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Research Article

Genetic Algorithms in Antennas and Smart Antennas Design Overview: Two Novel Antenna Systems for Triband GNSS Applications and a Circular Switched Parasitic Array for WiMax Applications Developments with the Use of Genetic Algorithms

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Genetic algorithms belong to a stochastic class of evolutionary techniques, whose robustness and global search of the solutions space have made them extremely popular among researchers. They have been successfully applied to electromagnetic optimization, including antenna design as well as smart antennas design. In this paper, extensive reference to literature related antenna design efforts employing genetic algorithms is taking place and subsequently, three novel antenna systems are designed in order to provide realistic implementations of a genetic algorithm. Two novel antenna systems are presented to cover the new GPS/Galileo band, namely, L5 (1176 MHz), together with the L1 GPS/Galileo and L2 GPS bands (1575 and 1227 MHz). The first system is a modified PIFA and the second one is a helical antenna above a ground plane. Both systems exhibit enhanced performance characteristics, such as sufficient front gain, input impedance matching, and increased front-to-back ratio. The last antenna system is a five-element switched parasitic array with a directional beam with sufficient beamwidth to a predetermined direction and an adequate impedance bandwidth which can be used as receiver for WiMax signals.

1. Introduction

The basic principles of genetic algorithms (GAs) and their applications in computer systems were presented by Holland [1] and de Jong [2] in 1975 and described in detail by Goldberg [3]. The GA starts forming, usually by random manner, an initial population of chromosomes (individuals). The performance of each individual is evaluated by the objective function or the fitness function, which determines the goal in each optimization problem. A high value on the objective function implies a good chromosome. After the initial chromosomes are created, a thoughtful selection strategy determines chromosomes which will take part in the process of evolution. More specifically, these individuals undergo transformations through stochastic, genetic operators to create offspring, according to the logic of domination of the fittest. Chromosomes are mated with each other (according different techniques) to give birth to the offspring in which there is genetic material from both parents, chromosomes. The two types of genetic operators are crossover in which new individuals are constructed by combining genetic material from preexisting ones and mutation, thus the modification of the genetic material for the synthesis of new individuals. The new set of chromosomes produced by this mating process forms the next generation chromosomes, although not impossible to save chromosomes from previous generation and to introduce the next. Then the performance of the new population individuals is calculated. In each generation the number of chromosomes is kept constant. This process is repeated for several generations, until a termination criterion is met [3–8].

A GA has significant advantages over traditional optimization techniques as follows [8].

(i) It can be applied in any problem.

(ii) It conducts a universal research in the solutions spaces.

(iii) It does not require prior knowledge of the optimization problem.

(iv) It does not depend on the initial conditions of the search.

(v) It optimizes continuous or discrete parameters.

(vi) It does not require derivative information on the cost function.

(vii) It works well with large number of variables.

(viii) It can be run in parallel on multiple computers.

(ix) It optimizes variables with quite complex cost surfaces.

(x) It provides a list of best parameters, not just a single solution.

(xi) It can encode parameters.

(xii) It can work with numerical data, with experimental data or analytical functions.

For these reasons, GAs have become a very popular optimization tool. Their computational modeling is applied on various problems in a wide range of disciplines, such as aerospace, operational research, social science, and quantum physics [2, 9–11]. In the field of electromagnetism, they have been applied in the design and optimization of the geometric characteristics of antennas and arrays [12–47], in EMC problems [48, 49], in multiobjective optimization problems of arrays, and in optimization problems using computational methods [50–58].

It is not certain that the solution ultimately provided by the GA is optimal. But in problems of electromagnetic nature and in particular issues of design and development of antennas, the following rules [8, 50], which are not binding, usually contribute in finding the global optimal solution, if of course this exists.

(i) The selection of appropriate coding depends on the test problem. Still, genes related to each other should be placed in adjacent positions in the chromosome. A typical example is the encoding of complex numbers, where two genes are used for the description of the amplitude and phase, respectively.

(ii) Population size is a critical factor. The number of generations determines whether they actually achieve convergence and the number of chromosomes determines how good the solution will be in the case of convergence. The larger the population is, the greater percentage of the solution space is investigated. On the other hand, this approach increases the computational cost in the performance of GA.

(iii) An important parameter for the performance of GA is the crossover probability p_c which can take values between 0.5 and 0.9. Higher values provide faster search space solutions. Values between 0.7 and 0.8 were proved effective in most problems [5].

(iv) The mutation probability p_m is always chosen relatively small, typically 0.15. Values greater than 0.15 enable the GA to escape from the local optima but can lead to removing individuals with excellent performance close to the global optimal one, delaying or preventing convergence [7].

(v) The use of elitism techniques is recommended.

When designing an antenna or array with the method of GAs, the output can be the synthesis of a desired radiation pattern, the minimization of the side lobes level of the radiation pattern, the composition of diagram with multiple lobes or nulls towards specific directions, and the achievement of input impedance matching at a single frequency point or frequency interval. The design parameters may include the positions of the elements of the array, their sizes, their current excitations, and so forth.

