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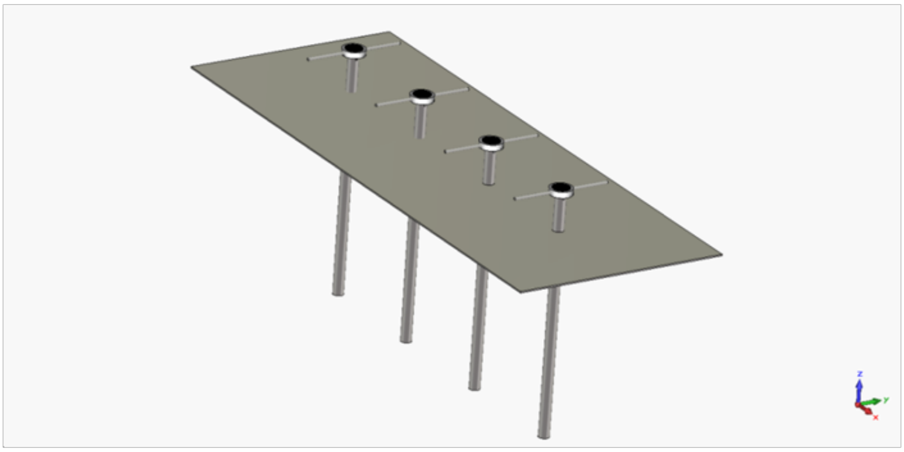

EM Characterization of MIMO Terminals in Non-isotropic Multipath Environments

Master of Science Thesis (Communication Engineering)

MUHAMMAD TABISH IFTIKHAR

Antenna Group, Department of Signals & Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, August 2010

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Cover: Four horizontal Dipole antenna array above a ground plane at a distance of 0.5 λ between elements.

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Abstract

Four horizontal dipoles antenna array with the effect of Balun above an infinite ground plane for use in a MIMO system is considered. MIMO systems are characterized by their maximum available capacity. The performance is reduced if there is correlation between different elements of MIMO array. The main idea behind MIMO is to establish independent parallel channels between multiple transmit and receive antennas. Each channel uses the same frequency, and transmission occurs simultaneously.

The first section of thesis describes the simulation of four horizontal dipole antenna array with the effect of Balun above an infinite ground plane by using commercial full-wave simulator (CST). Firstly, the simulation is done for a single dipole antenna, and then step by step to the final MIMO array simulation. There are two different excitations used, element port excitation and beam port excitation. Furthermore, CST gives the detailed information about the scattering parameters and far-field pattern in two different files.

The second section describes the calculation of simulation results in isotropic and non-uniform environments by using matlab codes. The embedded element pattern is calculated by the full-wave simulator (CST). Thereafter, these patterns are used to calculate the radiation efficiency of each embedded element, correlation between couple of elements, diversity gain and the maximum capacity in rich isotropic scattering environment and non-uniform environment. Furthermore, correlation is calculated by MEST (Multipath Environment Emulator for Simulation of MIMO Terminals) & pattern multiplication in non-uniform environments.

Finally, the simulated results of isotropic environment are compared with measurements in a reverberation chamber (provides the rich scattering environment). The measurements show very good agreement with simulations.

Keywords: Embedded element pattern, antenna arrays, antenna efficiency, correlation, antenna diversity, capacity, reverberation chamber.

Preface

This report is a master thesis to fulfill the partial requirements for the degree of 'Master of Science in Communication Engineering (Specialization in Wireless Communication)' at Chalmers University of Technology, Göteborg, Sweden. The work has been carried out in Antenna Group, Department of Signals & Systems, Chalmers University of Technology, during the period September 2009 to August 2010. The supervisors have been Nima Jamaly and Prof. Jan Carlsson. The examiner and supervisor for this research has been Prof. Per-Simon Kildal.

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I would also like to thank my supervisor and examiner Prof. Per-Simon Kildal for providing me an opportunity to conduct my master's thesis under him and for his guidance, support and expert knowledge in antennas is of great value.

I especially thankful to my parents, your advices, wisdom, guidance and love have not only helped me at every step of life but also have given me a confidence to deal and solve every problem coming in my way. I am also thankful to my great sisters, brother in law and my brother who is always there to guide me and help me. I am also thankful to my best friends Ahmed, Talha and Mujeeb for their moral support and helping me.

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Chapter 1

INTRODUCTION

This project basically evaluates EM performance of Multiple Input Multiple Output (MIMO) terminals in different scattering environments. The performance of MIMO terminals in isotropic rich scattering environment has already been evaluated. Isotropic environment refers to those environments with uniform angle of arrival (AOA) and balanced polarization for coming waves. Measurements results showed that AOA cannot be chosen uniformly distributed in realistic scenarios. This provokes us to implement different codes to simulate multipath environment. The code uses embedded element patterns, associated reflection coefficient (mutual coupling is inherent in embedded patterns) and the simulated power as its input parameters. These parameters can be found by measurement as well as using any commercial full-wave simulator (e.g. CST, HFSS, etc.). The performance of the MIMO system can be evaluated now with non-uniformly distributed AOA but balanced polarization for all angles of incidence. The next step will be to evaluate the performance of MIMO system with both - non-uniformly distributed AOA and unbalanced polarization for all angles of incidence. Polarization for coming waves is presumable considered as vertical (VER) and horizontal (HOR). Finally, the results obtained from MIMO system with respect to the two incident polarizations will be studied.

1.1 Background

To accomplish this project a good command over MATLAB programming and CST Studio is very crucial as it is the main technical part of the project. Some fundamental concepts in Wireless Communications & Antenna Engineering are of great importance. Project depends on Nima Jamaly extending his code to non-uniform environment.

1.2 Project Timeline

Month:																				
Week **Sub project:**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1. Literature Study & Learning CST Studio																				
2. Simulations																				
3. Measurements & Results																				
4. Project Documentation																				

Chapter 2

Project Background

Mobile telephony established low data rates and voice messages till now but technology has been upgraded to move forward to meet the needs for mobile technology. The telecommunication has been shifted to enhance data rate for MMS, video conferencing, etc. To be able to transmit high speed message we need to ensure to high enough signal-to-noise ratio (SNR) after reception through the fading radio channels. This can be achieved by diversity [2]. Diversity system receives different signals at receiver using different antennas. If transmitter and receiver consists two or more antennas then SNR is improved to obtain a high-quality communication system capacity, this is called Multi input multi output (MIMO) system.

