Contents

Chapter 1

Introduction to HFSS

HFSS is a commercial finite element method solver for electromagnetic structures from Ansys.The acronym originally stood for high frequency structural simulator.It is one of several commercial tools used for antenna design,and the design of complex RF electronic circuit elements including filters,transmission lines,and packaging. Thousands of engineers have used HFSS in the analysis of electromagnetic components.Initially used to model waveguide transitions,HFSS was quickly utilized for other engineering design challenges.HFSS is now used by designers in all segments of the electronics industry.HFSS often is used during the design stage,and is an integral part of the design process.

The mathematical model used by the HFSS:

HFSS uses a numerical technique called the Finite Element Method (FEM). This is a procedure where a structure is subdivided into many smaller subsections called finite elements. The finite elements used by HFSS are tetrahedral, and the entire collection of tetrahedral is called a mesh. A solution is found for the fields within the finite elements, and these fields are interrelated so that Maxwells equations are satisfied across inter-element boundaries, yielding a field solution for the entire, original, structure. Once the field solution has been found, the generalized S-matrix solution is determined.

The adaptive solution process and its importance to HFSS:

The adaptive solution process is the method by which HFSS guarantees that a final answer to a given EM problem is the correct answer. It is a necessary part of the overall solution process and is the key reason why a user can have extreme confidence in HFSSs accuracy. The adaptive analysis is a solution process in which the mesh is refined iteratively. Refinement of the mesh is localized to regions where the electric field solution error is high. This adaptive refinement increases the solutions accuracy with each adaptive solution. The user sets the criteria that control mesh refinement during an adaptive field solution. Most HFSS problems can only be accurately solved by using the adaptive refinement process.

The computational volume and its parts:

The computational volume, or solution space, is the volume within which HFSS explicitly calculates all EM fields. Any field quantities that are outside this volume can be derived from the fields within it.

The six general steps in an HFSS simulation:

There are six main steps to creating and solving a proper HFSS simulation.

- Create model/ Geometry: The initial task in creating an HFSS model consists of the creation of the physical model that a user wishes to analyze. This model creation can be done within HFSS using the 3D modeller. The 3D modeller is fully parametric and will allow a user to create a structure that is variable with regard to geometric dimensions and material properties. A parametric structure, therefore, is very useful when final dimensions are not known or design is to be tuned.
- Assign Boundaries: The assignment of boundaries generally is done next. Boundaries are applied to specifically created 2D (sheet) objects or specific surfaces of 3D objects. Boundaries have a direct impact on the solutions that HFSS provides; therefore, users are encouraged to closely review the section on Boundaries in this document.
- Assign Excitations: After the boundaries have been assigned, the excitations (or ports) should be applied. As with boundaries, the excitations have a direct impact on the quality of the results that HFSS will yield for a given model.
- Set up the solution: Once boundaries and excitations have been created, the next step is to create a solution setup. During this step, a user will select a solution frequency, the desired convergence criteria, the maximum number of adaptive steps to perform, a frequency band over which solutions are desired, and what particular solution and frequency sweep methodology to use.
- Solve: When the initial four steps have been completed by an HFSS user, the model is now ready to be analyzed. The time required for an analysis is highly

dependent upon the model geometry, the solution frequency, and available computer resources.

- Post process the results: Once the solution has finished, a user can post-process the results. Post processing of results can be as simple as examining the S-parameters of the device modelled or plotting the fields in and around the structure. Users can also examine the far fields created by an antenna. In essence, any field quantity or S,Y,Z parameter can be plotted in the post-processor. Additionally, if a parameterized model has been analyzed, families of curves can be created.

The three solution types:

When using HFSS, a user must initially specify what type of solution HFSS needs to calculate. There are three types of solutions available:

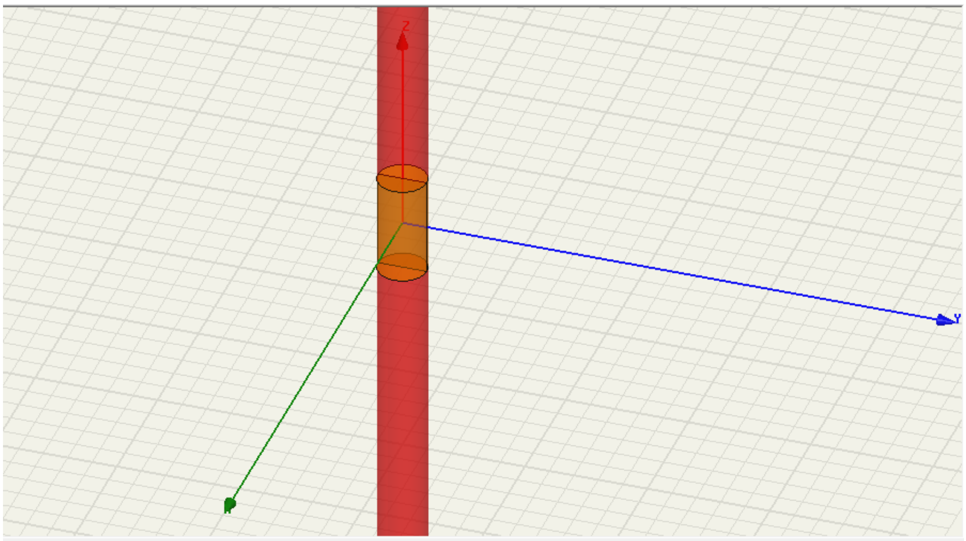
- Driven Modal: The Driven Modal solution type is used for most HFSS simulations, especially those that include passive, high-frequency structures such as microstrips, waveguides, and transmission lines.
- Driven Terminal: For simulations that deal with Signal Integrity, the newest solution type, Driven Terminal Mode, is used. These simulations generally include models that have multi-conductor transmission lines.
- Eigenmode: The eigenmode solver will provide results in terms of eigenmodes or resonances of a given structure. This solver will provide the frequency of the resonances as well as the fields at a particular resonance.