In [12] a printed dual band antenna is designed, using a GA that alters its geometrical characteristics. A method for reducing the side lobes of a planar square array is presented in [13], which is based on the use of a GA that modifies the weight coefficients in each element. In [15] a GA with a high mutation rate (30%) to minimize electromagnetic interaction (coupling) between two VHF-UHF antennas placed on the fuselage of a military aircraft is proposed. The technique of GAs is used to determine an optimal set of excitation coefficients and an optimal placement of elements of a nonuniform circular array [16], where the aim is to extract a radiation pattern with maximum reduction of the highest side lobe level, subject to the constraint of a constant beam width. A compact genetic antenna consisting of a set of leads that are connected in series and loaded with suitable loads is designed in [27]. The shape of the antenna, the positions of the elements, and the values of the loads are optimized using a GA of real encoding. In [29] a circular switched parasitic array of log-periodic dipole antennas (LPDAs) is introduced. The overall structure is subjected to an optimization procedure in order to achieve significant directivity and operational bandwidth at the 3.1 GHz–10.6 GHz frequency band with the use of the GAs technique. Beam steering is performed by selecting which one LPDA is attached to the signal source. Furthermore, design methods of wideband antenna using GAs are discussed in [36], while a GA optimizes an array of vertical dipoles over ground plane in [37]. A technique that combines the Schelkunoff method with a genetic algorithm for the synthesis of linear arrays with complex feed coefficients and random radiation patterns is mentioned in [39]. GA optimization of high-directivity microstrip patch antennas and miniature microstrip patch antennas have been dealt with in [46, 47], respectively.

Indicatively, in [59] a multicriteria optimization problem is presented. The design of a classical Yagi-Uda antenna and the design a modified Yagi-Uda antenna with additional parasitic elements in the region of the active element, which act as reflectors, are featured. Miscellaneous objective functions that combine requirements for directionality, the front-to-back ratio, and input impedance are examined. Any such requirement is introduced in the objective function and has its own weighting. Therefore interesting comparisons with different rates weight for various structures of classical and modified Yagi-Uda arrays with an operating frequency of 2.4 GHz are featured, while the optimal solutions are studied in regard of the bandwidth they achieve. The work in [60] deserves special mention, which develops a tailored GA of real imaging that alters the mechanisms (crossover and mutation) dynamically during the optimization. So, convergence is accelerated and the need for redefining the parameters decreases significantly. The efficiency of the method is demonstrated through application in intelligent adaptive arrays where the height of the side lobe is determined by appropriately choosing the amplitudes and/or phases of the weights of the elements.

A lot of attention has been paid to the concept of developing smart antennas for DVB-T applications utilizing the GAs technique in a series of works by the authors [61–63], where different array configurations for such applications are introduced. More specifically, [61] proposed a broadband switched-parasitic array suitable for switched-beam DVB-T applications in the IV UHF band. A broadband, seven-element switched-parasitic array having six available directive beam lobes was designed for the channels 51–69 of the V UHF band in [62], whereas a new technique for the design of broadband, circular switched-parasitic arrays for use as portable DVB-T receivers in the V UHF band was developed in [63]. In [64], the design of an optimized electronically steerable passive array radiator (ESPAR) antenna, for portable or mobile DVB-T reception, is proposed. Finally, a low-cost and profile switched-beam array, suitable for fixed and portable DVB-T applications in the V UHF band, is proposed in [65], where the array comprises eight wire elements lying on the horizontal plane and a set of four switching beam patterns is provided.

In the following sections of the paper, a modified planar inverted f antenna (PIFA) and a helical antenna above a ground plane are proposed for triband GNSS (GPS and Galileo) operation on the L1/L2/L5 bands. Their advantages are significant directivity, satisfactory impedance matching to the feeding line, and adequate front-to-back ratio. In order to achieve these objectives, both configurations are subjected to an optimization procedure by varying their physical dimensions.

A conventional PIFA is depicted in Figure 1. PIFA consists of a ground and a top plane, interconnected with shorting strip and a feed wire. By altering the dimensions of the top plate, the height above the ground plane, and the size of the ground plane itself, a variation of the resonant frequency and impedance bandwidth is observed. Firstly, a conventional PIFA is designed and the ultimate modified PIFA is obtained by changing the shape (inserting holes) of the top plate.

Thereafter, a helical antenna above a finite square ground plane operating in the axial mode suitable for GNSS applications is considered (Figure 2). The presence of the ground plane enhances the performance of the antenna in terms of bandwidth and directivity.

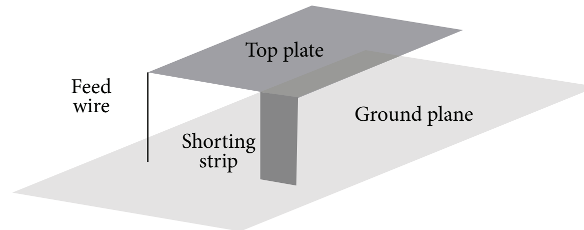


Figure 1: A conventional PIFA.

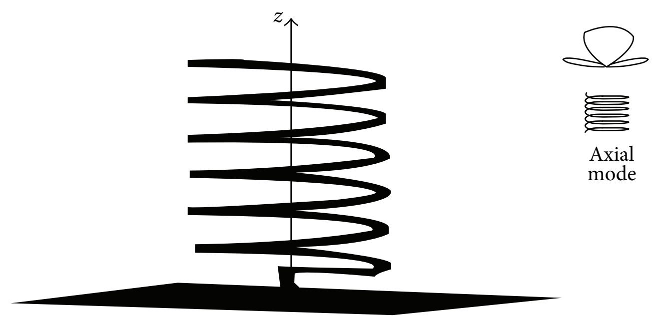


Figure 2: A helical antenna above ground plane operating on axial mode.

