CHAPTER 5

SIMULATIONS

In this chapter we will discuss in details the procedure of simulation of our transmission line model as well as cavity and CAD model of the RMSA. The simulations are carried out in Matlab platform. A brief description of the platform is discussed below.

5.1 The Matlab Platform

MATLAB is multi-paradigm numerical computational software for scientific and engineering applications. The name MATLAB is an abbreviation of Matrix Laboratory and its basic data type is a matrix. It was initially written to provide easy access to the matrix computation software packages, Linear System Package (LINPACK) and Eigen System Package (EISPACK) [47].

In addition to numerical computing, the MuPAD toolbox in MATLAB, allows the access of symbolic computing. The MATLAB is not required to be compiled or linked as is done in case of other high level languages, such as C or FORTRAN. The Matlab is a high performance fourth generation programming language for technical computing. Besides, it provides an interactive environment for algorithm development, data visualization, data analysis, modeling, and simulation of complex structures [48]. It has several built-in-functions, which provide efficient tools for linear algebra computations, numerical solution of ordinary differential equations, optimization, signal processing and support object oriented programming [48]. These features made MATLAB an efficient tool for research and teaching [48].

Cleve Moler of the University of New Mexico, successfully developed MATLAB in the late 1970s, which enabled students to access LINPACK and EISPACK without the knowledge of FORTRAN programming [52]. In 1984, Jack Little collaborated with Moler to re-develop MATLAB in C language and subsequently
founded Math Works in view of its commercial potential [52]. The rewritten libraries are associated with the name of its developer known as JACKPAC. Due to their tireless effort, as on today, there are more than one million MATLAB users globally from various backgrounds of engineering, science and other disciplines.

The key features of MATLAB are summarized below [48]:

i. High level language for technical computing
ii. Mathematical functions for numerical integration, Fourier transformation, statistics and interpolation
iii. 2-D and 3-D graphics functions for visualizations of data
iv. Tools for building custom graphical user interface (GUI)
v. Functions for integrating MATLAB based algorithms with external applications and languages, such as C, C++, Java, FORTRAN and Microsoft Excel.

The Matlab has expanded to cover a wide range of functionalities for various applications, and can be used conveniently as a simple programming language, where the sequence of codes resembles to mathematical statements. The collections of specialized functions called toolboxes are available in Matlab, written for applications such as Communication, Neural Network, image processing, control system and many other applications.

The Matlab platform has numerous advantages compared to conventional high level language, such as, C, C++ or FORTRAN for scientific and engineering computation. It has interactive system whose fundamental data type is the array. The Matlab automatically handle vectors, scalars, real and complex matrices as special cases of the basic data type and almost never have to declare the dimensions of a matrix. The software package has been commercially available from the inception of Math Works and presently number of registered users has been increased to more than a million. Matlab is widely used in academic and research institutions as well as industrial enterprises.

5.2 The simulation for transmission line, cavity and CAD models

Considering the transmission line, cavity and CAD model of RMSA as described in section (4.1.1) and (4.1.6), it is possible to simulate and analyze the
behavior of the antenna models. The model which shows best result with minimum error may be chosen for design purpose.

We simulate the models in MATLAB Platform. The Flow diagram of the simulation program is given in Fig.8.

![Flow diagram of the simulation Program](image)

**Fig. 8: Flow diagram of the simulation Program**

The simulations are carried out on the antenna parameters, considering transmission line, cavity and CAD model of RMSA in frequency domain and space domain. In the entire simulation process we have used frequency and substrate height as variable for a fixed value of relative permittivity.

5.2.1 The simulation for associated parameters of transmission line model

Initially the simulation is carried out to determine the optimal resonant frequency of RMSA and to study the performance of various models in correctly predicting parameters of the antenna.