MIMO system is used to transmit data using channel matrix instead of single radio channel. It can be used to increase the data rate using multiplexing technique and can also be used to increase the capacity of the system using diversity. The antennas used in MIMO system should contain sufficient spacing between them, if the distance between antenna elements is close, then, the capacity of the system will be decreased. There are two main factors involved which reduce the capacity, radiation efficiency of each element & correlation between each antenna element. The signal to noise ratio (SNR) and correlation are involved to calculate capacity of the system [2]. The maximum capacity can be achieved by decreasing the correlation between elements and increasing the maximum SNR.

The SNR is important factor because it is dependent upon radiation efficiency. In this master thesis, we will calculate radiation efficiency, correlation, diversity gain & mean effective gain using classical embedded element pattern.

The radiation pattern of a single element when all other elements are present and terminated with the characteristic impedance of the system, i.e. matched load is called 'Embedded Element Pattern' [3]. It is also called 'Active Element Pattern'. The radiation pattern of a single element when all other elements are removed but ground plane is present is called 'Isolated Element Patten'.

The excited element induces current at non-excited terminated elements. Therefore, the embedded element pattern could be very different as compared to isolated embedded element pattern.

MIMO system is made for Multipath Environment in which voltage of each element port is independent from other elements port and each port transmits or receives signal through embedded element pattern. By using embedded element pattern, radiation efficiency at each port and correlation between different elements can be calculated [2]. Both of these quantities will bestow diversity gain and maximum capacity.

As we know that, the realized gain is the product of directivity and radiation efficiency. So, the complex radiation field function of the embedded element pattern is defined as [2]:

$$G(\theta\,,\phi) = g_o[G_\theta(\theta\,,\phi)e^{j\phi_\theta(\theta\,,\ \phi)}\hat{\theta} + G_\phi(\theta\,,\phi)e^{j\phi_\theta(\theta\,,\ \phi)}\hat{\phi}] \qquad (2.1)$$

Where,

$$g_o = 10^{(G_o)_{dB}/20}$$

$(\mathrm{G_o})_{\mathrm{dB}}$ *Is Realized Gain*

The embedded element radiation field function of first element is calculated by exciting first element when all other elements are present and terminated by 50 Ω load is shown as $G_{emb}^{(1)}(\theta\,,\phi)$. Similarly for second, third, and so on, embedded element radiation field function is calculated. Radiation efficiency can be calculated, if we calculate directivity(D_o) from $G(\theta\,,\phi)$. The relationship between $G(\theta\,,\phi)$ and D_o is defined as [2]:

$$G_o = e_{rad}\,D_o \qquad (2.2)$$

Where,

$$G_o = g_o^2 \qquad (2.3)$$

2.1 Mutual Coupling:

Mutual coupling defines the electromagnetic interaction between antenna elements due to small distance. It always decreases the radiation efficiency. Mutual coupling influences the correlation between elements. When increasing the mutual coupling, the correlation between the antenna elements becomes higher; this has a negative effect on the diversity gain [6]. We can model diversity system by the help of two port network as shown in figure 2.1.

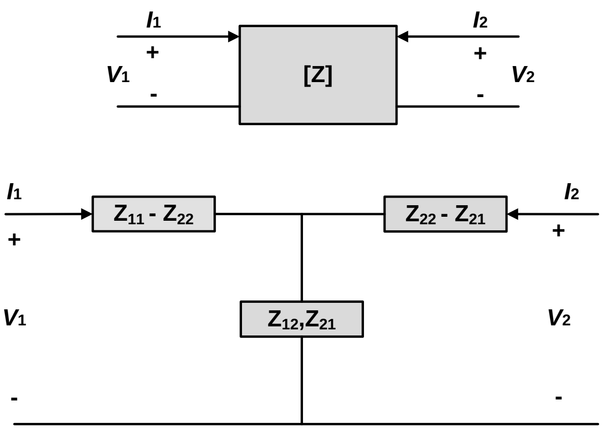

Figure 2.1: Two port network & T-equivalent.

The voltage and current relationship between two port networks can be defined as:

$$V_1 = Z_{11}I_1 + Z_{12}I_2 \tag{2.4}$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 \tag{2.5}$$

Mutual coupling Z_{mn} can be calculated by dividing voltage and current of m and n ports when all other ports are open, where m ≠ n.

$$Z_{12} = \frac{V_1}{I_2}\Big|_{I_1=0} \tag{2.6}$$

$$Z_{21} = \frac{V_2}{I_1}\Big|_{I_2=0} \tag{2.7}$$

Now, input impedance $Z_{11}$and Z_{22} can be defined as:

$$Z_{11} = \frac{V_1}{I_1}\Big|_{I_2=0} \tag{2.8}$$

$$Z_{22} = \frac{V_2}{I_2}\Big|_{I_1=0} \tag{2.9}$$

The total far-field pattern amplitude can be defined as [6]:

$$F(\theta,\varphi) = F_\theta(\theta,\varphi)e_\theta + F_\varphi(\theta,\varphi)e_\varphi \tag{2.10}$$

Where, F_θ & $F_\varphi$is the random amplitude and phase of electric field in θ and φ directions. And for "n" antennas, far-field pattern is defined as:

$$F_{\theta n}(\theta,\varphi) = F_{\theta n}(\theta,\varphi)e_\theta + F_{\varphi n}(\theta,\varphi)e_\varphi \tag{2.11}$$

Where n = 1, 2, 3 …

We have to calculate voltages here, V_1 and V_2 can be calculated by integrating far field function from θ = 0 to 180° and Ѻ = 0 to 360°

$$V_1(t) = C_1 \iint_\Omega F_1(\theta, Ѻ).\mathrm{F}(\theta, Ѻ)\mathrm{d}\Omega \tag{2.12}$$

$$V_2(t) = C_2 \iint_\Omega F_2(\theta, Ѻ).\mathrm{F}(\theta, Ѻ)\mathrm{d}\Omega \tag{2.13}$$

Where

$\Omega = (\theta, \varphi)$, θ = 0 to 180°, φ = 0 to 360°

And, C_1 & C_2 are the proportionality constants.

