Optimum Plannar Antenna Design Based on an Integration of IE3D Commercial Code and Optimization Algorithms

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Abstract **–** The optimum planar antenna design utilizing a simulation tool based an integration of IE3D commercial code as an electromagnetic computational engine and an add-on optimization algorithm is proposed in this paper. The work is motivated by the popularity of planar antennas and the need of customized designs in industrial applications, which can be effectively achieved by using simulation tools. Currently available commercial codes are reliable and relatively accurate in the analysis with more efforts tending to enhance the efficiency. The quality of the antenna design will mainly rely on an effective optimization algorithm that can be and should be developed independently according to engineers' own need since the variables and cost functions for optimization can be flexibly selected. The integration of existing analysis codes, as mentioned above, and self-developed algorithms will be most effective for an engineer in the customized antenna design. The concepts and strategies are addressed with numerical examples to validate.

I. INTRODUCTION

The fast growing of wireless communications has spurred an increasing need for customized antenna designs. Microstrip (or planar) antennas, which are conformal and can be integrated within devices' profiles, provide a very flexible design. In realistic applications, it however appears more constraints on the antenna design since portable devices usually have limited PCB space in irregular shapes. Thus a reliable computer-aided tool is very essential to less experienced engineers and capable of designing antennas in an effective fashion without ending up with tuning antenna parameters in an ad hoc manner, which is time consuming and inefficient.

Considering the development of design tools, currently available commercial codes such as IE3D and HFSS are very reliable and relatively accurate in the analysis with currently more efforts tending to enhance the efficiency. The quality of the antenna design will mainly rely on an effective optimization algorithm that can be and should be developed independently according to engineers' own need since the variables and cost functions for optimization can be flexibly selected. Thus it can be foreseen that more efforts of the engineers will be spent on developing a design procedure and algorithms to optimize their antenna designs. This work demonstrates the idea that an external design optimizer can work with a commercial EAD tool. An algorithm developer can choose either genetic algorithm or other optimizers for design optimization. The integration of existing analysis codes, as mentioned above, and self-developed algorithms will be most effective for an engineer in the customized antenna design.

This code integration concept is demonstrated in this work by using IE3D as the electromagnetic (EM) computation engine. A program is designed to automate the optimization process. The program monitors the optimization process and interacts with the computation engine. The process begins with an initial design. The computation engine returns prescribed performance parameters. The program next adjusts the stepping size of the adjustable parameters according to its built-in optimization algorithm. Above process is performed iteratively until the desired performance or the specified iteration number is met. Several optimization schemes have been implemented including classical Euler method, predictor correlator method and other nonlinear optimization methods. In this paper, generic algorithm (GA) [1-4] is employed to demonstrate the concept because it can be effectively employed to optimize discrete variables.

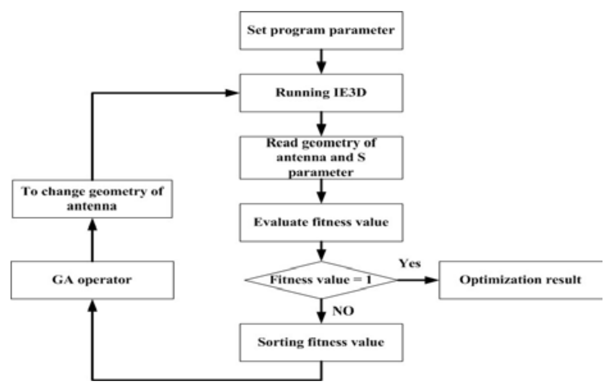
As to the application potential, such an add-on optimization program could be made more capable than the optimization functions provided by commercial simulation packages. Comparing to the existing GeneticEM optimizer of IE3D, which can tune multiple geometric parameters that is already defined in the initial design, an external add-on optimizer provides more degree of freedom in modifying the problem geometry. Though not demonstrated in the following design example, it is possible to have the optimizer choosing from a variety of antenna structures to meet specified performance needs. For example, the optimizer may be allowed to choose from either corner truncated patch or diagonally-fed square patch to produce circular polarization. Furthermore, an external add-on optimizer enables the developer to directly access the optimizing algorithm. GA related parameters such as the population size and gene number can be adjusted to achieve an efficient optimization according to the application characteristics. Design packages from different venders could also be coordinated using this intermediate program, and thus create most values in the antenna design.