Chapter 2

PARAMETERS

Our aim is to find the specifications (i.e. length, feed gap, thickness etc) for the design, which is used to implement practically i.e. to fabricate on the PCB. We are looking at the specifications in millimeter scale for our design.

The frequency of 750 MHz is used for all the HFSS analysis. The main reason is, 750 MHz gives the wavelength of 400mm ($\lambda = \frac{c}{f}$), which is suitable for the scale we are looking at and more practical for the analysis carried out in HFSS, in later stages.



2.1 HALF WAVELENGTH DIPOLE ANTENNA

Since the aim is to find the specifications for the fabrication of the design, the initial analysis was carried out for the half wavelength dipole. The length of half wavelength dipole was chosen to be 0.48λ. The reason is, from [Ballanis textbook] the thin dipole of length $(0.47 - 0.48)\lambda$ has the dipole impedance of value $(73 + 42.5j)\Omega$. The other specifications of the dipole such as thickness and feed gap were found for through various simulations. The criteria for choosing the thickness and the feed gap of the dipole are, to match the radiation resistance of 73Ω and the reactance nearly equal to 0Ω.

2.1.1 Thickness of the dipole

In theoretical calculations, the dipole is assumed to be thin having the thickness of $10^5\lambda$. But, it is hard to practically achieve this thickness and carry out the simulations. Hence several simulations were carried out in HFSS to arrive at a suitable thickness for the dipole, which can be fabricated. The thickness was varied in the range of (1-4) mm for a 0.48λ dipole and a suitable thickness was chosen.

Specifications

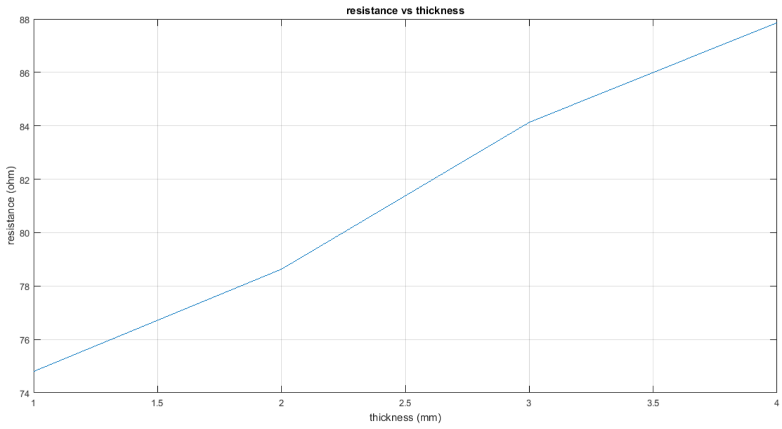
Frequency of operation = 750 MHz, Wavelength = 400mm

Length of the dipole = 0.48λ = 188mm

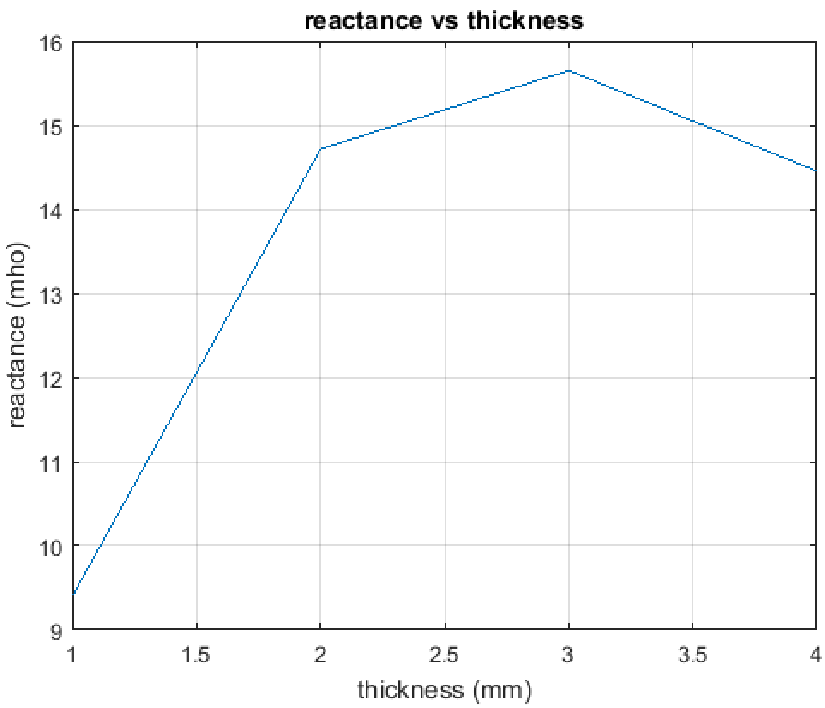
Feed gap length = 4mm

Thickness(mm)	Resistance(Ω)	Reactance(mho)
1	74.80	9.40
2	78.63	14.72
3	84.13	15.64
4	87.86	14.45