The voltage of cross covariance is used to derive the envelop correlation [6]:

$$\rho_e \approx |\rho_c|^2 = \frac{|\langle V_1(t)V_2^*(t)\rangle|^2}{\langle V_1(t)V_1^*(t)\rangle.\langle V_2(t)V_2^*(t)\rangle} \quad (2.14)$$

2.2 Antenna Efficiency:

The ratio of the power radiated to the total power supplied to the antenna at a given frequency is called 'Radiation Efficiency'. The total radiation efficiency for a loss less structure can be defined as [3]:

$$e_{rad} = e_{ref}\, e_{abs} \quad (2.15)$$

$$e_{abs} = \frac{P_{rad}}{P_{acc}} \quad (2.16)$$

Where

e_{abs} = efficiency due to the power dissipated, e_{ref} = reflection efficiency

P_{rad} = radiated power, P_{acc} = accepted power

The total radiation efficiency can be expressed much simple for a lossless structure by using scattering parameters. If we have four different antenna elements, then for first element, it can be defined as [3]:

$$e_{tot} = 1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2 - |S_{14}|^2 \quad (2.17)$$

Similarly, for j^{th} elements, it can define as:

$$e_{tot}^{j} = 1 - \sum_{i=1}^{n} |S_{ij}|^2 \quad (2.18)$$

The reflection efficiency is also calculated using scattering parameter. For first element, it can define as [3]:

$$e_{ref\,1} = 1 - |S_{11}|^2 \quad (2.19)$$

The dissipated efficiency is calculated by dividing radiation and reflection efficiency:

$$e_{diss} = \frac{1 - |S_{11}|^2 - |S_{12}|^2 - |S_{13}|^2 - |S_{14}|^2}{1 - |S_{11}|^2} \quad (2.20)$$

2.3 Antenna Correlation:

Antenna correlation is very important factor when we study diversity. We need to calculate it because diversity gain is reduced when correlation increases. Diversity can be improved by decreasing the correlation between the elements. The effect of correlation is very less at 0.5λ distance between elements and after that it remains constant [6]. This limit can be 0.6λ or even 0.7λ in other reference.

The envelope correlation can be calculated accurately by taking square magnitude of complex correlation [6]:

$$\rho_e \approx |\rho_c|^2 \tag{2.21}$$

Envelope correlation is a real and suitable value for calculation. There are two different methods to calculate correlation. One is far-field pattern and the other is s-parameters of the two port network.

The correlation coefficient using far-field pattern is defined as in [6]:

$$\rho_e \approx \frac{\left|\iint_{\Omega}(XPR.E_{\theta 1}(\theta,Ⓠ)E^*_{\theta 2}(\theta,Ⓠ)P_\theta(\theta,Ⓠ) + E_{Ⓠ1}(\theta,Ⓠ)E^*_{Ⓠ2}(\theta,Ⓠ)P_Ⓠ(\theta,Ⓠ)d\Omega\right|^2}{\iint_{\Omega}(XPR.G_{\theta 1}(\theta,Ⓠ)P_\theta(\theta,Ⓠ) + G_{Ⓠ1}(\theta,Ⓠ)P_Ⓠ(\theta,Ⓠ))d\Omega.\ \iint_{\Omega}(XPR.G_{\theta 2}(\theta,Ⓠ)P_\theta(\theta,Ⓠ) + G_{Ⓠ2}(\theta,Ⓠ)P_Ⓠ(\theta,Ⓠ))d\Omega} \tag{2.22}$$

Where

Ω = (θ, Ⓠ), θ = 0 to 180°, Ⓠ = 0 to 360°

XPR = cross correlation power ratio which is equal to P_V & P_H

P_V & P_H = mean incident power of vertical and horizontal wave

E_θ & $E_Ⓠ$ = comples electric field (θ & Ⓠ components)

P_θ & $P_Ⓠ$ = normalized angular power denity fuction of incoming wave

G_θ & $G_Ⓠ$ = antenna power gain pattern

The antenna power gain pattern G_θ & $G_Ⓠ$ is defined as in [6]:

$$G_\theta(\theta,Ⓠ) = |E_\theta(\theta,Ⓠ)|^2$$

$$G_Ⓠ(\theta,Ⓠ) = |E_Ⓠ(\theta,Ⓠ)|^2$$

The pattern measurement is necessary but its calculation is very difficult, while the measurement using s-parameter is comparably easy. The correlation coefficient in term of s-parameter can be defined as in [6]:

$$\rho_e \approx |\rho_c|^2 = \frac{|S^*_{11}S_{12} + S^*_{21}S_{22}|^2}{(1-(|S_{11}|^2+|S_{21}|^2)).(1-(|S_{22}|^2+|S_{12}|^2))} \tag{2.23}$$

The above formula is same for correlation coefficient using far-field pattern. As a point of caution, the latter is valid solely for isotropic environment cases.

There are two different antennas used in diversity system. Efficiency of diversity system goes down if we have less distance between antennas and it also creates losses.

It is not necessary that the correlation and efficiency depend on spacing. Correlation also depends on the environment effect and efficiency due to losses.

2.4 Diversity Gain:

The performance of diversity is calculated from diversity gain. It is time average quantity and there are many methods to calculate it. The diversity gain can be calculated from signal to noise ratio. The diversity gain is actually a difference, given in dB, between two curves as shown in figure 2.2.

