Optimization of a Microstrip Matching Circuit at Two Frequencies Using Taguchi's Method

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Abstract: Taguchi's Method optimization of experiment parameters for a double stub transmission line for matching at two frequencies is presented in this presentation. First, a three-dimensional Finite-Difference Time-Domain (FDTD) program (CEMS) is used to design a dielectric resonator antenna (DRA) for operation at 1.6 GHz and 2.5 GHz frequencies. To improve the matching at these frequencies, Sonnet is used to design a dual frequency matching circuit. The design is optimized by using Taguchi's method, where Sonnet is integrated with the method using the SonnetLab toolbox. In this contribution, the application and methodology of Taguchi's method as a global optimization technique is described and implemented. Limitations of the performance of the optimization technique due to the fitness function are investigated.

Keywords: Taguchi's method, input impedance matching, optimization

1. Introduction

Optimization is a technique used to achieve the best results possible. Through modifying input parameters, the optimization process searches for a better output so that system performance can be improved. Currently in electromagnetics (EM), circuit and antenna designs rely on modern optimization techniques to achieve better solutions. Traditional methods, e.g., trial-and-error, require numerous experiments to obtain an optimum or satisfactory results.

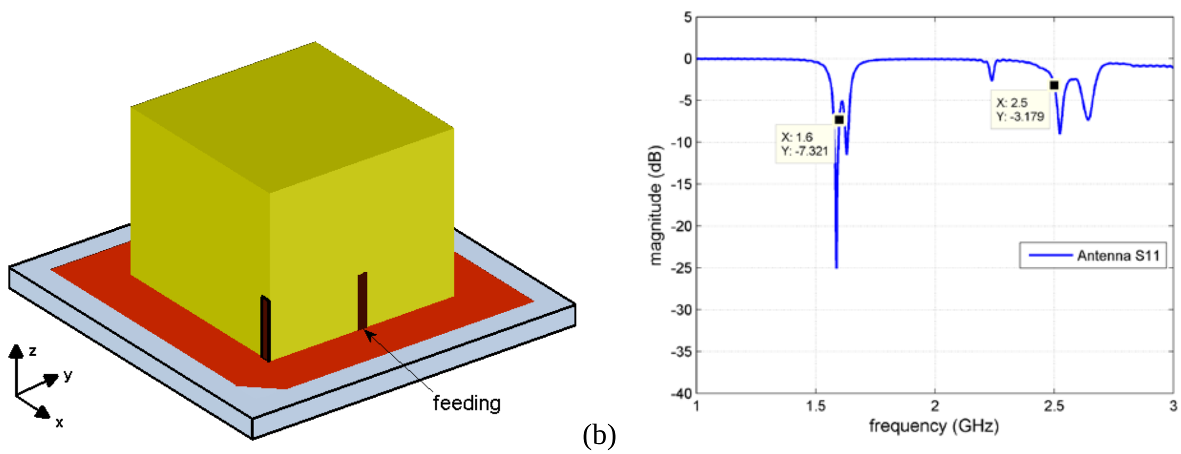
Some optimization techniques operate on a modified trial-and-error approach where the system parameters are varied at rates coinciding with the error between the desired and measured results. This type of methodology requires a large number of trials to achieve. Another possibility is to perform a full factorial experiment where all combinations of parameters in an experiment are used. This method can effectively find an optimal result at the cost of running too many trials costing time and money [1].

Taguchi's Method addresses the problem of the computational complexity of full factorial experiments by implementing the concept of orthogonal arrays (OA) to reduce the number of tests required in the full factorial search. Successful application of Taguchi's Method is more prevalent in fields such as chemical engineering, mechanical engineering [2], integrated chip manufacture, and power electronics as compared to EM [1]. Despite this, Taguchi's Method has been implemented in EM applications such as optimizing nonlinear microwave circuits [3], multi-objective optimization of Yagi-Uda antenna [4], optimizing antenna arrays [5-6], and more.

