Genetic algorithm optimization applied to planar and wire antennas

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Genetic Algorithm Optimization Applied to Planar and Wire Antennas

by

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Electrical Engineering.

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August 2007
Acknowledgements

This work was partially supported by Pro-Tech, of Alamo, CA. I would like to thank Dr. Giri for his guidance and financial support.

My sincerest thanks to:

Marinda. My role model, my big sister, and my biggest supporter in all I do.

My grandparents. Your love and support mean more to me than words can express. You make coming home one of my greatest joys.

My advisor, Dr. Venkataraman. Your guidance and support have been invaluable. Your dedication to teaching is an inspiration which has helped set me on the path to my own academic career.

My committee members, Dr. Amuso and Dr. Peskin. Your time and assistance on my academic journey are greatly appreciated.

My professors at RIT, especially Dr. Moon, Dr. Amuso, and Dr. Venkataraman. You have all caused my passion for learning to grow and have helped me realize the kind of teacher that I would one day like to be.

My friends. Last, but definitely not least. You have all made these past five years a treasure. I thank each of you for the smiles, the laughter, and the memories. Jimy and Avery, I can’t imagine school without you. Much of what I have accomplished would not have been done without you, including this thesis. Marie, Danny, and George, your timely distractions kept me laughing and sane, while your hard work kept me motivated and inspired.
Abstract

Antenna design has grown more stringent and difficult over the years as the world becomes strictly a wireless environment. The inherent tradeoffs that exist between gain, radiation pattern, bandwidth, and physical size and the multiple parameters that must be considered make antenna design a lengthy and tedious process. Methods have been devised which automate this complex process of antenna optimization through the use of genetic algorithms, particle swarm optimization, and simulated annealing. Genetic algorithms are capable of handling a large number of design parameters and work for optimization problems that have discontinuous or non-differentiable multi-dimensional solution spaces, making them ideal for antenna optimization. In the present work, a genetic algorithm has been used for size reduction in microstrip patch antennas and design tradeoff optimization between beamwidth and gain in helical antennas.

A method for reducing the size of microstrip patch antennas by up to 75% by removing rectangular and circular slots from the metal of the microstrip patch is presented. A solid patch antenna that resonates at 10 GHz is forced to resonant at 6 GHz through the removal of the different shaped slots. Given the number and shape of the slots, the genetic algorithm is used to optimize the size and location of the slot on the patch. The designs are obtained by interfacing the genetic algorithm and Ansoft High Frequency System Simulator (HFSS) and validated through design, construction, and testing.
High gain, with broad half-power beamwidths (HPBW) is traditionally extremely difficult to achieve due to the inherent tradeoff between the two. A genetic algorithm has been applied to design a helical antenna with a gain of 10 dB and HPBWs of 60 degrees. In order to achieve this, three physical parameters of the helix have been changed, namely the pitch, helix radius, and the ground plane geometry. The second objective is to create an antenna that displays different HPBWs in the two radiation planes. This could be extremely useful in many communication environments and there is yet no existing method to achieve this. The genetic algorithm produced a helical antenna that shows a 19 degrees difference in HPBW between the two radiation planes, while still displaying a 7 dB gain and low side lobes. Numerical Electromagnetic Code 4 (NEC4) is used, and a method of communication between MATLAB and NEC4 has been developed to make the genetic algorithm optimization possible.
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1 Introduction

1.1 Motivation

In recent years, the use of evolutionary algorithms to optimize antenna designs has shown tremendous growth. Genetic algorithms (GA) [1] are global optimization techniques that are based on the Darwinian theory of natural selection and evolution. Genetic algorithms offer many advantages over traditional numerical optimization techniques including the ability to use both continuous and discrete parameters, search across a wide sampling of the solution space, and handle a large number of variables. Derivative information of the performance surface is not needed by the GA, which eliminates many of the difficulties associated with traditional gradient-based algorithms. For these reasons, and the overall simplicity to both understand and implement, genetic algorithms have become a popular and powerful optimization technique.

Holland first introduced GA’s in 1975 [1], but they were not applied to practical problems till Goldberg in the late 80s and early 90s [1]. In the 90s, GA’s used within electromagnetics have been most often applied to antenna array design for array thinning, beamforming, and sidelobe minimization [1]. In the past few years, the use of genetic algorithms have spread to the design of single antennas in order to optimize parameters such as size, bandwidth, efficiency, radiation pattern, and gain [1].

The genetic algorithm searches the performance surface by randomly combining different values of each variable together to create a set of possible solutions. A fitness function is used to assign a fitness value to each possible solution within the set. Two
solutions that receive higher fitness values are then combined together to produce another possible solution that exhibit characteristics of both. This process of fitness ranking and recombining is repeated many times until an optimal solution is reached. A detailed explanation of genetic algorithms can be found in Chapter 2.

1.2 Microstrip Patch Antennas

Due to the huge demand for smaller cell phones and other mobile communication devices, it is becoming increasingly important to reduce the size of antennas. Due to the mass production nature of the cell phone market, it is also important for the antennas to be inexpensive and easy to produce.

Many techniques have been used to attempt to achieve this reduction in size with varying success. It has been shown that increasing the effective dielectric constant of the substrate will lead to decreased dimensions [2], [3]. While this approach is straightforward, the materials used to produce this high permittivity are generally lossy in nature, expensive, and can increase the sensitivity of the design to small changes in antenna dimensions. A superstrate can be added to achieve a higher dielectric constant [4], however, the required thickness of the superstrate adds to the fabrication process and can lead to a large patch profile.

Shorting pins can be used to reduce the size of a patch antenna to about half of the original dimensions [5]. When placed in the middle of the antenna, the shorting strips make use of image theory to act as a mirror and thus cause the antenna to behave as if it was double its actual length [6]. Shorting pins however often produce antennas with a narrow bandwidth and a low gain [7]. Decreasing the dimensions of a patch antenna
results in a strong reactive input impedance. This reactance can be equalized through capacitive loading, allowing size reduction. However, this loading reduces the efficiency of the antenna and shrinks the antenna bandwidth [6].

Altering the geometry of the patch antenna can cause a size reduction. Cutting slots into the patch force the surface currents to meander thus effectively creating a longer electrical length and reducing the size of the antenna. It had been shown that the gain of the antenna suffers when employing this method however, due to the ohmic loss from the increased surface current [6]. Cutting slots into the ground plane can also cause a size reduction [8].

Recently, evolutionary algorithms, such as a genetic algorithm (GA) and particle swarm optimization (PSO) have been used to optimize patch antennas [9], [10], [11], [12].

1.2.1 Genetic Algorithms and Microstrip Patch Antennas

The use of genetic algorithms in optimizing microstrip patch antennas is relatively recent, with the majority of research occurring in the past few years. The objective is to create novel, non-intuitive shapes that fulfill the optimization criteria, such as a broad bandwidth, dual frequency, or small physical dimension.

A genetic algorithm was used to determine the patch length and width and feeding point in the design of a coaxially fed circularly polarized rectangular patch antenna [9]. The fitness function was derived from the cavity model and evaluated such antenna characteristics as input impedance, effective loss tangent, and axial ratio [9]. A stacked patch antenna that exhibited broadband operation was designed using a GA. The GA
controlled numerous variables including the size of each patch, the thickness and permittivity of each dielectric slab, and the feed location. Method of moments software was used to analyze the fitness of each antenna based on broadside gain and input impedance [1]. The bandwidth of a microstrip patch antenna was also broadened by using a GA to optimize the feed network [14]. A dual-band microstrip patch antenna was designed using genetic algorithms to control the position of multiple slots or shorting pins between the patch and ground. Multiport analysis was used to determine the effects of the slots or pins on the input impedance, and thus assign fitness values to each of the antennas [15].

Genetic algorithms can also be used to change the shape of the patch itself and thus optimize the antenna. By dividing a regular square microstrip patch antenna into a grid of symmetrical squares, and using genetic algorithms to selectively remove the smaller metallic grid squares from the patch, novel non-intuitive shapes can be produced. This method has been employed to create dual-band antennas [16]. An example is presented in [17] where a microstrip patch antenna’s resonant frequency is reduced from 3 GHz to 1.8 GHz by dividing the patch into 9 by 9 cells and selectively eliminating certain cells from the metallic patch. The resonant frequency of the antenna was found using the software tool PATCH. This shift in resonant frequency creates a size reduction of 42% when the GA-optimized patch is compared to the standard square microstrip patch that would resonant at 1.8 GHz.
1.3 Helical Antennas

Helical antennas are popular for communication due to their broadband nature, high gain, and circular polarization. Conventional helical antenna design is accomplished through the use of multiple design graphs, empirically developed gain equations, and extensive hand-tuning. These graphs and equations have been developed over the five decades since the realization of the first helical antenna by Kraus in 1946 [18]. A few modifications have been made to the original helical antenna to improve its radiation characteristics. The geometry of the reflector that is positioned at the base of the antenna to reflect back radiation and improve forward gain has been altered into many different shapes. Squares, circles, cylinders, cones, and cup-shaped reflectors have all been used with varying success to increase the directivity of the helical antenna. The end of the helix can also be tapered in order to improve Voltage Standing Wave Ratio (VSWR), bandwidth, and axial ratio. Studies have shown that tapering leads to a more gradual helix-to-free-space transition and a reduction of reflected energy [19]. In addition to tapered ends, tapered feeds are also helpful in lowering axial ratio and VSWR. Using different pitch angles within the same helix, called a multi-pitch helix, can improve the gain, axial ratio, and antenna bandwidth and can also make the antenna resonant at multiple resonant frequencies [20].