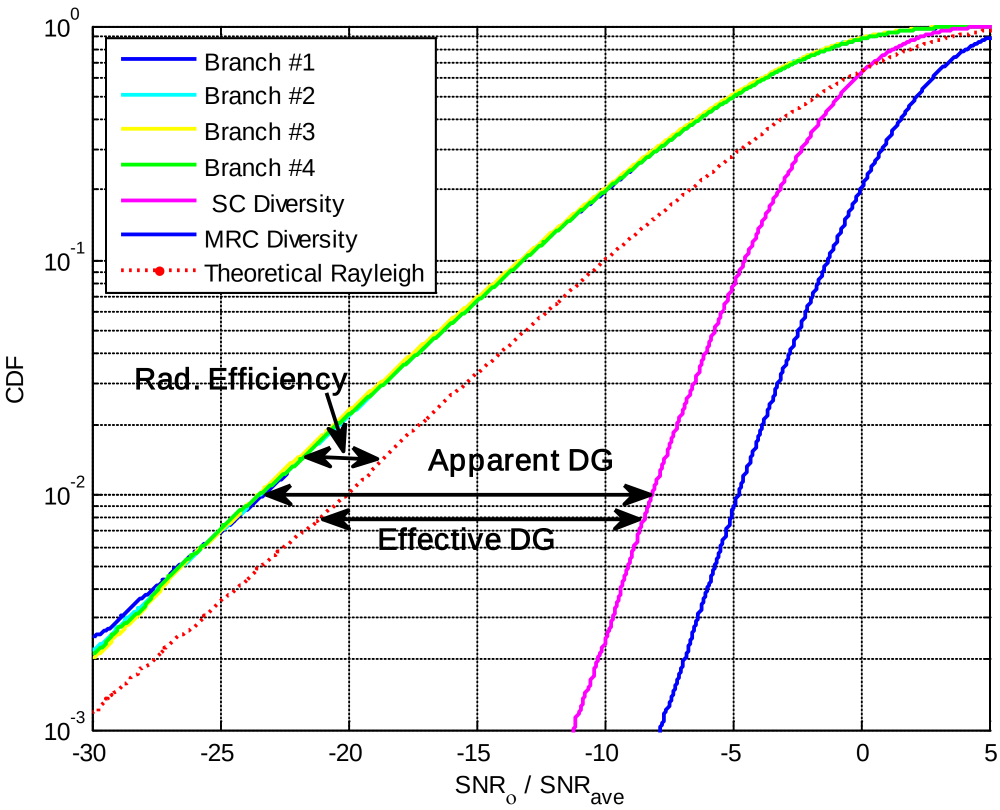

Figure 2.2: Diversity Gain for four different numbers of diversity antenna branches.

Figure 2.2 shows the apparent and effective diversity gain of four parallel dipoles above ground plane separate by 0.5 λ at 1.8 GHz. The received power of element antenna shift to left is because the radiation efficiency of element antennas is not 100%. The apparent and effective diversity are shown at 1% CDF level. When dipoles are sufficiently spaced, the difference between apparent diversity gain and effective diversity gain is negligible. The difference between apparent and effective diversity gain is mainly caused by mutual coupling, giving large absorption in the 50 Ohm load of the not-excited dipole, while correlation has in comparison a small effect. Please note that solely in isotropic environments the shifts of curves are the same as total embedded efficiency. Moreover, for that purpose the reference should be a single port terminal.

2.4.1 Apparent Diversity Gain:

Apparent diversity gain is the difference between power levels in dB (at a certain CDF level) between CDF of combined signal and CDF of signal at the port with the strongest average signal levels [1] as shown in figure 2.2.

2.4.2 Effective Diversity Gain:

Effective diversity gain is the difference between power levels in dB (at a certain CDF level) between CDF of combined signal and CDF of signal at the port of an ideal single antenna (corresponding to radiation efficiency of 100%), measured in the same environment [1] as shown in figure 2.2

$$Effective\ Diversity\ Gain = e_{max} \times ADG$$

2.5 Mean Effective Gain (MEG):

Mean Effective Gain (MEG) is the average of gain over different directions. MEG can be defined as the ratio of mean received power at the terminal and sum of the mean received power of horizontal & vertical (non-uniform angle of arrival) waves received by ideal isotropic antennas [6].

$$MEG = \frac{P_{rec}}{P_{ver} + P_{hor}} \qquad (2.24)$$

For calculation of MEG, we need channel model and radiation pattern of antenna. The main task is to find mean received power in multipath environments for both isotropic and non-uniform case. For isotropic environment, the total radiation efficiency can be calculated by received power using an ideal single port isotropic antenna and it will shift CDF curves to lower SNR value. For non-uniform case, the total radiation efficiency will also shift CDF curves to lower SNR value [12].

The definition of received power is defined as [12]:

$$P_L = \frac{\lambda^2}{4\eta^2 P_{avail}} \left| \sum_{k=1}^{N} \overrightarrow{G_k}(\theta, \varphi) \cdot \overrightarrow{E_k}(\theta, \varphi) \right|^2 \qquad (2.25)$$

Where,

P_L = received Power by the match termination.

N = number of incident wave.

η = antenna Efficiency.

(θ, ϕ) = indicates the direction of incoming wave.

Hence, we can write [12]:

$$P_{rec} = \frac{\lambda^2}{4\eta^2 P_{avail}} \iint_{4\pi} (|G_\theta|^2 P_\theta + |G_\phi|^2 P_\phi)\, d\Omega \qquad (2.26)$$

At this moment, we need to have reference antenna for calculation of total embedded efficiency. So, we decide two-port, dual isotropic antenna as our reference antenna. The total embedded efficiency of different branches (antennas) can be calculated by using reference antenna. Therefore, we should have to normalize reference antenna and it can be define as [12]:

$$P_{avail} = P_{rad} = \frac{1}{2\eta} \iint_{4\pi} \left(\left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2\right) d\Omega = \frac{1}{60} \qquad (2.27)$$

Now, mean effective gain (MEG) can be defined as [12]:

$$P_{rec} = \frac{1}{2\eta P_{avail}} \frac{\iint_{4\pi} (|G_\theta|^2 P_\theta + |G_\phi|^2 P_\phi) d\Omega}{(P_\theta + P_\phi)} \qquad (2.28)$$

From above equation, if P_θ & P_ϕ is equal to 1 (for balance polarize, unity power) then MEG will be equal to 0.5 (P_{rad} / P_{avail}) which is equal to the Total Embedded Efficiency. Therefore, for each branch, MEG is equal to the total embedded efficiency. If we use two-port, dual polarized isotropic antenna as a reference antenna then it would become total embedded efficiency. And, if we use single polarized antenna as a reference antenna then it would be (P_{rad} / P_{avail}).

For the isotropic environment, the MEG is equal to half of the total radiation efficiency [3]:

$$MEG = e_{rad} / 2 \qquad (2.29)$$

It is significant that the difference between MEG of different branches be as small as possible because difference increases the diversity gain decreases [6].

2.6 Channel Capacity:

Channel capacity is defined as the maximum amount of data to be transmitted for a reliable information transfer or Channel capacity is a measure of how many bit per second can be transmitted through a radio channel per Hz also referred as the ‘Spectral Efficiency’ [2].