Moreover, a broadband circular switched parasitic antenna (CSPA) with two active elements, suitable for WiMAx applications, is proposed. The array under consideration consists of five elements (dipoles); one fixed parasitic element is placed at the center of the structure, while the four remaining elements form a circle surrounding it. As displayed in Figure 3, two neighboring peripheral elements are connected to identical replicas of the source signal, while all the rest parasitic elements are short-circuited. The main beam direction is steered by switching the position of the active and the parasitic elements along the circumference of the array. The objective of this design is to obtain a configuration capable of producing four directional radiation patterns, covering the whole azimuth plane with main beams oriented towards 0°, 90°, 180°, and 270°. Moreover, 3 dB beamwidths of 90° and relative sidelobe levels of no more than −6 dB and a sufficient input impedance matching bandwidth are required. Due to symmetry, only the radiation pattern pointing towards 0° needs to be optimized. The frequency band that will be examined regards the [3300 MHz, 3800 MHz] band allocated for WiMax applications. Optimization parameters include the length of the central element, the length of the peripheral elements, and the radius of the array.

2. Materials and Method

Simulation and design of the aforementioned antenna systems are made feasible with the aid of the SuperNEC software package. SuperNEC is a hybrid MoM, UTD (uniform theory of diffraction) antenna and electromagnetic simulation

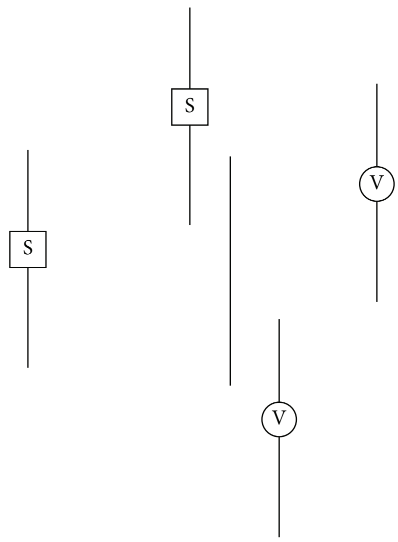


Figure 3: A 5-element CSPA.

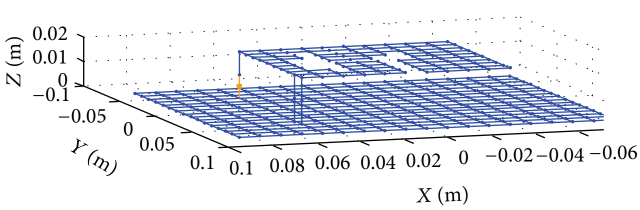


Figure 4: Implementation of the modified PIFA with SuperNEC.

program. The MoM primitives available in the code are wire segments, whereas the UTD primitives supported are dielectrically coated plates and elliptical cylinders. The MoM is a numerical electromagnetic technique used to compute the radiation pattern and input impedance of wire-structured antennas [66]. The optimization procedure per structure is performed by employing the GA module included in the package [67].

2.1. Design of the Modified PIFA. For software compatibility reasons, the ground plane, the top plate, and the shorting strip of the PIFA are modeled as wire grid plates. Moreover, the feed wire is excited by an applied field voltage source (Figure 4). The final PIFA structure is implemented in such a way that the input values of the user-defined dimensions for each component of this structure are given in terms of the number of wire segments, instead of their physical values. Taking into consideration that the segment length (seglen) is a fraction of the wavelength, λ, at 1575 MHz, the electrical size of the PIFA is kept constant. This concept ensures compatibility via the handling of the PIFA structure in the SuperNEC design procedure. Each segment length was selected to be equal to seglen = 0.05 λ.

The variation of parameters that took part in the GA optimization procedure is included in Table 1. The optimum value for the voltage standing wave ratio (VSWR) is 1 (with a characteristic impedance of 50 Ω as reference value) and the desired gain is 9 dBi. The objective function (OF) used to evaluate the solutions is given in (1). This function was built in SNEC, where the user is enabled to determine the required VSWR and gain values:

Table 1: Input parameters and results of the GA optimization procedure for the PIFA.

Parameter	Variation range	GA result
Top plate length	2 seglen–16 seglen	10 seglen
Top plate width	3 seglen–10 seglen	9 seglen
Ground plate length	2 seglen–24 seglen	20 seglen
Ground plate width	3 seglen–24 seglen	15 seglen
Height	1 seglen–4 seglen	2 seglen
Shorting strip width	1 seglen–4 seglen	1 seglen

$$\mathrm{OF} = \sum_n \left[\left(\frac{G(f_n)}{9} \right)^2 + \left(\frac{1}{\mathrm{VSWR}(f_n)} \right)^2 \right], \tag{1}$$

where f_n are the 3 frequency points of interest (1575, 1227, and 1176 MHz), while $G(f_n)$ and $\mathrm{VSWR}(f_n)$ are the front gain at ($\varphi = 0^\circ$, $\theta = 0^\circ$) and the VSWR values referring to the frequency point f_n.

The total population consists of 250 generations, with 60 chromosomes per generation. The selection method was population decimation, while adjacent fitness pairing was the mating scheme. The crossover point was chosen randomly and each chromosome was divided at a gene level. The mutation probability was equal to 0.15.

To obtain a more suitable configuration, which will be more compliant to the design constraints, the shape of the top plate is modified by deleting segments manually. The resulting structure is therefore a modified PIFA, depicted in Figure 4, and its dimensions are approximately 17.1 cm × 14.28 cm × 2 cm.