1.3.1 Genetic Algorithms and Wire Antennas

There are numerous parameters that must be considered when designing a helical antenna that all interact in different ways to affect the gain, input impedance, and radiation pattern of the antenna. Genetic algorithms are uniquely suited to handling a
large number of parameters and thus are a logical choice to use when designing antennas with many variables such as helical antennas. While no work has been done with helical antennas, genetic algorithms have been used to optimize various other types of wire antennas. Altschuler and Linden used genetic algorithms to design four different types of linear antennas in 1997 [21]. A loaded monopole was designed that delivered uniform power over the entire radiation hemisphere. Two different Yagi antennas were designed using a GA, one being a broadband antenna that exhibited very low side and back lobes and the other being a high gain antenna where side lobes were ignored. The final antenna designed by Altschuler and Linden was a “crooked-wire” antenna which was not based on any existing antenna geometry. Instead, the GA was allowed to place wires randomly within a predefined space in order to synthesize a small antenna that produced uniform gain with circular polarization. Linden used this concept a few years later when he was involved with developing an antenna for a National Aeronautics and Space Administration (NASA) mission that was required to be circularly polarized with a wide beamwidth and a large bandwidth [22]. Linden also used genetic algorithms to design a twisted Yagi antenna that exhibited circular polarization and high gain, making it an attractive alternative to the helical antenna [23].

1.4 Major Contribution of Present Work

A planar antenna and a wire antenna are optimized using a genetic algorithm for two different optimization criteria. In the present work, a new methodology of removing
solid slots from a microstrip patch antenna is used to cause the size reduction, rather than removing random pixels spread throughout the patch. The present work is the first to demonstrate genetic algorithm optimization of helical antennas.

A size reduction is achieved for a microstrip patch antenna by removing rectangular and circular slots from the copper of the patch. A genetic algorithm is used to optimize the dimensions and position of the slot to create a four GHz frequency shift and thus a 75% size reduction. The results are experimentally validated.

In order to apply the genetic algorithm to the helical antenna, a method of communication between Graphical Numerical Electromagnetic Code (GNEC) and MATLAB was developed. The effect of changing the various helical antenna parameters has been examined including non-uniform turn spacing, non-uniform helix radius, an elliptical antenna shape, an elliptical ground plane, and a cone-shaped ground plane. A helical antenna with 19 degrees of separation between the HPBWs in the two radiation planes with a gain of 7 dB has been achieved by using a genetic algorithm to vary the helix radius, and ground plane geometry while holding the remaining parameters constant. A helical antenna with a high gain of 10 dB and broad beamwidths of 60 degrees has also been optimized where all parameters are allowed to change.

1.5 Organization
This work is divided into 6 chapters. The first chapter is an introduction and gives the motivation for the work being presented. A summary of previous techniques used to reduce the size of patch antennas is presented, along with the work that has been done with patch antennas specific to genetic algorithms. A brief overview of the work done
with wire antennas using genetic algorithms is also presented. Chapter 2 gives an overview of genetic algorithms. Chapters 3 and 4 are detailed explanations of how the genetic algorithm is applied to the optimization problems. An explanation of how HFSS and GNEC are used to evaluate the antennas is presented along with the methods used to encode chromosomes and calculate the fitness of each individual. The results of the genetic algorithm optimization are presented in chapter 4, along with the specific GA parameters used for each separate algorithm run. The simulated results for all antennas are also shown in chapter 4. The experimental results from the microstrip patch antennas are shown in chapter 5. Lastly, chapter 6 gives a conclusion of the work and a list of future considerations.

2 Genetic Algorithms

As genetic algorithms (GA) are modeled after the processes of evolution and genetic recombination, the building blocks of the algorithms are named after genetic elements. Genes are the binary encoding of each problem variable, and all of the genes as a string are referred to as a chromosome. A set of chromosomes is called a population. Each chromosome in a population has a fitness associated with it, which is calculated through a fitness function. The chromosomes in each population are ranked from best to worst based on their fitness. The higher ranked chromosomes are mated to produce a new population that exhibits characteristics of the better individuals from the previous generation. Mutation is allowed to occur at a small probability. This process repeats until either a desired fitness has been achieved or a set number of generations has occurred. A simple GA has the following steps:
1. Generate an initial random population of chromosomes.

2. Evaluate the fitness of each population member.

3. Rank the individuals based on fitness.

4. Generate offspring by mating good individuals.

5. Mutate selected members of the offspring.

6. Terminate if conditions have been met or continue back to step 2.

The flow chart of a basic genetic algorithm just described is shown in Figure 2-1.

Figure 2-1: Flow chart for simple genetic algorithm
2.1 Defining Genes and Chromosomes

Each variable in the optimization problem must be coded as a gene, and all variables concatenated together form a chromosome. The sample chromosome shown in Figure 2-2 is composed of N parameters with each parameter containing 5 binary digits.

![Image](image_url)

**Figure 2-2: Example chromosome with N parameters composed of 5 binary digits each**

Each gene $q_n$ has a mapping from the chromosome space to the parameter space. It is important to fully understand the range and precision necessary for each variable so that the entire solution space can be explored and also to ensure that each gene, and thus each chromosome, generated by the GA is a realizable solution to the optimization problem.

2.2 Evaluating Fitness

The fitness function is the most important part of a genetic algorithm, as it is part of the algorithm that forms the connection to the physical problem being optimized. The fitness function must assign a number to each individual that is a measure of the goodness of the present individual in relation to the optimization goals. The success of the algorithm is dependent on how well the fitness function evaluates each solution in relation to the overall objectives of the optimization problem. The fitness function is generally the most time-intensive part of a genetic algorithm, so is also important when considering the time efficiency of the optimization algorithm.
2.3 **Selection of the Fittest**

There are many methods used to determine which individuals should be used as parents, the four most popular being population decimation, roulette wheel selection, tournament selection, and stochastic universal sampling.

In population decimation [1] the individuals are ranked from highest to lowest based on their fitness. A minimal fitness is chosen as the cut-off and any individuals with a lower fitness than this threshold is removed from the population. The remaining individuals are randomly paired to produce offspring and create the next generation. The advantage of population decimation is the simplicity of its implementation. However, this simplicity is offset by the tendency to eliminate unique characteristics of the population thus decreasing the diversity of the sample population at a very early stage.

Roulette wheel selection [1] assigns a selection probability to each individual in the population based on relative fitness values. Figure 2-3 shows how individuals are assigned a space on the wheel that is directly related to their relative fitness. The wheel is “spun” and the result of the spin selects the individual to use in the mating process. Individuals with high fitness values will be selected as parents more frequently than the less-fit individuals causing characteristics associated with higher fitness values to be represented more in subsequent generations. However, it can be seen that there is still a small probability that an individual with a low fitness value will be selected for the mating process, thus preserving their genetic information and maintaining a higher level of diversity.
In tournament selection [1], a sub-population of N individuals is chosen at random from the population and compete based on their fitness values. The individual with the highest fitness value wins the tournament and is selected as a parent in the mating pool. All the sub-population members are returned to the general population and the process repeats till the mating pool is full. Tournament selection acts much as roulette wheel selection, with the more fit individuals having a higher probability of selection while still maintaining the diversity of the population. The advantage of tournament selection is the absence of fitness ranking, which makes it a faster process than roulette wheel selection.

Stochastic universal sampling (SUS) [25] is much like roulette wheel selection, where all of the individuals in a population are assigned a selection probability based on relative fitness. In roulette wheel selection, each individual selected is a random “spin” of the wheel, so each individual selected requires its own “spin”. SUS uses a single random “spin” to select all of the individuals in the mating pool by selecting them at evenly spaced intervals. Figure 2-4 depicts the SUS selection process. First, the all the individuals are assigned a selection probability based on their relative fitness values, as
depicted by (a). The next generation population is split into evenly spaced slices as shown in (b), where 8 children, each child represented by a line, will be produced from the current 8 individuals in (a). The “child wheel” is randomly “spun” as shown in (c), and then overlaid over the parent wheel as shown in (d). The number of child lines that intersect the parent slices is the number of children that the parent will produce. In the illustrated case, individuals 1, 2, 3, 4, and 5 will be used once in the mating process, while individual 8 will be used three times, thus creating a next generation population of eight, as each pairing produces two children. SUS sampling retains the advantages of roulette wheel selection, while providing the advantage of speeding up the selection process by eliminating the need to generate multiple random selections.
2.4 Generating Offspring

Offspring are generated from two parents through the process of crossover. There are many variations of crossover, but the most popular methods include uniform, single-point, and multiple-point crossover. Single point crossover [1] is the simplest. A random location in the parent’s chromosome is selected and the portion preceding that location is
copied from parent 1 to child 1 and from parent 2 to child 2. The portion of the chromosome following this point is copied from parent 1 to child 2 and from parent 2 to child 1, as shown in Figure 2-5. Multiple-point crossover [1] is an extension of single point crossover, where more than one point is selected in the parent chromosome as shown in Figure 2-6.