For a single transmitter and receiver, channel capacity is well described by Shannon’s formula. When this formula is extended to MIMO systems, the resultant capacity is the sum of the capacities of parallel channels. That is,

$$C = \log_2 \left[\det \left(I_M + \frac{\rho}{N} H H^H \right) \right] \quad b/s/Hz \qquad (2.30)$$

Where,

H = M x N channel matrix with M receiver and N transmitter antennas.

$I_M(M \times M)$ = identity matrix, $(.)^H$ = donates the conjugate transpose.

ρ = signal to noise ratio (SNR) at any receiver branch,$\lambda_1, \lambda_2, \dots \dots ., \lambda_m$ are the nonzero Eigen values of HH^H $(M \le N)$

2.6.1 Ergodic Capacity:

Ergodic capacity is define as in fading channels, when channel unknown to the transmitter but known to the receiver. This can be expressed as [7]:

$$C = E\left(log_2\left[det\left(I_M + \frac{\rho}{N}HH^H\right)\right]\right) \quad b/s/Hz \qquad (2.31)$$

2.7 Channel Models:

Channel model is essential when we are dealing with non-uniform (real) or isotropic environments. It tells us the propagation of signals in different environments as well as the transfer function, for example, urban and rural areas. The different approaches can follow for both environments which will be discussed here.

2.7.1 Isotropic Environment:

It is the simplest type of channel model; waves are coming uniformly over the sphere encircling the terminal as shown in figure 2.3. The elevation plane (theta) and azimuth plane (phi) have sinus and uniform distribution to bestow a uniform AOA. In order to have Rayleigh distribution, the coming waves in each polarization shall be complex Gaussians of unit variance.

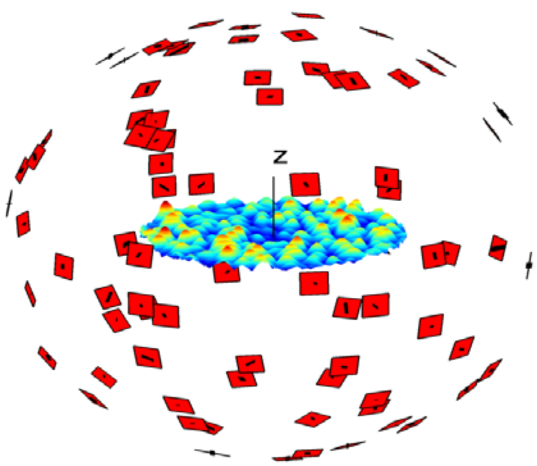

Figure 2.3: Isotropic Environment [15].

2.7.2 Non-uniform Environment:

When the signal is transmitted from an antenna in real environment, it reaches directly or indirectly at the receiver. But in multipath environment, most of time, it is not possible to get the signal directly. The signal get reflected, diffracted and scattered due to large building, mountains and trees as it propagates towards the terminal. The distribution of the signals is different in both vertical and horizontal plane.

The waves which are coming on receiving antenna get reflected with objects. The final object from which the wave will go directly to receiving antenna is considered as a secondary wave source. Also, the number of objects and their location in environment is statistically independent and terminal is moving randomly in environment. Therefore, we are assuming that the objects are uniformly distributed in azimuth plane [9].

According to theoretic model, objects are average distributed in elevation plan. It is dependent upon the objects spreading, height, and no waves are coming directly from on top of, and perpendicular (Ground). Therefore, according to central limit theorem, we could assume Gaussian distribution in elevation plane [9].

Therefore, the statistically model can have two angular density function $P_{\Theta}(\Theta, \varphi)$ & $P_{\varphi}(\Theta, \varphi)$ which are uniformly distributed in azimuth plane and Gaussian distributed in elevation plane as shown in figure 2.4 [9].

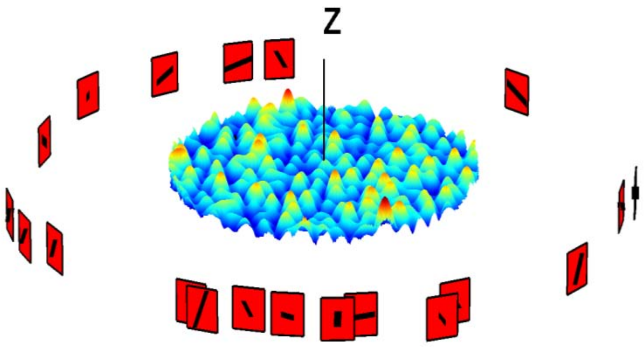

Figure 2.4: Non-uniform Environment (Azimuth plane) [15].

$$P_{\theta}(\theta, \varphi) = \frac{A_{\theta} e^{-(\theta-(\pi/2-m_V))^2}}{2\sigma_V^2} \tag{2.32}$$

Similarly, for φ component,

$$P_{\varphi}(\theta, \varphi) = \frac{A_{\varphi} e^{-(\theta-(\pi/2-m_H))^2}}{2\sigma_H^2} \tag{2.33}$$

Where,

θ = 0 to π

A_{θ} & A_{φ} = the amplitudes of P_{θ} & P_{φ}

m_V & m_H = Mean of incident angle of arrival for horizontal & vertical polarized wave

σ_V & σ_H = Standard deviation of incident angle of arrival for horizontal & vertical polarized wave

Laplacian and exponential distributions are also the type of azimuth channel model but they are not part of this project.

2.8 Multipath Environment Simulator:

Multipath environment Emulator for Simulation of MIMO Terminals performances (MEST) has been created in Antenna Group at Chalmers. The inputs to this software are embedded element patterns, reflection coefficients, and the maximum available power (P_{avail}) of the source by which the embedded element patterns are either simulated or measured. Also, the number of realized scenarios (or simply called realization), and the number of incident waves from different scatters. MEST outputs different MIMO parameters, like Apparent and Effective Diversity Gains, Mean Effective Gain (MEG), capacity, embedded element efficiencies, and finally spatial correlations between different elements [17].

In this code, the embedded element patterns of antennas are illuminated by several incident Electromagnetic (EM) plane waves, while each one bears random electric field of Rayleigh amplitude. In this master thesis, we presume balanced polarization for these coming waves, i.e. they are arbitrarily polarized. At each realized scenario, there are certain numbers of incident EM waves coming from different scatters located uniformly around the terminal. The electric fields of all these plane waves contribute together to give rise to voltages at different ports of our terminal [17].