2.2. Design of the Helical Antenna above Ground Plane. The SNEC implementation of the helical antenna above ground plate is displayed in Figure 5. Each GA solution string of the helix geometry (representing the corresponding varying parameters) comprised possible values of the space between the helix turns, the helix length, the radius of the bottom and top turns, and the size of the square plate. The height of the helix above the conductive plane and the wire radius were kept constant and were equal to 1 cm and 4 mm, respectively.

Again, the design requirements are to achieve a value of 1 and 9 dBi for the VSWR and the front gain, respectively; thus the objective in (1) is used. The selection method is population decimation, while adjacent fitness pairing is the mating scheme. The crossover point was chosen randomly and each chromosome is divided at a gene level. The mutation probability is equal to 0.15. The variation intervals of the GA structure parameters and the final results of the implementation of the GA algorithm are depicted in Table 2.

TABLE 2: Input parameters and results of the GA optimization procedure for the helical antenna.

Parameter	Variation intervals (mm)	Results (mm)
Turn spacing	5–20	17
Length of the helix	60.1–99.9	85.4
Base radius	20–40	38
Tip radius	25–35	27
Length (width) of ground plane	40–120	100

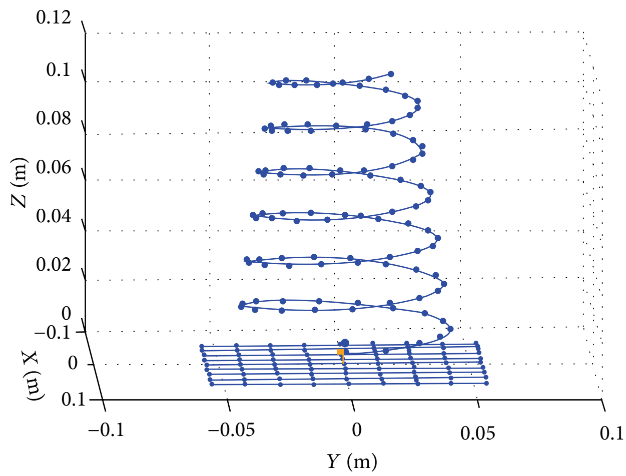


FIGURE 5: Implementation of the helical antenna above finite ground plane with SuperNEC.

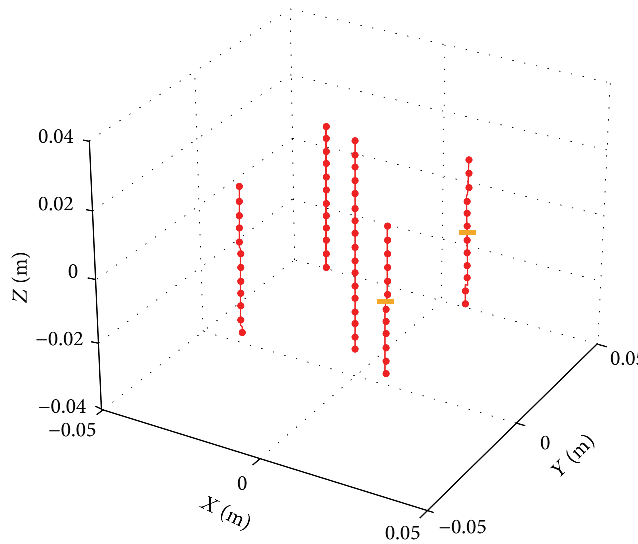


FIGURE 6: Implementation of the proposed circular switched parasitic array with SuperNEC.

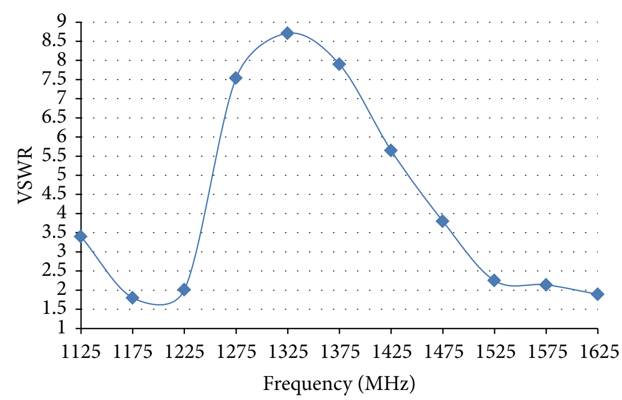


FIGURE 7: VSWR variation for the modified PIFA.

2.3. Design of the Circular Switched Parasitic Array. The SNEC implementation of a 5-element CSPA antenna, with two adjacent peripheral elements active, a central parasitic element short-circuited, and the remaining peripheral parasitic elements short-circuited, above a square wire grid plate is displayed in Figure 6.

As already being pointed out, only the radiation pattern pointing towards 0° needs to be optimized. The other three diagrams, which will have the same shape with the only difference that the main beams are oriented at the direction of 90°, 180°, and 270°, respectively, are obtained when the adjacent active elements are interchanged in a rotational manner around the array, because of the symmetry that this array exhibits.

A set of 360 points is used to specify the radiation pattern. Let $G(\varphi)$ be the directivity determined with an angular step of 1° and $G_{\max}$ the maximum directivity.

The objective function is formed as follows [68].