The thickness which gives the radiation resistance value of 73Ω or closer is chosen for the further analysis. From the above graph, the thickness of 1mm (radius of 0.5mm) is suitable, and henceforth in all the analysis the thickness of dipole is 1mm (radius = 0.5mm).



resistance vs thickness
resistance (ohm)
thickness (mm)
74
76
78
80
82
84
86
88
1
1.5
2
2.5
3
3.5
4



reactance vs thickness
reactance (mho)
thickness (mm)
9
10
11
12
13
14
15
16
1
1.5
2
2.5
3
3.5
4

2.1.2 Feed gap of the dipole

The feed gap of the dipole plays an important role in the value of impedance, because of the increase in the thickness of the dipole. The gap was varied in the range of (1-4) mm for a 0.48λ dipole and the thickness of 1mm, and a suitable feed gap length is chosen.

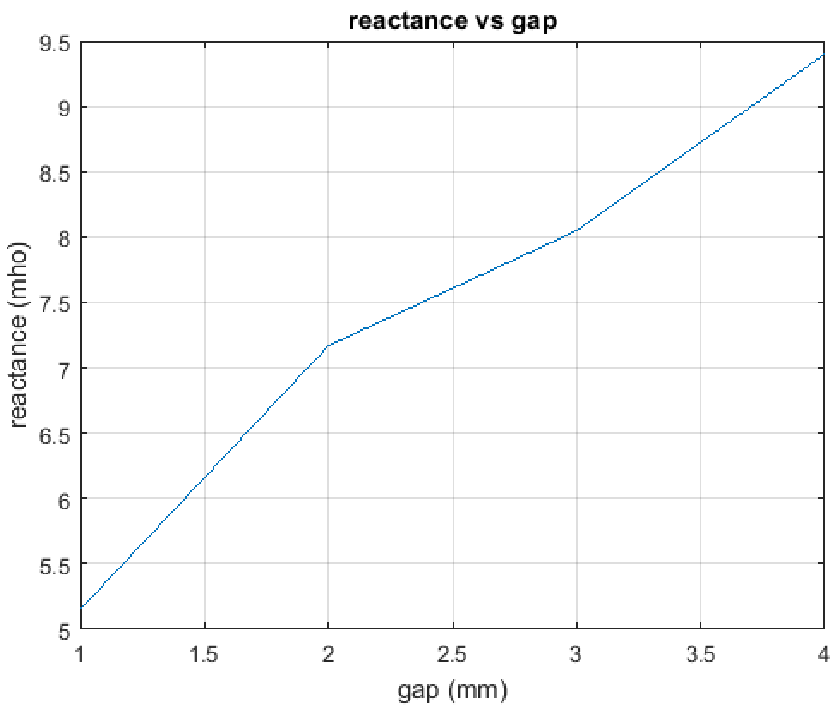
Specifications:

Frequency of operation = 750 MHz, Wavelength = 400mm

Length of the dipole = 0.48λ = 188mm

Thickness of the dipole = 1mm

Feed gap length(mm)	Resistance(Ω)	Reactance(mho)
1	74.40	5.15
2	74.46	7.16
3	74.36	8.04
4	74.80	9.40



There were no significant changes in the values of the radiation resistance. The suitable feed gap length of 4mm is chosen from the graph, considering both the thickness and feed gap results. This value of feed gap is used for initial analysis, but is changed later based on the design requirements.

Therefore for the dipole of length 0.48λ, thickness 1mm, and feed gap length 4mm, the impedance is $(74.4 + 5.15j)\Omega$.

2.1.3 Length of the dipole

The design requires dipoles of different lengths. The simulations were carried out in HFSS to compare the radiation resistance values of the dipoles of different lengths with the theoretical radiation resistances. The thickness and the feed gap length of the dipole are taken from the previous simulation results.

Specifications:

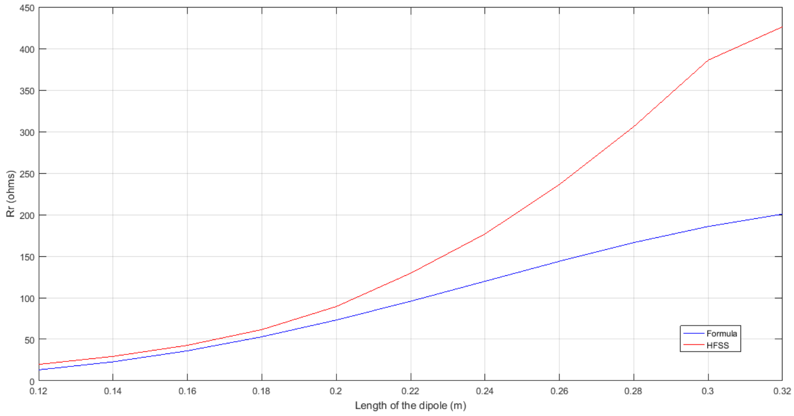
Frequency of operation = 750 MHz, Wavelength = 400mm