Now, in the second round of realization, the same number of scatter but with different positions of still uniform distribution are responsible for new sets of EM waves which, in turn, create our second voltage samples at ports of the terminal. This process of realizations continues to eventually result in sufficient number of voltage samples at input ports of the terminal. By further processing of these voltage samples, we can achieve Cumulative Density Function (CDF) curves of them as well as different MIMO parameters. As a point of caution, bear in mind that in parallel with terminal elements, we also need to expose an arbitrary reference antenna to the same set of incident waves at each scenario and use its received average power for normalization purposes [17].

There are two important points concerning MEST. First of all, we stress that the number of incident waves in each scenario is associated with richness of multipath environment. That is, the larger the number of incident wave, the richer the multipath environment. Moreover, that how large is the number of realization affiliates with the accuracy of the results; meaning that, the larger the number of realizations is, the more accurate the obtained desired parameters are [17].

The radiation efficiency and correlation occurs due to mismatch and mutual coupling is already incorporated in channel matrix (H) by the given precise formulation (2.25). The Ergodic capacity is calculated in measurement section by using 3x4 MIMO system which will give us total 10000 3x4 MIMO matrices [2].

Chapter 3

Antenna Simulation

Antenna design in the field of telecommunication engineering is a challenging simulation task. The structures of the antenna's are often complex and can be large in size. In addition, the radiation from antennas into free space has to be modeled accurately.

Computer Simulation Technology (CST) Microwave Studio is a part of the CST Design Studio that can be used to deign all kind of antennas like micro strip, waveguide, and helical antenna [16]. It provides a number of different solvers for different types of applications. Since no method works equally well in all application domains, the software contains four different types of simulation techniques, transient solver, frequency domain solver, integral equation solver and Eigen mode solver.

The most simple and useful tool is the transient solver, which can be used to obtain the entire broadband frequency behavior of the simulated antenna through only one calculation. It is based on the Finite Integration Technique (FIT). It is efficient for many kinds of high frequency applications such as connectors, transmission lines, filters, and antennas [16]. In this master thesis, we will use the transient solver for designing a four horizontal dipole antenna array with the effects of Balun above an infinite ground plane.

The CST is very efficient and user friendly software to design antenna simulation. The commercial full-wave simulator is used to design four horizontal dipole antenna arrays with the effect of Balun above an infinite ground plane. The simulator provides two main files, One has all the information of S-parameters for each frequency step which is called 'Touchstone' file as shown in Appendix – A.1, and, second file contains stimulated power, accepted power, radiation power, operating frequency and embedded element radiation field which is called 'Far-field' file as shown in appendix – A.2. The embedded patterns have the resolution of 1 degree x 1 degree in our simulations. . Each value of ϕ contains 180 values of θ and each θ value provides radiation pattern $G_{\theta}(\theta,\phi)$ and $G_{\phi}(\theta,\phi)$ for θ and ϕ components. It means we have total 65241 (181x361) radiation pattern values in dB.

3.1 Antenna Geometry

The dipole antenna is designed here for a research application operating at 1.8 GHz. The typical geometry of a dipole antenna and the dimension parameters are taken from Bluetest [13] shown in figure 3.1.

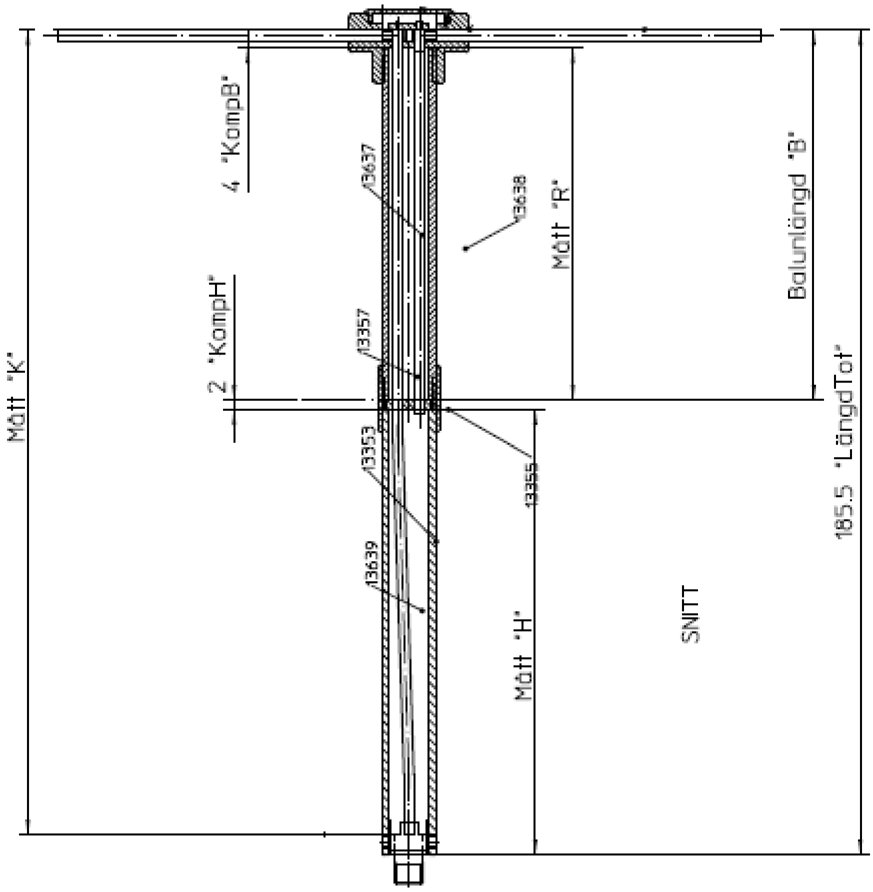

Figure 3.1: Model of Dipole Antenna with the Effect of Balun [13]

3.2 Design Parameters

The Matt 'K', 'R' and 'H' are the internal design and parameter values which are shown in the table 3.1. In this project, we have simulated four-dipole antenna array with the effect of Balun above an infinite ground plane using the Computer Simulation Technology (CST) version 2010.

