Statistical Modelling of Aperture Coupled Microstrip Patch Antenna; Simulation to Fabrication

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Abstract— Design and fabrication of resonant aperture coupled patch antennas at a particular frequency is a complex and difficult process because of the intrications involved in multilayer architecture. The design process requires correct formulations relating the output to input variables. In this paper we undertook the task to confront the design problems of electromagnetically aperture coupled patch antenna. Design methodology of antenna is presented taking all the parameters subjectively. The system parameters related to patch length and slot length are evaluated by CST and modeled to support the communication in extreme temperature constraints. For simulation, the polarization is linear and working frequency is 2.4 GHz. The novel approach in this design is that we have developed statistical equations to find the relationship between patch length, slot length, S11 to obtain best values of them at resonant working frequency. The computer-generated antenna has also been fabricated and is available to be used at the front end of RF transceiver.

Keywords— Multilayer Architecture, Design Equations, regression equation, correlation research, Patch length, Slot length, predictive model, predictor variable, method of least squares.

I. Introduction

The aerodynamic profile of the microstrip antenna in conjunction with its light weight makes it a preferable choice for many applications. A microstrip antenna in its fundamental form consists of a metallic patch on a ground substrate, which is an annexation of a microstrip transmission line. A number of theoretical and experimental studies have been performed *to analyse various parameters involves in designing of the* aperture-coupled microstrip patch antenna [1-7].The proposed solution is a statistical analysis to ascertain the almost equal values of required dimensions (length and width) for slot and patch of a Microstrip Aperture Coupled Patch Antenna.

There are two major contributions in this research work. First is formulation of design equations and selection of components under the constrained design. Second is formulation of regression equation and correlation research for the aperture coupled patch antenna.This analysis has been carried out by simulation of results for various values of slot and patch dimensions by using CST(R). The antenna under evaluation has also been fabricated and tested.

A. *Basic Structure of Microstrip Patch Antenna*

The basic design parameters for an aperture coupled patch antenna can be viewed in Figure 1. The whole structure consists of a rectangular patch of dimensions a x b. The metal antenna patch is printed on a substrate having some dielectric constant, ε_{ra}. The patch is fed by a microstrip line via a slot or aperture in the common ground plane. The common ground plane is positioned in between the patch and ground plane. The microstrip line is fed on another substrate, which has its own thickness and dielectric constant, ε_{rf}. Coupling between slot to dominant mode of the antenna and microstrip line occurs, because the slot/ aperture interrupts the longitudinal current flow in them as described in [6]. The parameters considered for the design of an aperture coupled microstrip patch antenna can be divided into three categories i.e Feed side, Antenna side and slot/aperture side.

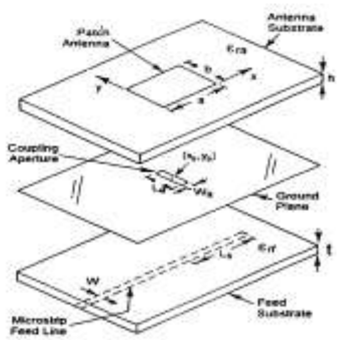

Figure 1. Exploded view of aperture coupled patch antenna

B. *Selection of Parameters for simulation/ analysis and Fabrication of Antenna*

Parameters are selected keeping in view the all possible design constrains. The detail of selected parameters vis a vis their values with rational is given in Table I.

TABLE- I

Design Parameters for Patch Antenna

Category	Parameters	Values	Rational
Feed Side	Thickness of Substrate	1.524 mm (Rogers TMM 10)	Rogers has low variations with temperature
	Relative Permittivity of Substrate	ε_r=9.2	higher values of permittivity allow better impedance match
	Feed line width	3.2 mm	For impedance matching (To avoid the use of impedance matching techniques the desired impedance is set to 50 Ω)
	Stub length	12.49 mm for 2.4 GHz	L_{stub}= λ/4=24.98mm/2 =12.49mm
Antenna side	Thickness of Substrate	1.575 mm (Duroid5800)	Duroid has low variations with temperature
	Relative Permittivity of Substrate	ε_r=2.2	Lower permittivity avoid spurious/surface waves and lower the value of ε_r higher the value of bandwidth
	Patch width	59 mm	To achieve larger bandwidths and to increase conductance of radiating slots, large Patch width selected
	Patch length	54 mm	$L\_patch = c/(2f\sqrt{\varepsilon_r})$
Slot/ Aperture side	Slot length	13.8 mm	$L_{slot} = W_{feed} + n*h$ Here n > 6 h=1.524 & $W_{feed=3.2}$
	Slot width	1.38 mm	It is usually designed with a ratio of 1/10 times the slot length

II. Simulation/Statistical Analysis for Patch Length

After designing the Patch antenna in CST as per values selected in Table-I, Simulation against various values of Patch Length are carried out .Results are shown in Figure-2.