Thickness of the dipole = 1mm

Feed gap length = 4mm

$Length(\lambda)$	$Impedance(\Omega)$	$RadiationResistance(\Omega)$	Reactance(mho)
0.3	21.909-220.29j	21.909	-220.29
0.35	31.216-158.93j	31.216	-158.93
0.4	44.854-91.577j	44.854	-91.577
0.45	64.471-19.819j	64.471	-19.819
0.5	92.863+55.182j	92.863	55.182
0.55	134.63+136.61j	130.72	133.27
0.6	205.75+229.16j	185.45	207.27
0.65	300.2+319.75j	238.32	253.84
0.7	469.54+406.17j	306.96	265.84
0.75	711.39+432.04j	355.5	216.02
0.8	1046.9+272.61j	361.293	94.18

As the length of the dipole increases the difference in the theoretical and the practical (HFSS) values of the radiation resistance also increases. The main reason can be, as the length of the dipole increases, the effect of circular current (current in the circumference of the cross section of the dipole) is pronounced, which is mainly because of the thickness of the dipole. Another reason being, smaller feed gap length when compared to the length of the dipole.



Several other simulations were carried out for the dipole of length 0.8λ to see whether the above effects can be reduced.

- The radius of the dipole was reduced to find the radiation resistance.

  Specifications:

  Frequency of operation = 750 MHz, Wavelength = 400mm

  Length of the dipole = 0.8λ = 320mm

  Feed gap length = 4mm

Radius(mm)	$Impedance(\Omega)$	$RadiationResistance(\Omega)$	Reactance(mho)
1	1049.6+308.47j	362.62	106.57
0.5	1046.5+648.37j	361.55	224
0.25	981.66+899.89j	339.16	310.90
0.125	950.07+1082j	328.24	373.82
0.0625	896.32+1252j	309.67	432.56

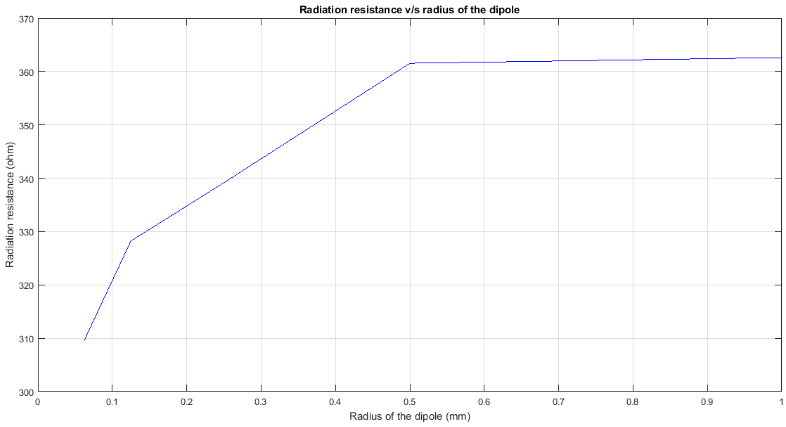
- For the radius of 0.0625mm, the feed gap length of the dipole was increased to see the changes in the radiation resistance.

  Specifications:

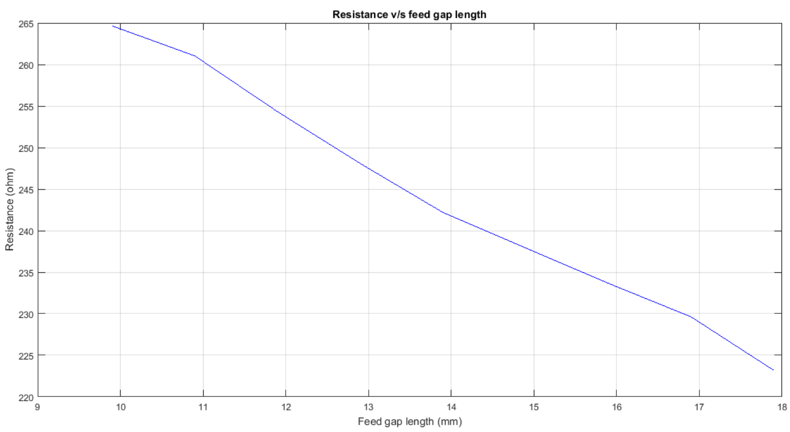
  Frequency of operation = 750 MHz, Wavelength = 400mm

  Length of the dipole = 0.8λ = 320mm

  Radius of the dipole = 0.0625mm



Feed gap length(mm)	$Impedance(\Omega)$	$RadiationResistance(\Omega)$	Reactance(mho)
9.9	766+1230j	264.65	425
10.9	755.54+1200j	261.033	414.5
11.9	736.12+1185j	254.323	409.4
12.9	718.07+1180j	248.087	407.67
13.9	701+1176j	242.19	406.29
14.9	688.65+1168.2j	237.922	403.53
15.9	676.32+1162.3j	233.66	401.46
16.9	664.62+1156.6j	229.620	399.3
17.9	646.43+1144.1j	223.1875	395.24



From the graphs 2.1.3 and 2.1.3, the difference between the theoretical and the practical values of the radiation resistance is reduced by decreasing the thickness and increasing the feed gap length.