In this presented study, Taguchi's Method optimization was integrated with Sonnet using SonnetLab and scripting in Matlab to optimize a microstrip matching circuit to match input impedance of a dielectric resonator antenna (DRA) at two frequencies. The antenna is designed using CEMS, a three-dimensional finite-difference time-domain (FDTD) program that is developed based on [7]. Then, the S-parameters file obtained from CEMS is integrated with a matching circuit in Sonnet using a Sonnet Netlist project. Then the matching circuit is optimized using a Matlab script of Taguchi's method that accesses Sonnet through SonnetLab.

2. The DRA Antenna and the Microstrip Matching Circuit

The final goal is to design an antenna that operates at 1.6 GHz and 2.5 Ghz, with a hemispherical radiation pattern and circular polarization. The antenna is intended for campers, who will use the antenna for both position location and communication. It is very difficult to achieve all these specifications with a simple antenna. Through a design process using three-dimensional software CEMS, a DRA antenna is achieved with the desired radiation characteristics, but with a poor matching at the desired frequencies. Figure 1 shows the DRA antenna and its return loss.



(a) (b)

Fig. 1. (a) The DRA antenna, and (b) its return loss. The size of the resonator is 20 mm in *x* and *y* directions, and the height is 16.5 mm. The dielectric constant is 40. The feeding strip is 5.5 mm long, and the parasitic strip is 6 mm long. The patch under the resonator is 30 mm on a side. Edge of the triangle cut is 4 mm. The substrate is 2 mm thick and its dielectric constant is 3.5.

In order to improve the input matching, a microstrip matching circuit is designed using Sonnet. Sonnet is preferred since it is very well suited for the analysis and design of planar circuits. The S-parameters file obtained from CEMS is integrated with a matching circuit in Sonnet. The matching circuit, shown in Fig. 2, is a double stub tuner. Here, four parameters are defined to optimize the circuit for matching at two frequencies: L1, L2, D1, and D2. Port 1 is the main input port to the circuit, while port 2 is the internal port which connects to the antenna. This circuit is integrated with the antenna S-parameters file using a Sonnet Netlist project. The Netlist project is accessed and controlled by SonnetLab, which is a free Matlab toolbox that enables users to control and automate Sonnet's 3D planar electromagnetic simulator. Then, a Matlab script is developed based on Taguchi's

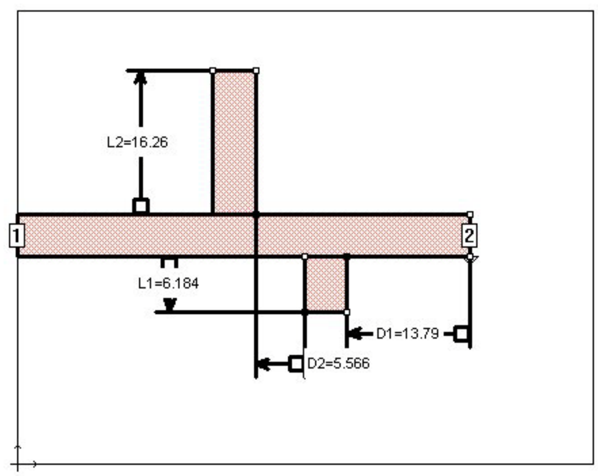


Fig. 2. Microstrip matching circuit in Sonnet. Dimensions are in millimeters. Strips are 4.8 mm wide. The substrate is 62 mils thick. The dielectric constant is 2.19.

method, where the script changed the design parameters and ran Sonnet simulations of the matching circuit using SonnetLab.

2. Taguchi's Method

The development of Taguchi's method is based upon the efficiency of orthogonal arrays (OAs) in the design of experiments. OAs provide an efficient method to control design parameters such that optimal results can be obtained with minimal runs [1]. A full factorial experiment of 4 tunable parameters, each of which is separated into 3 discrete levels, is prepared. The levels correspond to different numerical values relative to the minimum and maximum range of the parameter in question. For example if the optimization range of parameter 1 is [0, 8], the levels (1, 2, 3) for parameter 1 are (2, 4, 6). The exhaustive testing of the experiment would require $3^4 = 81$ trials.