![Figure 2-5: Example of single point crossover](image1)

![Figure 2-6: Example of multi-point crossover](image2)

Uniform crossover [1] is accomplished through the use of a randomly generated mask that contains the same number of binary bits as the parent chromosomes. The numbers in the mask indicate whether the bit from parent 1 or parents 2 should be translated to each child. Figure 2-7 shows an example of uniform crossover, where a 0 in the mask indicates for child 1 that the bit should taken from parent 1 and a 1 indicates that the bit should be taken from parent 2. The opposite is true for child 2, where a 0 indicates that the bit should come from parent 2 and a 1 indicates the bit should be from parent 1. In Figure 2-7, all bits taken from parent 1 are noted with a dot, and those lacking dots are from parent 2.
2.5 **Mutation**

Mutations are random changes in chromosomes at the bit level and occur by changing a “1” to a “0” or a “0” to a “1”. Mutations are important as they allow the algorithm to search outside the current solution region and increase the likelihood that the genetic algorithm will explore the entire solution space.
3 GA Optimization of a Rectangular Microstrip Patch Antenna

3.1 Design Criteria

In general, a microstrip patch will have a width of $\lambda_d/2$ and a length of $\lambda_d/2$, where $\lambda_d$ is related to the dielectric permittivity. The width of the patch controls the input impedance of the antenna and the length of the patch controls the resonant frequency. Designing a patch to resonate at a particular frequency involves only a few steps when using a simulation tool, such as Ansoft High Frequency System Simulator (HFSS). The four main design parameters for a microstrip patch antenna are the width and length of the patch, and the height and permittivity of the dielectric, shown in Figure 3-1.

![Figure 3-1: Microstrip Patch Geometry](image)

The permittivity and height of the dielectric are two of the most influential parameters on the operation of a patch antenna, yet it is often the case that these are predetermined and given as constraints when designing an antenna. Just the width and
length of the patch antenna are left for the designer to determine through a simple process.

The model for the patch antenna is created in HFSS, with the correct dielectric height, permittivity, and substrate dimensions. The patch antenna is then drawn on the substrate with the width and length dimensions of half a wavelength as mentioned previously. The patch will then be tuned to produce the exact input impedance, radiation patterns and gain that are needed for the design. The impedance of the antenna is altered by changing the width of the antenna. By correctly matching the input impedance, the gain of the antenna can be increased. The resonant frequency of the antenna can be adjusted through small changes in the length of the patch. There are many different tools within HFSS that help perform these adjustments, such as parametric sweeps, an optimization tool, and a tuning tool.

### 3.2 Genetic Algorithm Applied to the Patch Antenna

As reviewed in the first chapter, there are many known modifications that can be made to the standard rectangular microstrip patch antenna that will cause the properties of the antenna to change. One such modification is cutting slots out of the metallic patch, which causes meandering of the surface current. The increase of the current path leads to an increase in electrical length of the patch antenna, which in turn causes a downward shift in the resonant frequency. This shift in resonant frequency is analogous to a reduction in size, as a solid patch antenna that would resonate at this new reduced frequency would be much larger than the slotted antenna. It is this method of cutting
slots that will be used in conjunction with the genetic algorithm to create patch antennas that exhibit considerable size reductions.

A standard rectangular microstrip patch antenna that resonates as 10 GHz was used as the base antenna from which slots would be cut. The dimensions of this patch, 15mm by 9.063 mm, were constraints that had to be considered when applying the genetic algorithm to the optimization problem. Another constraint was the location of the lumped port, as it was necessary to ensure that the antenna could be excited for all geometries produced by the GA. Multiple shapes of different sizes are removed from the base 10 GHz antenna by the genetic algorithm. The variables in the optimization problem are only related to the size, and location of the slot as shown in Figure 3-2. All other antenna elements are constant, including the width and length of the patch antenna, the dielectric permittivity and height, the dimensions of the substrate, and the location of the feedpoint.
MATLAB is the software used to apply the genetic algorithm to the patch antenna. The variables that pertain to the different slot geometries are encoded into a binary string, the length dependent on the number and precision of the variables. Five different slots geometries are used in conjunction with the genetic algorithm, with each geometry requiring its own encoding scheme. The encoding/decoding involves determining the range and precision of each variable. The binary number encoding is translated to a physical quantity using the generalized formula

$$n' = \frac{n}{2^n_{\text{min}} - 1} * \left( n_{\text{max}}' - n_{\text{min}}' \right) + n_{\text{min}}'$$

where $n'$ is the physical quantity and $n$ is the binary encoded string.
Figure 3-3 shows an example of the decoding of a chromosome that removes a single slot from the center of the patch.

<table>
<thead>
<tr>
<th>Chromosome</th>
<th>Defined Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[10110 \ 00100 \ 00110]$</td>
<td>$1 \text{ mm} \leq l' \leq 13.4 \text{ mm}$</td>
</tr>
<tr>
<td>w</td>
<td>$0.2 \text{ mm} \leq w' \leq 6.4 \text{ mm}$</td>
</tr>
<tr>
<td>$0 = 00110$</td>
<td>$-41.25^\circ \leq \theta' \leq 41.25^\circ$</td>
</tr>
</tbody>
</table>

**Decoding Scheme**

- $l = 10110 = 11 \Rightarrow l' = (22 * 0.4 \text{ mm}) + 1 \text{ mm} = 9.8 \text{ mm}$
- $w = 00100 = 4 \Rightarrow w' = (4 * 0.2 \text{ mm}) + 0.2 \text{ mm} = 1 \text{ mm}$
- $\theta = 00110 = 3 \Rightarrow \theta' = (3 * 2.75^\circ) = 8.25^\circ$

Figure 3-3: Encoding used for single rectangular slot

To cut two slots from the antenna the patch was divided in half down the $y$-axis and the slot was restricted to the left side of the patch. The right side of the patch was constructed as the mirror of the left side. This simplified the chromosome encoding and also preserved the symmetry of the patch antenna’s radiation pattern. Figure 3-4 shows the decoding scheme used to cut two slots from the antenna.

<table>
<thead>
<tr>
<th>Chromosome</th>
<th>Defined Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[10111 \ 00100 \ 00110 \ 100]$</td>
<td>$0 \text{ mm} \leq l' \leq 7.5 \text{ mm}$</td>
</tr>
<tr>
<td>w</td>
<td>$0 \text{ mm} \leq w' \leq 3 \text{ mm}$</td>
</tr>
<tr>
<td>$C_x = 100 = 4 \Rightarrow C_x' = (4 * -1 \text{ mm}) = -4 \text{ mm}$</td>
<td></td>
</tr>
<tr>
<td>$\theta = 00010 = 3 \Rightarrow \theta' = (3 * 2.75^\circ) = 8.25^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

**Decoding Scheme**

- $l = 10111 = 11 \Rightarrow l' = (11 * 0.5 \text{ mm}) = 5.5 \text{ mm}$
- $w = 00100 = 2 \Rightarrow w' = (2 * 0.2 \text{ mm}) = 0.4 \text{ mm}$
- $C_x = 100 = 4 \Rightarrow C_x' = (4 * -1 \text{ mm}) = -4 \text{ mm}$
- $\theta = 00010 = 3 \Rightarrow \theta' = (3 * 2.75^\circ) = 8.25^\circ$

Figure 3-4: Encoding used for two rectangular slots

Crosses were cut from the patch using the exact same decoding scheme. Each slot was mirrored across a line perpendicular to the $y$-axis that cut directly through the center
of the slot, creating a cross-shaped slot. This cross was mirrored across the y-axis to create a symmetrical patch with even radiation characteristics as done with the two slot geometry.

To cut four slots, the patch was divided into fourths and the slot was restricted to the upper-left quadrant. The slot floated about this quadrant as the center variables, $C_x$ and $C_y$, were changed by the genetic algorithm. To create the entire patch, the upper-left quadrant was mirrored across both the $x$ and $y$-axis. Figure 3-5 shows the decoding scheme used to cut four slots from the patch.

![Figure 3-5: Encoding used for four rectangular slots](image)

The last slot geometry was circular arcs and required a slightly more complex decoding scheme. The patch was cut vertically in half and the arc was restricted to the left-side of the patch and was only allowed to move along the $x$-axis. The variables of the slot included the outer radius, the width, the location along the $x$-axis, and the option of being a $\frac{1}{2}$ or $\frac{3}{4}$ circle in any orientation around the center of the circle. Figure 3-6 shows the decoding scheme used to remove two arcs from the patch.
The next step in the genetic algorithm is to call a function that creates a visual basic script that when executed will build the antenna in Ansoft HFSS with the specified slot removed, the dimensions of the slot determined by the chromosome. The $S_{11}$ vector of the slotted antenna is determined by the full-wave solver, Ansoft HFSS, and returned to MATLAB. This interaction between MATLAB and HFSS is all done through a toolbox developed by Vijay Ramasami available for use through a public license. In MATLAB, the $S_{11}$ vector is used to calculate the input impedance. The resonant frequency of the patch is determined to be the frequency where the reactance of the input impedance becomes zero. The resonant frequency is assigned to that chromosome as its fitness value and the chromosome is ranked appropriately. Stochastic universal sampling is used.

### Decoding Scheme

<table>
<thead>
<tr>
<th>Chromosome</th>
<th>Defined Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r = 1011 = 11$</td>
<td>$0.25 \text{ mm} \leq r' \leq 3.25 \text{ mm}$</td>
</tr>
<tr>
<td>$w = 0010 = 2$</td>
<td>$0.2 \text{ mm} \leq w' \leq 3.2 \text{ mm}$</td>
</tr>
<tr>
<td>$C_x = 100 = 4$</td>
<td>$-7 \text{ mm} \leq C_x' \leq 0 \text{ mm}$</td>
</tr>
<tr>
<td>$\varphi = 001 = 1$</td>
<td>$180^\circ \leq \varphi' \leq 270^\circ$</td>
</tr>
</tbody>
</table>

- option 0 = ¾ circle with lower right quadrant missing
- option 1 = ¾ circle with lower left quadrant missing
- option 2 = ¾ circle with upper right quadrant missing
- option 3 = ¾ circle with upper left quadrant missing
- option 4 = ½ circle with left side missing
- option 5 = ½ circle with right side missing
- option 6 = ½ circle with top missing
- option 7 = ½ circle with bottom missing
to determine the mating pool, so the antennas with higher fitness values are represented more than antennas with the lower fitness values. Uniform crossover is used to produce the next generation. Mutation is allowed to occur within this new population and then the entire process repeats until the optimized antenna is found.