For the radius of 0.0625mm, the frequency of operation being 750 MHz, the HFSS throws the simulation error when the structure becomes larger, i.e. when many dipoles are added to the same structure.

Hence the radius of 0.5mm is considered for the simulation and the values are calibrated wherever necessary. The length chosen for the feed gap of the dipole will be discussed in the coming chapters (feed gap length is chosen based on the design requirement).

2.1.4 Mutual impedance between the dipole

To compare the mutual impedance values of the dipole for varying distances between them, with the theoretical values, the simulations were carried out in HFSS.

Specifications:

Frequency of operation = 750 MHz, Wavelength = 400mm

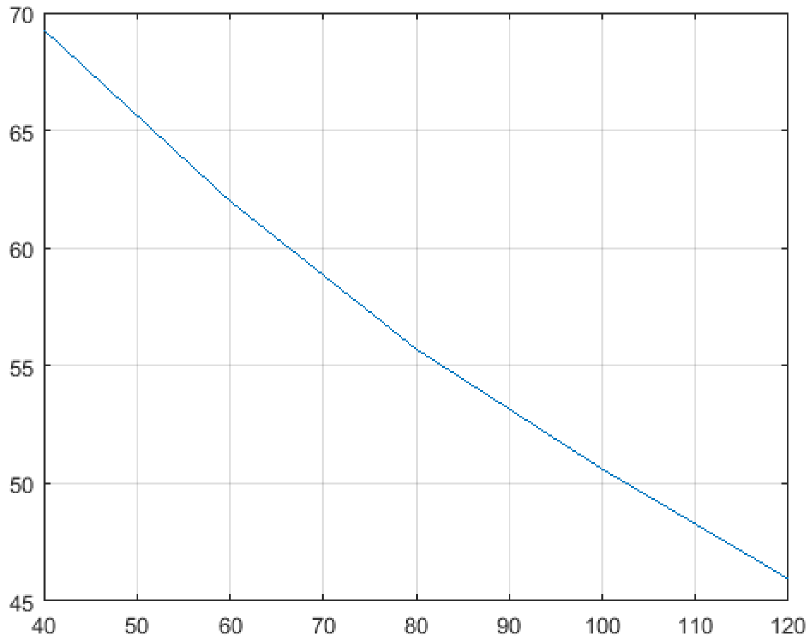
Length of the dipole = 0.48λ = 188mm

Thickness of the dipole = 1mm

Feed gap length = 4mm

Distance b/n the dipole antennas(λ)	$Mutual Impedance(\Omega)$
0.3	23.0780 -39.7240i
0.25	35.7730 -35.7950i
0.2	47.9470 -28.3710i
0.15	59.2560 -18.2360i
0.1	69.0570 - 5.5443i

From the graph 2.1.4, we can conclude both theoretically and practically (HFSS) that the mutual impedance between the two dipoles increases with the decrease in the length between the dipoles. We can also see that, for 0.25λ the theoretical and HFSS values of mutual impedance remains almost the same. Hence no calibration is required.


70
65
60
55
50
45
40
50
60
70
80
90
100
110
120

Chapter 3

Calibration required for the design

In our design, the dipole antennas are connected using a two wire transmission line. Theoretically, the dipoles and the transmission lines are analyzed discretely. However, in the practical scenario, these two structures would act as a single structure. HFSS is a tool which considers the dipoles, transmission line and stubs as a single structure and provides a full wave analysis. By comparing the results, the dissimilarities are reduced by suitable calibration and a realistic design can be arrived at. The transmission line, stubs and the dipole are perpendicular to each other.

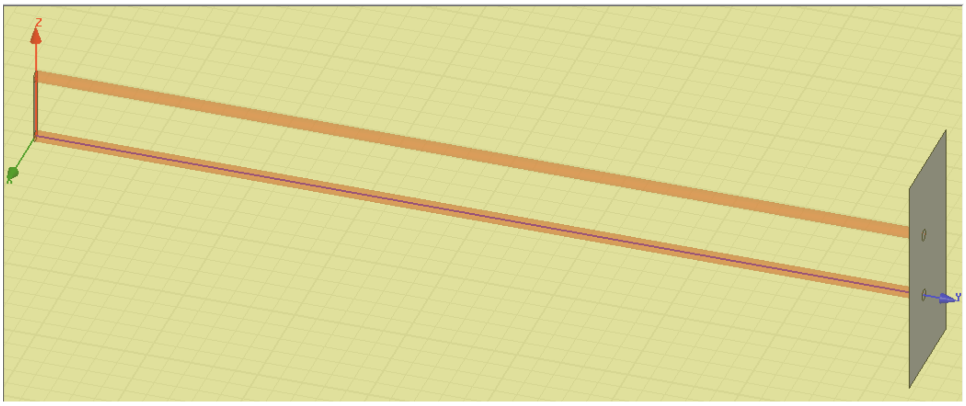
3.0.1 Transmission line calibration

The characteristic impedance equation of the two wire transmission line is given by,

$$Z_0 = 120ln(\frac{d}{a}) \tag{3.1}$$

To find the value of Z0 of a two wire transmission line in HFSS, the following steps are carried out:

- The short circuit load is taken and the input impedance at l = $\lambda/4$ is measured in HFSS.
- This ideally gives the Zin (the input impedance) value as infinity, but practical (HFSS) values are noted down.
- These values are noted down for different d/a values and are tabulated.



d/a	$Z_{in}(\Omega)$ =$(Z_0)^2/Z_L$
4	50-7135j
6	74.53-7238.3j
8	115.38-7763.4j
10	116.01-6780.4j
12	152.67-6978.4j

- The input impedance of the two wire transmission line is given by the formula

$$Z_{in}(l) = Z_0 \frac{Z_L + jZ_0 tan(\beta l)}{Z_0 + jZ_L tan(\beta l)} \tag{3.2}$$

where, Z_0 is the characteristic impedance of the transmission line,

Z_L is the impedance of the load,

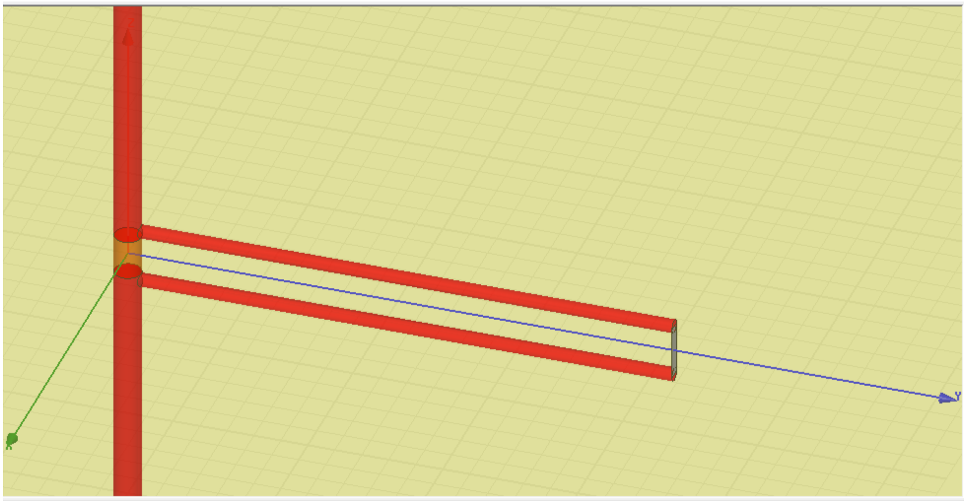
$\beta = 2\Pi/\lambda$, λ is the wavelength,

l is the length of the transmission line.

- For $l = \lambda/4$, Zin = (Z0)2 / ZL

$$Z_{in} = (Z_0)^2/Z_L \tag{3.3}$$

- Now the 0.48λ dipole ($Z_L = (74 + 5j)\Omega$) is placed as the load.
- The Z_{in} is noted down from HFSS.
- The above step is first carried out for the various values of d/a (ranging from 4 to 12), for a particular length of the transmission line.



d/a	$Z_{in}(\Omega)$ (l = 0.1λ)
4	0.0090389+117.87j
6	0.0088245+119.45j
8	0.024+158.93j
10	0.047+184.32j
12	0.0725+210.96j

- Similarly, the Z_{in} is noted for various length of the transmission line (ranging from 0.1λ to 0.4λ).

d/a	$Z_{in}(\Omega)$ (l = 0.2λ)	$Z_{in}(\Omega)$ (l = 0.3λ)	$Z_{in}(\Omega)$ (l = 0.4λ)
4	1.534+864.8j	1.2873-684.63j	0.043-108.33j
6	4.3827+1098.8j	2.8342-795.05j	0.1134-135.23j
8	7.5188+1243.5j	4.8059-851.59j	0.20398-165.97j
10	10.74+1378.8j	7.2805-914.24j	0.32378-181.53j
12	21.272+1625.7j	10.056-920.54j	0.4809-192.25j

- The impedance of dipole is substituted for Z_L and by combining equations 3.2 and 3.3; the value of Z_0 is calculated. The calculated Z_0 for one of the lengths is tabulated below,

d/a	$Z_0(\Omega)$ (formula)	$Z_0(\Omega)$ (HFSS)
4	166	154.504+0.02j
6	215	204.44+0.048j
8	249	245.47+0.099j
10	276	271.22+0.1382j
12	298	295.34+0.202j

- For a particular length of the transmission line, the Z_0 obtained by HFSS, for the various d/a can be plotted and compared with the formula.