Considering the resonant frequency of transmission line model, represented by equation (4.1) and equation (4.1a), it is possible to analyze the behavior of the model and compare the relative performances in correctly predicting the resonant frequency.
In order to evaluate the performance and accuracy of the models, we simulate them in Matlab platform considering different values of parameters, namely: (i) relative permittivity $\varepsilon_r$, (ii) center frequency $f_0$, (iii) substrate thickness $h$, and (v) free space wave length $\lambda_0$, to compute patch width $W$, effective dielectric constant $\varepsilon_{re}$ (eqn.4.2a-4.2e), fringing length extension $\Delta L$ (eqn.4.3 & eqn.4.25), and then to compute actual patch length $L$.

The simulated responses of resonant frequency, effective dielectric constant as a function of substrate thickness; frequency and fringing length extension, as a function of substrate height by considering transmission line and hybrid model (combination of cavity and transmission line model) are shown in Fig.9 (a) through Fig.9 (l).

![Transmission Line Resonant Frequency vs $f_0$](image)

**Fig.9(a):** Simulated response for resonant frequency of transmission line model for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$. 

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Fig. 9(b): Simulated response for resonant frequency of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ and h.

Fig. 9(c): Simulated response for resonant frequency of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ and h.
Fig. 9(d): Simulated response for resonant frequency of transmission line model for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 9(e): Simulated response for resonant frequency of transmission line model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$. 
Fig.9(f): Simulated response for resonant frequency of transmission line model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$.

Fig.9(g): Simulated response of effective dielectric constant of various design equations as a function of $h$, operating at 2.5 GHz with $\varepsilon_r=10.2$. 
Fig. 9(h): Simulated response of effective dielectric constant of various design equations as a function of $h$, operating at 2.5 GHz with $\varepsilon_r = 2.2$.

Fig. 9(i): Simulated response of frequency dependent effective dielectric constant of various design equations as a function of frequency with $\varepsilon_r = 10.2$ and $h=0.17$ mm.
Fig. 9(j): Simulated response of frequency dependent effective dielectric constant of various design equations as a function of frequency with $\varepsilon_r = 2.2$ and $h = 4.76$ mm.

Fig. 9(k): Simulated response for fringing length extension of transmission line and cavity model as a function of $h$, operating at 2.5 GHz with $\varepsilon_r = 2.2$. 

"Frequency Dependent Dielectric Constant vs Frequency"

"Fringing Length Extension ($\Delta L$) vs Substrate Thickness"
Fig. 9(l): Simulated response for fringing length extension of transmission line and cavity model as a function of $h$, operating at 2.5 GHz with $\varepsilon_r=10.2$.

5.2.2 The Simulation for radiation resistance, input resistance, directivity, gain and BW of transmission line model.

The simulations are carried out for radiation resistance, directivity, gain and BW of the RMSA by varying substrate thickness $h$, for a given frequency and relative permittivity (space domain) and then varying frequency (frequency domain) for a given substrate thickness and dielectric constant to study the performance and dependence of those parameters in predicting the behavior of the RMSA. The equations used for simulation are equation (4.2) for determination of effective dielectric constant, equation (4.3) for fringing length extension, equation (4.5) for actual length and equation (4.6) for effective width of the patch for a given relative permittivity and frequency in order to predict the radiation resistance given by equation (4.15), (4.17c) and (4.18d) also input resistance of transmission line given by (4.18) is obtained by performing numerical integration of equation (4.18a) with required feeding position. Similarly, by substituting radiation conductance from equation (4.17d) and (4.18e) in equation (4.35a) we get directivity. While, gain given by equation (4.36) is obtained by multiplying directivity by efficiency given by equation (4.34). The BW is related to antenna quality factor $Q$ and is given by equation (4.22) which can be obtained by substituting radiation
Q factor from equation (4.21b) in equation (4.22). The simulated responses in frequency domain and space domain are shown in Fig.10 (a) through 10(m).

Fig.10(a): Simulated response for radiation resistance of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ & h.

Fig.10(b): Simulated response for radiation resistance of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ & h.
Fig. 10(c): Simulated response for radiation resistance of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ & $h$.