The generalized process to cut a slot from the patch is outlined below.

- First, a random binary string of digits for the specified slot geometry is generated. This string is passed to a function which decodes the string into the slot variables, such as width, length, position, and angle.

- The specifics of the slot are passed to a second function which builds a visual basic script that will generate the 10GHz patch antenna minus the slot in HFSS.

- The visual basic script is executed and Ansoft HFSS simulates the slotted antenna and generates a file that includes the reflection coefficient ($S_{11}$) for the antenna at all frequencies within the specified range.

- MATLAB is used to calculate the input impedance of the antenna using the $S_{11}$ vector that was produced by HFSS. The frequency where the reactance of the impedance has gone to zero is identified as the resonant frequency of the patch and is assigned to that chromosome as the fitness value.

- The process repeats for all chromosomes (slotted antennas) within the population and then they are ranked. Stochastic universal sampling is used to select the antennas to use in the mating process and uniform crossover is implemented to create a new generation of antennas exhibiting characteristics of the good antennas from the
previous population. Mutation is allowed to occur to widen the sample space and the entire process repeats until an optimized antenna is found.

### 3.3 HFSS and the Fitness Function

In order to show the basics of HFSS modeling and the application of the fitness function, the base antenna with a 10 GHz resonance is examined. The substrate dimensions are 50mm by 50mm, with a thickness of 1/32” (0.793 mm), a permittivity of 2.32, and a loss tangent of 0.01. The patch dimensions are 15mm by 8.9mm and the airbox surrounding the antenna is 50mm x 50mm x 20mm. The patch is fed by a lumped port, 0.25mm in width, with an impedance of 100 Ω.

![Figure 3-7: Rectangular patch modeled in HFSS with lumped port excitation](image-url)
The $S_{11}$ is plotted on the Smith chart in Figure 3-8, and the frequency where the impedance becomes purely resistive is the resonant frequency of the patch. Figure 3-8 shows that the $S_{11}$ line crosses almost exactly in the middle of the Smith chart where the normalized impedance is 1, indicating a very good impedance match between the feed and the antenna. Plotting the $S_{11}$ versus frequency as shown in Figure 3-9, reveals the 10 GHz resonance at a return loss of more than 40 dB.

Figure 3-8: $S_{11}$ for matched 10GHz antenna
Figure 3-9: $S_{11}$ for matched 10GHz patch antenna

Figure 3-10 shows the base antenna with an arbitrary slot cut from the center, as this will occur when the genetic algorithm is applied to the optimization problem. The Smith chart plot of $S_{11}$ for this slotted antenna is shown in Figure 3-11 with the line crossing the axis to the right of the middle of the chart at 8.66 GHz. This point is still the resonant frequency of the antenna, but it indicates that the input impedance has increased from the original 100Ω to a new value.
The lumped port for the slotted patch antenna is matched to this new impedance of $268\,\Omega$ and the $S_{11}$ is plotted versus frequency in Figure 3-12 showing a return loss of 45 dB at the previously found resonant frequency. This demonstrates the way that the
fitness value (resonant frequency) is determined for each patch antenna created by the genetic algorithm.

Figure 3-12: $S_{11}$ for match antenna with arbitrary slot
4 GA Optimization of a Helical Antenna

4.1 Design Criteria

The geometry of a helix, shown in Figure 4-1, can be described completely using the following parameters:

\[
\begin{align*}
D &= \text{diameter of helix} \\
C &= \text{circumference of helix} = \pi D \\
S &= \text{spacing between turns (center to center)} \\
\alpha &= \text{pitch angle} = \tan^{-1}(S/\pi D) \\
L_1 &= \text{length of 1 turn} = \sqrt{C^2 + S^2} \\
n &= \text{number of turns} \\
L &= \text{axial length} = nS \\
\alpha &= \text{radius of helix wire conductor} \\
\alpha_c &= \text{radius of vertical feed wire} \\
\alpha_w &= \text{radius of wires in meshed ground plane} \\
D_g &= \text{diameter of ground plane}
\end{align*}
\]

Figure 4-1: Helical antenna geometry [26]
A helical antenna can radiate in many modes, but the two most common are the broadside mode, indicating that the maximum is located in the plane normal to the helix axis, and axial mode, where the maximum is located along the axis of the helix as depicted in Figure 4-2. The axial mode is the more practical mode of operation for communication purposes and will be used as the focus for further design considerations.

![Figure 4-2: Radiation pattern for (a) axial-mode helix, (b) broadside-mode helix](image)

The radiation pattern of the helical antenna is controlled by changing the design parameters in relation to the freespace wavelength, $\lambda_0$. To achieve circular polarization in the axial mode, the circumference of the helix must be in the range of $3/4\lambda$ to $4/3\lambda$ ($0.8\lambda \leq C \leq 1.2\lambda$ [18]) and the spacing should be approximately a quarter of a wavelength, which means that the pitch angle $\alpha$ is generally between 12° and 14°. The number of turns controls both the gain and the HPBW of the helical antenna, as greater turns produce a greater directivity [18].
It has been found that the wire radius has very little impact on the antenna performance between the values of 0.005\(\lambda\) and 0.05\(\lambda\) [27]. The helix is generally fed with a short length of vertical wire, and it has been empirically found that this vertical wire should have a radius about ten times smaller than the helix wire radius for input impedance purposes [27]. It has also been found that neither the size nor the geometry (square or circular) of the ground plane is critical providing that the minimum side length (diameter for the circle) is greater than \(3/4\lambda\). The diameter of the conductor also has a negligible effect on the radiation pattern, but does alter the input impedance [27].

### 4.2 Exploring Constraints

In order to effectively apply the genetic algorithm to helical antenna design, the various parameters were explored to better understand the limits of each. NEC4 (Numerical Electromagnetic Code version 4) [29] was used to investigate the effects of the parameters on the radiation pattern of a helix at a frequency of 1 GHz.

#### 4.2.1 Helix Circumference

The first parameter explored was the circumference of the helix. The circumference of the helical antenna presented in Figure 4-3 was varied from 0.75\(\lambda\) to 1.35\(\lambda\) by increments of 0.1\(\lambda\) and the resulting radiation pattern in the \(\phi=0^\circ\) (xz) plane is shown in Figure 4-4. It can be seen that as the circumference increases the gain of the antenna also increases. While this is desirable, notice that as the gain increases side lobes begin to develop in the radiation pattern which is often undesirable. This shows that there must be a trade off between gain and side lobe level when adjusting the circumference of a helical antenna.
4.2.2 Number of Turns

The next parameter that was varied was the number of turns. As can be seen from Figure 4-5, as the number of turns increased so did the gain of the helix. However, once
again side lobes developed as the gain increased. This reinforces the tradeoff between gain and sidelobe level that was discovered when varying the helix circumference.

![Gain as the Number of Turns Varies](image)

**Figure 4-5:** Gain (dB) in $\phi=0$ (xz) plane as the number of turns varies. All other parameters are as shown in Figure 4-3 with $C=0.95\lambda$.

### 4.2.3 Helix Excitation

The length of the wire that is used to excite the antenna was the next parameter that was examined. Two different configurations were used to feed the antenna as shown in Figure 4-6. The first configuration is an L shaped feed where a vertical wire is joined to a horizontal wire which feeds the helix. The second feed configuration is one slanted wire that runs up from the ground plane to the helix.
The space between the ground plane and the helix was varied between 2.5 and 15 cm and the resulting radiation patterns are shown in Figure 4-7 and Figure 4-8. Notice the very pronounced side lobes that begin to develop when the feed wire’s length is increased beyond 7.5 cm. The gain of the antenna decreases as the length of the feed wire increases, showing that the shortest length of wire produces the highest gain and the most desirable radiation pattern. Figure 4-9 shows that the slanted wire feed produces a higher gain than the L feed, making it the better configuration to use when exciting the helical antenna.
Figure 4-7: Gain (dB) in $\phi=0^\circ$ (xz) plane as length of the feed wire varies ($L_{\text{feed}}$). All other parameters are as shown in Figure 4-3 with $C=0.95$.

Figure 4-8: Gain (dB) in $\phi=0^\circ$ (xz) plane as length of the feed wire varies (Slanted Wire). All other parameters are as shown in Figure 4-3 with $C=0.95$.
4.2.4 Helix Pitch

The pitch of the helix was varied from 10 to 20 degrees and the resulting radiation pattern is shown in Figure 4-10. Surprisingly, almost no difference in gain or radiation pattern is detected between the extremes of 10 to 20 degrees.
4.2.5 Ground Plane Diameter

The ground plane diameter was varied from $1\lambda$ to $5\lambda$ and the resulting radiation pattern is shown in Figure 4-11. The gain seems to be largely unaffected by the diameter of the ground plane, but there is an obvious change in side lobe level. Interestingly, it seems that the side lobes do not follow a distinct pattern. At a ground plane diameter of $5\lambda$ the side lobes are the smallest, but at $4\lambda$, the next largest diameter, the side lobes are the largest. Figure 4-11 shows that the size of the ground plane does alter the radiation pattern of the helical antenna, though it seems to have very little effect on gain.