Within the main lobe, which is shaped by taking into account 89 points, the error term is

$$e_1 = \frac{1}{89} \sum_{\phi=-44^\circ}^{44^\circ} \left[\left(\frac{G(\phi)/G_{\max} - 0.5}{0.5} \right)^2 u \left(0.5 - \frac{G(\phi)}{G_{\max}} \right) \right], \quad (2)$$

where $u(x)$ is the step function defined as

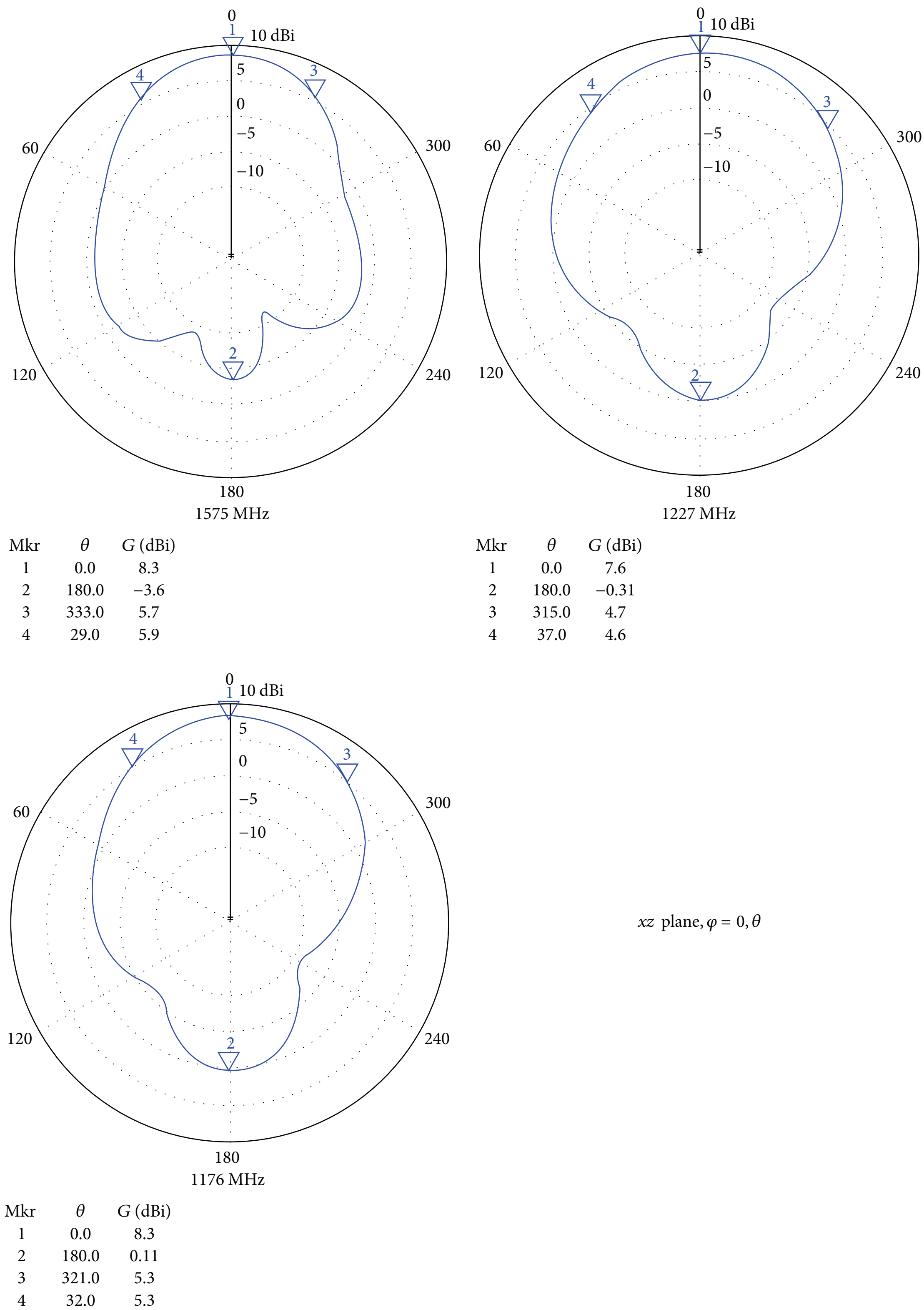
$$u(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0. \end{cases} \quad (3)$$

At the main lobe ends the desired lobe level is 3 dB below the maximum gain; thus the associated error term is

$$e_2 = \frac{1}{2} \sum_{f} \sum_{\phi=\pm 45^\circ} \left(\frac{G(\phi)/G_{\max} - 0.5}{0.5} \right)^2. \quad (4)$$

Outside the main lobe, where there exist 269 points, the relative sidelobe level should not exceed −6 dB. Therefore, the error term is

$$e_3 = \frac{1}{269} \sum_{f} \sum_{\phi=46^\circ}^{314^\circ} \left[\left(\frac{G(\phi)/G_{\max} - 0.25}{0.25} \right)^2 u \left(\frac{G(\phi)}{G_{\max}} - 0.25 \right) \right]. \quad (5)$$



1575 MHz

Mkr	θ	G (dBi)
1	0.0	8.3
2	180.0	−3.6
3	333.0	5.7
4	29.0	5.9

1227 MHz

Mkr	θ	G (dBi)
1	0.0	7.6
2	180.0	−0.31
3	315.0	4.7
4	37.0	4.6

1176 MHz

Mkr	θ	G (dBi)
1	0.0	8.3
2	180.0	0.11
3	321.0	5.3
4	32.0	5.3

Figure 8: Radiation patterns at xz plane for the modified PIFA at 1575 MHz, 1227 MHz, and 1176 MHz.

