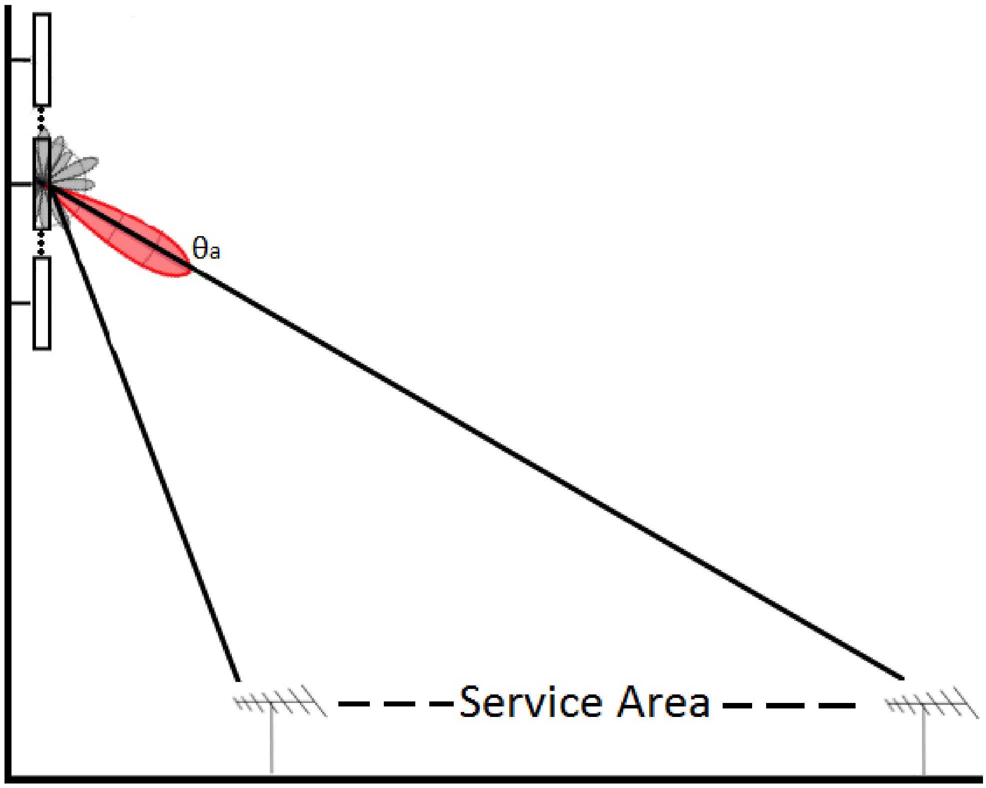


Figure 23. Desired main lobe in elevation plane (vertical plane) radiation pattern.

4.2 Implementation

The designed collinear antenna array which will undergo optimisation consists of 7 dipoles vertically oriented. Due to that fact, the radiation pattern is omni-directional on the horizontal plane and thus the antenna array can be used in a DVB-T or FM broadcasting station with vertical polarisation. The radiation pattern on the vertical (elevation) plane and the matching depends on the geometry of the collinear antenna array as well as on the phase and amplitude of the excitation signals applied to the feeding gap of each dipole. The geometry of the array is specified by the dipole lengths L_m, m (1,...,7) and the inter-dipole distances D_m, m (1,...,6). Each excitation signal is complex and therefore is specified by its amplitude A_m, m (1,...,7) and its phase φ_m, m (1,...,7). Given the values of the parameters mentioned above (i.e. L_m ,D_m ,A_m , φ_m), the antenna array is modelled using CST Microwave Studio and it is analysed using its time domain solver [4], [5]. The work demonstrated in this chapter is based on published papers [6]-[8].

The results derived from the time domain solver and implemented by the optimisation methods is the variation of the antenna array gain G(θ), and the input impedances at the feeding points of the dipoles. In fact, G(θ) determines the far-field radiation pattern on the vertical plane, which is subject to shaping by the optimisation methods according to the conditions for optimum main lobe shaping and for low side lobes. The goal of the optimisation for the main lobe shaping is to design a main lobe with a 2° down-tilt in this study, and where the gain G, is spread across the service area (92° - 170°) in a manner that the reception is uniform for all the angles. For convenience purposes, G(θ) is normalised with respect to its maximum value G_{max}, where G_{max} is equal to G(92°). Thus, the normalised desired gain is given by:

$$G_{norm,desired}(\theta) = 20\log_{10}\frac{\cos 92°}{\cos\theta}, \qquad 92° \leq \theta \leq 170° \qquad \textbf{(20)}$$

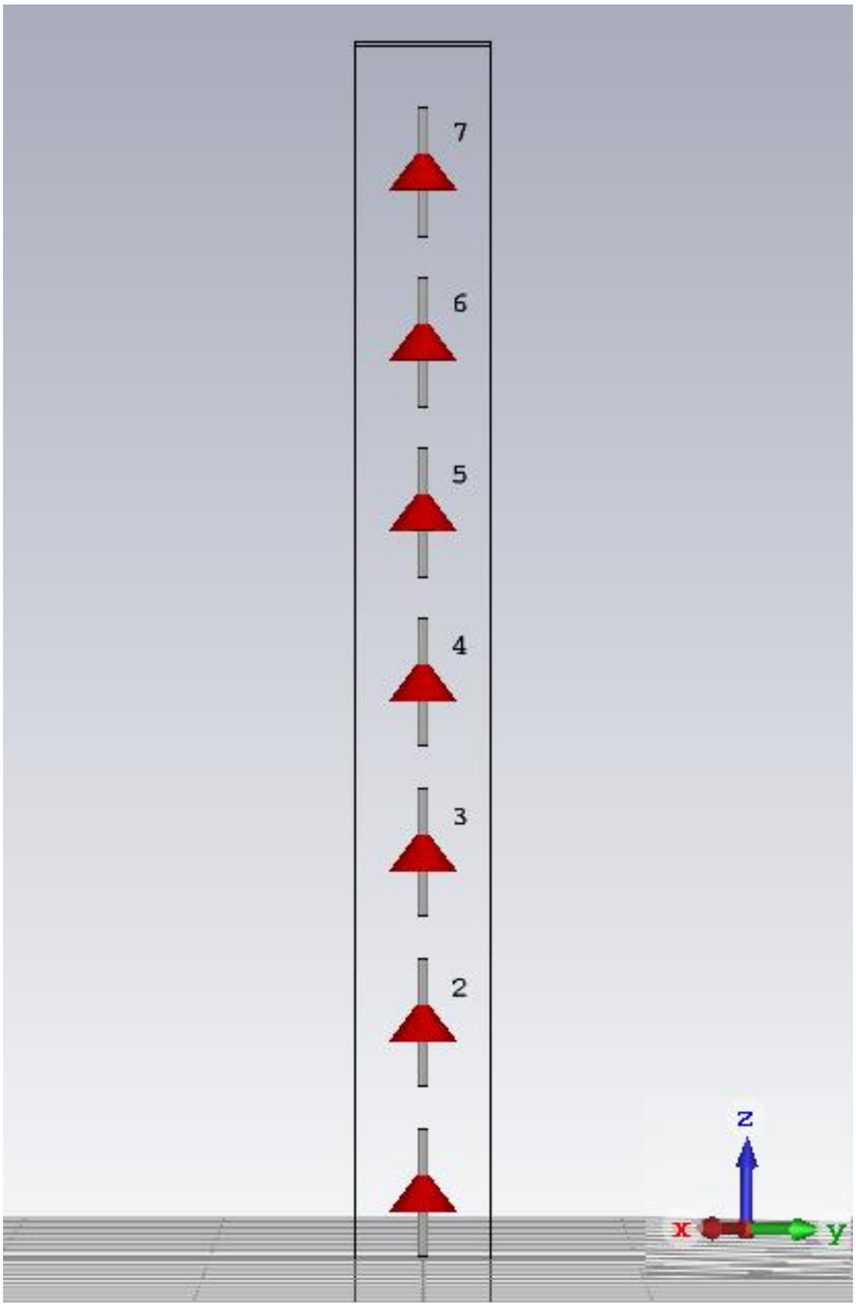


Figure 24. Collinear antenna array with 7 dipoles design in CST Microwave Studio

Figure 25. Antenna tower with a collinear array in the city of Milan, Italy

The goal to minimise the Side Lobes Levels (SLL) for the rest of the radiation pattern, so that energy is not wasted where it is not needed suggests that the side lobes outside the service area need to be minimised to a maximum value of $G_{SLL} \leq (G_{max} - 20dB)$. Naturally, the side lobes, within the service area (92° - 170°), are not considered as side lobes for minimisation because they contribute to useful coverage. In addition, each dipole of the array must satisfy the impedance-matching condition (SWR ≤ 1.2), which translates to $S_{ii} \leq -21dB$.

A fitness function is developed for the optimisation of the collinear antenna array, which satisfies the three conditions mentioned previously. Therefore, the fitness function is designed as a sum of these three conditions, where each condition is multiplied with a respective weight. The first term $Fitness_1$ corresponds to the condition for optimum main lobe shaping and is described by the following formula:

$$Fitness_1 = |G_{norm,desired}(\theta_{92}) - G_{norm,calculated}(\theta_{92})| + |G_{norm,desired}(\theta_{93}) - G_{norm,calculated}(\theta_{93})| + ... \quad \textbf{(21)}$$
$$... + |G_{norm,desired}(\theta_{170}) - G_{norm,calculated}(\theta_{170})|$$

The terms $Fitness_2$ and $Fitness_3$ correspond to the SLL and S_{ii} minimisations respectively, have positive values and vanish only when the optimum values are reached, and they are described by the following two formulas:

$$Fitness_2 = SLL_{desired} - \max(SLL_{desired}, SLL_{calculated}) \quad \textbf{(22)}$$

$$Fitness_3 = S_{ii,desired} - \max(S_{ii,desired}, S_{ii,calculated}) \quad \textbf{(23)}$$

Finally, for any values of L_m, D_m, φ_m and A_m the fitness function is evaluated by the expression:

$$Fitness = W_1 \cdot Fitness_1 + W_2 \cdot Fitness_2 + W_3 \cdot Fitness_3 \quad \textbf{(24)}$$

The coefficients W_1, W_2, W_3 are weight factors, and they declare the importance of the corresponding term that compose the Fitness function. Fitness decreases from positive values to zero, as the three aforementioned conditions tend to be met. When the global minimum value of Fitness is found ($Fitness_{min}$ = 0), all the requirements are satisfied and the optimisation terminates successfully, otherwise, the algorithm is set to terminate at 5000 evaluations, which is enough for the algorithms to produce a fitness value close to the best possible that can be found.

4.3 Simulated results

In order to get the best possible results from IWO with a limited number of iterations, four optimisation cases have been investigated in this study:

- **Case 1.** Individual lengths, distances, and phases, with uniform amplitude excitation for all dipoles.
- **Case 2.** Common lengths and distances and individual phases, with uniform amplitude excitation for all dipoles.
- **Case 3.** Individual lengths, distances, phases, and amplitude excitations for all dipoles.
- **Case 4.** Common lengths and distances and individual phases and amplitude excitations for all dipoles.

Some of the geometrical elements of the collinear antenna array are fixed for optimum results and are not optimised. Such elements are, the radius of all dipoles which is set to r = 2mm and the feeding gap in the middle of the dipoles which is set to gap = 10mm. The collinear antenna array was optimised for the UHF channel 24, with 498MHz as its centre frequency which translates to wavelength equal to λ = 602.0mm. The limits applied for the lengths L_m of the dipoles are from 0.300λ to 0.700λ, for the distances between dipoles D_m from 1mm to λ, for the phases φ_m from -180° to 180° where not uniform and for the amplitudes A_m from 1 to 1000 where not uniform. Due to the fact that the fitness function value strongly depends on the gain values across the service area, the weight factor of the S-Parameters optimisation function $Fitness_3$, was substantially increased, to achieve optimum tuning results for both cases.

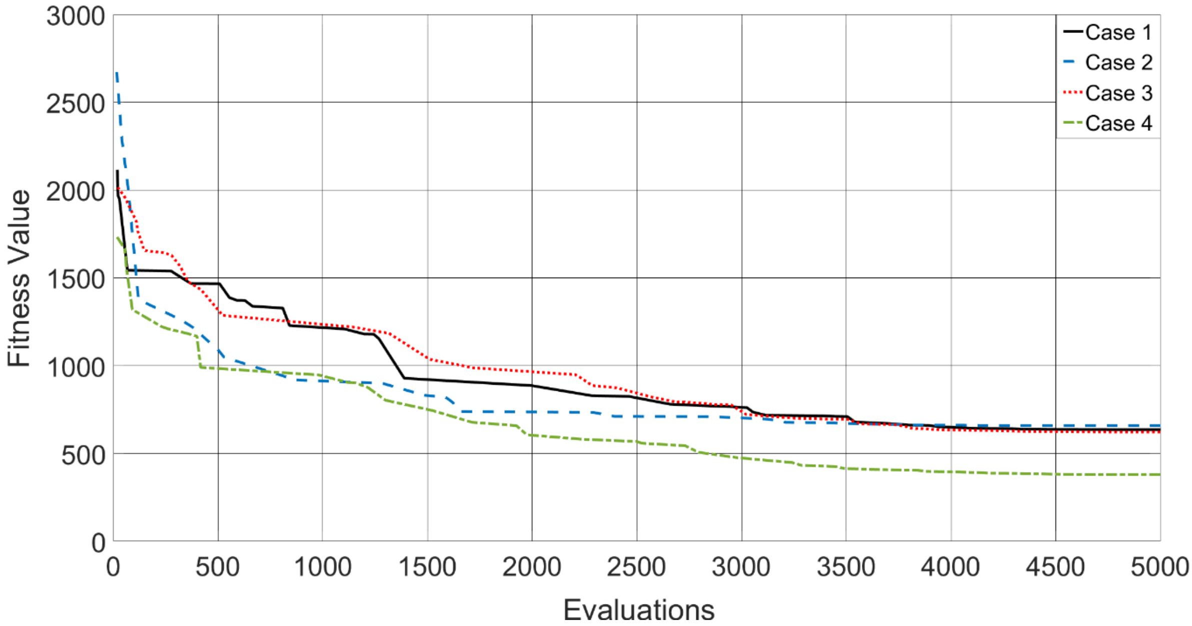


Figure 26. Convergence diagram of IWO per studied case

Figure 26, which present the fitness convergence of IWO for each case indicates that the optimisation successfully designed antenna arrays tuned for the specified centre frequency of 498MHz. However, Case 4 was optimised more successfully as it can be confirmed on the polar and S_{ii} diagrams. The reason behind this, would be due to the increased dependence of gain and main lobe tilting on the amplitude and the phase of the excitation signal. Hence, lessening the optimised parameters by using the same value for all lengths as well as distances helps the algorithm converge to the best possible solution.