Table 3.1: Antenna Design Parameters			
No	**Parameter**	**Value (mm)**	**Description**
1	DipR	1.0	Dipole Radius
2	Length	34	Dipole arm length
3	PortR	3.5	Distance between two dipoles arms (twice)
4	Height	22	Dipole height above ground plane
5	CcR	0.6	Core conductor radius
6	Shield	0.5	Coaxial cable shield
7	OutCr	0.15	Outer conductor radius
8	BalunL	42.5	Balun length (Short at 42.5 mm)
9	CondR	1.25	Solid conductor radius (Balun)
10	Gplane	400 x 16 x 2.8	Ground plane

The table 3.1 contains all the information of designing antenna but we need the information about CST parameter just like Boundary condition, excitation, analysis and field monitor. The table 3.2 has the configuration setting parameter used in CST.

Table 3.2: CST Configuration Parameters

No	Parameter	Description
1	Units	Dimension (mm), Frequency (GHz) and Time (Sec)
2	Model(Geometry)	According to figure 3.1
3	Background material	Normal (Not a PEC)
4	Boundary Condition	Open (Add Space)
5	Excitation Port	Discrete Ports at 50 Ω
6	Analysis	Central frequency at 1.8 GHz with a sweep b/w 1.4 to 2.2 GHz
7	Field Monitor	E-field and Far-field at 1.8 GHz

3.3 Antenna Design

The dipole antenna has been fed from center and contains insulator cover to protect from radiation, and Balun is used for feeding of this unsymmetrical terminal. We have divided the design task in different steps. Each step will discuss briefly the design of the antenna characteristic (Reflection Coefficient and Radiation pattern). The different configuration of four dipoles antenna array have been studied with the start from single dipole.

3.3.1 Case – 1: Dipole Antenna with Incremental Gap:

The dipole antenna with incremental feed gap is consisted of very small feed gap approximate 1 mm as shown in the figure 3.2.