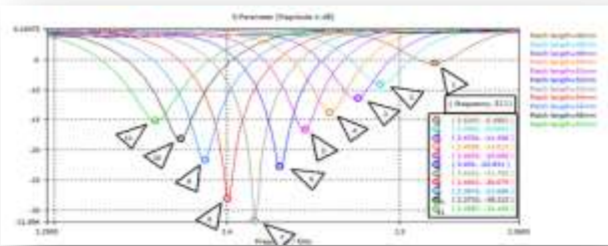

Figure 2. screen shots of CST Simulation of Patch Length

Results shows how patch length effects on the output parameters. We performed a regression analysis for this data and obtained the following output against various cases.

Case1: Output variable S11 and Input variable Patch Length

TABLE -II
Correlations

Correlations		S11	patch length
Pearson Correlation	S11	1.000	-.618
	patch length	-.618	1.000
Sig. (1-tailed)	S11	.	.021
	patch length	.021	.
N	S11	11	11
	patch length	11	11

For 11 different patch lengths, the mean value is 51.2 mm and S11 is -17.6 dB in simulation by CST. Correlations results are shown in table -II

Pearson correlation coefficient shows that patch length's effect size on S11 is R^2 = 38.2 % and they are related to each other in opposite directions, i.e. increase in patch length decreases S11 and vice versa. If *r* is Pearson correlation coefficient then the effect size is calculated as $R^2 = r^2 * 100$.

TABLE-III
Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics: R Square Change	F Change	df1	df2	Sig. F Change
1	.618[a]	.382	.313	6.59024	.382	5.559	1	9	.043

The Table-III shows F-test result. F-test measures goodness of fit of our regression model to predict the observed values. The obtained F value is 5.56 > 1 and has a significance of $p = 0.043 < 0.05$. This shows satisfactory results that our model is good enough to predict observed values. Similar results are again provided in Analysis of Variance or ANOVA Table-IV.

TABLE-IV
ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	241.431	1	241.431	5.559	.043[a]
	Residual	390.882	9	43.431		
	Total	632.313	10			

The table shows that out of the total variance SS_T = 632.31, our model is significantly telling about systematic variance SS_M = 241.431 units and is unable to justify unsystematic variance (hidden factors) of SS_R = 390.882 units. The table-V gives the values of b coefficients for the modelled S11 regression equation.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
	B	Std. Error	Beta			Zero-order	Partial	Part
1 (Constant)	55.690	31.174		1.786	.108			
patch length	-1.413	.599	-.618	-2.358	.043	-.618	-.618	-.618

TABLE- V

Coefficient Values

Using these values, the regression equation for dependaent variable S11 is:-

$$S11 = -1.413(Patch\ length) + 55.69 \ldots\ldots..(1)$$

This statistical regression model can now be used to predict the outcome variable S11 for any value of patch length.

Case 2: Output variable f_r and Input variable Patch Length

For different patch lengths the mean value of resonant frequency obtained in simulation results of CST is 2.43 GHz and mean patch length is 51.9 mm.

TABLE- VI

Pearson correlation coefficient

Correlations		resonant frequency	patch length
Pearson Correlation	resonant frequency	1.000	-.999
	patch length	-.999	1.000
Sig. (1-tailed)	resonant frequency	.	.000
	patch length	.000	.
N	resonant frequency	11	11
	patch length	11	11

Pearson correlation coefficient given in Table- VI shows that patch length's effect size on resonant frequency f_r is R^2 = 99.8 % and they are related to each other in opposite directions, i.e. increase in patch length decreases f_r and vice versa. If r is Pearson correlation coefficient then the effect size is calculated as $R^2 = r^2 * 100$.

TABLE- VII

Model for F-test measures

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.999[a]	.997	.997	.00300	.997	3037.465	1	9	.000

The obtained F value is > > > 1 and has a significance of $p < 0.0001$. This shows satisfactory results that our model is good enough to predict observed values. Similar results are again provided in Analysis of Variance or **ANOVA** table-VIII.

TABLE- VIII

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.027	1	.027	3037.465	.000[a]
	Residual	.000	9	.000		
	Total	.027	10			

The table shows that out of the total variance SS_T = 0.027, our model is significantly telling about systematic variance SS_M = 0.027 units there is no unjustifyable unsystematic variance (hidden factors) of SS_R = 0.000 units. The Table-IX of c**oefficients values**, gives the values of b coefficients for the modelled f_r regression equation.The regression equation for dependaent variable S11 is:-

TABLE -IX

Coefficients values

Model	**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**			
	B	**Std. Error**	**Beta**			**Zero-order**	**Partial**	**Part**
1 (Constant)	3.214	.014		226.589	.000			
patch length	-.015	.000	-.999	-55.113	.000	-.999	-.999	-.999

$$S11 = -0.015(Patch\ length) + 3.214 \ldots\ldots (2)$$

III. Simulation Results for Changing Slot Length

Screen shot in Figure-3 of CST(R) is provided to see how slot length effects on the output parameters.