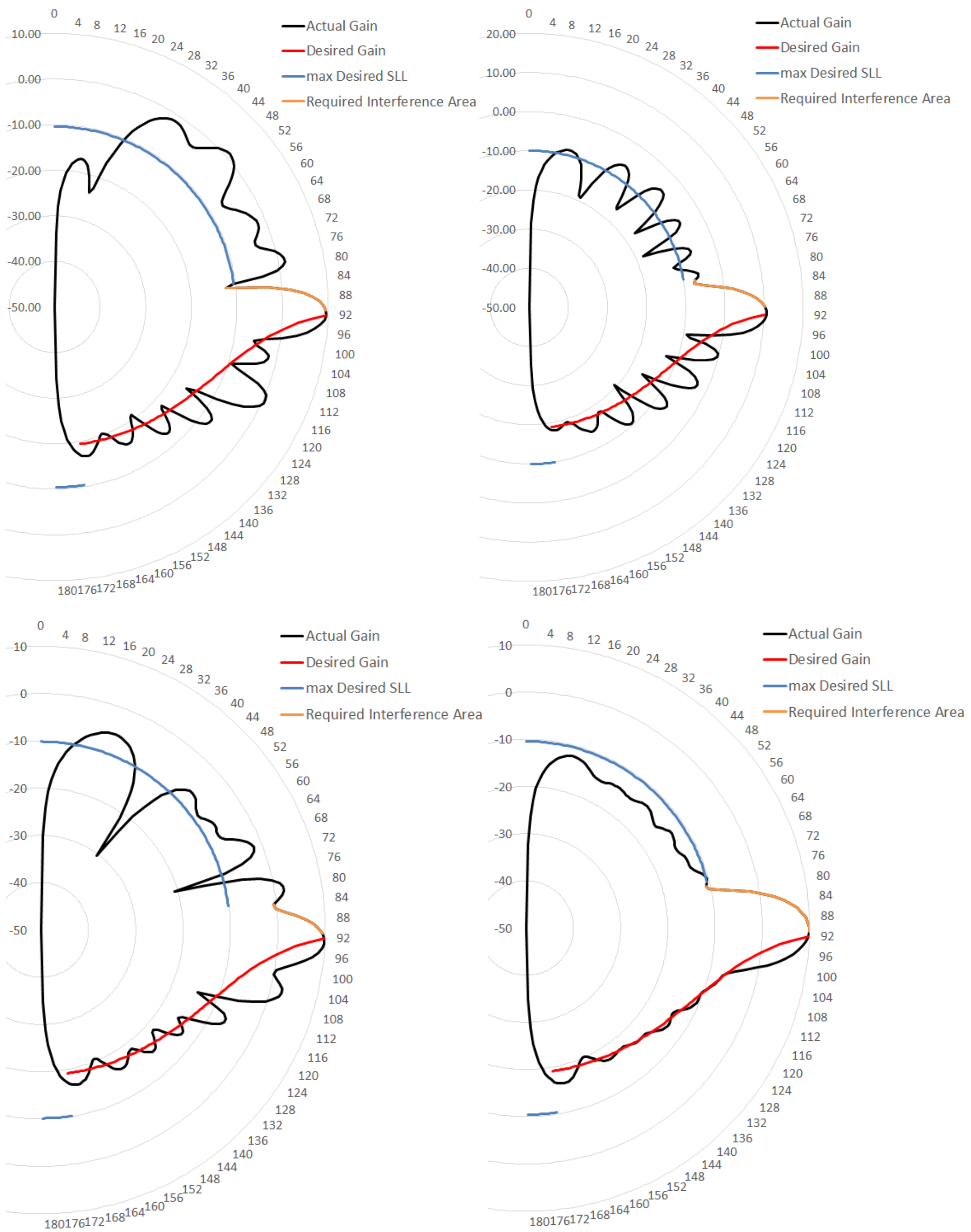


Figure 27. Polar diagrams of optimised arrays per case.

Upper left - Case 1, Upper Right - Case 2, Lower Left - Case 3, Lower Right - Case 4

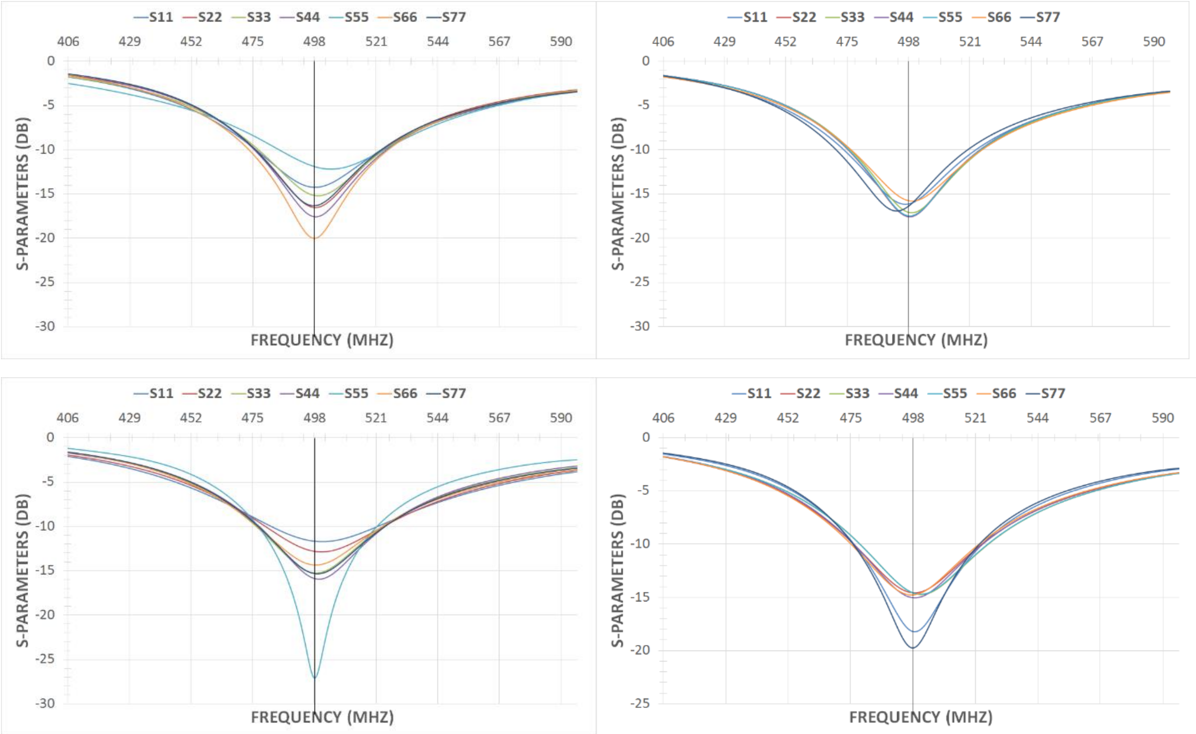


Figure 28. S_{ii} diagrams of optimised arrays per case.
Upper left - Case 1, Upper Right - Case 2, Lower Left - Case 3, Lower Right - Case 4

4.4 Conclusions

The IWO optimisation method was applied on a collinear antenna array modelled in CST MWS, in order to achieve lobe shaping on the radiation pattern of the model, which spreads the gain of the array equally across a service area for four different cases. The case which produced the best results within a 5,000 evaluations limit, was the case with one common variable for the lengths of dipoles, one common variable for the distances between the dipoles and individual values for the phases and amplitudes of the signal fed to the dipoles, due to the fact that the requested outputs from the optimisation method is minimised and it was easier for the algorithm to converge the fitness function within the 5,000 evaluations limit. Increasing the total number of evaluations could show an overturn in results. However, a number of 5,000 evaluations is a realistic number with regards to computation time.

4.5 References

[1] Jain and S. Yadav, "Design and analysis of compact 108 element multimode antenna array for massive mimo base station", *Progress In Electromagnetics Research C*, vol. 61, pp. 179-184, 2016. Available: 10.2528/pierc15110502.

[2] S. Karimkashi, A. Kishk and D. Kajfez, "Antenna Array Optimisation Using Dipole Models for MIMO Applications", *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 8, pp. 3112-3116, 2011. Available: 10.1109/tap.2011.2158976.

[3] Kampitaki, Dimitra & Hatzigaidas, A & Papastergiou, A & Lazaridis, P & Zaharis, Zaharias, "Dual-frequency splitter synthesis suitable for practical RF applications", *WSEAS Trans. on Communications*, Vol. 5, no. 10, 1885-1891, 2006.

[4] Balanis, *Antenna theory, Analysis and Desing*, 2nd ed. John Wiley & Sons, 1997, pp. 551-566.

[5] Z. Zaharis, "Radiation pattern shaping of a mobile base station antenna array using a particle swarm optimisation based technique", *Electrical Engineering*, vol. 90, no. 4, pp. 301-311, 2007. Available: 10.1007/s00202-007-0078-y.

[6] P. I. Lazaridis, E. N. Tziris, Z. D. Zaharis, T. D. Xenos, V. Holmes, J. P. Cosmas and I. A. Glover, "Comparative study of broadcasting antenna array optimisation using evolutionary algorithms," *2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC)*, Seoul, 2016, pp. 1299-1301, Available: 10.1109/URSIAP-RASC.2016.7601166.

[7] E. N. Tziris, P. I. Lazaridis, B. Mehrdadi, V. Holmes, I. A. Glover, Z. D. Zaharis, A. Bizopoulos and J. P. Cosmas, "Comparison of Evolutionary Optimisation Algorithms for FM-TV Broadcasting Antenna Array Null Filling," *19th International Conference on Circuits, Systems, Communications and Computers (CSCC'15)*, 2015.

[8] P. I. Lazaridis, Z. D. Zaharis, C. Skeberis, T. D. Xenos, E. N. Tziris and P. B. Gallion, "Optimal design of UHF TV band log-periodic antenna using invasive weed optimisation," *2014 4th International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE)*, Aalborg, 2014, pp. 1-5, Available: 10.1109/VITAE.2014.6934491.

5 A MODIFIED VERSION OF THE INVASIVE WEED OPTIMISATION METHOD (mIWO)

5.1 Introduction

Current research has shown that the IWO method has proven to be a very solid optimisation method for electromagnetic applications, where in most cases as seen in previous chapters of this thesis exhibited better results in comparison with other popular optimisation methods (DE, PSO, Taguchi etc.). Room for improvement is always present and in this chapter an attempt to improve even further its optimisation output, a non-linear seed production index α is proposed. By employing this index, the seed production of each grown weed is altered, depending on its fitness value. To conclude which value of α is the most appropriate depending on the optimisation problem, several different values were tested on well-established test functions and compared to each other and to the conventional IWO method as well, where the seed production is linear. This work presented in this chapter is based on the published papers [2] and [3].

5.2 Methodology and comparison on test functions

As described in chapter 2.4 of this thesis the reproduction of each grown weed is described by the following linear formula:

$$X_s = \text{int}\left(\frac{F_w - F_s}{F_w - F_b}\right) X_{MAX} \qquad \textbf{(25)}$$

The linearity of this formula can be altered by adding a non-linear seed production index α as in the following:

$$X_s = \text{int}\left[\left(\frac{F_w - F_s}{F_w - F_b}\right)^{\alpha}\right] X_{MAX} \qquad \textbf{(26)}$$

In the case that a = 1, (26) is identical to (25), which means that the modified IWO turns into its conventional version and the seed production is linear, where in any other case the linearity of the conventional method is modified. In Figure 29 the number of produced seeds per weed fitness for several different values of α, i.e., 0.7, 1, 2 and 3 is depicted.

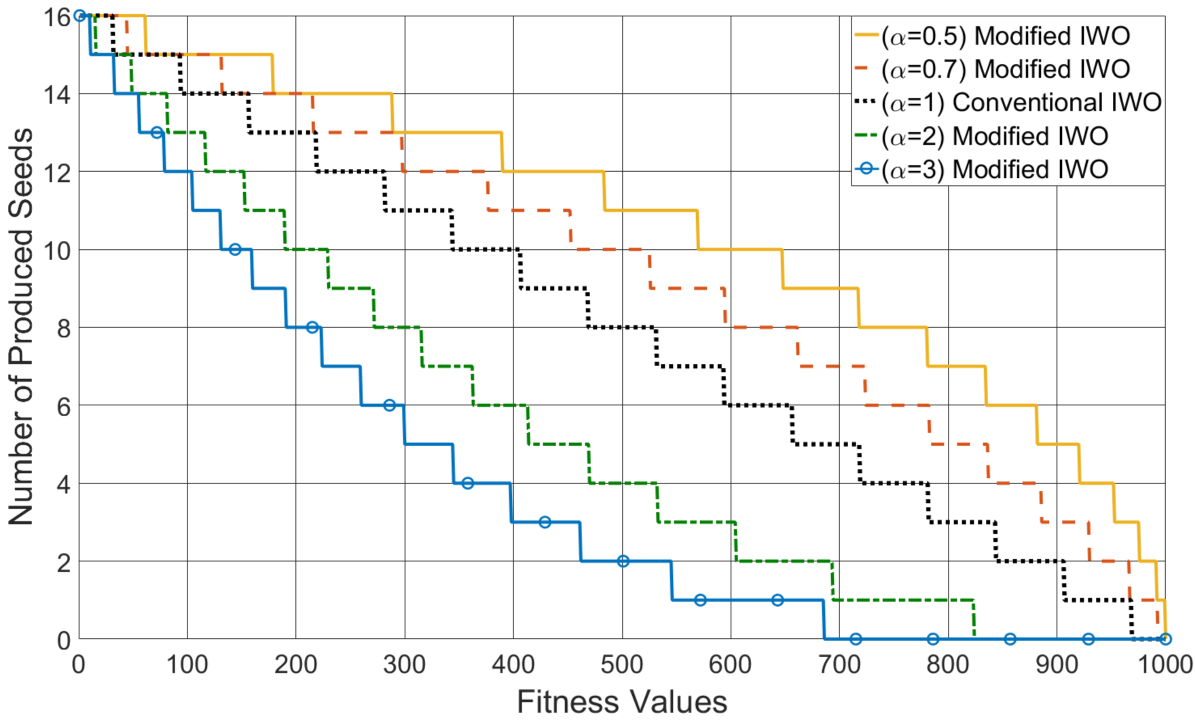


Figure 29. Number of produced seeds per weed versus the fitness value of the weed for various values of index α

By increasing α, the seed production is reduced for all the weeds, although, the reduction is greater for the weeds with high fitness values, whereas the lower the fitness value, the lesser the reduction of seed production up to an unsignificant point. Therefore, increasing the value of α is a way to benefit from the greater exploration of the "good" weeds without delaying the optimisation process by consuming time on an equal exploration of the "bad" weeds. However, using too large values of α can have a negative impact. Excessive increase of its value can cause an inability to appropriately exploit weeds with quite good fitness values, because a large α forces even the "good" weeds to undergo a substantial decrease of seed production. As a result of that, the optimisation process may get stuck on a local optimum solution, which indeed corresponds to a good fitness but far from the best possible one.

On the other hand, lowering the value of the non-linear index to $\alpha < 1$ the seed production is increased for all the weeds, yet the increase of seeds from "good" weeds is greater than that of "bad" weeds. This translates to a larger search space where more potential best solutions are existent for the optimisation method. Similarly, lowering its value excessively, and thus α approaches to 0, the search space is increased to a point where the algorithm will be unable to locate the best possible solution. Therefore, the proper adjustment of the value of α according to the optimisation problem, is critical, and assists the modified IWO to achieve better performance than the conventional IWO.