This paper is formatted in the following order. Section 2 addresses the implementation strategies of this code integration as well as the interface to interact with the IE3D. Section 3 demonstrates the concepts by considering a dual-band antenna design for the applications of Wi-Fi [5] and dedicated short range communication systems (DSRC) [6]. Finally a short discussion is presented in section 4 for a conclusion.

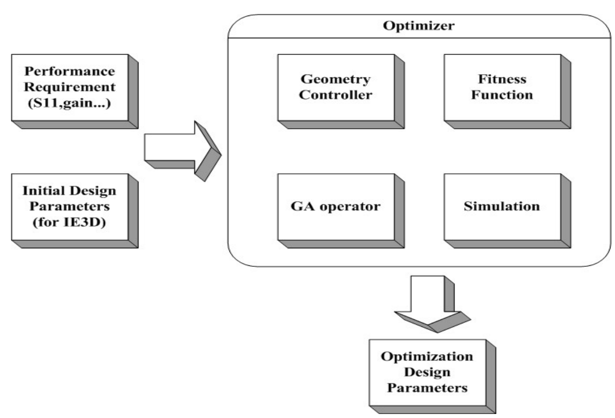
II. IMPLEMENTATION STRATEGIES

A. General Concepts and the Program Structure

The general concept of this work is composed by a general procedure of an antenna design optimization as illustrated in Fig. 1(a). It starts with an initial guess of the antenna structure and parameter inputs to classify the antenna performance expectations through an EM analysis, where the analysis is performed by IE3D. The antenna performance is justified by a comparison with the expectation through an evaluation of a cost function or fitness function. If the expectation is reached, then the design procedure stops. Otherwise, a new design with improved performances is created based on the values of the fitness function, where the new antenna structure is produced by a genetic algorithm procedure. This new antenna structure is used in the next iteration (or next generation) for EM analysis to justify the performance with respect to the expectation. This procedure continues until the expectation is reached. To realize the concepts with respect to the utilization of IE3D as an EM analysis engine with an add-on procedure of generic algorithm to adjust the antenna's parameters, the implementation of the program structure is illustrated in Fig. 1(b). It begins with the establishment of an automation control program that first sets up the program control parameters such as the desired antenna performance and the maximum number of iteration, and then establishes the procedure of code control and optimization algorithm. The initial antenna design is performed by IE3D program to yield the analysis of antenna performance parameters, which is used to generate the fitness value. Thus the parameters with respect to the antenna operation such as the operational frequency bands are input through IE3D GUI. The main body of the automation program is composed by four blocks as illustrated in Fig. 1(b). The "geometry controller" specifies the parameters and variables of the antenna structure to be optimize such as the dimensions and coordinates of particular geometries in the structure, which are used in the "GA operator block" to produce new values for creating new antenna structure with superior performances. The "GA operator" implements the GA algorithm. Also the antenna performance with respect to the design anticipation is evaluated in the "fitness function" block to justify whether the expectation has been reached based on the analysis of "simulation" block which uses the IE3D as the EM analysis tool. If the fitness value meets the prescribed conditions of requirement, we can declare that a satisfying design is found. Otherwise, the GA operator will sort designs according to the fitness values, then generate new designs as well as new values of the parameters for the next generation from superior designs.



(a) Optimization Procedure.



(b) Automation Control Program Structure.

Fig. 1. The demonstration of the antenna design optimization procedure as well as the program structure of the proposed strategies to integrate IE3D commercial analysis code with an optimization algorithm based on genetic algorithm.

B. Generic Algorithm for Antenna Design Optimization ("GA operator" block)

GA is employed to optimize the antenna structure to meet the prior requirement of the antenna operation. It sorts the design according to computed values of the fitness function, and creates a better design according to the superior designs in the previous generations as illustrated in Fig. 2 (a), where eight genes (n = 8, each gene corresponds to a set of parameter's values for an individual antenna structure) were assumed to generate superior new antenna designs. The fitness function is computed for each gene, and compared to justify the superiority of the antenna performance. In Fig. 2 (a) a larger fitness value indicates a superior performance of the antenna associated with this gene. The superior genes are retained while the rest is abandoned in the next generation, where new offspring genes are produced from the superior parent genes (i.e., the superior genes retained in the previous generation) to form the same number of genes in the competition based on a roulette wheel parent selection. The creation of the new offspring genes uses either crossover or mutation methods as illustrated in Fig. 2 (b). The crossover method means that design parameters are swapped between two parent designs, while the mutation method implies that a parameter of the parent design is replaced with a randomly generated number. The decision of using either crossover or mutation method is also random. The selection of parent designs is done via the roulette wheel method, that is, a superior design is assigned to a larger piece in the wheel, which is equivalent to a larger probability density value. Therefore, stronger parents are more likely to produce more children.