The $OA(N,k,s,t)$ notation defines an orthogonal array where *S* is a set of *s* levels and a matrix *A* of *N* rows and *k* columns and entries from *S*. In every $N \times t$ subarray of *A*, each *t*-tuple based on *S* appears exactly the same times as a row [1]. In this case, an $OA(9,4,3,2)$, as can be seen in Table 1, could be used to reduce the number of trials from 81 to 9.

There are three fundamental properties of OAs that highlight the utility of Taguchi's Method. The first is that while the full factorial strategy requires 81 trials, the $OA(9,4,3,2)$ needs only 9 trials. Statistical results demonstrate that the optimum outcome from the OA is close to that obtained from the full factorial approach. Second, all possible combinations of up to *t* parameters occur equally, which ensures a balanced and fair comparison of levels for any parameter and any interactions of parameters. In short, the OA is optimized as the results of the trials are uncorrelated. Thirdly, any $N \times k'$ subarray of an existing $OA(N,k,s,t)$ is still an OA with notation $OA(N,k',s,t')$. This makes the selection of an OA from an existing OA database easy even with experiments of varying number of parameters and requirements.

Table 1: $OA(9,4,3,2)$

Trial	Parameter 1 Level	Parameter 2 Level	Parameter 3 Level	Parameter 4 Level
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The optimization procedure for Taguchi's Method starts with the selection of a proper OA and the design of a suitable fitness function. The OA selection mainly depends upon the number of optimization parameters, *N*, while compensation for the non-linear nature of the system can be tuned through *s* [1].

For the design of the double stub transmission line, there are 4 parameters to be chosen: the length (L1) and distance (D1) of the first stub from the load impedance (antenna) and then the length (L2) and distance (D2) of the second stub from the first stub. The initial optimization ranges for L1, D1, L2, D2 were L1=[5, 30], D1 = [0, 40], L2 = [5, 40], and D2 = [0, 66.8].

The fitness function is designed with respect to the optimization goal. Fitness is a measurement of the difference between the optimization goal (*0* value) and the obtained value from the current inputs. The smaller the fitness value, the better the match between the obtained value and the desired value. With the design goal of minimizing return loss the ensuing fitness function is

$$Fitness = [S_{11}(1.6GHz)]^2 + [S_{11}(2.5GHz)]^2 , \tag{1}$$

where $S_{11}(f)$ denotes the input port reflection coefficient at frequency *f*. Ideally we would like to achieve at least -10 dB matching at both operational frequencies but the fitness function is designed to converge to where the most combined power is transmitted.

After designing the fitness function, input parameters with which the experiments are conducted are chosen. When the OA is used, the corresponding numerical values for the three levels of each input parameter need to be determined. In the first iteration, the value for level 2 is selected at the center of the optimization range. The values of levels 1 and 3 are calculated by modifying the value of level 2 with the variable called level difference *LD*. The level difference of the first iteration (LD1) is determined by

$$LD_1 = \frac{\max - \min}{\# levels - 1} , \tag{2}$$

where min and max are the lower and upper bound of the optimization ranges, respectively.

After determining the input parameters, the fitness function for each experiment can be calculated. Fitness values are converted into signal-to-noise (S/N) ratio (η) in Taguchi's method using

$$\eta = -20\log(Fitness) , \tag{3}$$

where *Fitness* is the fitness function (1). These results are used to build a response table for the first iteration by averaging the S/N ratio for each parameter *n* and each level *m* using

$$\overline{\eta}(m,n) = \frac{s}{N} \sum_{i,OA(i,n)=m} \eta_i . \tag{4}$$

Finding the largest S/N ratio in each column can identify the optimal level for that parameter. Once the optimum levels are identified, a confirmation experiment is performed using the combination of the optimal levels identified in the response table. The fitness value obtained from the optimal combination is regarded as the fitness value of the current iteration [1].