![Figure 4-11: Gain (dB) in $\varphi=0$ (xz) plane as the diameter of the ground plane varies. All other parameters are as shown in Figure 4-3 with $C=0.95\lambda$.](image)

4.2.6 Helical shape

The shape of the helical antenna was altered in an attempt to split the half-power beamwidths in the two planes. The $x$-axis circumference of the helix was set as a constant $0.95\lambda$ and the $y$-axis circumference was increased to $3\lambda$ to create an elliptically shaped antenna. Figure 4-13 and Figure 4-14 show that the gain in both planes increases
as the ratio of y-axis circumference to x-axis circumference is increased to 2 and then quickly drops off again as the ratio is increased to 3. At the ratio of 3, a null has appeared at 0 degrees in both planes, which is the desired direction of communication and is therefore undesirable. Figure 4-15 plots the φ=0° (xz) and φ=90° (yz) radiation patterns on the same plot to determine if there is a difference in HPBWs caused by the elliptical shape of the antenna. While there does seem to an increase in the HPBW differences, the change is very small and is accompanied with the development of side lobes. The increase in gain between the circular and elliptical antennas is quite noticeable, but can be attributed to the circumference increase that was explored previously.

Figure 4-12: NEC4 Helical antenna used to explore ellipse shape of helix
Figure 4-13: Gain (dB) in $\varphi=0^\circ$ (xz) plane as the ratio of x-plane to y-plane helix circumference changes

Figure 4-14: Gain (dB) in $\varphi=90^\circ$ (yz) plane as the ratio of x-plane to y-plane circumference changes
4.2.7 Ground Plane Angle

The helical antenna was returned to its circular shape and the angle of the ground plane was explored. The circular ground plane is tilted up away from the horizontal so as to form a cone shape. The expected result of an increase in gain and a decrease in half-power beamwidths was observed as shown in Figure 4-17.
4.2.8 Ground Plane Shape

Another attempt to split the half-power beamwidths involved changing the geometry of the ground plane from a circle to an ellipse. The diameter of the ground plane on the y-axis was fixed at $2\lambda$ and the diameter along the x-axis was allowed to increase to $6\lambda$ in order to create a ratio of 3 to 1. Figure 4-19 shows that the elliptical
ground plane did not cause the HPBWs to be separated, and in fact caused a loss of gain and the development of side lobes.

Figure 4-18: NEC4 Helical antenna used to explore the ellipse ratio of the ground plane (x-axis max. dimension)

Figure 4-19: Gain (dB) in $\varphi=0^\circ$ (xz) plane and $\varphi=90^\circ$ (yz) plane as the ratio of x-axis to y-axis ground plane diameter changes
In a final attempt to separate the HPBW in each plane, both the helix and the
ground plane were constructed as an ellipse with a 2 to 1 ratio. The first configuration
constructed the maximum dimension of the ground plane along the y-axis and the
maximum dimension of the helix along the x-axis so that the two would be elliptical in
opposite planes as shown in Figure 4-20. The resulting radiation pattern is shown in
Figure 4-21. The radiation pattern has definitely changed as a result of the elliptical
antenna and ground plane, but not necessarily in a favorable way. There is no
improvement in gain and the hoped for separation between HPBWs did not occur. The
beams broadened in both planes without a significant loss in gain which is desirable, but
the side lobe levels increased.

The second configuration aligned the maximum dimension of both the helix and
the ground plane along the y-axis so that both were elliptical in the same plane. Figure
4-22 shows the radiation pattern that results from this configuration and it is surprisingly
almost identical to the pattern produced when the helix and ground plane are elliptical in
opposite planes.
Figure 4-20: NEC4 model showing both an elliptical antenna (y-axis max. dimension) and an elliptical ground plane (x-axis max. dimension)

n=4
C_{x-plane} = 0.95 \lambda
\alpha = 13'\n\hbar = 2.5 \text{ cm}
\alpha_x = 9.05 \text{ mm}
\alpha_y = 2 \text{ mm}
\alpha_i = 2 \text{ mm}
D_g in y-plane = 2\lambda.
\frac{D_{gx}}{D_{gy}} = 2
\frac{C_{y-plane}}{C_{x-plane}} = 2

Gain with an Elliptical Ground Plane and an Elliptical Helix in Opposing Planes

Figure 4-21: Gain (dB) as a function of ground plane ellipse (x-axis max. dimension) and antenna ellipse (y-axis max. dimension)
4.3 Genetic Algorithm Applied to the Helix

The first step in applying the genetic algorithm to helical antenna design was to
determine the goals of the antenna. Two different objectives were attempted with the
genetic algorithm. The first objective was a high gain antenna, with low side lobes and
with different HPBWs in the $\phi=0^\circ$ (xz) and $\phi=90^\circ$ (yz) planes. The separation of the two
planes has not been previously accomplished, and it was hoped that the genetic algorithm
would produce some interesting antennas. The second objective was to produce a helical
antenna with a high gain, broad beamwidths, and low side lobes. A high gain with broad
half-power beamwidths is extremely difficult to accomplish using conventional helical
design graphs as the gain decreases as the half-power beamwidths increase. Low side
lobes are desirable in order to maximize the power in the direction of desired
communication and minimize interference from undesired directions.
The next step was determining the parameters that would be varied by the genetic algorithm. The variables were selected based on the study presented in the previous section. The number of turns was set at four due to the radiation pattern that is produced with virtually no side lobes. The lack of side lobes in the radiation pattern was also the reason that the slanted feed wire at a height of 2.5cm was used and that the ratio of x-plane helix circumference to y-plane helix circumference was set as a 1 to 1, meaning that the helix would be a true circle and not elliptical. The shape of the ground plane was also fixed as a true circle with a diameter of 2.5λ as it seems to offer the best trade off between gain and side lobe level. The variables of the helix are then constrained to the spacing between turns, or the pitch angle, and the circumference of the antenna. The effect of each has been explored many times when each is a constant variable for the entire antenna [27], but little work has been done to investigate the effect of allowing the spacing and circumference to vary from turn to turn. The angle of the ground plane will also vary to help produce a high gain antenna, with low side lobes. The chromosome to represent each helical antenna is a binary string of 50 digits that is decoded as follows. Each turn is assigned a turn spacing, S (n), a starting radius, R1 (n), and an ending radius, R2 (n). Each of these parameters is a 4 digit number, thus making up the first 48 digits of the 50 digit chromosome. The last 2 digits indicate which ground plane angle should be included in the antenna model, 0°, 5°, 10°, or 15°. A sample chromosome with the corresponding decoding scheme is shown in Figure 4-23.
MATLAB is used to apply the genetic algorithm to the helical antenna and GNEC is used to determine the radiation pattern of each new antenna. MATLAB writes a data file that contains all the commands necessary to build the helical antenna in GNEC. GNEC is then called by the command window through a batch file. GNEC analyzes the antenna and produces an output file that contains all information pertaining to the helical antenna. MATLAB then searches this output file and reads the information pertaining to the radiation pattern in the $\phi=0^\circ$ (xz) and $\phi=90^\circ$ (yz) planes. In MATLAB this information is used to calculate the HPBW, the angle at which the maximum gain occurs, the value of the maximum gain, and the gain of the side lobes in both planes. All of these parameters are used to determine the overall fitness of each antenna as described in the next section.

The genetic algorithm executes as follows:

- To start the algorithm, a random string of binary numbers 50 digits long is generated in MATLAB. The string contains the specifics of the helix spacing and circumference for each turn, and the angle of the ground plane.

**Figure 4-23: Encoding used for helical antenna**

<table>
<thead>
<tr>
<th>Defined Ranges</th>
<th>Decoding Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \text{ cm} \leq S \leq 10.5 \text{ cm}$</td>
<td>$S(1) = 100110 \rightarrow S(1) = (9*0.5 \text{ cm}) + 3 \text{ cm} = 7.5 \text{ cm}$</td>
</tr>
<tr>
<td>$0.3 \lambda \leq R1 \leq 1.6 \lambda$</td>
<td>$R1(1) = 00011 \rightarrow R1(1) = (1*0.25 \text{ cm}) + 1 \text{ cm} = 1.25 \text{ cm} = 0.42 \lambda$</td>
</tr>
<tr>
<td>$0.3 \lambda \leq R2 \leq 1.6 \lambda$</td>
<td>$R2(1) = 1100 = 12 \rightarrow R2(1) = (12*0.25 \text{ cm}) + 1 \text{ cm} = 4 \text{ cm} = 1.33 \lambda$</td>
</tr>
<tr>
<td>$\theta = 0^\circ, 5^\circ, 10^\circ, \text{ or } 15^\circ$</td>
<td>$\theta = 10 = 2 \rightarrow \theta = \text{ option 3 } = 10^\circ$</td>
</tr>
</tbody>
</table>
• The chromosomes are passed to a second function which writes the data file that will be used by GNEC to build the helical antenna, complete with the circular ground plane tilted at the specified angle.

• A batch file is executed, which causes GNEC to analyze the data file and produce a text-based output file that contains the specifics of the antenna’s operation.

• MATLAB searches this text file and reads the information needed to construct the radiation pattern. The half power beamwidth, maximum gain, angle at which this maximum gain occurs, and the side lobe level are extracted from the radiation pattern for both the φ=0° and the φ=90° planes. These parameters are used to create a weighted fitness between 0 and 1 as described in the next section.

• The chromosomes are ranked according to fitness and stochastic universal sampling is used to select the individuals used to generate the next generation. The probability of crossover was set to 80%. Uniform crossover is used to mate the individuals and mutation is allowed to occur at a probability of 1% per bit. The process repeats with this new population until the stop criterion is met.