In this work, the following formulations are found to work well for the crossover method [7] to produce an offspring gene X_o,

$$X_o = 0.5X_{p,1} + 0.5X_{p,2} \tag{1}$$

$$X_o = 1.5X_{p,1} - 0.5X_{p,2}, \tag{2}$$

and

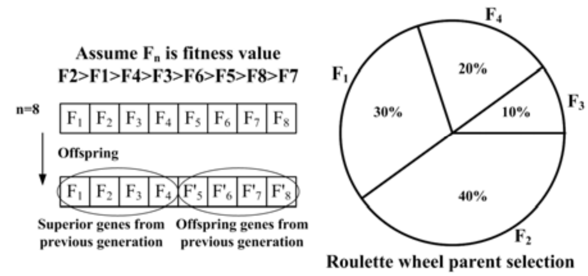
$$X_o = -0.5X_{p,1} + 1.5X_{p,2} \tag{3}$$

where $X_{p,1}$ and $X_{p,2}$ are the superior parent genes. Also mutation can use the following formulation,

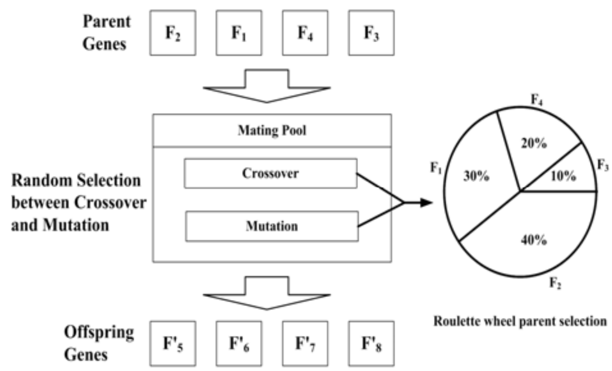
$$X_o = X_p + \Delta X \tag{4}$$

where X_p is the superior gene and ΔX is an random number.

After the number of the iteration has been reached, the gene with largest fitness value (or best performance) is employed to determine the optimized antenna structure.



(a) The general concept of GA.



(b) Methods to produce superior offspring genes.

Fig. 2. Illustrations of genetic algorithm to generate new antenna structures with superior performance.

C. Interface to Interact with IE3D Code

(1) *Initial parameter setup*

An initial antenna design is first performed within the framework of IE3D. The fundamental parameters such as the sampled frequencies, radiation patterns and geometry of antenna structure should be assigned tentatively. Figure 3 shows the input for a demonstration example of a simple microstrip antenna design for WLAN applications, where the antenna geometry is shown in Fig. 3 (a) with the return loss of antenna obtained in Fig. 3 (b). The parameter setup page of IE3D is shown in Fig. 3 (c), where the parameters designated will be used throughout the procedure of the antenna design within the proposed work of this paper. Three important parameters on this setup pages are the sampled frequencies, cell sizes and the "After setup" operation selection. In this case, 31 sampled frequencies between 2.3 GHz and 2.6 GHz are selected for IE3D analysis, which will be used in the later optimization of return loss. The cell size should be properly selected to assure accurate analysis at the sampled frequencies. The "After Setup" should select "Invoke IE3D" so that the required data files of antenna geometry (filename.geo file) and return loss data (filename.sp file) will be created, which can be used later as an interface to interact with IE3D and the GA algorithm for antenna design optimization. Note that if "Create .sim file only" is selected, then only the file to record the simulation procedure (filename.sim file) is created.