To find the optimal value of α, the IWO algorithm is tested on 14 different test functions with several different values of it. A PSO and a DE algorithm participate in this comparison. All the algorithms employ populations of 20 particles and are applied to every test function using 30 dimensions (i.e., 30 variables), except two test functions which are defined in a 2D space due to their nature. The test functions used, were implemented in MATLAB software and the code written that defines them is shown on Table 5 along with the search domain.

Each optimisation algorithm is executed 500 times per test function with 2,000, 5,000, 20,000 and 50,000 fitness evaluations per execution and the final fitness value is recorded per execution and per test function. Every set of 500 final fitness values per test function and per algorithm is used to calculate the statistical mean final fitness (Mean Fit) and the respective standard deviation (Std Dev). These statistical results are summarised in the Tables 6-9. The bottom rows of these tables demonstrate that the proper value of α for optimisation results, due to the fact that optimum results substantially depend on the number of evaluations. Hence, it is important to identify the problem and properly adjust mIWO so that the best possible results are yielded in comparison with the conventional IWO.

Table 5. Test functions definitions

FUNCTION	MATLAB CODE	SEARCH SPACE

ACKLEY	`function y = ackley( x )`
	`n=length(x);`
	`s=0;`
	`q=0;`
	`for j = 1:n`
	`    s=s+x(j).^2;`
	`    q=q+cos(2*pi*x(j));`
	`end`
	`y=20+exp(1)-20*exp(-0.2*sqrt((1/n)*s))-exp((1/n)*q);`
	`end`
		-32.768, 32.768

DEJONG1	`function y = dejong1(x)`
	`n = length(x);`
	`s = 0;`
	`for j = 1:n`
	`    s=s+x(j)^2;`
	`end`
	`y=s;`
	`end`
		-5.12, 5.12

DEJONG3	`function y = dejong3( x )`
	`n=length(x);`
	`s=0;`
	`for j=1:1:n`
	`    s=s+abs(x(j));`
	`end`
	`y=s;`
	`end`
		-2.048, 2.048

DEJONG4	`function y = dejong4( x )`
	`n=length(x);`
	`s=0;`
	`for j=1:1:n`
	`    s=s+j*x(j)^4;`
	`end`
	`y=s;`
	`end`
		-1.28, 1.28

EASOM	function y = easom(x) y=-cos(x(1))*cos(x(2))*exp(-(x(1)-pi)^2-(x(2)-pi)^2); end	-100, 100

EGG	function y = egg(x)
	n=length(x);
	s=0;
	for j=1:1:n-1
	    s=s-(x(j+1)+47)*sin(sqrt(abs(x(j+1)+x(j)/2+47)))-sin(sqrt(abs(x(j)-
	x(j+1)-47)))*x(j);
	end
	y=s;
	end
		-512,
		512

GRIEWANK	function y = griewank(x)
	n = length(x);
	s=0;
	p=1;
	for j=1:1:n
	    s=s+x(j)^2;
	    p=p*cos(x(j)/sqrt(j));
	end
	y=1+(1/4000)*s-p;
	end
		-600,
		600

HOLDER	function y= holder(x)
	fact1 = sin(x(1))*cos(x(2));
	fact2 = exp(abs(1 - sqrt(x(1)^2+x(2)^2)/pi));
	y=-abs(fact1*fact2);
	end
		-10,
		10

LEVY	function y = levy(x)
	n=length(x);
	for j=1:n
	    w(j) = 1 + (x(j) - 1)/4;
	end
	term1 = (sin(pi*w(1)))^2;
	term3 = (w(n)-1)^2 * (1+(sin(2*pi*w(n)))^2);
	s=0;
	for j=1:n-1
	    wi = w(j);
	    s=s+(wi-1)^2 * (1+10*(sin(pi*wi+1))^2);
	end
	y=term1+s+term3;
	end
		-10,
		10

MICHALEWICZ	function y = michalewicz(x)
	m=10;
	n=length(x);
	s=0;
	for j=1:1:n
	    s=s+sin(x(j))*(sin(j*x(j)^2/pi))^(2*m);
	end
	y=-s;
	end
		0,
		pi

RANA	function y = rana(x)
	s=0;
	n=length(x);
	for j=1:1:n-1
	    s=s+x(j)*sin(sqrt(abs(x(j+1)+1-
	x(j))))*cos(sqrt(abs(x(j+1)+1+x(j))))+(x(j+1)+1)*cos(sqrt(abs(x(j+1)+1-
	x(j))))*sin(sqrt(abs(x(j+1)+1+x(j))));
	end
	y=s;
	end
		-500,
		500

RASTRIGIN	function y = rastrigin(x)
	n = length(x);
	s = 0;
	for j = 1:n
	    s = s+x(j)^2-10*cos(2*pi*x(j));
	end
	y = 10*n+s;
		-5.12,
		5.12

ROSENBROCK	function y = rosenbrock(x)
	n = length(x);
	s = 0;
	for j = 1:n-1;
	    s = s+100*(x(j+1)-x(j)^2)^2+(1-x(j))^2;
	end
	y = s;
	end
		-2.048,
		2.048

SCHWEFEL	`function y=schwefel(x)`
	`s=0;`
	`n=length(x);`
	`for j=1:1:n`
	`    s=s+x(j)*sin(sqrt(abs(x(j))));`
	`end`
	`y=-(1/n)*s;`
	`end`
		-500,
		500

SHUBERT	`function y = shubert( x )`
	`s1=0;`
	`s2=0;`
	`for j=1:1:5`
	`    s1=s1+j*cos((j+1)*x(1)+j);`
	`    s2=s2+j*cos((j+1)*x(2)+j);`
	`end`
	`y=s1*s2;`
	`end`
		-10,
		10

SINEWAVE	`function y = sinewave( x )`
	`n = length(x);`
	`s=0;`
	`for j=1:1:n-1`
	`    s=s+0.5+(sin(sqrt(x(j+1)^2+x(j)^2))^2-`
	`0.5)/(1+0.001*(x(j)^2+x(j+1)^2))^2;`
	`end`
	`y=s;`
	`end`
		-100,
		100

Table 6. Test functions vs EA for 2,000 Evaluations per execution (blue is best - normalised)

	DE		PSO		IWO a=0.5		IWO a=0.7		IWO a=1		IWO a=2		IWO a=3	
	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean
ACKLEY	0.76	5.95	0.23	0.61	0.28	8.17	0.36	6.89	0.44	5.1	0.15	1.33	0	0
DEJONG1	2.38	5.07	0.11	0.07	2.89	12.28	2.34	8.45	1.53	4.77	0.23	0.64	0	0
DEJONG3	0.32	1.6	0	0	0.4	4.98	0.36	4.09	0.29	3.11	0.22	1.24	0.12	0.53
DEJONG4	0.54	0.64	0	0	0.47	1.02	0.31	0.58	0.16	0.26	0.01	0.01	0	0
EASOM	0	0	0	0	0	0	0	0	0	0	0.04	0	0.04	0
EGG	60.16	4469.9	606.9	-1604	0	1294	71.08	976	176.02	568	252.22	206	261.42	0
GRIEWANK	8.26	17.98	0.37	0.31	10.09	42.27	7.64	28.66	5.06	15.93	0.79	2.29	0	0
HOLDER	0.2	0.04	0.6	0.03	0	0	0	0	0	0	0	0	0	0
LEVY	0	0.32	0.59	0	1.82	9.58	1.94	8.22	1.63	6.03	2.02	4.1	2.51	4.74
MICHALEWICZ	0	7.02	1.46	0	0.28	2.54	0.35	2.16	0.48	1.6	0.72	1.02	0.77	1.03
RANA	1047.9	0	390.35	1998.5	0.12	1657.4	0	1539.2	4.94	1326.3	73.86	982.8	93.22	871.3
RASTRIGIN	0.41	147.1	1.81	0	0.13	86.08	0.63	73.89	0	60.03	1.59	37.42	2.83	28.61
ROSENBROCK	12352.4	13477.85	61.33	122.2	3655.7	7881.15	1958.6	4279.65	882.4	1929.35	70.07	223.87	0	0
SCHWEFEL	7.84	93.27	9.46	29.45	0	24.05	0.47	18.85	1.49	11.48	3.32	0.8	3.75	0
SHUBERT	1.45	0.26	0	0	0	0	0	0	0	0	0	0	0	0
SINEWAVE	0	1.28	0.3	0.01	0.11	0.24	0.17	0.18	0.21	0.1	0.26	0	0.29	0.05
TOTAL BEST	4	2	4	7	5	3	4	3	4	3	2	4	7	10

Table 7. Test functions vs EA for 5,000 Evaluations per execution (blue is best - normalised)

	DE		PSO		IWO a=0.5		IWO a=0.7		IWO a=1		IWO a=2		IWO a=3	
	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean
ACKLEY	1.51	5.21	0.7	1.06	0.15	2.7	0.07	1.93	0	1.21	0.03	0.26	0.1	0
DEJONG1	1.39	1.41	0.04	0.01	0.17	0.49	0.1	0.25	0.04	0.1	0.01	0.01	0	0
DEJONG3	0.34	0.56	0.06	0	0.21	1.28	0.14	0.92	0.1	0.6	0	0.14	0	0.03
DEJONG4	0.29	0.18	0	0	0	0	0	0	0	0	0	0	0	0
EASOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EGG	1208.9	3590	676.9	1634	0	299	96.9	101	74.9	11	212.9	0	251.9	156
GRIEWANK	4.84	5.56	0.21	0	0.54	1.95	0.25	1.11	0.06	0.59	0	0.26	0.09	0
HOLDER	0.17	0.03	0.87	0.08	0	0	0	0	0	0	0	0	0	0
LEVY	0	0	1.65	2.84	0.53	1.3	0.61	1.06	0.62	0.99	0.95	1.17	1.89	2.29
MICHALEWICZ	0.05	11.78	0.55	0	0	5.17	0.05	4.93	0.21	4.75	0.38	4.59	0.53	4.84
RANA	1152.5	6451	310.6	547	0	326	32.3	149	42	67	76.1	3	112.9	0
RASTRIGIN	23.28	114.82	0.38	0	0	34.55	1.64	27.87	0.02	21.35	2.86	18.87	5.15	23.09
ROSENBROCK	6326.33	3850.72	0	10.05	110.53	196.14	106.73	150.05	78.43	81.49	69.63	23.54	57.13	0
SCHWEFEL	21.34	56.9	7.57	38.8	1.53	2.1	0	1.8	2.88	0	2.12	5.8	5.15	8.4
SHUBERT	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0
SINEWAVE	0	2.16	0.52	10.18	0.16	0.69	0.24	0.58	0.2	0.59	0.26	0.64	0.28	0.7
TOTAL BEST	3	3	4	8	8	4	5	4	5	5	6	5	6	9

Table 8. Test functions vs EA for 20,000 Evaluations per execution (blue is best - normalised)

	DE		PSO		IWO a=0.5		IWO a=0.7		IWO a=1		IWO a=2		IWO a=3	
	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean
ACKLEY	1.61	6.31	0.83	2.54	0.04	0.29	0.03	0.17	0	0.06	0.04	0	0.14	0.04
DEJONG1	0.51	0.23	0	0	0	0	0	0	0	0	0	0	0	0
DEJONG3	0.21	0.08	0.07	0.01	0.01	0.04	0.01	0.03	0.01	0.02	0	0	0	0
DEJONG4	0.18	0.08	0	0	0	0	0	0	0	0	0	0	0	0
EASOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EGG	416	0	473	6378	0	3009	61	3132	71	3265	157	3650	207	4106
GRIEWANK	2.26	1.6	0.1	0.04	0.06	0.29	0.05	0.2	0.04	0.11	0	0.02	0	0
HOLDER	0.1	0.01	0.8	0.07	0	0	0	0	0	0	0	0	0	0
LEVY	1.25	3.33	2.78	5.84	0.04	0	0	0.08	0.11	0.23	0.58	0.76	1.48	1.66
MICHALEWICZ	1.95	0.06	0.09	0	0	3.03	0.11	2.88	0.15	3.09	0.25	3.97	0.37	4.5
RANA	119.1	0	328.9	4538	29.3	3511.1	5.8	3434	0	3511	70.2	3687	117.8	3837
RASTRIGIN	0	0	4.73	23.02	2.23	19.26	1.82	21.68	1.96	22.03	4.75	30.87	7	37.37
ROSENBROCK	3891.29	1225.36	0	1.21	13.36	7.38	8.23	3.75	9.54	3.37	2.85	0	4.56	2.97
SCHWEFEL	2.08	0	10.8	81.7	0	17.5	0.86	19.9	1.75	24	2.68	32.9	2.8	40.4
SHUBERT	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
SINEWAVE	0.44	1.55	0.33	0	0.02	0.89	0	0.88	0.02	0.94	0.03	1.16	0.05	1.42
TOTAL BEST	2	6	5	6	8	6	7	5	7	5	7	8	7	7

Table 9. Test functions vs EA for 50,000 Evaluations per execution (blue is best - normalised)

	DE		PSO		IWO a=0.5		IWO a=0.7		IWO a=1		IWO a=2		IWO a=3	
	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean	std	mean
ACKLEY	1.76	6.48	1.11	2.67	0.04	0.01	0	0	0.05	0	0.04	0	0.14	0.01
DEJONG1	0.89	0.12	0	0	0	0	0	0	0	0	0	0	0	0
DEJONG3	0.07	0	0.01	0	0	0	0	0	0	0	0	0	0	0
DEJONG4	0.13	0.04	0	0	0	0	0	0	0	0	0	0	0	0
EASOM	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EGG	287	0	502	6486	9	2284	0	2502	1	2639	135	3214	91	3583
GRIEWANK	1.87	1.09	0.12	0.05	0	0.01	0	0	0	0	0	0	0	0
HOLDER	0.08	0.01	0.76	0.07	0	0	0	0	0	0	0	0	0	0
LEVY	1.87	3.66	3.64	6.63	0	0	0.05	0.02	0.14	0.08	0.47	0.34	1.43	0.9
MICHALEWICZ	0	0	0.03	0.4	0.06	2.32	0.07	2.44	0.67	2.53	0.34	3.39	0.43	4.13
RANA	176.2	0	379.1	4516	0	3138	6.2	3181	3.9	2979	86	3394	106.2	3516
RASTRIGIN	0	0	5.92	25.89	1.36	15.14	1.99	15.76	2.23	18.83	5.75	27.52	7.86	35.15
ROSENBROCK	2004.55	541.89	1.79	0	1.66	10.7	0	11.03	1.1	11.21	5.91	12.79	5.72	14.37
SCHWEFEL	3.58	0	9.95	83.4	0	3.7	0.74	8.1	1.5	12.4	2.77	22.3	3.36	31.9
SHUBERT	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0
SINEWAVE	0.57	0	0.32	1.82	0	2.18	0.07	2.2	0.03	2.35	0.06	2.6	0.05	2.87
TOTAL BEST	3	9	4	6	11	7	10	8	7	8	7	8	7	7

5.3 Conclusion

In this chapter, a novel variant of the IWO method called mIWO was proposed with the introduction of the non-linear seed production index α. It was demonstrated that with the most proper value of α for any given electromagnetic optimisation problem, the resulting output of the optimisation method was significantly improved in comparison with the conventional IWO method. A conclusion which was drawn was that the greater the number of evaluations, the smaller the index should be and the other way around. Hence, a problem where computation time is insignificant, a greater number of evaluations can be run with $\alpha<1$, whereas for problems that evaluations need a substantial amount of time, then $\alpha>1$ will return optimal results with less evaluations. This conclusion came after thorough testing of the different values of α on some of the most established test functions.