Fig. 10(d): Simulated response for radiation resistance of transmission line model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$. 
Fig. 10(c): Simulated response for input resistance of transmission line model as a function of frequency with different $\varepsilon_r$, $h$ and feed position at $x_0 = L_e/4$.

Fig. 10(f): Simulated response for directivity of transmission line model for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig. 10(g): Simulated response for directivity of transmission line model for thin substrate as a function of frequency with different $\varepsilon_R$ and $h$.

Fig. 10(h): Simulated response for directivity of transmission line model (single slot) as a function of $h$ operating at 2.5 GHz with different $\varepsilon_R$. 
Fig.10(i): Simulated response for gain of transmission line model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$.

Fig.10(j): Simulated response for BW% of transmission line model for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig. 10(k): Simulated response for BW% of transmission line model for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 10 (l): Simulated response for BW% of transmission line model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$. 
5.2.3 The simulation for associated parameters of cavity model

Considering the cavity model resonant frequency given by equation (4.24), (4.24a), and (4.24b), we simulate and analyze the behavior of the model and compare the relative performances with the performance of the other models in predicting the resonant frequency correctly in frequency and space domain. In the simulation we have used frequency and substrate height as variable for a fixed value of relative permittivity.

The equations used for simulation are equation (4.2e) for determination of effective dielectric constant, equation (4.25) for fringing length extension, equation (4.5) for actual length and equation (4.6) for effective width of the patch for a given relative permittivity and frequency in order to predict the radiation resistance (single slot) given by equation (4.26a), radiation resistance (two slot) given by equation (4.28), input resistance given by equation (4.29a), and equation (4.29b).

Similarly directivity of cavity model given by equation (4.35) is simulated through the numerical integration and also directivity (two slot) given by equation (4.35a) is simulated by substituting the corresponding radiation conductance expression of cavity model given by equation (4.27e).

The expression of gain, given by equation (4.36) is simulated by taking the product of directivity (eqn.4.35 and eqn.4.35a) and efficiency given by equation (4.34).

In the same manner the cavity model BW given by equation (4.33) is obtained by substituting total Q-factor in the corresponding BW expression and are simulated by varying frequency and substrate height for given dielectric constant.

The simulated responses of resonant frequency, radiation resistance, input resistance; directivity, gain and BW as a function of frequency and substrate height of cavity model are shown in Fig.11 (a) through Fig.11 (w).
Fig. 11 (a): Simulated response for resonant frequency of cavity model (TM$_{01}$ mode) for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 11(b): Simulated response for resonant frequency of cavity model (TM$_{01}$ mode) for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig.11 (c): Simulated response for resonant frequency of cavity model (TM$_{10}$ mode) for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig.11 (d): Simulated response for resonant frequency of cavity model (TM$_{10}$ mode) for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig. 11 (e): Simulated response for resonant frequency of cavity model \((\text{TM}_0\text{I mode})\) as a function of \(h\), operating at 2.5 GHz with different \(\epsilon_r\).

Fig. 11 (f): Simulated response for resonant frequency of cavity model \((\text{TM}_{10} \text{ mode})\) as a function of \(h\), operating at 2.5 GHz with different \(\epsilon_r\).
Fig. 11 (g): Simulated response for radiation resistance of cavity model (single slot) as a function of substrate thickness operating at 2.5 GHz with different $\varepsilon_r$.

Fig. 11(h): Simulated response for radiation resistance of cavity model (two slot) as a function of substrate thickness operating at 2.5 GHz with different $\varepsilon_r$. 
Fig.11 (i): Simulated response for radiation resistance (odd mode) of cavity model as a function of frequency with different $\varepsilon_r$ and h.

Fig.11 (j): Simulated response for radiation resistance (even mode) of cavity model as a function of frequency with different $\varepsilon_r$ and h.
Fig. 11 (k): Simulated response for input resistance (even mode) of cavity model as a function of h, operating at 2.5 GHz with different \( \varepsilon_r \).