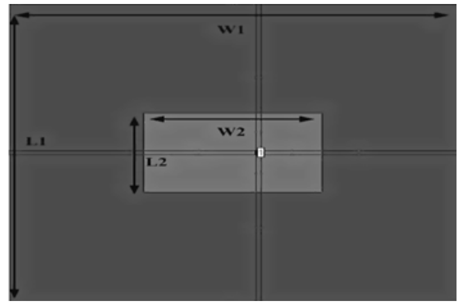
The selection of the initial antenna design plays a significant role for the success of the optimization procedure. It should provide the essential possibility to achieve the design goal since the optimization procedure tends to minor tune of the antenna structure. For example, if a dual band antenna design is of interest, the initial antenna design should provide a dual band operation, and the GA will tune the antenna structure to adjust the operational bands to the designated bands of interest.

(2) *Interaction via the IE3D's input and output files*

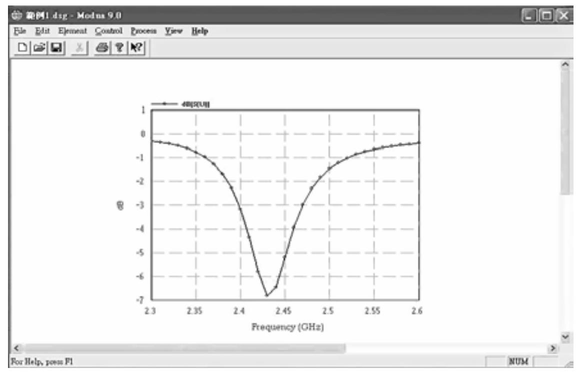
Once the initial antenna geometry as well as the run parameters are designated, they are recorded in data files as the inputs to control the IE3D analysis in each iteration without any changes throughout the entire antenna design procedure except the antenna geometry file (i.e., filename.geo) that records the coordinates of the initial antenna geometry as shown in Figure 4 and will be changed at each iteration by the GA procedure to obtain new antenna design with superior performance. Note that a new design will be created if any of the coordinates is changed, and re-running IE3D will result in the performance analysis of the new antenna. The antenna performance such as the return loss of the example demonstrated in this paper will be recorded in a data file (i.e., filename.sp) as shown in Figure 5, which will be used to compute the fitness functions for the use in the GA to create the coordinates of a new antenna structure.

(3) *Execution of IE3D program based on DOS command*

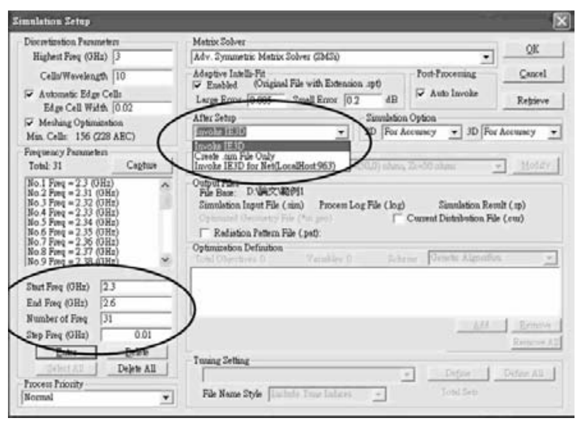
The execution of the entire antenna design procedure is performed within the controls of the automation program. The program shall know when to call the IE3D for the EM analysis, when the IE3D has completed the analysis, and where to pass the parameters of IE3D to the GA operator. The access of the IE3D is performed through the DOS command by setting the common paths in "C:\autoexec.bat" so that the paths can be linked as the computer starts. The commands are shown in Figure 6 where the first line shows the path to find the IE3D program and the second line shows the path of the automation program. The IE3D execution is performed through a run-time function. In Virtual Fortran, the command is "AA=RUNQQ ("IE3D","filename.sim")", where the "filename.sim" passes the IE3D parameters to the IE3D for execution. The **RUNQQ** function executes a new process for the operating system using the same path, environment, and resources as the process that launched it. The launching process is suspended until execution of the launched process is complete. "AA" is dummy variable to record the status of the function execution. If the program executed with **RUNQQ** terminates normally, the exit code of that



(a) Antenna geometry.



(b) IE3D parameter setup page.

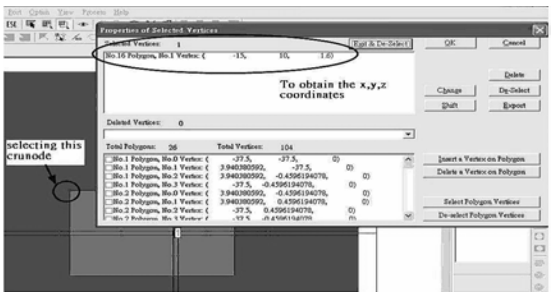


(c) Return loss of the antenna.