4.4 The Fitness Function

Due to the multi-objective nature of optimizing the helix, a method for calculating the overall fitness of each antenna had to be developed. There were two different mapping schemes, based on the desired objective of the GA. The first objective was to create a split in HPBWs, so the target HPBW in the φ=0° (xz) plane was given a value of 30 degrees and the HPBW in the φ=90° (yz) plane was given a target value of 60 degrees.
The mapping from the actual HPBW to a fitness between 0 and 1 was accomplished by using the graphs in Figure 4-24 and Figure 4-25.

Figure 4-24: Mapping used to determine $\phi=0$ (xz) plane HPBW fitness

Figure 4-25: Mapping used to determine $\phi=90$ (yz) plane HPBW fitness
The second genetic algorithm objective of achieving broad beamwidths in both planes used the same graph in Figure 4-25 to determine the fitness for HPBW in both the $\phi=0^\circ$ (xz) and $\phi=90^\circ$ (yz) planes.

For both objectives it was important that the maximum gain of the antenna occur at an angle that is close to zero degrees. The fitness of this objective was determined using the graph shown in Figure 4-26. The gain of the antenna was mapped to a line that started at a gain of 0 dB and extends to a value of 1 at 15 dB as shown in Figure 4-27.

![Fitness Value Mapping for Max Gain Angle](image)

**Figure 4-26:** Mapping used to determine fitness value for maximum gain angle
Side lobe level fitness was calculated by determining the difference between the max gain in the main beam and the max gain in the side lobe. This difference is divided by the max gain of the main beam so that the highest value is normalized to 1, which occurs when there is no side lobe at all.

These separate fitness values are then all multiplied by another number between 0 and 1 that is a measure of how important each objective is to the overall goal of the genetic algorithm. Finally, these weighted fitness values are all summed together to create the overall fitness of the antenna that is used by the genetic algorithm. The genetic algorithm that was used to attempt to split the half-power beam widths used a weight set as shown in Figure 4-28 and the genetic algorithm that attempted to achieve a high gain antenna with broad beam widths used a weight set as shown in Figure 4-29. The HPBW in the $\varphi=0^\circ$ plane (HPBW0) is multiplied by weight 1, the HPBW in the $\varphi=90^\circ$ plane (HPBW90) is multiplied by weight 2, the angle at which the maximum gain occurs in the
φ=0° plane (Angle0) is multiplied by weight 3, the angle at which the maximum gain occurs in the φ=90° plane (Angle90) is multiplied by weight 4, the maximum gain in the φ=0° plane (Max Gain0) is multiplied by weight 5, the maximum gain in the φ=90° plane (Max Gain90) is multiplied by weight 6, the normalized difference between the maximum gain of the main beam and the maximum gain of the side lobes in the φ=0° plane (SLDiff0) is multiplied by weight 7, and the normalized difference between the maximum gain of the main beam and the maximum gain of the side lobes in the φ=90° plane (SLDiff90) is multiplied by weight 8.

![Weight Set Diagram](image)

Figure 4-28: Weight set used to split HPBW
Figure 4-29: Weight set used to generate broad beamwidths
5 Genetic Algorithm Results

5.1 Patch Antenna

The first slot geometry that was implemented was the single, centered slot with a target resonant frequency of 6 GHz. A population size of 15 was used, with an 80% probability of crossover, and a mutation per bit probability of 3%. The GA was run eight times with different seeds for the random number generator. The convergence results from these eight runs are used to produce an average convergence graph as shown in Figure 5-1. The optimized slots from all the runs are summarized in Table 1, along with the input impedance and the gain of the antenna. The time it took for each generation is shown, along with the specific generation in which the optimized antenna was produced. The antenna obtained when a seed of 50 was used is highlighted as the antenna has the lowest input impedance and the highest gain. The optimized antenna is shown in Figure 5-2, with an 10.6 mm by 1 mm slot angled at 11° away from the horizontal.

<table>
<thead>
<tr>
<th>Seed</th>
<th>Time/gen. (min)</th>
<th>Convergence generation</th>
<th>Slot Dimensions (mm)</th>
<th>Theta (deg.)</th>
<th>Resonant Frequency (GHz)</th>
<th>Input Impedance (Ω)</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>26.3</td>
<td>1</td>
<td>10.2 x 1.8</td>
<td>-11</td>
<td>5.92</td>
<td>120</td>
<td>4.96</td>
</tr>
<tr>
<td>23</td>
<td>28.8</td>
<td>5</td>
<td>13.4 x 5.2</td>
<td>-8.25</td>
<td>6.01</td>
<td>196</td>
<td>4.98</td>
</tr>
<tr>
<td>114</td>
<td>25.4</td>
<td>4</td>
<td>11 x 1.6</td>
<td>5.5</td>
<td>6.01</td>
<td>218</td>
<td>5.04</td>
</tr>
<tr>
<td>200</td>
<td>27.9</td>
<td>1</td>
<td>10.6 x 2.2</td>
<td>8.25</td>
<td>5.85</td>
<td>200</td>
<td>5.04</td>
</tr>
<tr>
<td>1001</td>
<td>21.5</td>
<td>10</td>
<td>12.2 x 4</td>
<td>-5</td>
<td>5.99</td>
<td>151</td>
<td>5.05</td>
</tr>
<tr>
<td>19</td>
<td>25.9</td>
<td>3</td>
<td>13 x 4.8</td>
<td>-11</td>
<td>6.18</td>
<td>259</td>
<td>5.21</td>
</tr>
<tr>
<td>50</td>
<td>24.5</td>
<td>3</td>
<td>10.6 x 1</td>
<td>11</td>
<td>6.01</td>
<td>110</td>
<td>5.27</td>
</tr>
<tr>
<td>System clock</td>
<td>27.2</td>
<td>4</td>
<td>11.4 x 0.8</td>
<td>-8.25</td>
<td>6.01</td>
<td>160</td>
<td>5.03</td>
</tr>
</tbody>
</table>

Table 1: Summary of Single Slot Results
The $S_{11}$ of the slotted antenna is shown in Figure 5-3 along with the $S_{11}$ of the original solid patch. The $S_{11}$ at 6 GHz is still a respectable 40 dB, but it can be seen that some gain and bandwidth is lost as a result of the 4 GHz frequency shift. Figure 5-4 shows that the shape of the radiation pattern has not been altered by the removed slot, as it is still an omni-directional pattern in both planes.
Figure 5-2: 6 GHz antenna with centered slot

Figure 5-3: $S_{11}$ for 6 GHz antenna with centered slot
Only one run was performed for all of the following geometries, as just a comparison between the input impedance and gain of the resulting antennas was desired. No emphasis should be placed on the quickness of the GA convergence as it is just a single run and not an average convergence across multiple runs.

The next slot geometry included two slots that were allowed to move along the $x$-axis of the patch. The genetic algorithm was given a target frequency of 6 GHz, requiring a 4 GHz frequency shift. A population size of 15 with an 80% probability of crossover, a mutation per bit probability of 3%, and uniform crossover were used to produce the 6 GHz antenna with two slots. Figure 5-5 shows that it took 17 generations for the algorithm to converge to the target frequency. The slots are 7 mm long, 0.2 mm
wide, and angled at 13.75 degrees away from the horizontal. The slot is centered at 4 mm from the center of the patch on the x-axis as shown in Figure 5-6. Figure 5-7 shows that the antenna is resonating at 6 GHz with a return loss of almost 40 dB.

Figure 5-5: Convergence graph for 6 GHz antenna with two slanted slots

Figure 5-6: 6 GHz antenna with two slanted slots
Four slots were implemented by allowing the slots to move in both the \( x \) and \( y \) directions. The genetic algorithm was given a target frequency of 6 GHz, requiring a 4 GHz frequency shift. A population size of 10 with an 80% probability of crossover, a mutation per bit probability of 3%, and uniform crossover were used to produce the 6 GHz antenna with four slots. It only took eight generations for the genetic algorithm to converge to a fitness of 6 GHz, as shown in Figure 5-8. The slots are 7.5 mm long, 0.4 mm wide, and angled at 35.75 degrees away from the horizontal. The slot is centered at 6 mm from the center of the patch along the \( x \)-axis and 1.5 mm from the center of the patch along the \( y \)-axis as shown in Figure 5-9. Figure 5-10 shows that the antenna is resonating at 6 GHz with a return loss of almost 45 dB.
Figure 5-8: Convergence graph for 6 GHz antenna with four slanted slots

Figure 5-9: 6 GHz antenna with four slanted slots
In order to show the versatility of the genetic algorithm, a target frequency of 6.5 GHz was used for the slot geometry of two arcs. The arcs were allowed to move along the $x$-axis, and had the possibility of being $\frac{1}{2}$, or $\frac{3}{4}$ arcs in any orientation around the center of the arc. A population size of 15 with an 80% probability of crossover, a mutation per bit probability of 3%, and uniform crossover were used to produce the 6.5 GHz antenna. After five generations the genetic algorithm had converged to the maximum fitness of 6.5 GHz as shown by Figure 5-11. The slots have an outer radius of 2.85 mm with a width of 0.6 mm and are centered at 2.5 mm away from the center of the patch on the $x$-axis as depicted in Figure 5-12. Figure 5-13 shows that the antenna is resonating at the desired 6.5 GHz with a return loss of almost 45 dB.
Figure 5-11: Convergence graph for 6.5 GHz antenna with 2 circular slots

Figure 5-12: 6.5 GHz antenna with 2 circular slots
The target frequency was once again altered to show that the genetic algorithm can work for any target frequency. A target frequency of 7 GHz was used with a slot geometry of two crosses. A population size of 10 with an 80% probability of crossover, a mutation per bit probability of 3%, and uniform crossover were used to produce the 7 GHz antenna. It took 15 generations for the algorithm to find an antenna that resonated at the target frequency, as shown by the convergence graph in Figure 5-14. The slots were constructed by cutting one slanted slot and then mirroring this slanted line horizontally to create the symmetrical cross, therefore the slots can be described by a length and a width. The length of the cross-shaped slots is 6.5 mm, and is measured from the upper left of the slot to the lower right, and the width of 1.2 mm is measured as the y-axis difference of each ‘arm’ of the cross. Each arm of the cross is angled at 30.25 degrees away from the horizontal and each cross is centered 4 mm from the middle of the
patch on the \( x \)-axis. Figure 5-16 shows that the antenna is resonating at the desired 7 GHz with a return loss of almost 45 dB.