Table 3: Input parameters and results of the GA optimization procedure for the 5-element circular switched parasitic element with two active elements.

Parameter	Range of variation	Step of variation	GA result	Results in physical dimensions
Length of central element	$0.05\lambda_o : 2.05\lambda_o$	$0.05\lambda_o$	$0.8\lambda_o$	6.31 cm
Length of peripheral elements	$0.05\lambda_o : 2.05\lambda_o$	$0.05\lambda_o$	$0.55\lambda_o$	4.34 cm
Distance between central and peripheral elements	$0.05\lambda_o : 0.5\lambda_o$	$0.05\lambda_o$	$0.4\lambda_o$	3.16 cm

Table 4: Properties of the proposed modified PIFA.

Frequencies	VSWR	Gain (dBi)	Front-to-back ratio (dB)	3 dB beamwidth
L1 (1575 MHz)	2.14	8.8	12.4	56°
L2 (1227 MHz)	1.86	7.6	7.91	82°
L5 (1176 MHz)	3.41	8.3	8.19	71°

Table 5: Properties of the proposed helical antenna above ground plane.

Frequencies	VSWR	Gain (dBi)	Front-to-back ratio (dB)	3 dB beamwidth
L1 (1575 MHz)	1.94	10	25	60°
L2 (1227 MHz)	1.58	9.5	10.27	62°
L5 (1176 MHz)	1.77	9.1	8.64	64°

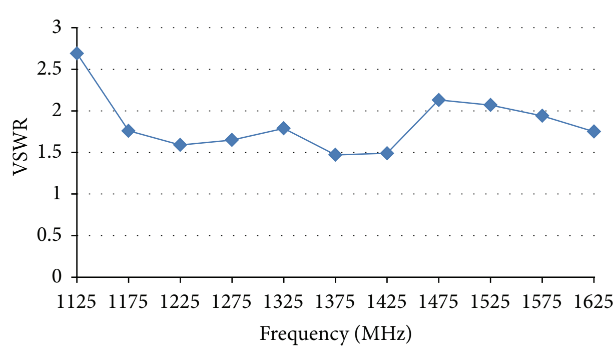


Figure 9: VSWR variation for helical antenna above ground plane.

In order to simultaneously attain a driving impedance matching to 50 Ω feeding line at each active element, an additional error term is computed as

$$e_4 = \text{abs}\left(\frac{R_{\text{in}} - 50}{50}\right)^2 + \text{abs}\left(\frac{X_{\text{in}}}{50}\right)^2, \quad (6)$$

where R_{in} and X_{in} correspond to the real and imaginary part of the input impedance, respectively.

Given the fact that the designed procedure aims at the achievement of the desired attributes over a frequency band, the procedure described so far is repeated for a number of discrete frequencies P lying within this band and the total cumulative error is calculated as

$$\text{err} = \frac{1}{P} \sum_{p=1}^{P} \sum_{i=1}^{4} w_i e_i \left(f_p\right), \quad (7)$$

where

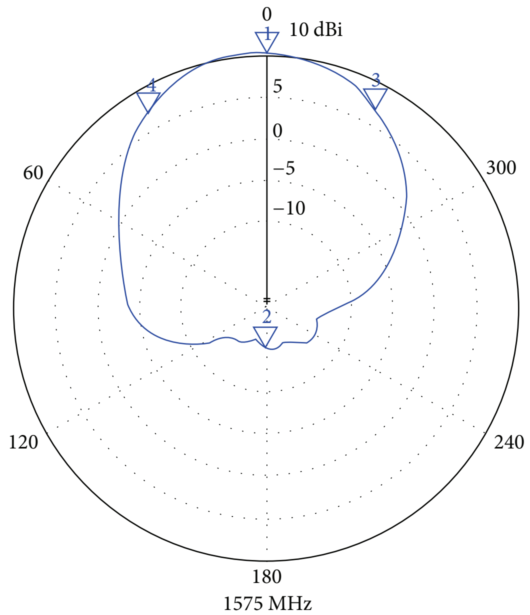
$$f_p = f_L + (p - 1) \frac{f_U - f_L}{P - 1} \quad (8)$$

are uniformly distributed frequency points in the bandwidth interval $[f_L, f_U]$ and $e_i(f_p)$ is the ith relative error which refers to frequency point f_p.

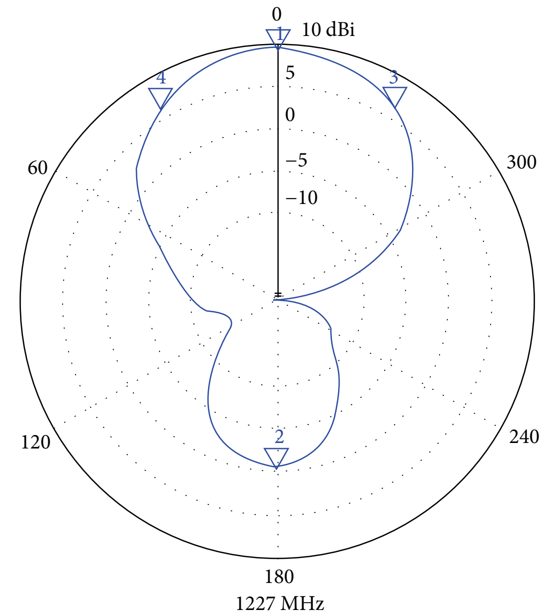
After the total error is found, the objective function is estimated as