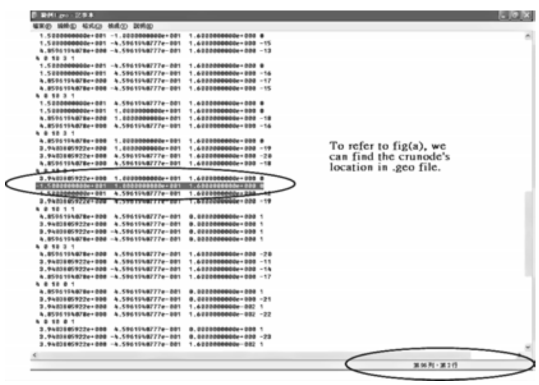
Fig. 3. An example of an initial antenna design using IE3D for WLAN applications. In (a) the dimensions of the geometry are W1 = 75 mm, W2 = 30 mm, L1 = 75 mm and L2 = 20 mm with a thickness 1.6 mm for an Fr4 substrate ($\varepsilon_r = 4.4$).

program is returned to "AA". If the program fails, -1 is returned to "AA".

This usually involves identification of numerical accuracy or other limitations, solution convergence, numerical and physical modeling error, and parameter tradeoffs. However, it is also permissible to address issues such as ease-of-use, set-up time, run time, special outputs, or other special features.



(a) IE3D GUI window for the coordinates of the polygon's vertex.



(b) Geometry file records the coordinates of the polygon's vertex.

Fig. 4. The IE3D GUI and *.geo file to record the coordinates of the antenna structures.

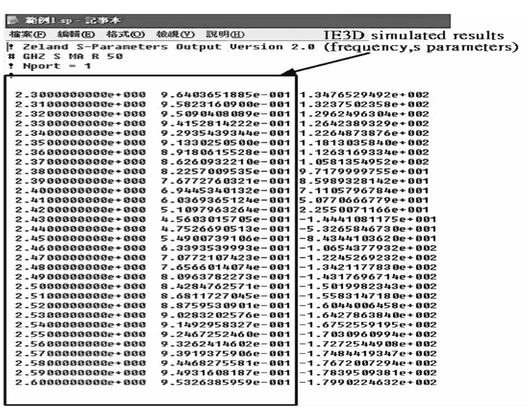


Fig. 5. The IE3D *.sp file to record the return loss at sampled frequencies.

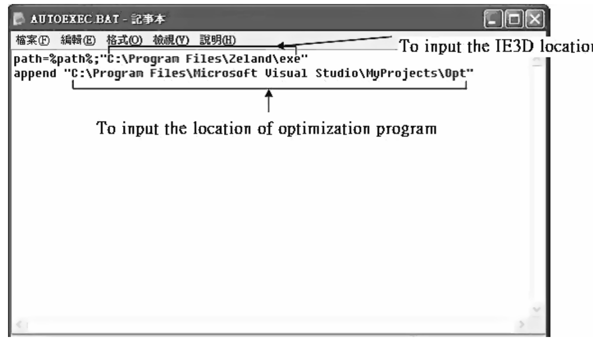


Fig. 6. The setting of the "C:\autoexec.bat" for the common paths setup.

III. DEMONSTRATION EXAMPLES: DUAL BAND PATCH DESIGNS

The proposed strategies are demonstrated by considering a dual band microstrip patch antenna design for the applications of Wi-Fi [5] and dedicated short range communications (DSRC) [6] where the operational frequency bands of 2.45 GHz and 5.8 GHz are pursued. Thus the GA operator uses a fitness function based on the return loss spectra to evaluate the performance of a design. The fitness function for n^{th} gene is defined by

$$F_n = \frac{1}{\left(\sum_{m=1}^{m} C_{nm}\right) + 1} \tag{5}$$

where

$$C_{nm} = \begin{cases} S_{11}(f_m) - S_{11}^*(f_m) & \text{if} \quad S_{11}(f_m) > S_{11}^*(f_m), \\ 0 & \text{if} \quad S_{11}(f_m) \le S_{11}^*(f_m) \end{cases} \tag{6}$$