![Graph showing GA Fitness Convergence](image)

**Figure 5-14: Convergence graph for 7 GHz antenna**

![Antenna with crossed slots](image)

**Figure 5-15: 7 GHz antenna with crossed slots**
Figure 5-16: $S_{11}$ for 7 GHz antenna with two cross-shaped slots

All of the antennas presented are summarized in Table 2, with the percent size reduction that has been achieved, the input impedance, the maximum gain, and the -10 dB $S_{11}$ bandwidth. Radiation plots for the two slot, four slot, two arc, and two cross antennas can be found in the appendix. Multiple slot geometries have been tried in order to determine which geometry resulted in not only a large size reduction but also a high gain. While three of the geometries produced size reductions of 73%, it is obvious that the single slot is the best slot geometry due to the lower input impedance and higher gain.
Table 2: Summary of results

<table>
<thead>
<tr>
<th>Slot Geometry</th>
<th>Resonant Frequency (GHz)</th>
<th>Size Reduction (%)</th>
<th>Input Impedance (Ω)</th>
<th>Max Gain (dB)</th>
<th>-10 dB S11 BW (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Patch</td>
<td>6.00</td>
<td>NA</td>
<td>220</td>
<td>5.85</td>
<td>150</td>
</tr>
<tr>
<td>Single Centered Slot</td>
<td>6.01</td>
<td>73%</td>
<td>110</td>
<td>5.27</td>
<td>80</td>
</tr>
<tr>
<td>Two Slots</td>
<td>6.03</td>
<td>73%</td>
<td>295</td>
<td>2.93</td>
<td>60</td>
</tr>
<tr>
<td>Four Slots</td>
<td>5.99</td>
<td>73%</td>
<td>210</td>
<td>2.83</td>
<td>60</td>
</tr>
<tr>
<td>Solid Patch</td>
<td>6.49</td>
<td>NA</td>
<td>165</td>
<td>6.98</td>
<td>160</td>
</tr>
<tr>
<td>Two Arcs</td>
<td>6.48</td>
<td>47%</td>
<td>465</td>
<td>3.74</td>
<td>70</td>
</tr>
<tr>
<td>Solid Patch</td>
<td>7.01</td>
<td>NA</td>
<td>170</td>
<td>7.05</td>
<td>190</td>
</tr>
<tr>
<td>Two Crosses</td>
<td>6.99</td>
<td>38%</td>
<td>390</td>
<td>5.44</td>
<td>100</td>
</tr>
</tbody>
</table>

5.2 Helical Antenna

5.2.1 HPBW Separation

The first objective attempted was to produce a helical antenna with high gain, low side lobes, and HPBWs that were different in the two different planes. Various parameters were changed within the genetic algorithm to attempt to realize this objective. Initially, the variables of the optimization problem were restricted in hopes that fewer variables would allow the genetic algorithm to converge to an acceptable answer quickly. While a truly optimal antenna was not produced through the restricted combinations, a few promising antennas with decent fitness values were developed through its application.

The first promising antenna occurred when the starting and ending turn radiuses R1(n) and R2(n) were set equal to each other so that the radius of each turn varied
uniformly. The spacing between each turn was still allowed to vary independently of the other turn spacings, but the ground plane was restricted to a flat circle. The antenna with the highest fitness that resulted from this combination of variables is shown in Figure 5-17. The turn spacings from top to bottom are 9, 5.5, 8.5, and 9 cm respectively, the turn radiuses are 4.25, 2.75, 2.5, and 2.75 cm, also from top turn to bottom turn, and the ground plane is flat.

Figure 5-17: Antenna that exhibits a high gain

Figure 5-18 shows the fitness of each objective (prior to weighting) and the total fitness of the best antenna. The HPBW in the \( \varphi=0 \) (xz) plane and the maximum gains in both planes contributed the most to the total fitness of the antenna, which results in an antenna with a reasonably high gain. The low fitness value of the HPBW in the \( \varphi=90 \) (yz) plane indicates that there will be little separation between the HPBWs in the two planes, which is confirmed by the radiation pattern shown in Figure 5-19. The radiation pattern reveals 35 degree HPBWs in both planes, a max gain of 11.4 dB in both planes and the highest side lobe \( \sim 11 \) dB down from the main beam.
The next promising antenna was found when the genetic algorithm allowed the turn starting and ending radiiuses to vary independently, but the turn spacing was fixed at 6.93 cm and the ground plane was restricted to a flat, circular geometry. The best antenna that
was produced from this combination is shown in Figure 5-20, with starting radiuses of 4, 8, 0.5, and 10 cm and ending radiuses of 6, 2, 8, and 1 cm from top turn to bottom turn.

The dominant desired feature of the antenna is the split HPBWs, as shown by Figure 5-22.

![Figure 5-20: Antenna that has 19 degrees of separation between HPBWs](image)

Figure 5-21 shows the fitness of each objective (prior to weighting) and the total fitness of the best antenna. The HPBW in the $\varphi=0$ (xz) plane and HPBW in the $\varphi=90$ (yz) plane contribute the most to the total fitness. This indicates that there will be a decent amount of separation between the HPBWs in the two planes, which is confirmed by the radiation pattern shown in Figure 5-22. The HPBW in the $\varphi=0$ (xz) plane is 44 degrees with a gain of 6.84 dB and the HPBW in the $\varphi=90$ (yz) plane is 63 degrees with a gain of 6.59 dB.
For the next genetic algorithm run, the turn spacing was allowed to vary and the starting and ending radiiuses were allowed to change independently. The ground plane was still restricted to a flat circle. This configuration produced an antenna with a high gain and low side lobes, but the HPBW's are almost identical. The turn spacing is 4.5, 10,
8.5, and 7 cm from top turn to bottom turn with starting radiiuses of 2, 3.75, 2.25, and 4.25 cm and ending radiiuses of 3.75, 2, 2.25, and 1.75 cm respectively, as shown in Figure 5-23.

Figure 5-23: Antenna with high gain

Figure 5-24 shows the fitness of each objective (prior to weighting) and the total fitness of the best antenna. The HPBW in the $\phi=0$ (xz) plane and the maximum gains in both planes once again contributed the most to the total fitness of the antenna, which produces a high gain antenna with almost identical HPBWs. The radiation pattern shown in Figure 5-25 reveals a HPBW of 39 degrees in the $\phi=0$ (xz) plane with a gain of 10.24 dB and a HPBW of 36 degrees in the $\phi=90$ (yz) plane with a gain of 10.13 dB. The highest side lobe is -13 dB down from the main beam.
Finally, all helix parameters were allowed to vary independently including the turn spacing, the starting turn radius, the ending turn radius, and the angle of the ground plane. This produced an antenna, shown in Figure 5-26, with turn spacings of 5.4, 7.8,
7.8, and 8.7 cm, starting turn radiuses of 6.3, 3.6, 7.8, and 7.8 cm, ending turn radiuses of 4.2, 3.6, 1.8, and 8.1 cm, and a ground plane angle of 10 degrees.

Figure 5-26: Antenna with 16 degrees between HPBW

Figure 5-27 shows the fitness of each objective (prior to weighting) and the total fitness of the best antenna. The HPBW in both planes contribute the most to the overall fitness of the antenna, indicating that a separation should be seen between the two planes. The radiation pattern for this antenna shows a medium gain, 16 degrees HPBW separation, and relatively high side lobes. The HPBW in the $\phi=0$ (xz) plane is 30 degrees with a gain of 4.16 dB, the HPBW in the $\phi=90$ (yz) plane is 46 degrees with a gain of 4.44 dB. The highest side lobe is only 8 dB down from the main lobe, which is a quite high for most receiving and transmitting purposes. This was expected however, due to the relatively low fitness value of side lobe level shown in Figure 5-27.
5.2.2 Broad Beamwidth

The best antenna to result from the genetic algorithm had a turn spacing of 9.5, 9, 7.5, and 4 cm from top turn to bottom turn with starting turn radiuses of 2, 3.75, 3.25, and
1 cm and ending turn radiuses of 3.75, 2.75, 3.75, and 3.25 cm. The ground plane is angled at 5 degrees.