  Specifications:

  Frequency of operation = 750 MHz, Wavelength = 400mm

  Length of the dipole = 0.48λ = 188mm

  Thickness of the dipole = 1mm

  Feed gap length = 4mm

  a=0.5mm

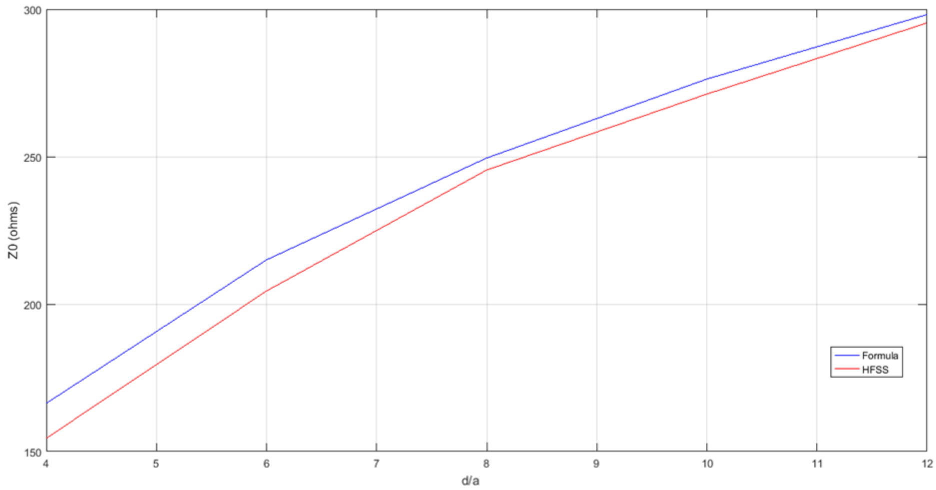


Figure 3.1: Z_0 vs transmission line length

The difference in the results is mainly because of the reason that the formula for the characteristic impedance of the transmission line does not take into account the skin effect, whereas HFSS does. Also the formula for the characteristic impedance of the transmission line is more suitable for $d >> a$, hence the difference between the theoretical and HFSS results decreases as the d/a increases.

In the formula of characteristic impedance of the transmission line, Z_0 value has to be greater than 80Ω, since $d >= 2a$. Hence the theoretical calculations are carried out for $Z_0 = 200\Omega$. From the graph 3.0.1 for $Z_0 = 200\Omega$, $d/a = 5.8$mm. On fixing a = 0.5mm, we get d = 2.9mm.

3.0.2 Reactance calibration

The reactance values of each of the dipoles in an array are obtained by the MATLAB code using the Iteration method. The reactance value (from the calculation) is achieved by placing the stubs in series with the dipole.
Since $d >> a$ gives better HFSS results (results are closer to the formula), the value of d/a is chosen to be equal to 8 for the stubs. The Z_{in} values for $d/a = 8$, and various lengths of the transmission line is obtained by simulations.
The input impedance of the transmission line of length l is,

$$Z_{in} = jZ_0 tan(\beta l) \tag{3.4}$$

where, Z_0 is the characteristic impedance of the transmission line
$\beta = 2\Pi/\lambda$, λ is the wavelength,
l is the length of the transmission line.
Specifications:
Frequency of operation = 750 MHz, Wavelength = 400mm
a=0.5mm d=4mm, $d/a = 8$
Here $Z_0 = 249.53\Omega$ (for formula)

Length of the transmission line(λ)	$Z_{in}(\Omega)$ (formula)	$Z_{in}(\Omega)$ (HFSS)
0.1	180.9j	0.047+184.32j
0.15	342.72j	0.186+363.05j
0.2	766.34j	1.1228+852.17j
0.25	Infinity	115.38-7763.4j
0.3	-766.34j	4.8059-851.59j
0.35	-342.72j	0.385-320.1j
0.4	-180.9j	0.20398-165.97j
0.45	-80.91j	0.14179-69.672j

The graph 3.0.2 will be used to calibrate the length of the stub for the given impedance values.

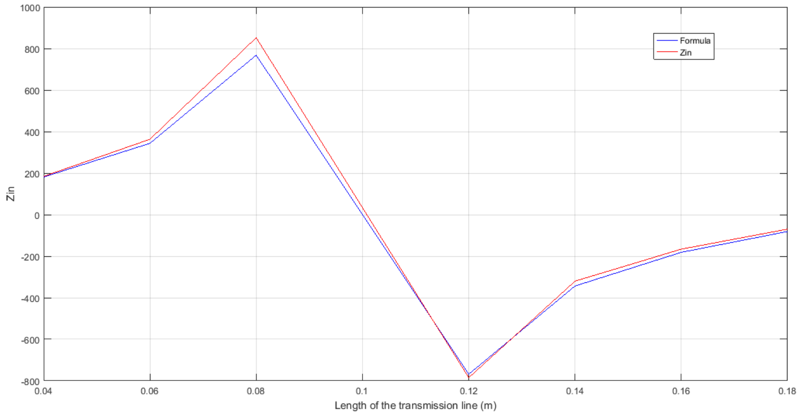


Figure 3.2: Z_{in} vs transmission line length

3.0.3 Reactance calibration

The d/a for both the transmission line and the stub has been obtained. These values are used to find the feed gap length of the dipole; hence the required structure of the design is achieved.

Therefore, the length of the gap of the dipole feed is given by = d/a of transmission line + d/a of stub 2 * radius of the transmission line = 2.9 + 4 1 = 5.9mm.

The resistance and reactance values for the various lengths of the dipole, for above gap is simulated using HFSS. These values will be useful in calibration.