and M sampled frequency points are selected in the designated frequency bands with f_m being the sampled frequency so that we can handle dual band or multiple band designs. For each frequency point, if the simulated S_{11} (in dB) is lower than the prescribed S^*_{11}, C_{nm} is assigned as 0. Otherwise, the difference in simulated and desired values in dB is assigned to C_{nm}. The summation of C_{nm} contributes to the denominator of F_n. A proper design, which meets the S_{11} specifications in all bands, will yield a fitness value of one (F_n =1) that is the largest value to occur in the optimization procedure. Also the larger value of F_n implies a superior performance as required in the GA procedure.

Figure 7 shows the geometry of the proposed dual band antenna design, which is basically a patch printed on a substrate which is placed by Z_1 beyond a ground plane. The patch is fed slightly off center. There are several slots cut into the patch, which perturb the fields to yield multiple resonant modes. Those geometric parameters such as the slot position, slot length, slot width and patch dimensions can be altered to yield different designs, and thus can be used as parameters in the GA operator to create new design by changing their values according to the algorithm. The initial design with the dimensions shown in Table 1 is capable of creating two resonance frequencies as shown in the return loss of Fig. 8. The GA procedure tends to adjust the resonant frequencies to the designated frequencies of interest. In the procedure, each subsequently created design by GA is fed to the IE3D program for performance analysis, where the return losses at sampled frequencies are simulated and used to compute the fitness function as defined in equation (5). If the fitness value has not met the prior designated requirement, it is fed back to the GA operator to produce a new design of the next generation.

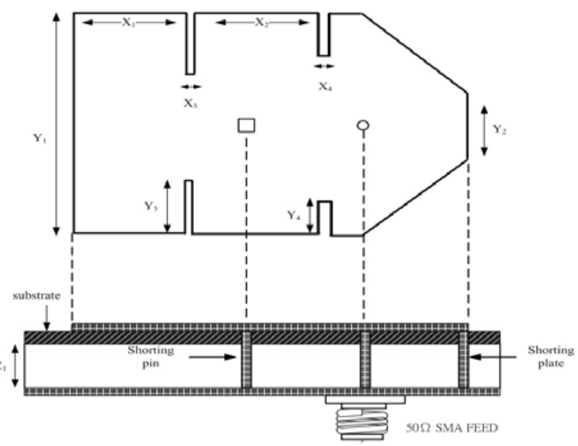


Fig. 7. Geometry of the initial patch antenna design.

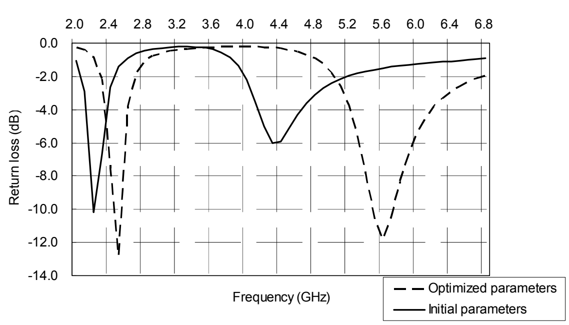


Fig. 8. Comparison of simulated reflection spectra of the patch before and after optimization.

In this case, the optimization goal is to obtain the first resonance at 2.45 GHz with a return loss smaller than -7 dB, which is equivalent to a VSWR of 2.5, and the second resonance should be broad enough to cover the 5.2 GHz to 6 GHz band. An optimized design was derived by altering eight geometric parameters sequentially as shown in Table 1. For each parameter, four iterations were executed. The optimization process took on a Pentium IV machine of 2.4 GHz with 512 GB RAM, approximately 36 hours to complete. In each IE3D simulation, antenna performance was examined from 2 GHz to 6.8 GHz with a 0.1 GHz frequency step. The cell size is one fifteenth of a wavelength. Most of the time was spent on the IE3D program, which is proportional to the complexity of the simulated structure, and the time spent on the GA operator is negligible. Figure 8 shows the comparison of return loss spectra of the initial and optimized designs. According to this figure, both resonant bands are shifted up and the higher band fits the 5.2 GHz to 5.8 GHz range. The optimized values of the antenna dimensions are also shown in Table 1.

Table 1. The initial and optimized values of the antenna dimensions as illustrated in Fig. 7.