5.4 References

[1] Mehrabian and C. Lucas, "A novel numerical optimisation algorithm inspired from weed colonisation", *Ecological Informatics*, vol. 1, no. 4, pp. 355-366, 2006. Available: 10.1016/j.ecoinf.2006.07.003.

[2] E. N. Tziris, P. I. Lazaridis, Z. D. Zaharis, J. P. Cosmas, K. K. Mistry and I. A. Glover, "Optimised Planar Elliptical Dipole Antenna for UWB EMC Applications," *in IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 4, pp. 1377-1384, Aug. 2019, Available: 10.1109/TEMC.2019.2923781.

[3] E. N. Tziris et al., "Invasive weed optimised planar elliptical dipole antenna for ultra-wideband EMC applications," *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, 2018, pp. 233-236, Available: 10.1109/ISEMC.2018.8393772.

6 PLANAR ELLIPTICAL DIPOLE ANTENNA OPTIMISATION FOR UWB EMC APPLICATIONS

6.1 Introduction

The progression of science around wireless communications has been rapid for the past years and with the new emerging technologies such as the Internet of Things, a broad set of new technological equipment came to the surface and that stretches the expectation that wireless communications will grow more rapidly than ever before. Such expectations indicate that the research on Electromagnetic Compatibility (EMC) becomes progressively more necessary.
According to Federal Communications Commission's (FCC) regulation, ultra-wideband (UWB) radio technology refers to technology that has an absolute bandwidth greater than 500 MHz or a fractional bandwidth greater than 0.2. Figure 30 depicts a typical UWB spectrum. This differs from narrowband technologies, where the fractional bandwidth is typically less than 0.1.

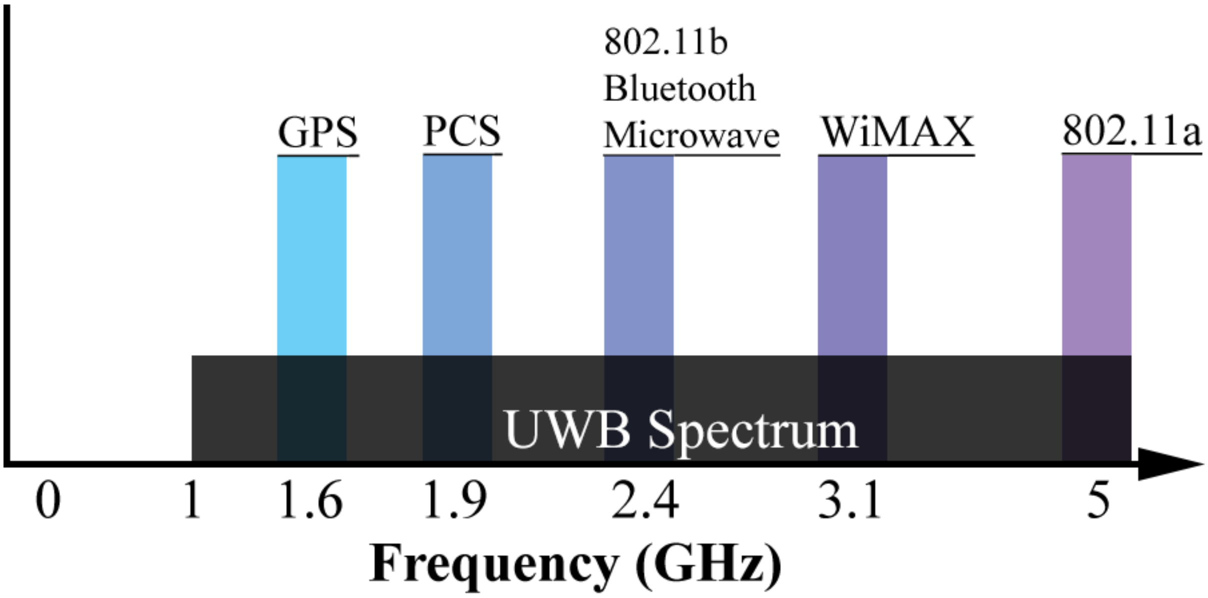


Figure 30. 1–5 GHz UWB spectrum displaying several current technologies and their corresponding frequencies within that spectrum.

Particularly, since the 3.1GHz to 10.6GHz spectrum was released for unlicensed use, UWB antennas have gathered more attention and many designs have been proposed and studied thus far [1]. The most standard types of UWB antennas are the biconical antenna, the discone antenna and the log-periodic dipole array (LPDA). Another not so frequent type of antennas, is the planar monopole, which is engineered on PCB, and it demonstrates respectable radiation characteristics for bandwidths up to 10GHz. Among other structures, the planar elliptical dipole has been proposed as a miniature antenna with solid broadband radiation characteristics, which displays a return loss less than –10dB for elements with size equal to 0.20λ and an efficiency of 50% for elements with size equal to 0.14λ, unlike the traditional broadband dipole elements which are required to be approximately equal to a half wavelength in length for efficient radiation characteristics [2]-[6]. All these translate to a compact antenna with large bandwidth and adequate efficiency.

In the state of the art, there is a plethora of planar elliptical dipole antennas presenting their wideband capabilities. Their radiation characteristics are comparable to those of a biconical antenna. Even so, due to their miniature nature, they are less expensive to fabricate [9]-[14]. Efforts have been made to improve the performance of such antennas and to simplify their design. For the sake of simplification and cost reduction, improved bottom fed structures have arisen to get around the use of baluns along with elliptical slots, which have been added so that the operating bandwidth is expanded. [15]-[19].

In this chapter, which is based on papers [6]-[8], 3D electromagnetic simulation is put to use for the further advancement of such antennas. The up to now implemented EAs along with the novel mIWO are employed and compared since they have proven to be very effective tools for electromagnetic applications [20], and with the aid of CST EM 3D a UWB antenna for EMC applications is developed. The algorithms are used here to optimise the geometrical parameters of the antenna, which will result in the desirable radiation characteristics. The goal is to generate an antenna which is described as compact size and low cost, and operates over the ultra-wide frequency range of 1GHz to 5GHz with sufficiently high realised gain and gain flatness over this spectrum. Gain flatness is considered the maximum variation of the realised gain over a frequency range. An antenna that combines all these features, would be considered a robust candidate for UWB EMC measurements.

6.2 Implementation

The parameters that define the geometry of a planar elliptical dipole antenna with elliptical slots are:

1. the outer length
2. the outer width
3. the inner length of the slots
4. the inner width of the slots

5. the feeding gap between the two ellipses
6. the offset between the inner and outer ellipses
7. the substrate length
8. the substrate width

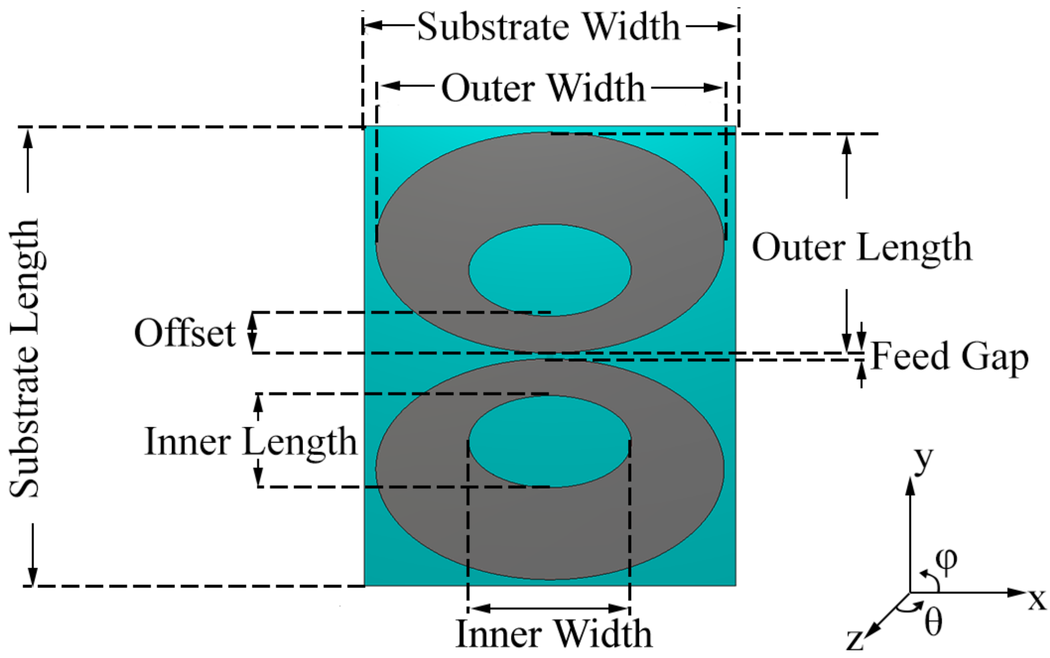


Figure 31. Geometrical parameters of a planar elliptical dipole antenna

The feeding is applied between its two elliptical segments, it is called the feed gap and it is simulated as a discrete face port in CST MWS, that has a characteristic impedance of 50Ω. The feeding of the fabricated antenna was done with an SMA connector attached to the top and bottom of each respective ellipse. The dielectric substrate used for the fabrication, is the Rogers RT/duroid 5880LZ, which is suitable for microstrip circuit applications, and its characteristics are part of the simulation. The characteristics of the substrate are its relative permittivity ε_r, which is equal to 2, its thickness, which is equal to 2.54mm (0.1inch) and the copper thickness which is 0.035mm. The substrate's characteristics are not optimised since it is not feasible to be changed. The fabrication of the antenna shown in Figures 34 and 35 was carried out in Huddersfield University facilities and its dimensions are described in Table 11. The desired operating frequency range is defined from 1GHz to 5GHz. The antenna presented in [19] is the base of the antenna design modelled in CST MWS. Therefore, we can choose initial values for the above parameters equal to those given in [19] and set a limit to a maximum deviation of 30% from the given ones. In this way, a lower and an upper boundary limit can be specified per geometrical parameter. This rule is not applied on the ellipse offset and the feeding gap due to the fact that they are parameters with strong effects on the behaviour of the antenna. Hence, the deviation of their value is extended for better optimisation results. All the initial values and the respective boundaries are summarised in Table 10.

The goal is to find the best set of values for the parameters to satisfy the following criteria for the spectrum of 1GHz to 5GHz.

1. S11 parameter (i.e., the return loss), S11 ≤ -10dB
2. Boresight (i.e., at $\theta = 0$ as shown in Figure 31) realised gain RG $\geq$ 2dBi
3. and the gain flatness GF $\leq$ 2dB

Table 10. Geometrical parameter values to be optimised

Parameter	Initial Value (mm)	Lower Boundary (mm)	Upper Boundary (mm)
Substrate Length	106.00	74.20	137.80
Substrate Width	85.00	59.50	110.50
Ellipse Outer Length	38.00	26.60	49.40
Ellipse Outer Width	79.00	55.30	102.70
Ellipse Inner Length	19.50	13.65	25.35
Ellipse Inner Width	37.50	26.25	48.75
Ellipse Offset	3.50	1.00	7.00
Feeding Gap	1.50	1.00	3.00

A fitness function is set for the antenna optimisation, which is a linear combination of three terms, that are defined according to the previously mentioned requirements. Each term is multiplied by a respective weight w_1, w_2 and w_3 which are used to determine the importance of every term and in this way the chances of satisfying only one requirement against the rest are moderated. Due to the fact that S_{11} and RG are considered of equal importance, the weights are set to be equal as well. On the other hand, due to its lower importance, w_3 is equal to 1/4 of the previous weights. The terms that comprise the fitness function are:

$$T_1 = \max(S_{11,\max}, S_{11,desired}) - S_{11,desired} \quad \textbf{(27)}$$

$$T_2 = RG_{desired} - \min(RG_{\min}, RG_{desired}) \quad \textbf{(28)}$$

and

$$T_3 = \max(GF_{actual}, GF_{desired}) - GF_{desired} \quad \textbf{(29)}$$

where $S_{11,desired}$=-10dB, $RG_{desired}$=2dBi, $GF_{desired}$=2dB, $S_{11,max}$ and RG_{min} are respectively the maximum S_{11} and the minimum RG found over the entire band, and finally $GF_{actual}=RG_{max}-RG_{min}$ (RG_{max} is the maximum RG found over the entire band). Consequently, the fitness function is described as:

$$Fit = w_1 T_1 + w_2 T_2 + w_3 T_3 \quad \textbf{(30)}$$

where $w_1=w_2=4$ and $w_3=1$. From (30), it is obvious that Fit has positive values and converges to 0 once all three terms are fulfilled.

The algorithms employed to optimise the antenna geometry are DE, PSO, Conventional IWO, Modified IWO with α=2 and Modified IWO with α=3. By considering the complexity of the optimisation process where CST simulations are involved when fitness calculations are demanded by the optimisation algorithms, populations of 15 particles were used for all the algorithms. All algorithms are executed five times in total and the best result of each algorithm are acquired for comparison. Each execution stops after 2,500 evaluations, which is realistic amount with time in mind. Simulations were executed on an Intel i7-7820X CPU, along with 16GB of RAM. GPU acceleration functionality was disabled in CST Studio. With the time domain solver of CST each evaluation took 30 seconds to complete. Not to further increase computation time, a fair amount of 50,000 mesh cells was set in CST configuration. Magnetic symmetry in the yz-plane and electric symmetry in the xz-plane is considered for the antenna CST model.

6.3 Simulated and measured results

The best fitness convergence graph achieved by every algorithm is displayed in Figure 32. Evidently, the modified IWO with a=2 demonstrates exceptional performance. Table 11 shows the optimised values of the antenna's geometrical parameters derived from the EAs, while Table 12 shows the respective antenna characteristics. From Figure 32, it is understandable that the results derived from the modified IWO with α=2 are superior against its other forms, and thus, results from the modified IWO with α=3 and the conventional IWO are excluded from Tables 11 and 12.

If the results shown in this chapter are to be compared with the original results in [19], the conclusions that are drawn are that S_{11} is stabilized steadily below the -10dB limitation between 1-5GHz which equals to better tuning across the spectrum, and a more controlled gain with better flatness and greater peak values. An additional note is that the operating bandwidth in [19] is 1.1–11GHz, whereas in this work, bandwidth was limited to 1-5GHz.

That is because the antenna beyond 5GHz does not exhibit exceptional Gain, and by reducing the operating spectrum, it becomes easier for EAs to achieve greater results.