Fig. 11 (l): Simulated response for input resistance (odd mode) of cavity model as a function of h, operating at 2.5 GHz with different \( \varepsilon_r \) and feed \( x_f = L/4 \).
Fig.11(m): Simulated response for input resistance (TM_{010} mode) of cavity model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$ and feed $x_t = L/1.96$.

Fig.11(n): Simulated response for input resistance (TM_{100} mode) of cavity model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$ and $y_t = W/4$. 


Fig.11 (o): Simulated response for directivity (single slot) of cavity model as a function of frequency with different $\varepsilon_r$ and $h$.

Fig.11 (p): Simulated response for directivity of cavity model as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig.11(q): Simulated response for gain (two slot) of cavity model as a function of frequency with different $\varepsilon_r$ and $h$.

Fig.11(r): Simulated response for directivity (single slot) of cavity model as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$. 
Fig. 11 (s): Simulated response for directivity (two slot) of cavity model as a function of h, operating at 2.5 GHz with different $\varepsilon_r$.

Fig. 11(t): Simulated response for gain dB (two slot) of cavity model as a function of h, operating at 2.5 GHz with different $\varepsilon_r$. 
Fig. 11 (u): Simulated response for BW of cavity model for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 11 (v): Simulated response for BW of cavity model for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig.11 (w): Simulated response for BW of cavity model as a function of \( h \), operating at 2.5 GHz with different \( \varepsilon_r \).

5.2.4 The simulation for associated parameters of CAD model

The CAD model of the RMSA is modeled as a parallel RLC circuit with a series reactance based on the theory of cavity model and can be used to calculate the input impedance at any resonant frequency with the prior knowledge of resonant input resistance, resonant frequency, and BW of the patch [8].

The CAD model is the extension of cavity model in which rigorous numerical integrations are avoided and simple expression can be used to predict the antenna performance very accurately. We simulate and analyze the behavior of the model and study the performances of the patch antenna parameters, namely: (i) resonant frequency (ii) radiation resistance, (iii) input resonant resistance, (iv) probe reactance, (v) directivity, (vi) efficiency, (vi) gain and (vii) BW in frequency and space domain. In the simulation we have used frequency and substrate height as variable for a fixed value of relative permittivity.

The equations used for simulation are equation (4.2b) and equation (4.2e) for determination of effective dielectric constant, equation (4.25) for fringing length
extension. Similarly, equation (4.5) and (4.5a) are used to simulate the actual length and effective length. Equation (4.6) is used to simulate the effective width of the patch for a given relative permittivity and frequency in order to evaluate the key antenna parameters.

The resonant frequency of CAD model the given by equation (4.38) is simulated in frequency and space domain. The input resonant resistance is given by equation (4.39) and (4.39a) is simulated in frequency and space domain and probe reactance given by equation (4.40) is simulated in space domain only. Similarly, directivity for CAD model expression given by equation (4.48) is also simulated in frequency and space domain. While radiation efficiencies given by equations (4.41), (4.42) and gain given by equation (4.49) are also simulated for frequency and substrate thickness as variables. In the same manner BW of the CAD model given by equation (4.47) and (4.47a) are simulated by varying frequency and substrate height for given dielectric constant.

The simulated responses of radiation frequency, radiation resistance, input resistance; directivity, efficiency, gain and BW as a function of frequency and substrate height are shown in Fig.12 (a) through Fig.12 (o).

Fig.12(a): Simulated response for resonant frequency of CAD model (magnetic current) for thick substrate as a function of frequency with different $\varepsilon_r$ and h.
Fig. 12(b): Simulated response for resonant frequency of CAD model (magnetic current) for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 12(c): Simulated response for resonant frequency of CAD model (magnetic current) as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$. 
Fig. 12 (d): Simulated response for input resistance of CAD model as a function of frequency with different $\varepsilon_r$, h and feed position at $x_0 = L_e/4$.