Parameter	**Initial Values(mm)**	**Optimized Values(mm)**
X1	4	8
X2	2	8.5
X3	2	0.5
X4	2	1
Y1	16	18
Y2	18	5.2
Y3	4	4.5
Y4	4	2.9
Z1	4	3.2

To validate the optimization scheme, we manufactured the initial and optimized patch designs and measured their reflection coefficients. Figure 9 shows the two return loss spectra. The null levels are slightly different from simulation results. However, the curves exhibit a similar trend in the movement of resonant ban locations. The difference can be attributed to the error in selecting material parameters. Nevertheless, the result indicates the proposed approach can effectively predict the performance changes due to geometric variation, which in turn validate the optimization scheme.

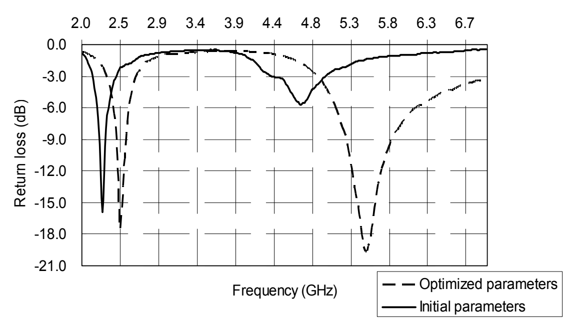
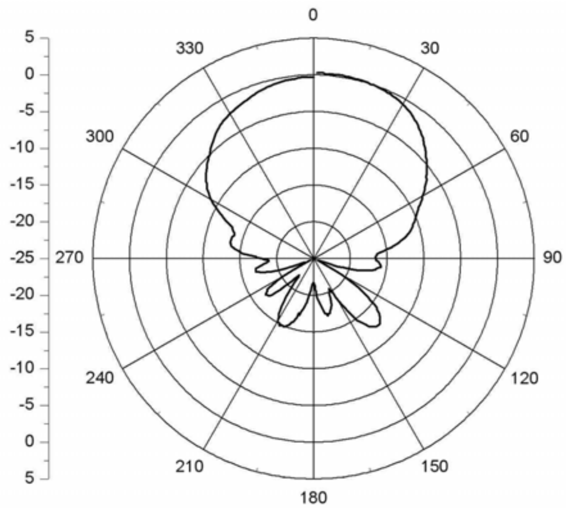
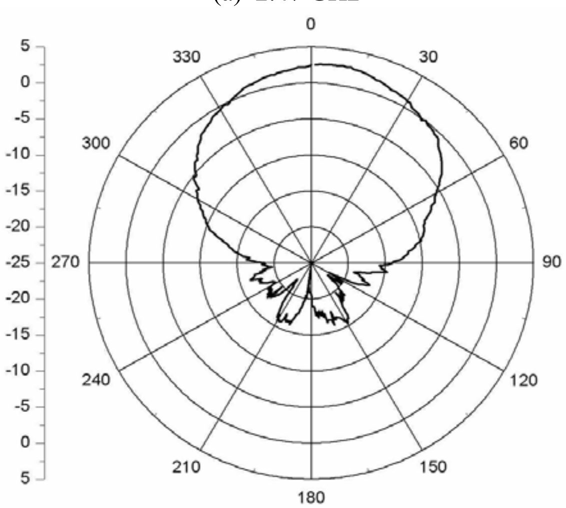


Fig. 9. Comparison of measured reflection spectral of initial and optimized designs.

The radiation patterns of the antenna were measured and shown in Fig. 10 at 2.47 GHz and 5.6 GHz, where the patterns as well as the beamwidths meet the general behaviors of a general planar microstrip antenna. Also gains of these two bands are 0.23 dBi and 2.5 dBi, respectively.



(a) 2.47 GHz



(b) 5.6 GHz

Fig. 10. The radiation patterns of the dual band patch antenna at 2.47 GHz and 5.6 GHz.

IV. CONCLUSION

In this work, we integrated the GA-based design optimizer and IE3D simulation tools within the automation control program. The validness of this optimizer is verified via the optimization of the dual band patch design for the applications of Wi-Fi and DSRC applications. Both the simulation and measurement results confirm improvement in antenna bandwidth performance and demonstrate that the optimizer developed can contribute to design automation.

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