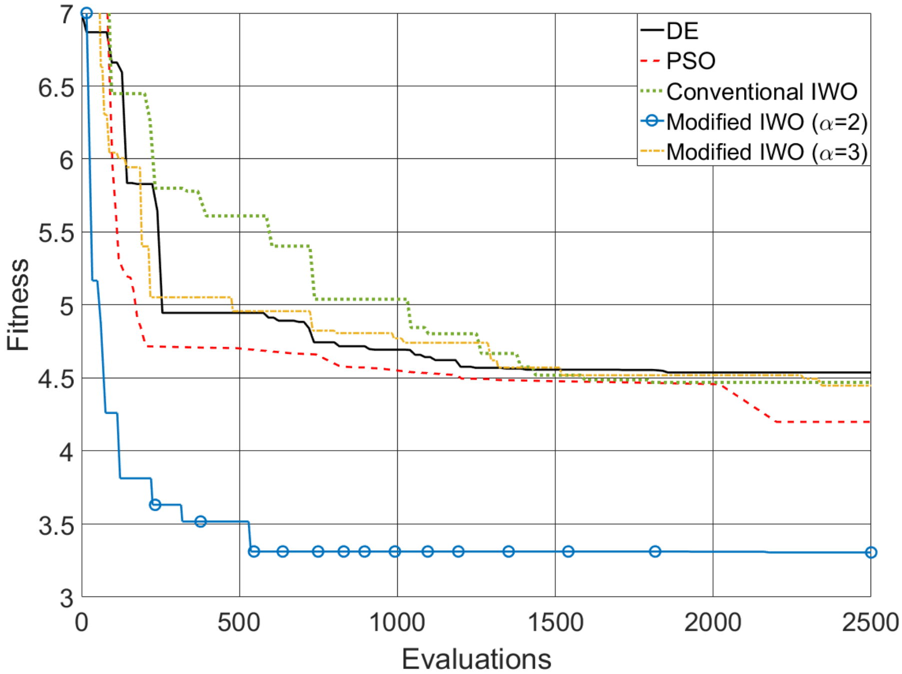


Figure 32. Best fitness convergence graphs achieved by DE, PSO, conventional IWO, modified IWO with α=2 and modified IWO with α=3, for the optimisation of a planar elliptical dipole antenna.

The antenna's geometry extracted from the modified IWO with α=2 was fabricated and experimentally measured in terms of S11. The comparative results of S11 are given in Figure 36, while comparative results of RG are shown in Figure 37. The fabricated antenna is shown in Figure 33. For the results shown in Figure 36 regarding the fabricated antenna, measurements were performed in an anechoic chamber at the site of National Physical Laboratory in Teddington, UK as in Figures 34 and 35.

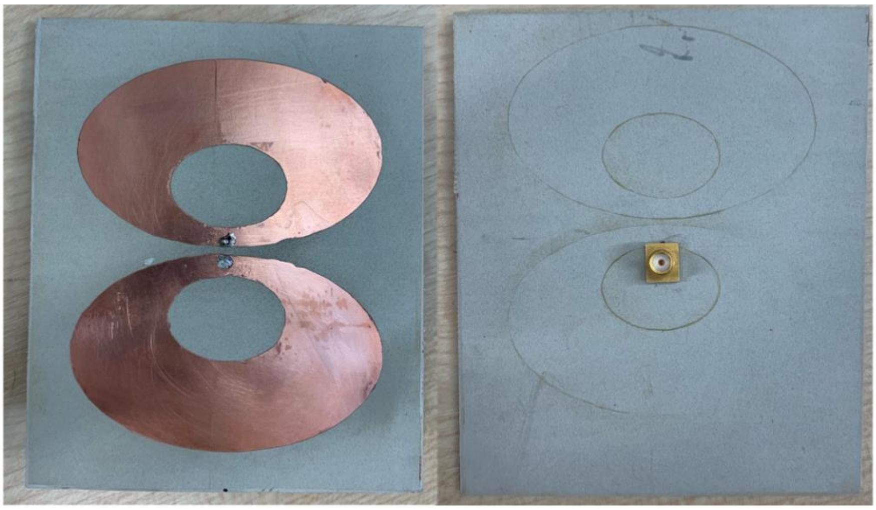


Figure 33. Fabricated antenna front (left) and back (right) side

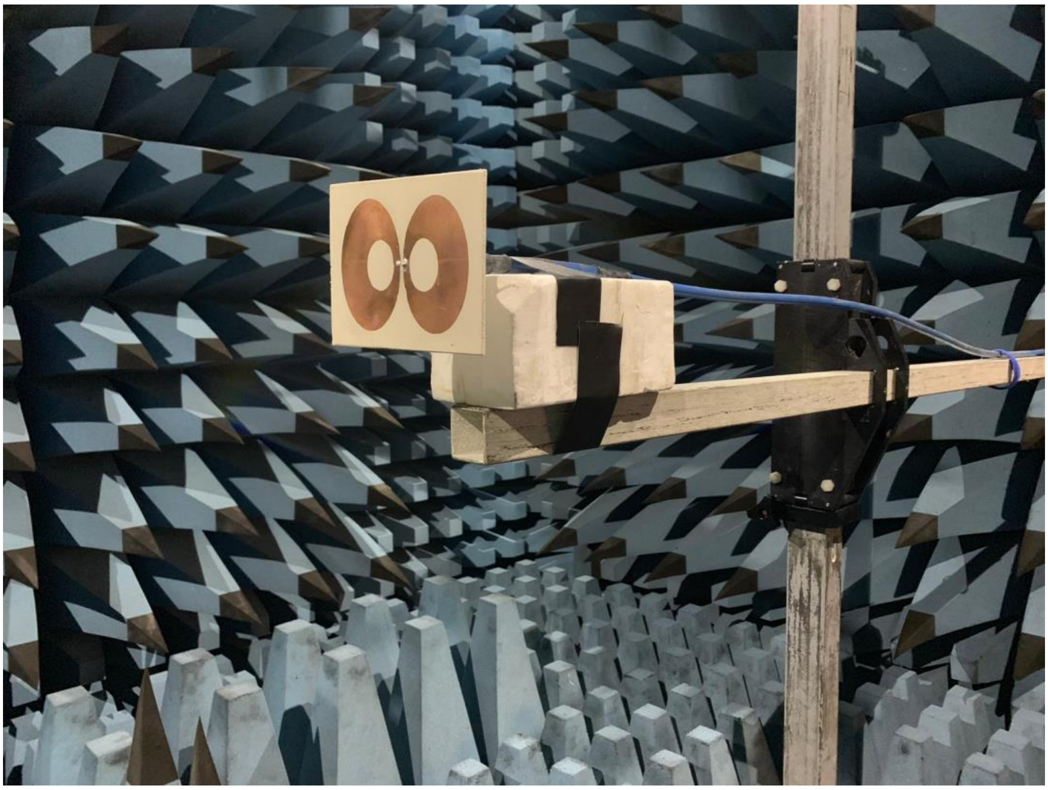


Figure 34. Measurement of planar elliptical dipole antenna in an anechoic chamber at NPL, UK 1

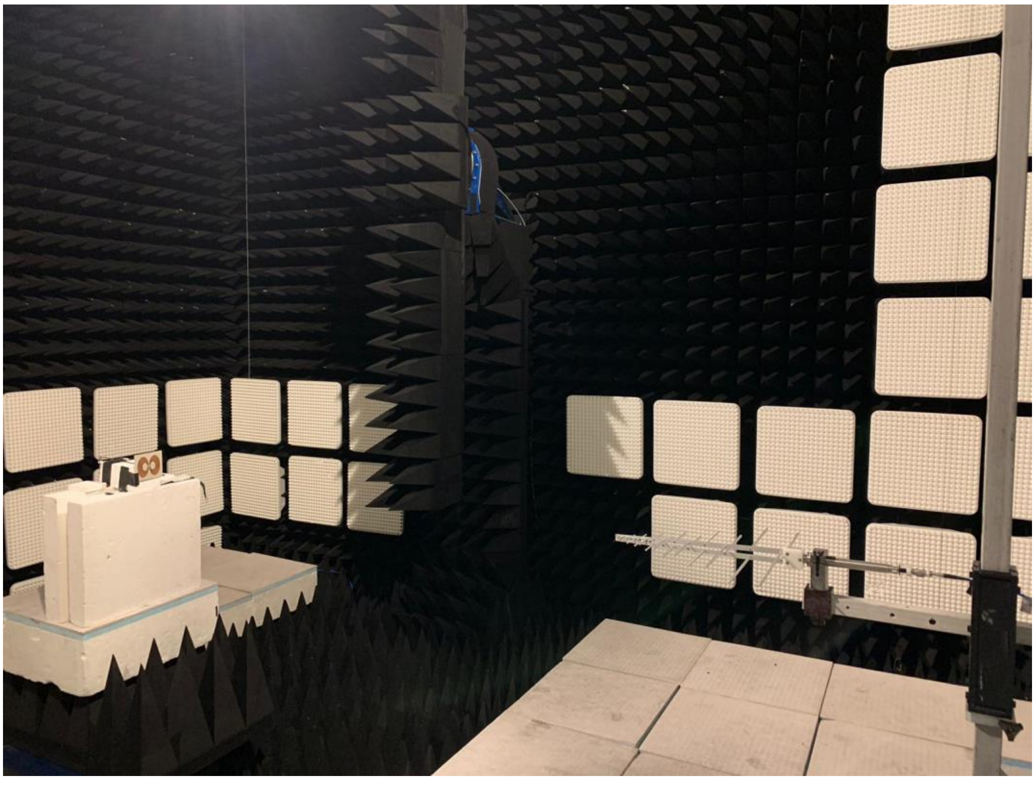


Figure 35. Measurement of planar elliptical dipole antenna in an anechoic chamber at NPL, UK 2

Table 11. Optimised values of antenna's geometrical parameters

Parameter	mIWO (α=2)	PSO	DE
Substrate Length (mm)	116.92	112.74	103.97
Substrate Width (mm)	99.09	90.44	85.42
Ellipse Outer Length (mm)	48.56	48.59	48.6
Ellipse Outer Width (mm)	77.71	78.25	79.77
Ellipse Inner Length (mm)	21.74	20.08	20.27
Ellipse Inner Width (mm)	30.38	37.85	39.55
Ellipse Offset (mm)	5.23	6.47	5.86
Feeding Gap (mm)	1.42	1.31	1.00

Table 12. Desired and optimised values of antenna's radiation characteristics

Antenna Characteristics	Desired Values	mIWO (α=2)	PSO	DE
$S_{11,max}$ (dB)	–10.00	–11.12	–9.99	–9.95
RG_{min} (dBi)	2.00	1.62	1.75	1.77
GF (dB)	2.00	2.9	3.46	3.61

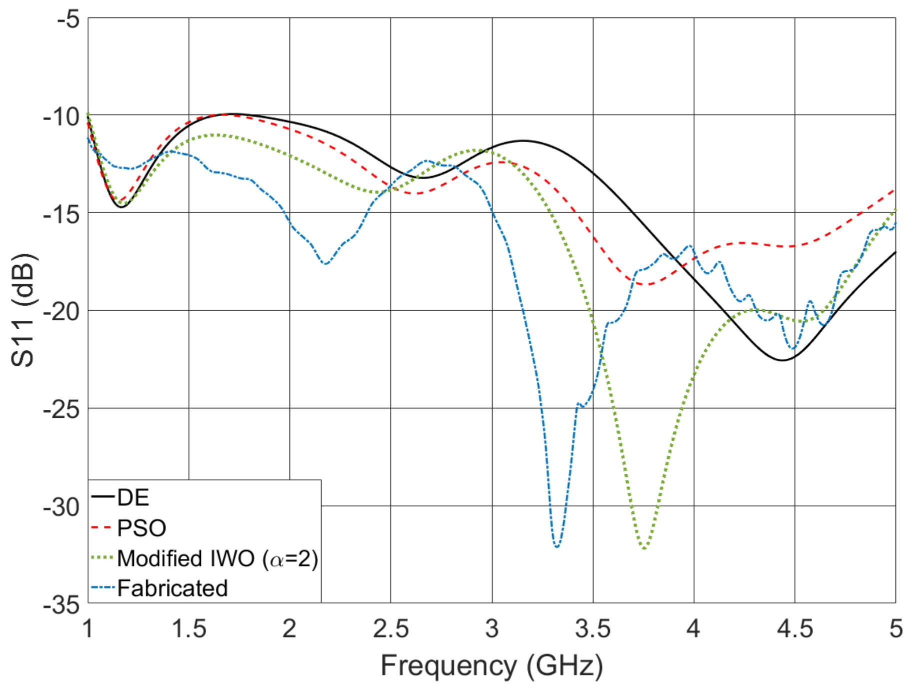


Figure 36. S_{11} of the planar elliptical dipole antenna optimised by DE, PSO and modified IWO with α=2, and S_{11} of the fabricated antenna according to the modified IWO based geometry.

In order to calculate the radiation characteristics of the fabricated antenna, another reference antenna is required. In this case, the Schwarzbeck USLP-9143B log-periodic antenna was used as the reference antenna. The fabricated antenna and the reference antenna are placed at a separation distance of 2m and both of them are placed 1.2m above the ground.

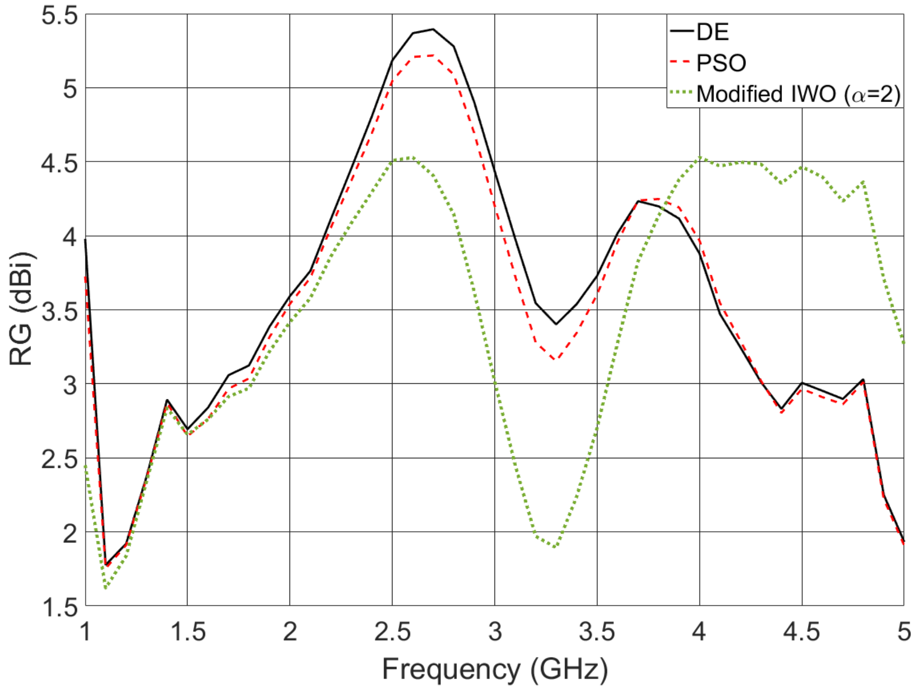


Figure 37. RG of the planar elliptical dipole antenna optimised by DE, PSO and modified IWO with α=2.