Fig. 12(e): Simulated response for input resistance of CAD model as a function of h, operating at 2.5 GHz with different $\varepsilon_r$ and feed position at $x_f = L/4$. 
Fig. 12(f): Simulated response of probe inductive reactance as a function of h with $\varepsilon_r=2.5$, 4.35, 10.2 and coaxial probe radius $r_0 = 0.64$ mm.

Fig. 12(g): Simulated response for directivity of CAD model as a function of frequency with different $\varepsilon_r$ and h.
Fig. 12(h): Simulated response for directivity (dB) of CAD models as a function of $h$, operating at 2.5 GHz with different $\varepsilon_r$.

Fig. 12(i): Simulated response of surface wave model radiation efficiency for thin substrate as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig. 12(j): Simulated response of surface wave model radiation efficiency for thick substrate as a function of frequency with different $\varepsilon_r$ and $h$.

Fig. 12(k): Simulated response for gain in dB of CAD model as a function of frequency with different $\varepsilon_r$ and $h$. 
Fig. 12(i): Simulated response for gain in dB of CAD model as a function of substrate thickness operating at 2.5 GHz with different permittivity.

Fig. 12(m): Simulated response for BW of CAD model for thick substrate as a function of frequency with different permittivity.
Fig. 12(n): Simulated response for BW of CAD Model for thin substrate as a function of frequency with different permittivity and substrate thickness.

Fig. 12(o): Simulated response for BW of CAD Model as a function of substrate thickness operating at 2.5 GHz with different permittivity.
5.2.5 The simulation for various other associated parameters

The simulations are also carried out to study: (a) the dependence of substrate thickness \( h \), relative permittivity \( \varepsilon_r \), and frequency \( f \) on power pattern, (b) effect of finite size ground plane on fractional change in resonant frequency, (c) effect of probe radius on fractional change in resonant frequency and (d) tolerance on length on resonant frequency.

The equations used for simulation are equation (4.2b) and (4.2e) for evaluating optimum values of effective dielectric constant, equation (4.3) and (4.25) for fringing length extension, equation (4.5) and (4.5a) for actual length and effective length respectively. Similarly, equation (4.6) and (4.4a) are used to find the effective width of the patch and frequency dependent width for a given relative permittivity and frequency in order to evaluate the key antenna parameters.

The \( E \) and \( H \) plane power pattern given by equation (4.37) and (4.37a) and frequency dependence expression of feed width given by equation (4.4a) are simulated with substrate height \( h \) and operating frequency \( f_r \) as variable for a given \( \varepsilon_r \) to find out the required feed width at operating frequency.

The effect of finite size ground and effect of probe radius on fractional change in resonant frequency given by equation (4.50), (4.50a) and (4.51) respectively are simulated with frequency and substrate thickness as variable for fixed value of relative permittivity \( \varepsilon_r \). In the same manner the effect of tolerance in patch length on fractional change in resonant frequency given by equation (4.52), (4.52a) and (4.52b) are simulated by varying substrate height for a given dielectric constant.

The simulated responses are shown in \textbf{Fig.13 (a)} through \textbf{Fig.13 (f)}. 
Fig.13(a): Simulated response of E plane power pattern of rectangular patch at 2.5 GHz with $\varepsilon_r=2.53, 3.8 & 9.7$ and substrate height $h=1.27, 1.5 & 1.59$ mm.

Fig.13(b): Simulated response of H-plane power pattern of rectangular patch at 2.5 GHz with $\varepsilon_r=2.53, 3.8 & 9.7$ and substrate height $h=1.27, 1.5 & 1.59$ mm.
Fig. 13(c): Simulated response of Feed line width as a function of frequency with \( \varepsilon_r = 2.5, 4.35 & 10.2 \) and \( h=4.76, 3.175 & 2.2 \) mm for a given 50 ohm match.

Fig. 13(d): Simulated response of Fractional change in resonant frequency as a function of \( h \) with \( \varepsilon_r = 2.53, 3.8 & 9.7 \) operating at 2.5 GHz.
Fig.13(c): Simulated response of fractional change in resonant frequency as a function of \( h \) with \( \varepsilon_r = 2.53, 3.8, 9.7 \), extension of ground plane \( d = 6h \) on all sides.