$$\text{OF} = \frac{1}{1 + \sqrt{\text{err}}}. \quad (9)$$

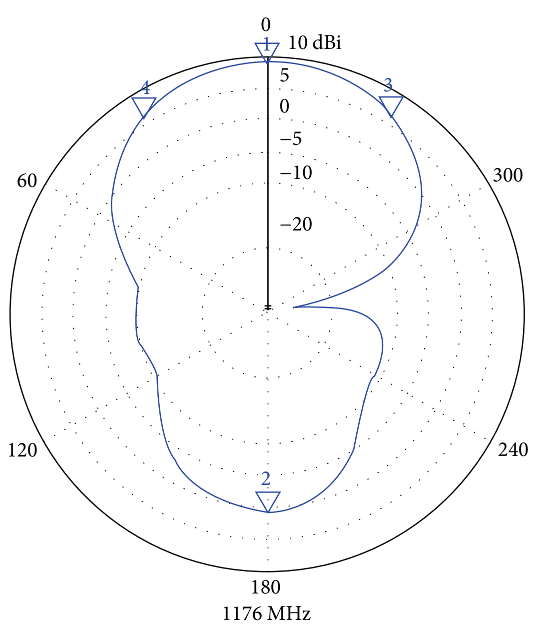
During the specific design, 5 frequency points are involved in the overall process, uniformly distributed in the interval [3300 MHz, 3800 MHz], in order to guarantee that the final configuration exhibits broadband attributes with respect to radiation patterns and the input impedance.



Mkr	θ	G (dBi)
1	0.0	10
2	181.0	−15
3	331.0	6.9
4	31.0	7



Mkr	θ	G (dBi)
1	360.0	9.5
2	180.0	−0.76
3	329.0	6.6
4	31.0	6.4



Mkr	θ	G (dBi)
1	360.0	9.1
2	180.0	0.49
3	328.0	6.1
4	32.0	6.2

xz plane, $\varphi = 0, \theta$

Figure 10: Radiation patterns at xz plane for the helical antenna above ground plate at 1575 MHz, 1227 MHz, and 1176 MHz.

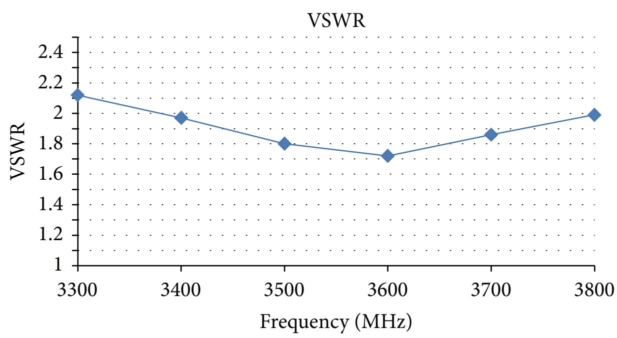


Figure 11: VSWR variation for the circular SPA with two active elements.

Let λ_o be the wavelength at 3800 MHz. In Table 3, the range of each component parameter taking part in the optimization procedure is shown. The wire radius of each element is $0.008\,\lambda_o$. A total of 250 generations are simulated, with 60 chromosomes per generation. The selection method is population decimation, while adjacent fitness pairing is the mating scheme. The crossover point is chosen randomly and each chromosome is divided at a gene level. The mutation probability is equal to 0.15.

3. Results

3.1. Numerical Results of the Modified PIFA. In Table 4 the properties of the resulting configuration are summarized.

The VSWR variation of the modified PIFA is plotted in Figure 7.

The far field patterns of the PIFA are plotted in Figure 8. As it can be drawn out from this figure, the highest gain is computed at the ($\varphi = 0^\circ, \theta = 0^\circ$) directions. Its value is totally appropriate for the GNSS applications, where this antenna is intended to operate.

3.2. Numerical Results of the Helical Antenna above Ground Plane. The dimensions of the resulting structure are approximately 10 cm × 10 cm × 10 cm, as it can be extracted from Table 2. In Table 5 its attributes are summarized.

A remarkable characteristic concerns the low values of VSWR, which are always below 2.

The VSWR variation for the helical antenna is plotted in Figure 9.

The far field patterns of the helical antenna are plotted in Figure 10. As it can be drawn out from this figure, the highest gain is computed at the ($\varphi = 0^\circ, \theta = 0^\circ$) directions. Its value is totally appropriate for the GNSS applications, where this antenna is intended to operate.

3.3. Numerical Results of the Circular Switched Parasitic Array. The final results of the algorithm are included in Table 3. In Figure 11, the variation of VSWR at each feed point within the frequency band of [3300 MHz–3800 MHz] is plotted. It is important that VSWR is kept below 2 for the entire frequency zone of interest.

Table 6: Properties of radiation patterns of the CSPA.

Frequencies	Gain (dBi)	Front-to-back ratio (dB)	3 dB beamwidth
3300 MHz	6.3	7.11	90°
3500 MHz	5.2	8.3	100°
3800 MHz	4.5	6.8	96°

The azimuth far field radiation patterns for this structure at 3300 MHz, 3500 MHz, and 3800 MHZ are also presented in Figure 12. The shape of the radiation pattern generally satisfies the specifications within the frequency range of 3300 MHz–3800 MHz. More details are provided in Table 6.

The main advantages of employing this specific antenna system include the following.