Overall, all algorithms produced antenna geometries with exceptional characteristics very close to the optimal. It is demonstrated on Figure 36, that in all cases it was accomplished to keep S_{11} values below the maximum desired over the entire frequency range. On Figure 37 it is evident that despite exceptional performance overall, the α=2 mIWO demonstrates better GF across the spectrum. On the other hand, DE and PSO demonstrate higher RG values for the biggest part of the frequency range.

The radiation patterns of the optimised antenna geometries are displayed in Figures 38-40 for four different frequencies of the studied spectrum for further examination of the optimised antenna's characteristics. The displayed frequencies are 1, 2.3, 3.6 and 5 GHz. In the region of 1GHz to 3 GHz, the antenna is mostly omnidirectional in the H-plane and exhibits two symmetrical lobes in the E-plane. Beyond 3GHz, side lobes appear in the H-plane. The same effect happens in the E-plane for frequencies beyond 5GHz, resulting thus in a gradual reduction of the boresight RG.

The resulting antenna from this optimisation is a lightweight, compact and low-cost structure, which is easy to construct and displays exceptional radiation characteristics. Therefore, it is a promising tool for EMC applications, such as UWB radiation measurements and spectrum surveillance.

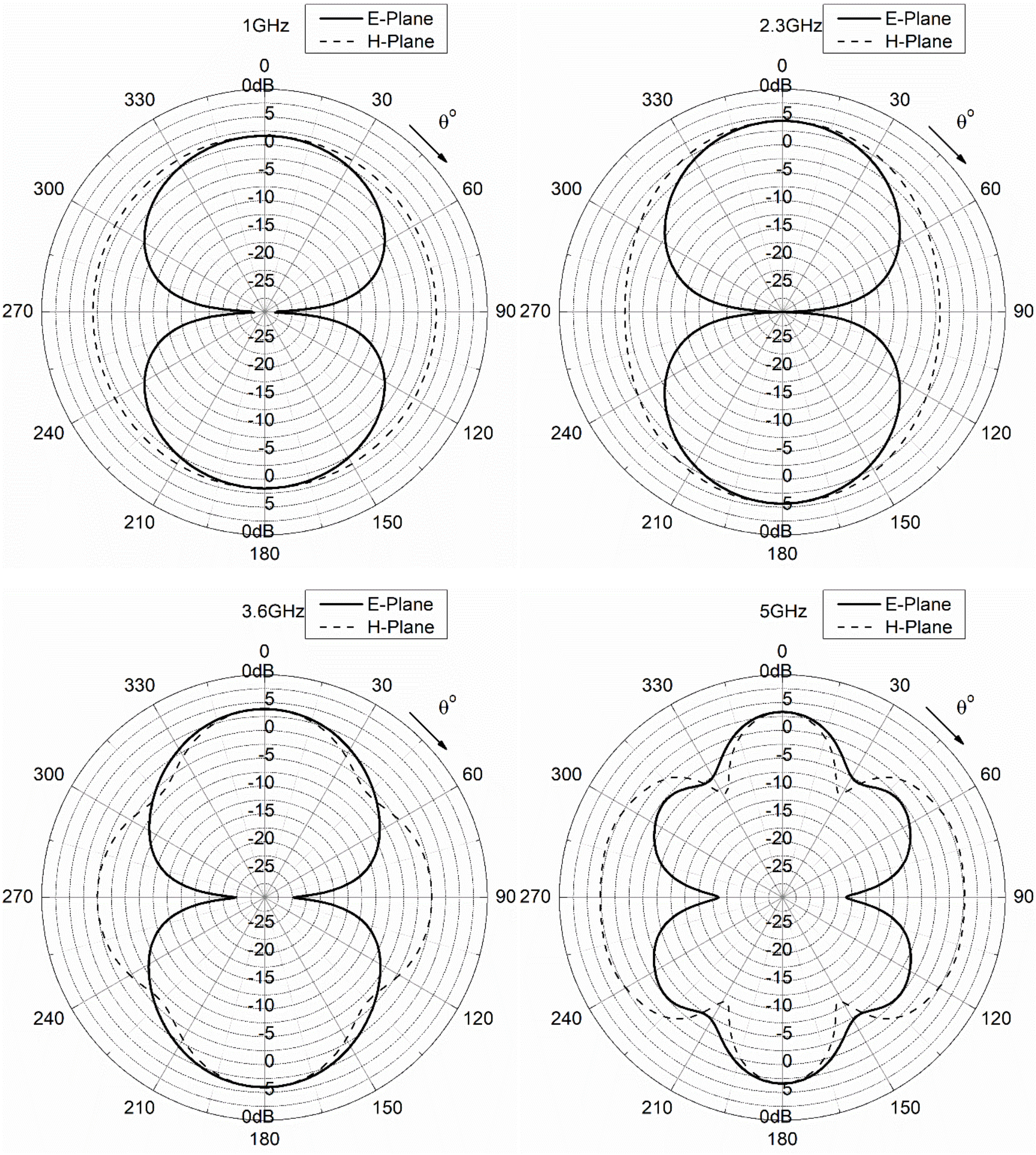


Figure 38. Radiation pattern of the modified IWO based (with α=2) planar elliptical dipole antenna for 1GHz, 2.3GHz, 3.6GHz and 5GHz.

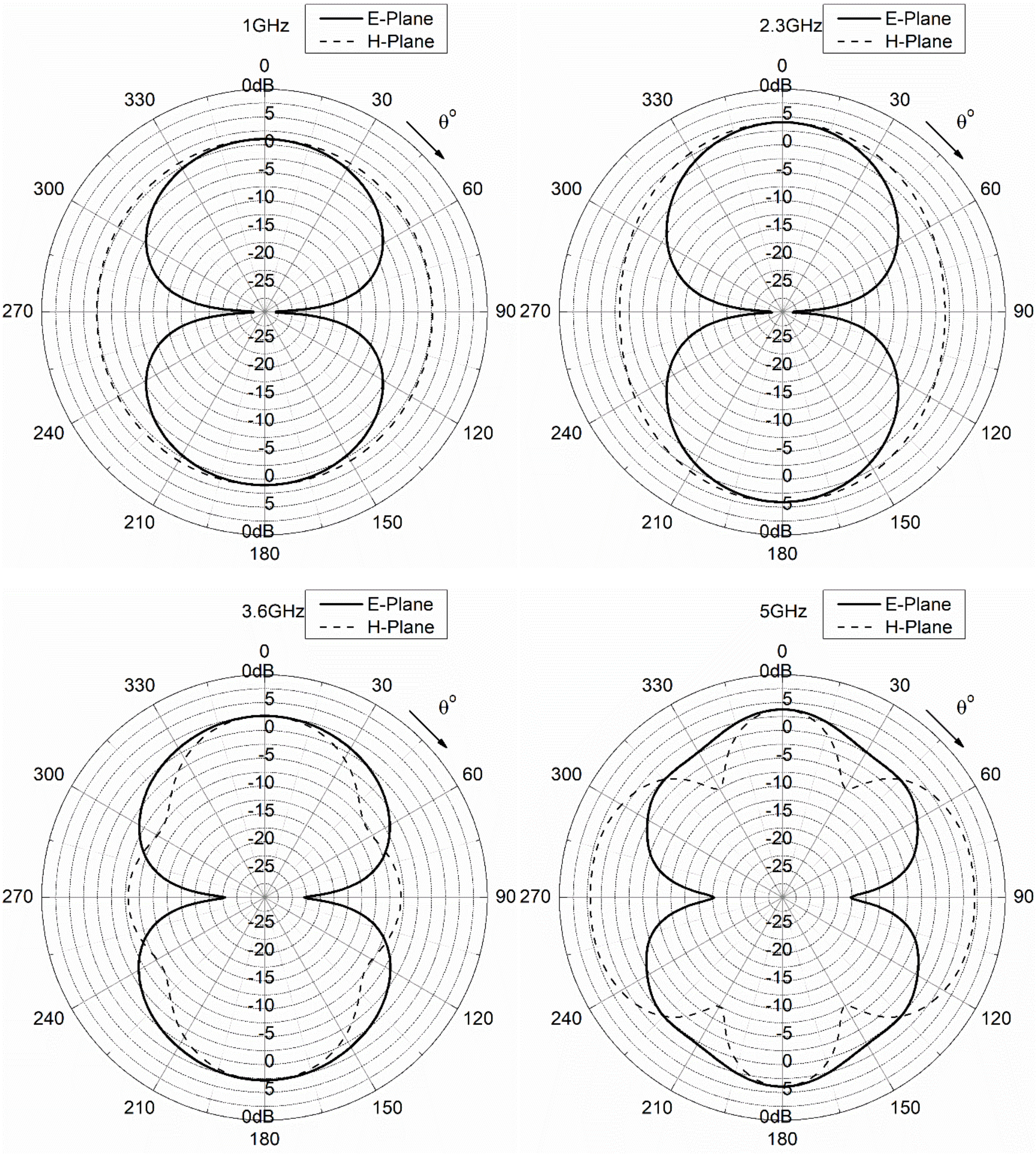


Figure 39. Radiation pattern of the PSO based planar elliptical dipole antenna for 1GHz, 2.3GHz, 3.6GHz and 5GHz.

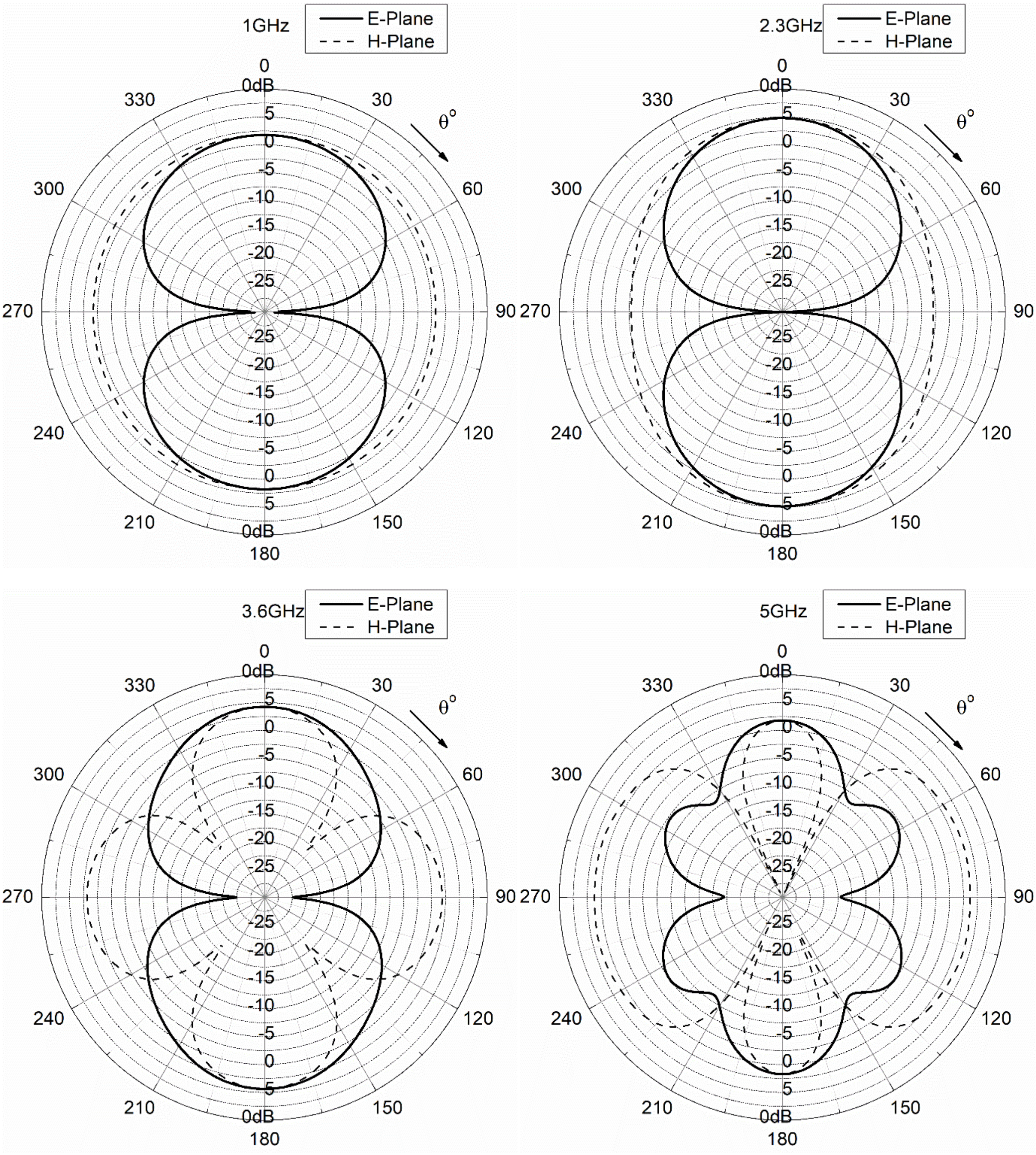


Figure 40. Radiation pattern of the DE based planar elliptical dipole antenna for 1GHz, 2.3GHz, 3.6GHz and 5GHz.

6.4 Conclusions

The geometrical parameters of a planar elliptical dipole antenna with elliptical slots were optimised for specific requirements regarding S_{11}, RG and GF over an UWB between 1GHz and 5GHz, by utilising four EAs, the conventional IWO, two different versions of a modified IWO called mIWO, the inertia weight version of PSO and a DE algorithm based on the DE/rand/1 strategy. The antenna design has been modelled in CST MWS software and the time domain solver it provides was used since it is a well-suited tool for broadband analysis. The derived antenna geometries by the aforementioned algorithms adequately satisfy the set requirements, whereas the α=2 mIWO version shows exceptional results and proves to be a robust candidate in the electromagnetics optimisation field.

6.5 References

[1] G. Adamiuk, T. Zwick and W. Wiesbeck, "UWB Antennas for Communication Systems", *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2308-2321, 2012. Available: 10.1109/jproc.2012.2188369.

[2] G. S. Kevanishvili, Z. I. Sikmashvili, I. G. Kevanishvili, K. V. Kotetishvili, A. B. Asanidze and G. G. Chikhladze, "About the electromagnetic compatibility of dipole antenna," *2008 13th International Seminar/Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory*, 2008, pp. 73-76, Available: 10.1109/DIPED.2008.4671807.

[3] F. Lin, Y. Qi, J. Fan and Y. Jiao, "0.7–20-GHz Dual-Polarised Bilateral Tapered Slot Antenna for EMC Measurements", *IEEE Transactions on Electromagnetic Compatibility*, vol. 56, no. 6, pp. 1271-1275, 2014. Available: 10.1109/temc.2014.2330291.

[4] Q. Wu, X. Ding and D. Su, "A Compact Dipole Antenna With Curved Reflector for 1.0–4.2 GHz EMC Measurement", *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 6, pp. 1289-1297, 2015. Available: 10.1109/temc.2015.2468072.

[5] M. G. Aram, H. Tahmasbi and H. Aliakbarian, "An ultra-wideband miniaturised printed dipole antenna for EMC measurements," *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE*, 2017, pp. 1-4, Available: 10.1109/EMCEurope.2017.8094687.