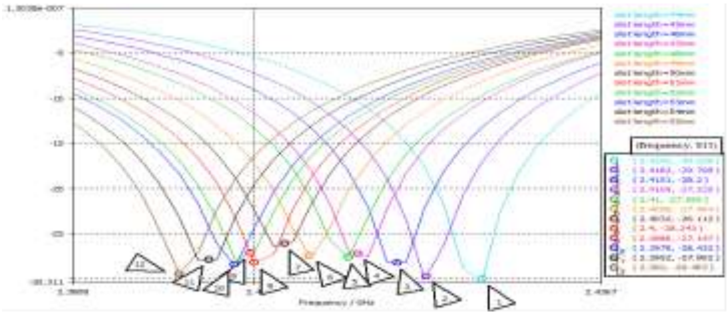

Figure 3. screen shots of CST Simulation of Slot Length

Case 1: Output variable S11 and Input variable Slot Length

For different slot lengths, the mean value is 84.5 mm and S11 is -28.124 dB. Pearson correlation coefficient shows that slot length's effect size on S11 is R^2 = 0.0196 % and they are related to each other in opposite directions. This value is indeed a very very low value to consider. If *r* is Pearson correlation coefficient then the effect size is calculated as $R^2 = r^2 * 100$.

TABLE-X
Correlation coefficient

Correlation		S11	slot length
Pearson Correlation	S11	1.000	-.014
	slot length	-.014	1.000
Sig. (1-tailed)	S11	.	.482
	slot length	.482	.
N	S11	12	12
	slot length	12	12

TABLE-XI
Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.014[a]	.000	-.100	1.21256	.000	.002	1	10	.965

The table **Model Summary** shows F-test result.The obtained F value is < < 1 and has a non significant p as value of $p > 0.05$. This shows that our model is not good enough to predict observed values. Similar results are again provided in Analysis of Variance or **ANOVA** table XII. The table shows that out of the total variance SS_T = 14.706, our model is non significantly telling about systematic variance SS_M = 0.003 units there is unable to justify unsystematic variance (hidden factors) of SS_R = 14.703 units.

TABLE-XII
ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	.003	1	.003	.002	.965[a]
Residual	14.703	10	1.470		
Total	14.706	11			

Case 1:Output variable f_r and Input variable Slot Length.

For 11 different slot lengths , the mean value is 84.5 mm and resonant frequency f_r is 2.405 GHz.Pearson correlation coefficient shows that patch length's effect size on resonant frequency is R^2 = 9 % and they are related to each other in same directions. This value is indeed a very low value to consider. If *r* is Pearson correlation coefficient then the effect size is calculated as $R^2 = r^2 * 100$.

TABLE-XIII
Correlation coefficient

Correlations		resonant frequency	slot length
Pearson Correlation	resonant frequency	1.000	.300
	slot length	.300	1.000
Sig. (1-tailed)	resonant frequency	.	.171
	slot length	.171	.
N	resonant frequency	12	12
	slot length	12	12

TABLE-XIV
Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.300[a]	.090	.000	.00928	.090	.991	1	10	.343

The obtained F value is < 1 and has a non significant p value of $p > 0.05$. This shows that our model is not good enough to predict observed values. Similar results are again provided in Analysis of Variance or **ANOVA** table-XV, shown below.

TABLE-XII
ANOVA

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	.000	1	.000	.991	.343[a]
Residual	.001	10	.000		
Total	.001	11			

IV. Antenna Fabrication

After the optimization of each parameter of proposed antenna and getting successful results through simulation we fabricated this antenna, for this purpose we used double side PCB in which FR-4 material is used for middle layer and a very thin layer of copper is fully clad on both sides of FR-4. The thickness of all three layers depends on our application and design. ORCAD(R) software was used as PCB designing. Screen printing technique is used to transfer the image of feed, Patch and ground plane on the PCB sides and then this PCB was etched. The final fabricated antenna as shown below in Figure 4 and 5.

Figure 4. Front side of Fabricated Antenna

The Vector Network analyzer (VNA) was used to Verify the simulated result

Figure 5: back view of the Fabricated Antenna

V. Conclusions and Findings

From the observations made in the above section, it is seen that the output dependent variable S11 and resonant frequency f_r is mainly effect by patch length. In theory we can also calculate these outputs from derived mathematical formulae but our statistical analysis shows that there is still some unexplained unsystematic variance for S11 and f_r that needs to be catered about. We tried to resolve this issue by seeing the effect of slot length on these outputs but this was not very effective. It did explain to some extent about f_r but not S11.
Therefore we make two proposals out of this research in the design of aperture coupled patch antennas

1) Because of the presence of unexplained variance (SS_R) it is better to avoid direct mathematical equations for finding S11 and f_r but instead use the regression models which we have proposed in this paper.
2) For future work we propose to continue finding the covariate(s) affecting these outputs to explain the residual variance (which is fairly large in case of S11).

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