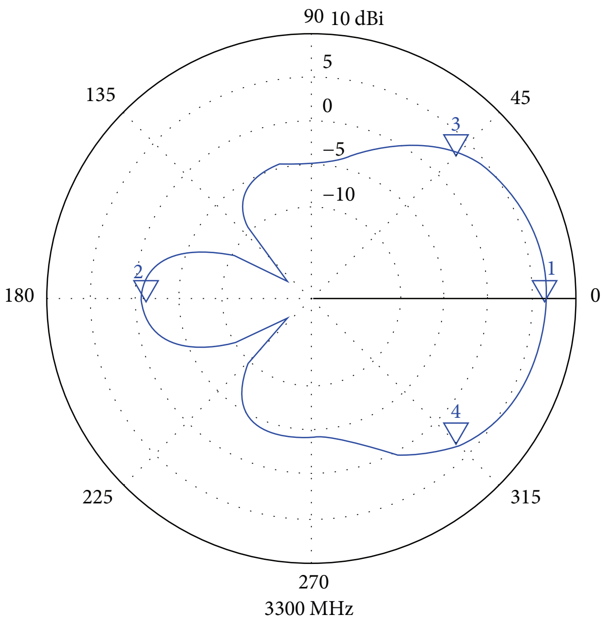
(i) In a fading environment the user has the possibility to select among the four predefined beams the one that provides highest signal level.

(ii) As it can be extracted from Table 6, the array exhibits significant front gain (4.5–6.3 dBi), outperforming conventional dipoles already used for WiMax applications. This can be proved very effective in cases where the Wimax service providers are not allowed to increase their radiated power to improve their coverage.

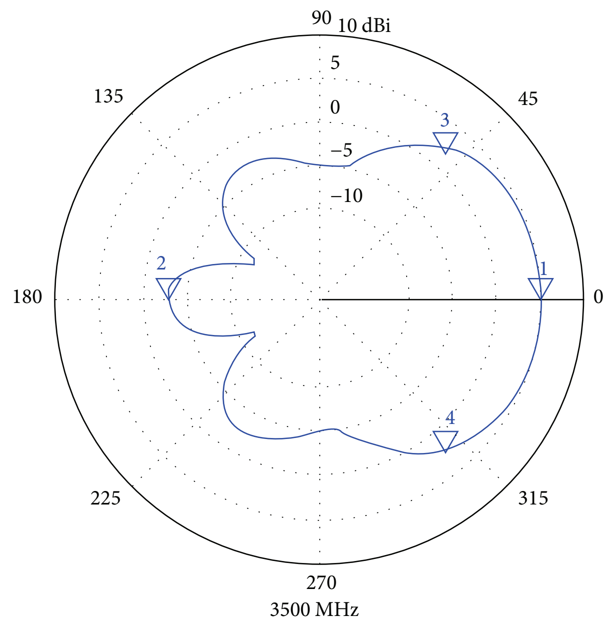
(iii) Its overall size is considered rather compact and therefore easy to be installed.

4. Conclusions

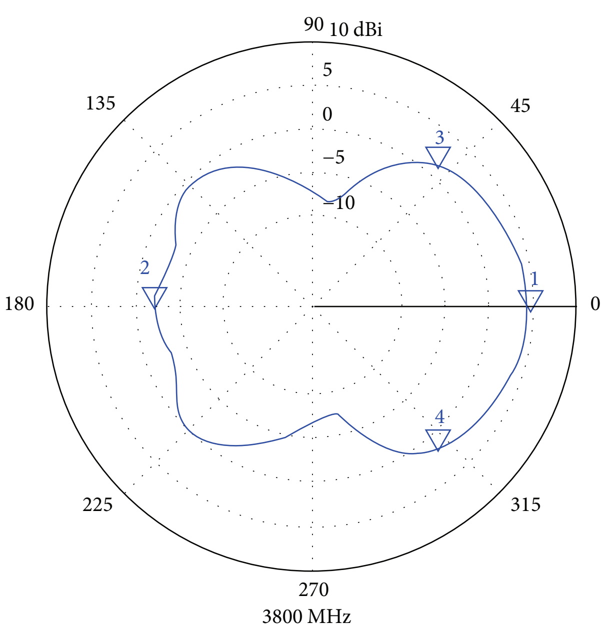
This paper aims to present the new challenges and the progress in the field of GAs methods in antenna engineering. Firstly, the application of GA to several antenna design and optimization problems covering diverse areas of interest is cited. Subsequently, in order to demonstrate how a GA is employed in antenna design, three antenna systems are developed, proposed for modern commercial applications: a modified PIFA and a helical antenna for GNSS solutions and a SPA for WiMAx solutions. In all of these cases, where the optimal design of an antenna structure is searched out, each member of the population in the GA is an antenna representing a possible solution and therefore its electromagnetic properties are analyzed. By applying the mechanisms of GA, the final configuration is derived, which satisfies the most of the design requirements.



Mkr	ϕ	G (dBi)
1	0.0	5.3
2	180.0	−0.81
3	45.0	3.3
4	315.0	3.3



Mkr	ϕ	G (dBi)
1	0.0	5.2
2	180.0	−3.1
3	50.0	2.2
4	310.0	2.2



Mkr	ϕ	G (dBi)
1	0.0	4.5
2	180.0	−2.3
3	48.0	1.5
4	312.0	1.5

xy plane, $\theta = 90, \varphi$

Figure 12: Radiation patterns at xy plane for the CSPA at 3300 MHz, 3500 MHz, and 3800 MHz.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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