Figure 5-29: Antenna that exhibits broad beamwidths and high gain

Figure 5-30 shows the fitness of each objective (prior to weighting) and the total fitness of the best antenna. The max gain and HPBW fitness values contribute the most to the overall fitness, signifying that the radiation pattern should display high gain with HPBWs close to the desired 60 degrees. The radiation pattern shown in Figure 5-31 reveals that the HPBW in the $\varphi=0$ plane is 57 degrees and is 56 degrees in the $\varphi=90$ plane. A max gain of 10.21 dB occurs in both planes, at 0 degrees in the $\varphi=0$ plane and at 1 degree in the $\varphi=90$ plane. Only one side lobe exists which is 17 dB down from the main lobe, and is located in the $\varphi=0$ plane at ~90 degrees.
In order to analyze that genetic algorithm results, a four turn helical antenna was designed using the ARRL Antenna Book design equations. The antenna was designed for an 8 dB gain with 61 degree HPBWs in both planes. The antenna has a uniform spacing of 6.4 cm and a uniform radius of 4.05 cm and was modeled in GNEC using a circular ground plane with a diameter of 2.5λ. The radiation pattern produced by GNEC is shown in Figure 5-32, with a maximum gain of 6.8 dB and a HPBW of 65 degrees in the φ=0
plane and a HPBW of 61 degrees in the ϕ=90 plane. Comparing the radiation pattern of the conventionally designed antenna to the antenna produced by the genetic algorithm shows that the GA antenna has a greater gain by 3.3 dB.

![Comparison of Conventionally Designed Helix vs. GA Designed Helix](image)

**Figure 5-32**: Gain (dB) for genetic algorithm helix and conventionally designed helix.

### 5.3 Discussion

A genetic algorithm was applied to helical antenna design with varying success. Figure 5-33 is a convergence graph that was produced by the genetic algorithm that was attempting to optimize a helical antenna for high gain, broad HPBWs, and low side lobes. A convergence graphed that showed a good genetic algorithm performance would quickly converge to a fitness value that is close to 1, indicating fulfillment of the optimization criteria. However, this convergence graph does not converge to a high fitness value, but instead seems to hover around a fitness value that is very close to the initial fitness value of generation 0.
This lack of convergence to a high value indicates that the genetic algorithm is not producing better and better antennas each generation, which is the ultimate goal of any optimization technique. This is not to say that some good results did not come of the genetic algorithm. The helical antennas presented were all produced through the genetic algorithm, and met the optimization criteria with varying degrees of success.

There are a few logical reasons that cause this lack of convergence. The most significant factor in the limited success of optimizing the helical antenna was the overall optimization objectives themselves. The objectives were chosen to produce interesting antennas that far outperform existing conventional helical antenna designs. Creating a separation between HPBW's has not previously been reported and it was unknown whether it was physically possible to do this with only one helical antenna structure. The
second objective of requiring an extremely high gain and broad beamwidths is also unreasonable, as shown by section 5.2. This section shows that increasing antenna gain requires that the HPBWs become smaller, and likewise, increasing the HPBWs causes a drop in gain. While this was a well-known design trade-off, the genetic algorithm was applied in hopes that a non-intuitive design could be realized that finally evaded this inconvenient trade-off.

Another factor that contributed to the genetic algorithms limited success was the number of objectives that were included in the fitness function. Eight different antenna properties were included within the helical antenna fitness function, and these eight different properties react differently to the changing geometry of the helix. An increase in gain will almost always be coupled with a decrease in HPBW, which makes it very difficult to decide exactly what antenna is truly the best antenna. A multi-objective algorithm should be used in place of the weighted-sum approach. A multi-objective algorithm would return many antennas as the “best” antennas, some exhibiting high gain, some with broad HPBWs, and some with no side lobes. In fact, the results that were presented are a small version of the Pareto front that would have been generated by a multi-objective genetic algorithm. A designer would then be able to examine the many “best” answers that the genetic algorithm produces and pick the antenna that matches the needs of the designer the closest.
6 Experimental Validation for Patch Antenna

All of the antennas were built and tested to validate the results obtained from Ansoft HFSS. The antennas are shown next to a solid patch antenna that resonates at the same frequency as the GA antenna to show the dramatic size reduction that was achieved. The $S_{11}$ for the single slot antenna is shown in Figure 6-2, and the remaining $S_{11}$ network analyzer results can be found in the appendix. The hardware results are summarized in Table 3, showing the simulation resonant frequency and $S_{11}$ after adding the feed network and the actual resonant frequency and $S_{11}$ as measured by the network analyzer.

Figure 6-1: Single slot antenna with 6 GHz solid microstrip antenna
Figure 6-2: S11 (dB) as measured by the network analyzer and HFSS simulation results for the single slot antenna

Figure 6-3: Double slot antenna with 6 GHz solid microstrip antenna
Figure 6-4: Quad slot antenna with 6 GHz solid microstrip antenna

Figure 6-5: Double arc slot antenna with 6.5 GHz solid microstrip antenna
Table 3: Summary of Hardware Results

<table>
<thead>
<tr>
<th>Slot Geometry</th>
<th>Simulation Resonant Frequency (GHz)</th>
<th>Measured Resonant Frequency (GHz)</th>
<th>Simulation S11 (dB)</th>
<th>Measured S11 (dB)</th>
<th>Size Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Patch</td>
<td>5.97</td>
<td>5.98</td>
<td>-21.57</td>
<td>-23.37</td>
<td>-</td>
</tr>
<tr>
<td>Single Centered Slot</td>
<td>6.02</td>
<td>6.02</td>
<td>-23.65</td>
<td>-15.82</td>
<td>73</td>
</tr>
<tr>
<td>Two Slots</td>
<td>6.00</td>
<td>6.14</td>
<td>-13.4</td>
<td>-17.04</td>
<td>73</td>
</tr>
<tr>
<td>Four Slots</td>
<td>5.99</td>
<td>6.06</td>
<td>-18.73</td>
<td>-14.17</td>
<td>73</td>
</tr>
<tr>
<td>Solid Patch</td>
<td>6.52</td>
<td>6.58</td>
<td>-43.2</td>
<td>-24.87</td>
<td>-</td>
</tr>
<tr>
<td>Two Arcs</td>
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<td>6.50</td>
<td>-30.4</td>
<td>-26.47</td>
<td>47</td>
</tr>
<tr>
<td>Solid Patch</td>
<td>7.05</td>
<td>7.06</td>
<td>-56.1</td>
<td>-37.02</td>
<td>-</td>
</tr>
<tr>
<td>Two Crosses</td>
<td>7.03</td>
<td>7.06</td>
<td>-22.3</td>
<td>-22.76</td>
<td>38</td>
</tr>
</tbody>
</table>

All of the antennas show a decent return loss (greater than 15 dB) and resonant frequencies extremely close to the frequencies predicted by Ansoft HFSS. The slight differences between the simulation and actual results can be contributed to the feed network. While extreme care was taken when designing the microstrip feed network, a perfect match was not achieved for every antenna. It should also be noted that additional power was lost due to the repeated soldering of the connectors to the antennas.
7 Conclusion and Future Work

7.1 Microstrip Patch Antenna

A genetic algorithm was successfully applied to a rectangular microstrip patch
antenna to reduce the size by removing rectangular and circular slots from the copper
patch. Given the number and shape of the slot, the genetic algorithm is used to optimize
the size and location of the slot on the patch. Patch size reduction up to 75% has been
achieved with a radiation pattern typical of microstrip patch antennas. Various slot
shapes and numbers have been tried in order to optimize for gain as well as size
reduction. While there is a loss in gain between solid patch antennas and the optimized
antennas, this could be easily compensated through the use of an antenna array.

7.2 Helical Antenna

A method for communication between GNEC and MATLAB has been developed
that is imperative to the functioning of the genetic algorithm. An extensive study of the
various helical parameters has been performed, which included many unique
modifications to the helix shape and the ground plane shape. A helical antenna with 19
degrees of separation between the HPBWs in the two radiation planes with a gain of 7 dB
has been achieved by using a genetic algorithm to vary the helix radius, and ground plane
geometry. A helical antenna with a high gain of 10 dB and broad beamwidths of 60
degrees has also been optimized by varying all parameters.
7.3 Future Work

The following are proposed extensions to the present work concerning patch antennas:

1. Include input impedance as part of the genetic algorithm fitness function. By doing this the genetic algorithm can be used to create patch antennas that exhibit large size reductions but also reasonable input impedances that are easy to match to any feed network.

2. Modify the genetic algorithm to achieve size reduction and dual-band capabilities through the removal of slots.

The following are proposed extension to the present work concerning helical antennas:

1. Use a multi-objective genetic algorithm (MOGA) in place of the weighted-sum genetic algorithm. MOGA are well-suited for optimization problems that include multiple, conflicting objectives and offers the distinct advantage of a Pareto front.

2. Modifications to the ground plane beyond those explored in this work are necessary. By using different shaped reflectors it should be possible to shape the antenna beam patterns in the two planes and create two different HPBWs in the different planes.

3. Experimental testing should be performed in order to validate the simulated results.
References


Appendix

Figure A-0-1: Radiation pattern for 6 GHz antenna with two slots

Figure A-0-2: Radiation pattern for 6 GHz antenna with four slots
Figure A-0-3: Radiation pattern for 6.5 GHz antenna with two circular slots

Figure A-0-4: Radiation pattern for 7 GHz antenna with two cross-shaped slots
Figure A-0-5: S11 (dB) as measured by the network analyzer and HFSS simulation results for the double slot antenna.

Figure A-0-6: S11 (dB) as measured by the network analyzer and HFSS simulation results for the four slot antenna.
Figure A-0-7: $S_{11}$ (dB) as measured by the network analyzer and HFSS simulation results for the double arc antenna.

Figure A-0-8: $S_{11}$ (dB) as measured by the network analyzer and HFSS simulation results for the double cross antenna.
Figure A-0-9: S11 (dB) as measured by the network analyzer and HFSS simulation results for the solid 6 GHz antenna

Figure A-0-10: S11 (dB) as measured by the network analyzer and HFSS simulation results for the solid 6.5 GHz antenna
Figure A-0-11: $S_{11}$ (dB) as measured by the network analyzer and HFSS simulation results for the solid 7 GHz antenna.