[6] E. N. Tziris et al., "Invasive weed optimised planar elliptical dipole antenna for ultra-wideband EMC applications," *2018 IEEE International Symposium on Electromagnetic*

Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC), 2018, pp. 233-236, Available: 10.1109/ISEMC.2018.8393772.

[7] K. K. Mistry, P. I. Lazaridis, Z. D. Zaharis, T. D. Xenos, E. N. Tziris and I. A. Glover, "An optimal design of printed log-periodic antenna for L-band EMC applications," *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, Singapore, 2018, pp. 1150-1155, Available: 10.1109/ISEMC.2018.8393968.

[8] E. N. Tziris, P. I. Lazaridis, Z. D. Zaharis, J. P. Cosmas, K. K. Mistry and I. A. Glover, "Optimised Planar Elliptical Dipole Antenna for UWB EMC Applications," *in IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 4, pp. 1377-1384, Aug. 2019, Available: 10.1109/TEMC.2019.2923781.

[9] H. G. Schantz, "Planar elliptical element ultra-wideband dipole antennas," *IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No.02CH37313)*, 2002, pp. 44-, Available: 10.1109/APS.2002.1018152.

[10] P. Cerny and M. Mazanek, "Optimised Ultra Wideband Dipole Antenna," *2005 18th International Conference on Applied Electromagnetics and Communications*, 2005, pp. 1-4, Available: 10.1109/ICECOM.2005.205035.

[11] H. G. Schantz, W. Beeler and D. Dickson, "UWB planar bulbous dipole antennas," *2005 IEEE Antennas and Propagation Society International Symposium*, 2005, pp. 475-478 vol. 2A, Available: 10.1109/APS.2005.1551848.

[12] Zhang, Y. Xu and W. Wang, "Ultra-wideband microstrip-fed planar elliptical dipole antenna", *Electronics Letters*, vol. 42, no. 3, p. 144, 2006. Available: 10.1049/el:20064073.

[13] Junsheng Yu et al., "Study of an ultra wideband planar elliptical dipole antenna," *2009 International Conference on Microwave Technology and Computational Electromagnetics (ICMTCE 2009)*, 2009, pp. 49-52, Available: 10.1049/cp.2009.1270.

[14] W. Toh, X. Qing and Z. Chen, "A Planar UWB Patch-Dipole Antenna", *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 9, pp. 3441-3444, 2011. Available: 10.1109/tap.2011.2161553.

[15] J. Powell and A. Chandrakasan, "Differential and single ended elliptical antennas for 3.1-10.6 GHz ultra wideband communication," *IEEE Antennas and Propagation Society Symposium*, 2004., 2004, pp. 2935-2938 Vol.3, Available: 10.1109/APS.2004.1331993.

[16] Chun-Chi Lee, Chia-Wei Wang, R. Y. Yen and Hsin-Sheng Huang, "Broadband printed-circuit elliptical dipole antenna covering 750 MHz–6.0 GHz," *2008 International*

Conference on Microwave and Millimeter Wave Technology, 2008, pp. 1207-1209, Available: 10.1109/ICMMT.2008.4540648.

[17] Bo Tian, Cunqian Feng and Mingchun Deng, "Planar miniature elliptical monopole antenna for ultra wideband radios," *2008 International Conference on Microwave and Millimeter Wave Technology*, 2008, pp. 1240-1242, Available: 10.1109/ICMMT.2008.4540657.

[18] G. Whyte, F. Darbari, I. McGregor, I. Glover and I. Thayne, "Different Feeding Geometries for Planar Elliptical UWB Dipoles, and the Excitation of Leakage Current," *2008 38th European Microwave Conference*, 2008, pp. 1382-1385, Available: 10.1109/EUMC.2008.4751722.

[19] H. Nazli, E. Bicak, B. Turetken and M. Sezgin, "An Improved Design of Planar Elliptical Dipole Antenna for UWB Applications", *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 264-267, 2010. Available: 10.1109/lawp.2010.2046999.

[20] P. I. Lazaridis et al., "Comparison of evolutionary algorithms for LPDA antenna optimisation," *in Radio Science*, vol. 51, no. 8, pp. 1377-1384, Aug. 2016, Available: 10.1002/2015RS005913.

7 NOTCHED CIRCULAR PATCH ANTENNA FOR L1 GPS AND IRIDIUM BANDS OPTIMISATION

7.1 Introduction

Patch antennas are becoming increasingly popular, because they are low-cost and low-profile structures, while they are characterised by easy fabrication. Hence, they are a very popular choice throughout the antenna industry. In the state of the art, patch antenna geometries with circular polarisation have been proposed [1]-[5]. Here, a notched circular patch antenna with pin feeding on its back surface is designed using the CST Microwave Studio. The antenna is optimised by applying the conventional IWO method and the mIWO presented in Chapter 6. The antenna geometry must have characteristics suitable for operation in two different frequency bands, i.e., the L1 GPS and Iridium bands. These characteristics are required for every frequency inside these two bands and are as follows:

1. $S_{11} \leq -10$dB to ensure good matching to the feeding source,
2. Electric field with axial ratio AR ≤ 10 dB at direction normal to the antenna surface (i.e., z-axis, see Figure 41) in order to achieve nearly circular polarisation, and
3. High realised gain (RG) at direction normal to the antenna surface in order to establish a sufficient satellite communication link.

The geometry of the proposed design is shown in Figure 41 and consists of a circular patch with two notched edges, a dielectric substrate, and a ground plane. The patch is fed by a pin on its back surface. The important parameters for achieving circular polarisation are the pin's offset (i.e., the pin's distance from the patch centre) and the pin's angular position in the xy-plane (i.e., angle φ) as well as the length and width of the notches. On the other hand, the antenna matching is mainly affected by the patch diameter and the side (length or width) of the substrate, which is considered here to be square-shaped. The geometry parameters of the antenna along with their upper and lower boundaries used by the mIWO algorithm are listed in Table 13. These boundaries (except that of the pin's angular position) have been normalised with respect to the wavelength λ_{GPS} of the L1 GPS band. Due to the symmetry of the patch with respect to the x-axis and y-axis, the pin's angular position can be searched within the 1st quadrant of angle φ, i.e., between 0 and 90 degrees. The boundaries of the rest of the parameters are chosen with great tolerance to give the optimisation methods all the freedom they need to find the optimal value of each parameter. This chapter is based on papers [6] and [7].

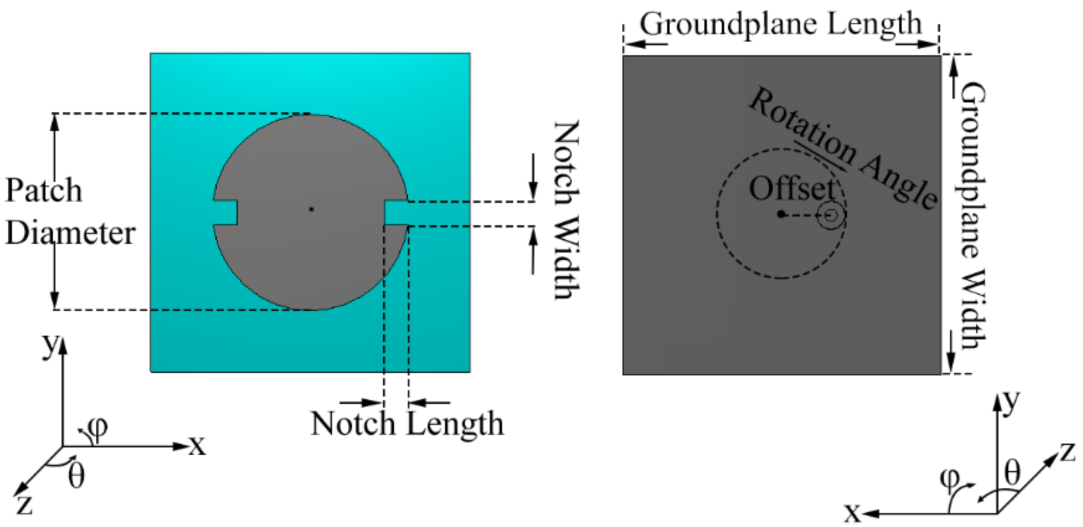


Figure 41. Front side (left) and back side (right) of the proposed antenna

Table 13. Antenna geometry parameters and their optimisation boundaries

Parameter	**Lower Boundary**	**Upper Boundary**
Patch Diameter (λ_{GPS})	0.2	0.6
Ground Plane Side (λ_{GPS})	0.5	2
Notch Length (λ_{GPS})	0	0.04
Notch Width (λ_{GPS})	0	0.04
Pin's Offset (λ_{GPS})	0	0.1
Pin's Angular Position (degrees)	0	90

7.2 Implementation

To optimise the proposed antenna geometry, a proper fitness function must be created. Nevertheless, the difficulty in solving this optimisation problem stems from the fact that the requirements must be satisfied for every frequency inside the L1 GPS and Iridium bands. To help the optimisation algorithms come to a solution, it is better to redefine the requirements in a looser form:

1. Since every resonance has a certain bandwidth, the requirement for $S_{11} \leq -10$dB at every frequency inside the above bands may be achieved by demanding $S_{11} \leq -30$dB only at the centre frequencies (1.57 and 1.62 GHz) of these two bands. Thus, the requirement for dual band impedance matching may be satisfied by demanding

$S_{11,GPS} \leq -30$dB and $S_{11,IR} \leq -30$dB, where $S_{11,GPS}$ and $S_{11,IR}$ are the values of S_{11} in dB at 1.57 and 1.62 GHz, respectively.

2. The requirement for nearly circular polarisation may be satisfied by demanding $AR_{GPS} \leq 10$dB and $AR_{IR} \leq 10$dB, where AR_{GPS} and AR_{IR} are the values of AR in dB at direction normal to the antenna surface ($\theta = 0°$) at 1.57 and 1.62 GHz, respectively.
3. The requirement for high RG at direction normal to the antenna surface ($\theta = 0°$) may be satisfied by demanding values of RG above a certain boundary, e.g., 10dBi, at the centre frequencies of both operating bands. Therefore, we demand $RG_{GPS} \geq 10$dBi and $RG_{IR} \geq 10$dBi, where RG_{GPS} and RG_{IR} are the values of RG in dBi for $\theta = 0°$ at 1.57 and 1.62 GHz, respectively.

The fitness function is formulated as a linear combination of three respective terms, each satisfying every requirement as follows:

$$\text{Fitness} = w_1 T_1 + w_2 T_2 + w_3 T_3 \quad \textbf{(31)}$$

where,

$$T_1 = \max(S_{11,\text{GPS}}, S_{11,\text{IR}}, -30) + 30 \quad \textbf{(32)}$$

$$T_2 = \max(\text{AR}_{\text{GPS}}, \text{AR}_{\text{IR}}, 10) - 10 \quad \textbf{(33)}$$

$$T_3 = 10 - \min(\text{RG}_{\text{GPS}}, \text{RG}_{\text{IR}}, 10) \quad \textbf{(34)}$$

As the optimisation procedure minimises the fitness function, every term is forced to be minimised as well, thus satisfying the respective requirement. The three terms have been formulated in such a way that values of $S_{11,GPS}$ or $S_{11,IR}$ below –30dB, values of AR_{GPS} or AR_{IR} below 10dB, and values of RG_{GPS} or RG_{IR} above 10dBi do not affect the value of the respective term since the respective requirement is considered to have already been satisfied. Also, all the terms are structured in such a way that they always have a positive value and a minimum value equal to zero, which implies a minimum value equal to zero for the fitness function as well. The weights w_1, w_2 and w_3 are used to balance the minimisation of the three terms. Here, $w_1 = w_2 = w_3 = 1$ because the three requirements are considered to be of equal importance.

The simulations were performed on a workstation utilizing an Intel i7-7820X running at 4GHz along with 16GB of RAM and no GPU acceleration. The average time per fitness evaluation was approximately 3 minutes using the time domain solver of CST MWS. The simulated antenna model consists of 300000 mesh cells and no electric or magnetic symmetry exists. The substrate's relative permittivity ε_r was set equal to 2, and its thickness equal to 2.54mm (0.1inch), while the copper thickness is 0.035mm. These are the characteristics of a

Rogers RT/duroid 5880LZ substrate used very widely in patch antenna applications. These three characteristics have fixed values, and thus, are not subject to optimisation. The optimisation process was executed 5 times for 5 different values of α, and with 2000 fitness evaluations per execution. All the executions employed populations of 15 weeds, while the fitness function variation versus the number of fitness evaluations was recorded for every execution. All these variations are shown in Figure 42, whereas the optimised values of the antenna geometry parameters derived from all the executions are summarised in Table 14. An important observation on Figure 42 is that better fitness values are achieved for $\alpha > 1$ until the point of 1500 fitness evaluations. This observation confirms that $\alpha > 1$ is the best choice for a limited amount of fitness evaluations.

7.3 Simulated Results

Table 14. Optimised values of the antenna geometry parameters

Parameter	**mIWO α = 0.5**	**mIWO α = 0.7**	**IWO α = 1**	**mIWO α = 2**	**mIWO α = 3**
Patch Diameter (mm)	73.7	73.4	73.6	73.6	73.4
Ground Plane Side (mm)	287.9	185.6	115.6	222.2	144.1
Notch Length (mm)	6.8	5.3	7.1	6.6	7.2
Notch Width (mm)	6.9	6.3	6.3	6.6	6.1
Pin's Offset (mm)	14.7	12.4	13.0	11.8	11.5
Pin's Angular Position (degrees)	46.8	41.6	45.0	46.1	46.3

It is evident that the best antenna geometry is produced with $\alpha = 2$ and its computed radiation characteristics are shown in Figures 43, 44 and 45. This geometry exhibits excellent S_{11} values inside the L1 GPS and Iridium bands, while satisfactory values of AR and RG are achieved at the centre frequencies of both bands for $\theta = 0°$. These values are:

AR_{GPS} = 10.5dB, AR_{IR} = 9.8dB, RG_{GPS} = 8.4dBi and RG_{IR} = 8.3dBi.

Current state of the art patch antennas used for satellite communications present great gain and circular polarisation for single band scenarios such as in [4], whereas there are also designs with broadband capabilities, at the expense of multiple patches as in [2]. The results presented here, show that this was a novel successful effort of a dual band antenna for two very popular frequency bands (1.57GHz and 1.62GHz) in satellite communications with circular polarisation.