Fig.13(f): Simulated response of fractional change in resonant frequency as a function of \( h \) with \( \varepsilon_r = 2.53, 3.8, 9.7 \) & coaxial radius \( r_0 = 0.64 \) mm, at 2.5 GHz.
5.2.6 The Simulation for comparison of parameters of transmission line, cavity and CAD model

A comparative study is carried out on transmission line, cavity and CAD model parameters namely: (i) resonant frequency, (ii) resonant input resistance, (iii) directivity, (iv) radiation efficiency, (v) gain, (vi) reflection coefficient, (vii) VSWR and (viii) BW, by simulating for different substrates permittivity and thickness. The model which accurately predicts the antenna performance can be selected for design purpose. The models are simulated in frequency and space domain and the responses are shown in Fig.14 (a) through 14(t).

Considering resonant frequency of the transmission line model given by equations (4.1) and (4.1a), resonant frequency of the cavity model given by equations (4.24), (4.24a) and (4.24b) and resonant frequency of the CAD model given by equation (4.38), we simulate resonant frequency of all the three models to study the performances of the patch antenna at different circumstances, namely: (a) variation of substrate height and (b) dielectric constant in a given operating frequency. On the other hand the radiation resistance of transmission line, cavity and CAD model given by equations (4.15), (4.17c), (4.28), and (4.39a) respectively and corresponding input resonant resistance with feed position are simulated in space domain with substrate height as variable with fixed value of \( \varepsilon_r \). Similarly, directivity, efficiency, gain, reflection coefficient, VSWR and BW at operating frequency 2.5 GHz are compared by simulating for all the three models in space domain and frequency domain. We have used substrate height (space domain) as variable for a fixed value of relative permittivity and resonant frequency at 2.5 GHz, while we have used operating frequency (frequency domain) as variable for fixed value of \( h \) and \( \varepsilon_r \). Finally to visualize the relative performance of the models in predicting, fundamental antenna parameters, namely: (i) resonant frequency, (ii) resonant input resistance with specific feed location or probe, (iii) directivity, (iv) gain in dB, and (v) BW the simulation is carried out and the simulated responses in the form of bar plots are shown in Fig.14(u) through Fig.14 (z). Further we have also performed combine simulation of BW using data of Table 11 for all the three models and measured values including error bar plot for individual model with measured BW to study relative performances of the models. The simulated responses are shown in Fig.15 (a) through Fig.15 (e).
Fig. 14(a): Simulated response of fractional change in resonant frequency of transmission line & cavity model, as a function of observed frequency with $\varepsilon_r=4.35$, $h=1.59$ mm & maximum tolerance in length $\Delta L=0.04$ mm.

Fig. 14(b): Simulated response for resonant frequency of transmission line and cavity model as a function of $h$ with $f_0=2.5$ GHz.
Fig. 14(c): Simulated response for radiation resistance of transmission line and cavity model (even mode) as a function of $h$, operating at 2.5 GHz with $\varepsilon_r=2.2$.

Fig. 14 (d): Simulated response for radiation resistance of transmission line and cavity model (odd mode) as a function of $h$, operating at 2.5 GHz with $\varepsilon_r=2.5$. 
Fig. 14(c): Simulated response for input resistance of transmission line, cavity & CAD model as a function of normalized feed with $f_r = 2.5 \text{ GHz}$ & $\varepsilon_r = 4.35$.

Fig. 14(f): Simulated response for input resistance of transmission line & cavity model (odd mode) as a function of normalized feed, with $f_r = 2.5 \text{ GHz}$ & $\varepsilon_r = 2.5$. 

Fig. 14(g): Simulated response for directivity of transmission line, cavity & CAD model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r=2.5$.

Fig. 14(h): Simulated response for directivity in dB of transmission line, cavity & CAD model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r=2.5$. 
Fig. 14 (i): Simulated response for efficiency of horizontal electric & surface wave model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r=2.2$.