If the results from the current iteration fail to meet termination criteria, the process is repeated in the next iteration with a reduced optimization range for a converged result. The *LD* of the current iteration LD_i is modified by a reduced rate (*rr*) to obtain the *LD* of the next iteration LD_i+1. Both linear and Gaussian reduced rates were used in the simulation. The linear reduced level difference can be described by

$$LD_{i+1} = rr \times LD_i , \tag{5}$$

where *rr* is a constant value in the range [.5,1). The larger the value of *rr*, the slower the convergence rate of the problem. The Gaussian reduced level difference can be described by

$$LD_{i+1} = rr(i) \times LD_i , \tag{6}$$

where

$$rr(i) = e^{-(i/T)^2} , \tag{7}$$

and T is the duration width of the Gaussian function. The Gaussian function reduces the LD slowly during the first several iterations to offer the optimization process more degrees of freedom while decreasing the LD at a faster rate to speed up the convergence. The procedure is repeated until the experimental results for all 9 experiments converge to the same result.

3. Results

The simulation results yielded by Sonnet using Taguchi's Method can be seen in Table 2. All of the simulation results met our desired performance of at least -10 dB matching at each frequency. As expected, as the value of *rr* increases, so does the matching at the two operational frequencies. This comes at a cost of an increased number of trials required for final convergence. This is most clearly seen in the *rr* = 0.9 case where 570 trials is needed as compared to the 140 and 150 trials when *rr* is 0.5 and 0.7, respectively. However, if return loss needs to be minimized as much as possible, the large number of trials is justified by the performance.

Using Gaussian reduced rate yielded much better results as compared to the linear reduced rate. This comes at the cost of somewhat higher computation although the use of the Gaussian reduced rate greatly outperforms the results yielded by the linear reduced rate. The best solution occurred with a Gaussian duration of 16 and the associated results can be seen in Fig. 3. The optimum values of L1, L2, D1, and D2 are shown in Fig. 2. Although it is expected that the final converged solution should improve with increased Gaussian duration, this is not so.

Table 2: A comparison between the results of using the linear and Gaussian reduced functions

Linear Reduced Rate (*rr*)	S_{11}(1.6 GHz) (dB)	S_{11}(2.5 GHz) (dB)	# of trials
0.5	-13.3044	-18.3468	140
0.7	-10.0206	-19.481	150
0.9	-12.5396	-27.9618	570
Gaussian Duration (*T*)			
15	-16.77	-33.63	160
16	-16.0367	-35.953	170
17	-15.7474	-29.9408	180
18	-16.5308	-31.7012	190
19	-16.5782	-27.6231	200
20	-15.914	-27.676	230

4. Conclusions

We were able to achieve our desired performance of at least -10 dB matching at our dual frequencies at 1.6 and 2.5 GHz. It is also shown that the Gaussian reduced rate function outperforms the linear reduced rate noticeably in this simulation. By comparing the S_{11} values in Fig. 3, we were able to achieve a much improved matching through using Taguchi's Method to optimize the design of two stubs.

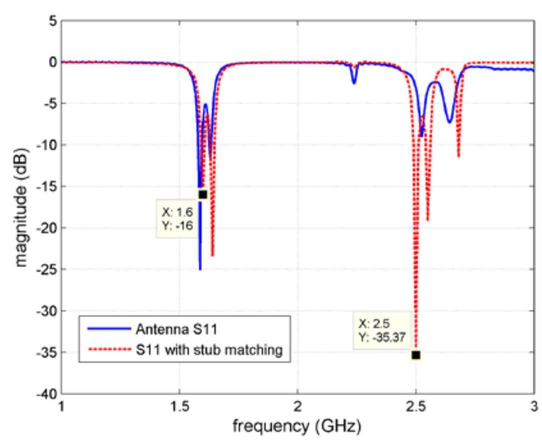


Fig. 3. Input impedance of the antenna before matching and after matching.

There was a discrepancy where the best simulation results came from a Gaussian duration of 16 instead of 17 through 20, as would have been expected. As previously mentioned in Section 2, The Gaussian function reduces the LD slowly during the first several iterations to offer the optimization process more degrees of freedom while decreasing the LD in successive iterations at a faster rate to speed up the convergence. Because of the increase in Gaussian duration, it is believed that the rate of change in the LD starts to increase quickly at a point where the LD has not yet converged to the optimal solution point and the fine tuning at smaller LD values causes the solution to diverge to a less optimal result.

With this in mind, close attention should be paid to deciding the Gaussian duration width as an increased width may not necessarily translate to a better solution even though there are a greater number of total trials needed for convergence.

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