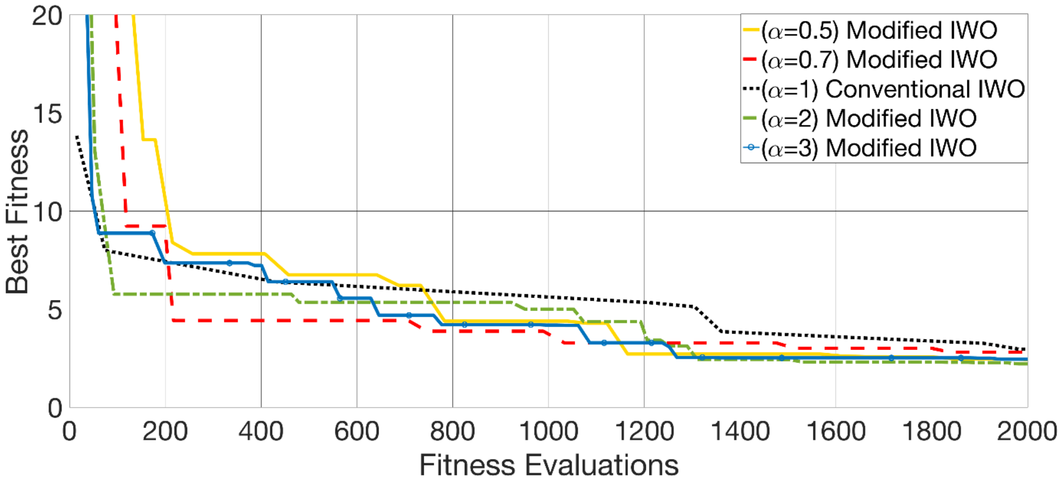


Figure 42. Fitness function variation for five different values of index α

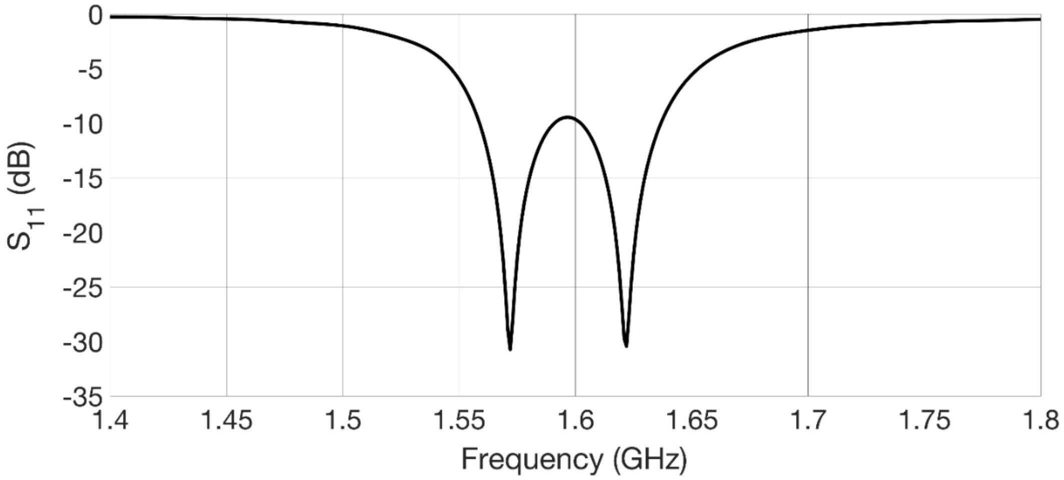


Figure 43. S_{ii} of the proposed antenna optimised using IWO with α=2

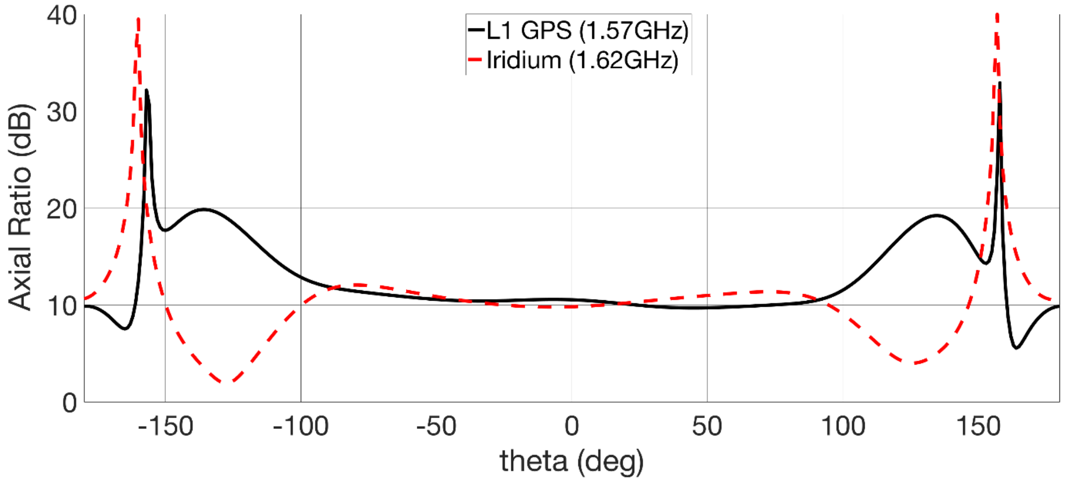


Figure 44. Axial ratio of the proposed antenna optimised using mIWO with α = 2

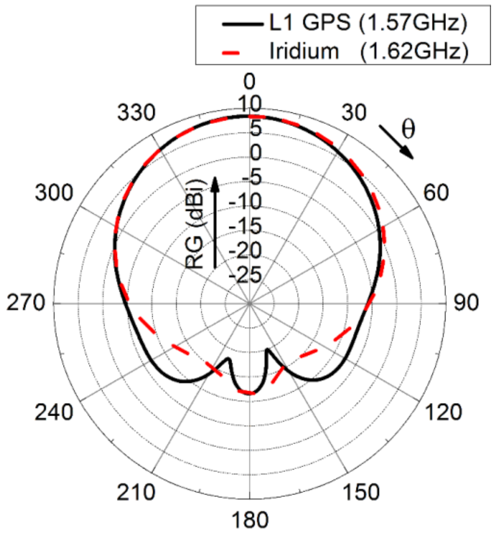


Figure 45. Radiation patterns in the yz-plane (φ = 90°) of the proposed antenna optimised using mIWO with α = 2

7.4 Conclusion

The modified and conventional IWO methods have been applied on a notched circular patch antenna with ground plane and pin feeding on its back surface. This geometry was chosen due to its compact size and its light weight, and because this antenna has a straightforward, easy, and low-cost fabrication. The optimised antenna presents excellent matching inside the L1 GPS and Iridium bands, while also exhibiting nearly circular polarisation and good realised gain values at the centre frequencies of both operating bands. All the above make the optimised antenna an appropriate candidate for dual frequency operation in the L1 GPS and Iridium bands.

7.5 References

[1] S. Long, Liang Shen, D. Schaubert and F. Farrar, "An experimental study of the circular-polarised elliptical printed-circuit antenna", *IEEE Transactions on Antennas and Propagation*, vol. 29, no. 1, pp. 95-99, 1981. Available: 10.1109/tap.1981.1142549.

[2] M. Haneishi, S. Yoshida and N. Goto, "A broadband microstrip array composed of single-feed type circularly polarised microstrip antennas," *1982 Antennas and Propagation Society International Symposium*, 1982, pp. 160-163, Available: 10.1109/APS.1982.1148877.

[3] M. Haneishi, T. Nambara and S. Yoshida, "Study on ellipticity properties of single-feed-type circularly polarised microstrip antennas", *Electronics Letters*, vol. 18, no. 5, p. 191, 1982. Available: 10.1049/el:19820132.

[4] M. S. Shakhirul et al., "1.575 GHz Circular Polarisation wearable antenna with three different substrate materials," *2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, 2014, pp. 43-46, Available: 10.1109/APACE.2014.7043807.

[5] P. Sharma and K. Gupta, "Analysis and optimised design of single feed circularly polarised microstrip antennas", *IEEE Transactions on Antennas and Propagation*, vol. 31, no. 6, pp. 949-955, 1983. Available: 10.1109/tap.1983.1143162.

[6] E. N. Tziris, P. I. Lazaridis, K. K. Mistry, Z. D. Zaharis, J. P. Cosmas, B. Liu and I. A. Glover, "1.62GHz Circularly Polarised Pin-Fed Notched Circular Patch Antenna," *2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC)*, Meloneras, 2018, pp. 1-3, Available: 10.23919/URSI-AT-RASC.2018.8471447.

[7] K. K. Mistry, P. I. Lazaridis, E. N. Tziris, Z. D. Zaharis, B. Liu, T. D. Xenos and I. A. Glover, "A Design of Elliptical Edge-Fed Circularly Polarised Patch Antenna for GPS and Iridium Applications," *2018 2nd URSI Atlantic Radio Science Meeting (AT-RASC), Meloneras*, 2018, pp. 1-4, Available: 10.23919/URSI-AT-RASC.2018.8471443.

8 CONCLUSION

8.1 Summary

The aim of this thesis, was to prove through research, using well-established software available during the fulfilment of this thesis, that EAs are very effective tools for use in the electromagnetics industry. The focus in this research was directed at some state-of-the-art algorithms which are the DE, PSO, IWO, ADIWO and Taguchi algorithms. The development of those algorithms was achieved by coding their mathematical functions in MATLAB, and because of that, it was possible to run simulated experiments even within MATLAB itself but even with external software i.e., NEC and CST MWS which could provide very credible electromagnetic simulations of geometries. Each algorithm was extensively investigated and many research papers were found, using these algorithms as optimisation methods for different applications of electromagnetics, with particular aim to those regarding antenna array optimisations.

To put these algorithms to the test in electromagnetic applications, several different experiments which would have real-world applications were developed, and all algorithms were employed and compared to find out which is best suited per application. Such experiments are the null-filling optimisation for FM-TV broadcasting antenna array, where the very simple, yet existent issue of very weak signal (null) in several spots of a service area that many broadcasting antennas suffer from, is optimised using EAs with exceptional success.

Further to a simple theoretical linear array, more complex antenna geometries was developed such as the LPDA antenna, which was optimised for better radiation characteristics such as maximum gain, gain flatness, which means that gain values are approximately equal throughout the serviced spectrum, low return loss on the serviced spectrum and low front-to-rear ratio to efficiently radiate the signal. A definite and consequential conclusion of that experiment would be that the performance of such optimised antenna compared to that of an LPDA antenna that was designed using the classical Carrel’s method would be considered much more superior. To this point it is evident that IWO mostly outperformed the rest of the algorithms, showing some substantially better optimisation results.

For the most accurate antenna simulations, a collinear antenna array meant for broadcasting at a flat surface area with equal gain across all distances of the service area was developed with the help of CST MWS. By utilising the interface between CST MWS and MATLAB, it was possible to apply the different collinear antenna geometries generated by the EAs in MATLAB directly into CST MWS, simulate them and acquire their radiation characteristics back to MATLAB to measure their fitness function until the optimisation is concluded. Since IWO was the optimisation method that returned the best results in previous experiments, it was chosen for this experiment and evidently, it returned satisfactory results. The antenna was optimised for the UHF frequency of 498MHz and as previously stated, for equal gain across a flat service area. The geometry optimisation was executed in four different cases. One with individual lengths, distances, and phases, with uniform amplitude excitation for all dipoles; one with common lengths and distances and individual phases, with uniform amplitude excitation for all dipoles; one with individual lengths, distances, phases, and amplitude excitations for all dipoles, and lastly, one with common lengths and distances and individual phases and amplitude excitations for all dipoles. The case where the algorithm succeeded the most was the one with common lengths and distances and individual phases and amplitude excitations. That would be due to the fact that the amplitudes and phases have a greater impact on the desired characteristics, whereas lengths and distances have a secondary role.

Given that IWO proved to be the most sound in the previous experiments, and since it was found that previous research was conducted on improving the existing conventional algorithm, i.e. the ADIWO method, a novel modified version of the existing IWO method was proposed, the so called mIWO, where with the addition of the non-linear seed production index α, the number of seeds produced by each grown weed depending on its fitness value is ruled differently than on the conventional IWO. This modification was thoroughly tested on some of the most well-established test functions e.g. De Jong, Auckley, Rastrigin, Rosenbrock, Schwefel, Shubert etc. and it was found that the most proper value of α is decided by the total number of evaluations that an experiment is run for. It was observed that the more the evaluations, the lower the value of α should be, and the other way around. Of course, it should not be overseen that extreme low or high values of α can have an immensely negative impact on the optimisation. Having established that mIWO, with the proper α value performs better than the conventional method on the test functions, it was also tested on two real world applications, where it was also compared with other algorithms and the conclusions which derived from the test functions were confirmed.

One of the applications is a planar elliptical dipole antenna model, which was optimised for operation on a UWB 1-5GHz for EMC applications. The model the was the result of the optimisation was fabricated and it was tested in an anechoic chamber for the most accurate possible results, and these results are compared to the simulated ones for confirmation. Another application with successful results was that of a notched circular patch antenna which was optimised for L1 GPS and Iridium satellite communications with circular polarisation requirement.

Overall, the main conclusion of this research would be that EAs are very valuable tools in the field of the electromagnetics and further research is necessary to ensure to continuous improvement of antenna reception, as it is a field of interest in many different fields, such as Aerospace and Aviation, Satellite Communications and many more. Looking into all the optimisations that were carried out in this thesis, it is evident that EAs are capable of optimising simple electromagnetic problems such as null filling to more complex antenna designs such as the LPDA and the collinear array. It should also be noted that the proposed novelty mIWO is extending the capabilities of IWO, and it was shown that with the right configuration it can exhibit more superior results than the conventional method, which was proven both in well-established test functions as well as in actual complex electromagnetic problems

8.2 Future work

This research covered novelty ways of designing antenna geometries along with novelty modifications on existing optimisation methods. It was demonstrated in depth that EAs are capable of producing antenna geometries with outstanding radiation characteristics, specially when compared to geometries deriving from classical design methodologies. Despite of that, there are quite a few points that would benefit from improved optimisation methodologies. An example of that would be the congestion caused by new technologies in the frequency spectrum which is constantly updated. The 5G band for instance, replaced the deprecated analogue TV and it is very close to the DVB-T band. Instantly, a problem that comes with this, is the necessity of band rejection in antennas to address interference issues that would otherwise will occur.

These facts, would be considered enough to put efforts in bringing many more optimisation methods in the field of electromagnetics. Some examples of different methodologies are the Trust Region Framework, the Covariance Matrix Adaptation Evolutionary Strategy, the Nelder Mead Simplex Algorithm, the Decap Optimisation and many more, which are finding their way into reputable software. In addition, optimisation is also necessary in electromagnetic applications other than antenna designs. An example of that would be the optimisation of the tuning parameters of coverage prediction models i.e. Longley-Rice, ITU-R P.1546, and the Hata-Davidson model, which is a process that can prove to be very complex and hence, susceptible to errors.

It was also demonstrated that existing optimisation methods have plenty of room for improvement. As it is seen in this research, a not so significant addition to an existing algorithm such as adding a non-linear seed production index, can lead to substantially beneficial outcomes such as improving the optimisation capabilities of the conventional method. The state of the art includes combination of local and global best for PSO, initialisation variation of IWO with the use of Taguchi, the Adaptive IWO which was used in part in this thesis and many more. It is understandable that either combinations of the aforementioned techniques or entirely novel approaches could possibly improve even further the output of EAs.

As mentioned, there is already previous research on improving existing algorithms as well as existing antenna designs, and it must be noted that it is necessary to keep this subject to current research because of its key value in the industry that it is an essential part of. As a final word, the author's expectations are for further research on improving existing optimisation methods to be utilised in the field of electromagnetics and many more, where they can make a difference by bringing out the best, of many different antenna designs.

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