Fig. 14(j): Simulated response for efficiency of horizontal electric dipole, CAD & surface wave model as a function of $h$, operating at 2.5 GHz with $\varepsilon_r=2.2$. 
Fig. 14(k): Simulated response for gain of transmission line, cavity & CAD model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r=2.5$.

Fig. 14(l): Simulated response for gain (dB) of transmission line, cavity & CAD model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r=2.5$. 
Fig.14(m): Simulated response for reflection coefficient (dimensionless) of transmission line, cavity & CAD model as a function of frequency with h=1.524 mm and $\varepsilon_r=2.5$.

Fig.14(n): Simulated response for reflection coefficient in dB of transmission line, cavity and CAD model as a function of frequency with h=1.524 mm and $\varepsilon_r=2.5$. 
Fig. 14(o): Simulated response for VSWR of transmission line, cavity ($TM_{01}$ mode) & CAD model as a function of frequency with $h=1.524$ mm and $\varepsilon_r=2.5$.

Fig. 14(p): Simulated response for VSWR in dB of transmission line, cavity ($TM_{01}$ mode) & CAD model as a function of frequency with $h=1.524$ mm and $\varepsilon_r=2.5$. 
Fig. 14(q): Simulated response for VSWR of transmission line, cavity \((TM_{10})\) & CAD model as a function of frequency with \(h=4.76\) mm & \(\varepsilon_r=10.2\).

Fig. 14(r): Simulated response for VSWR in dB of transmission line, cavity \((TM_{10})\) & CAD model as a function of frequency with \(h=4.76\) mm and \(\varepsilon_r=10.2\).
Fig. 14(s): Simulated response for BW of Transmission line, cavity and CAD model as a function of substrate thickness operating at 2.5 GHz with $\varepsilon_r = 2.5$.

Fig. 14(t): Simulated response for BW of transmission line, cavity & CAD model as a function of frequency with substrate thickness h=4.76 mm $\varepsilon_r = 2.5$. 
Fig. 14(u): Simulated response for resonant frequency of cavity, CAD and transmission line model with $\varepsilon_r=2.2$ and $h=1.524$ mm

Fig. 14(v): Simulated response for radiation resistance of CAD, measured [46], cavity & transmission line model operating at 2.5 GHz with $\varepsilon_r=2.5$, $h=1.524$ mm
Fig. 14(w): Simulated response for gain in dB of cavity, CAD and transmission line model operating at 2.5 GHz with $\varepsilon_r=2.2$ and $h=4.76$ mm.

Fig. 14 (x): Simulated response for gain in dB of cavity, CAD & transmission line model operating at 2.5 GHz with $\varepsilon_r=2.2$ and $h=0.17$ mm.
Fig. 14 (y): Simulated response for BW of CAD, cavity and transmission line model operating at 2.5 GHz with $\varepsilon_r=2.2$ and $h=0.17$ mm

Fig. 14(z): Simulated response for BW of CAD, cavity and transmission line model operating at 2.5 GHz with $\varepsilon_r=2.2$ and $h=4.76$ mm
Fig.15(a) : Simulated response for BW of CAD, cavity, transmission line model and measured [51] with different values of \( \varepsilon_r \) and \( h \).

Fig.15(b) : Simulated response for comparison of BW of transmission line model and measured [51] values with different values of \( \varepsilon_r \) and \( h \).
Fig. 15(c): Simulated response for comparison of approximate BW% of transmission line model and measured [51] values with different values of $\varepsilon_r$ & h.

Fig. 15(d): Simulated response for comparison of BW of cavity model and measured [51] values with different values of $\varepsilon_r$ and h.
Fig.15(e) : Simulated response for comparison of BW of CAD model and measured [51] values with different values of $\varepsilon_r$ and $h$.

In the next chapter of the thesis, we will discuss in details the simulated results of the proposed Transmission line, Cavity and CAD models of RMSAs.