Specifications:

Frequency of operation = 750 MHz, Wavelength = 400mm

Thickness of the dipole = 1mm (radius = 0.5mm)

Feed gap length = 5.9mm

$Length(\lambda)$	$Impedance(\Omega)$	$Radiation Resistance(\Omega)$	Reactance(mho)
0.3	24.069-262.47j	24.069	-262.47
0.35	33.447-201.33j	33.447	-201.33
0.4	45.407-119.64j	45.407	-119.64
0.45	63.027-30.457j	63.027	-30.457
0.5	86.646+57.974j	86.646	57.974
0.55	121.58+153j	117.144	153
0.6	170.64+251.82j	154.345	251.82
0.65	247.1+367.29j	196.170	367.29
0.7	359.2+488.64j	235.099	488.64
0.75	558.03+621.33j	279.015	621.33
0.8	905.94+709.21j	312.994	709.21

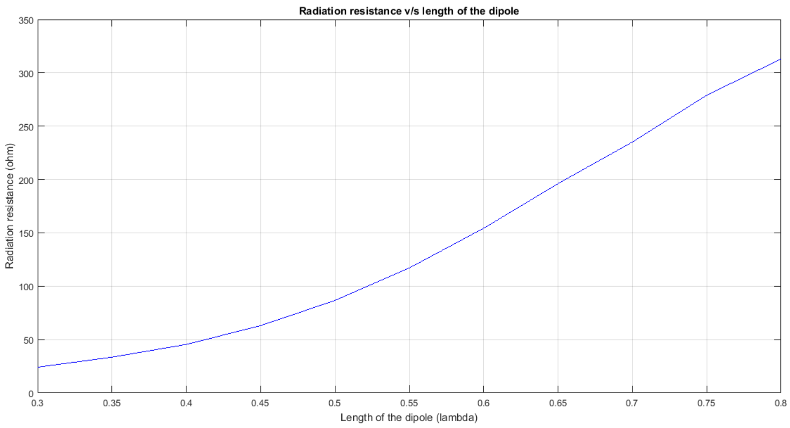


Figure 3.3: Radiation resistance vs dipole length

Figure 3.4: Reactance vs dipole length

Chapter 4

Calculation of length of dipole and stub

Method of calculating the length of the dipoles and stubs of the array

- The length and the reactance of each of the dipole is obtained by the Iteration method.
- The characteristic impedance of the transmission line remains fixed in all the arrays i.e. $Z_0 = 200\Omega$ and d/a = 5.8 (a = 0.5mm and d = 2.9mm) is obtained from the graph 3.0.1.
- The length from the Iteration method is used to find the theoretical value of the resistance of the dipole.
- These values are mapped back to the lengths in graph 3.0.3, which gives the length of the dipole in HFSS.
- This length is used to find the reactance of the dipole from the graph 3.0.3.
- Using the values of dipole reactance from the graph and the theoretical reactance from the code, the additional reactance required is obtained. This is the reactance of the stub.

  The required value of reactance = X

  The reactance of the dipole = X_R

  The reactance of the stub x = X X_R

  The length of the stub is obtained from the graph 3.0.2.

Generally the stub length obtained will be greater than $\lambda/4$. This would result in additional mutual coupling between the dipoles and the stubs. Hence the required reactance of the stub is divided into half and placed on the either sides of the dipole.

General specifications:

Frequency of operation = 750 MHz, Wavelength = 400mm

Feed gap length of the dipole = 5.9mm

Thickness of all the elements = 1mm (radius = 0.5mm)

The characteristic impedance of the transmission line $Z_0 = 200\Omega$.

d/a = 5.8, a = 0.5mm, d = 2.9mm

The characteristic impedance of the stub = 249.5Ω

d/a = 8, a = 0.5mm, d = 4mm

When simulated on HFSS for 3 and 4 dipole arrays, the main lobe of the radiation pattern obtained using the HFSS was slightly lesser than the theoretical pattern. Also the radiation pattern obtained using the HFSS had a huge back lobe when compared with the theoretical pattern. The main reason was, mutual coupling between the dipoles and the stubs. Hence a measure was taken to reduce the mutual coupling.

Initially, as described earlier, stub was placed on either sides of the dipole to avoid the mutual coupling. But later it was found that the reactance value was negative, hence the single stub was placed only on one side of the dipole, but alternating sides in an array, as shown in the figure4.0.1.

4.0.1 Uniform array Results

Figure 4.1: Reactance vs dipole length

The results from the MATLAB code for 4 dipole uniform array

$Length of the dipole (\lambda)$	$Resistance(\Omega)$	Reactance(mho)
0.786	190	60.13
0.852	210	217.17
0.693	160	6.240
0.652	140	0

By using the graphs 3.0.2, 3.0.3 and 3.0.3 graph for calibration, the new values of the length of the dipole and the stubs are obtained.

$New length of the dipole (\lambda)$	$Reactance of the stub (\Omega)$	Length of the stub(mm)
0.645	-289.87	144.6
0.675	-207.83	155.2
0.605	-248.76	149.5
0.585	-210	154.8

Figure 4.2: 4 dipole uniform array radiation pattern

Upon this change, the main lobe of the radiation pattern was improved, but the back lobe was still present.
Similarly, the simulation was carried out for 5 dioles uniform array.

Figure 4.3: 5 dipole uniform array radiation pattern

4.0.2 Super directive array Results

For the Super directive array, the method mentioned in the previous section was used to find the length of dipole and the stub, from the MATLAB simulation outputs.

Figure 4.4: 4 dipole uniform array radiation pattern

Figure 4.5: 5 dipole uniform array radiation pattern