- **Simulation Diagram:**

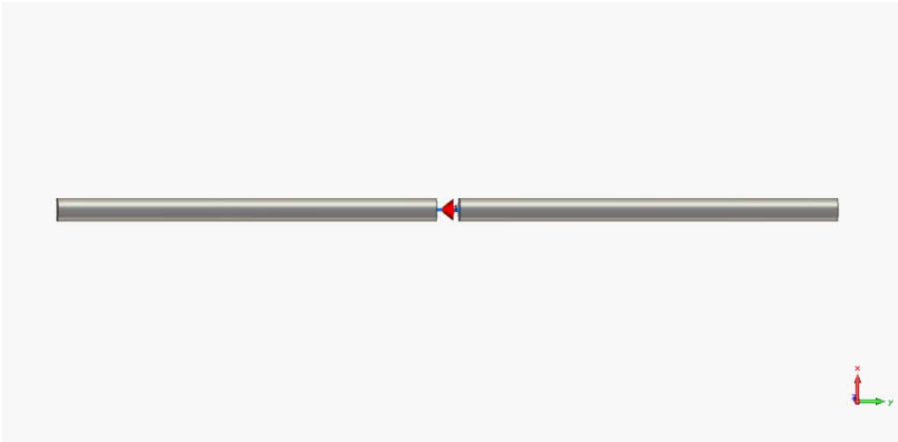

Figure 3.2: Dipole Antenna with incremental gap

- **Reflection Coefficient:**

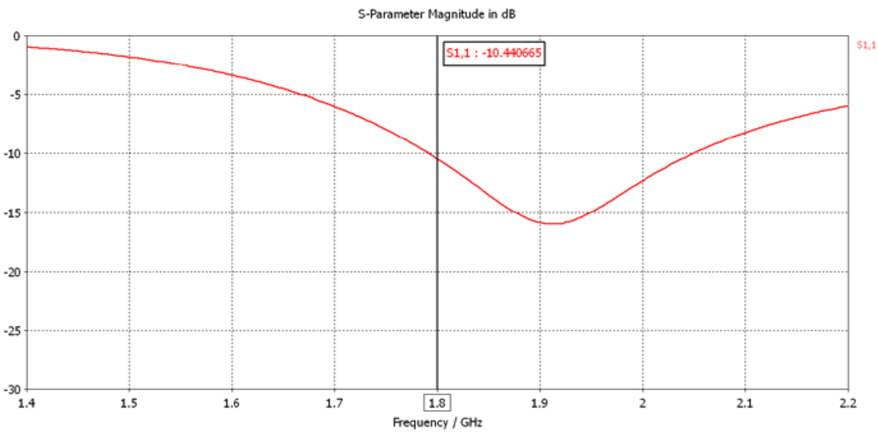

Figure 3.3: Reflection Coefficient of Incremental Dipole Antenna

- **3-D Radiation Pattern**

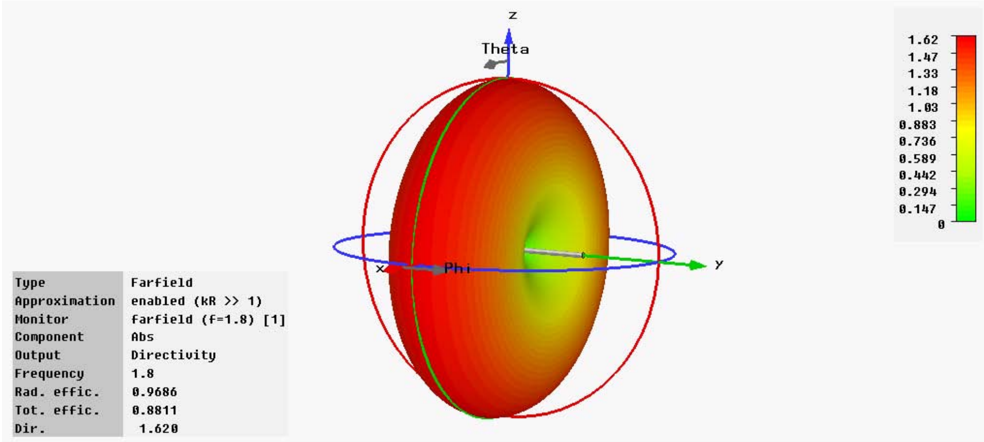

Figure 3.4: Radiation Pattern of Incremental Dipole Antenna

- **E-field Radiation:**

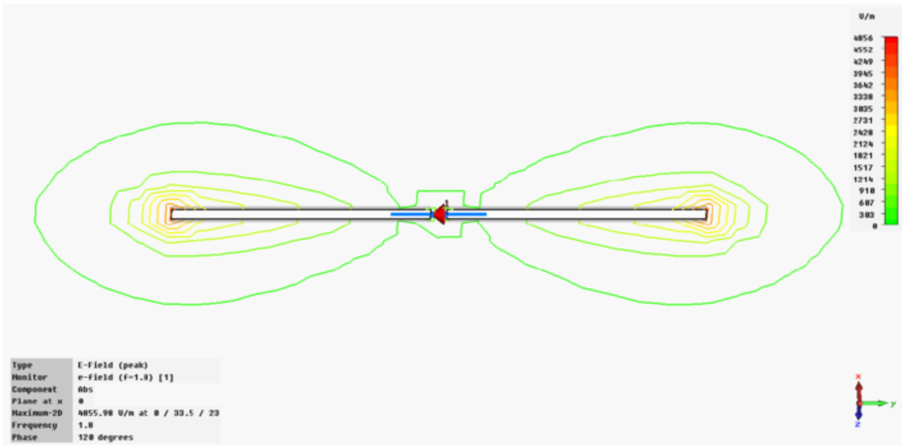

Figure 3.5: E-field Radiation of Incremental Dipole Antenna

The figure 3.3 shows the reflection coefficient (S11) of incremental dipole antenna. The S11 is -10.44 dB at a frequency of 1.8 GHz which shows that 90.96% matching and 9.03% signal is reflected back. And the figure 3.4 shows the 3D-radiation pattern of incremental dipole at 1.8 GHz. It looks like a donut which is the ideal radiation pattern of a dipole and it also describes the total efficiency which is 0.8811. Finally figure 3.5 shows the e-field radiation from both arm of dipole. The green signal is showing the minimum signal strength where as red shows maximum.

3.3.2 Case – 2: Dipole Antenna without Incremental Gap:

The dipole antenna without incremental gap has a large space (feed gap) between feeding point (dipoles arms) as shown in figure 3.6.

- **Simulation Diagram:**

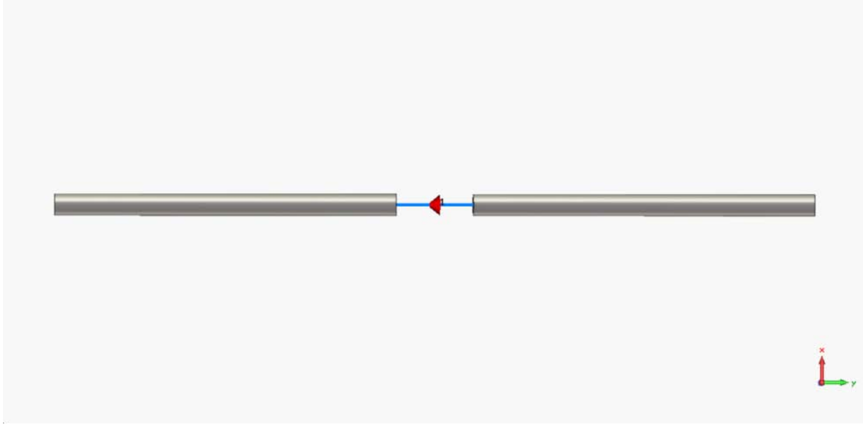

Figure 3.6: Dipole Antenna (without Incremental Gap)

- **Reflection Coefficient:**

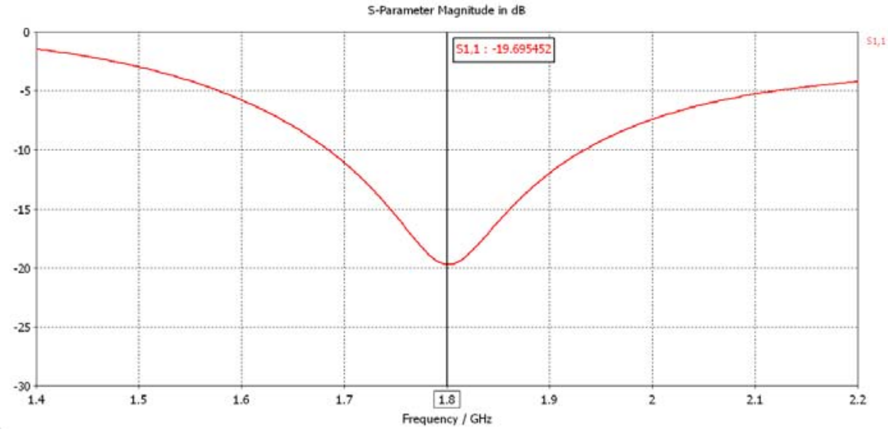

Figure 3.7: Reflection Coefficient of Dipole Antenna (without Incremental Gap)

- **3-D Radiation Pattern**

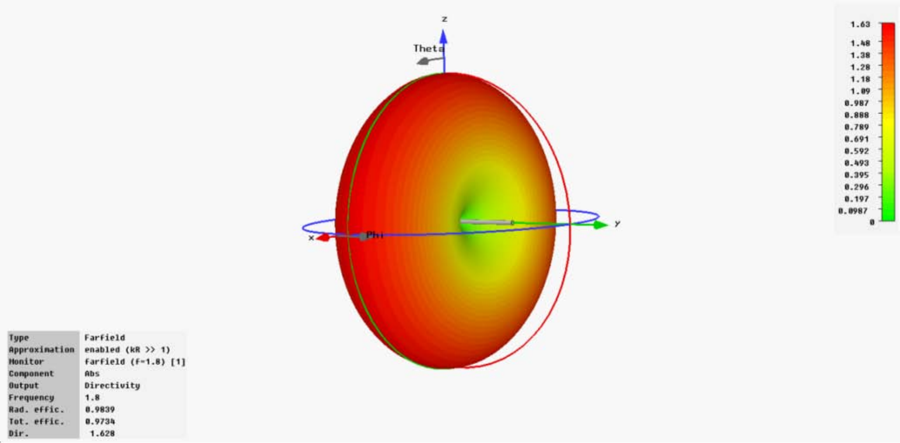

Figure 3.8: Radiation Pattern of Dipole Antenna (without Incremental Gap)

- **E-field Radiation:**

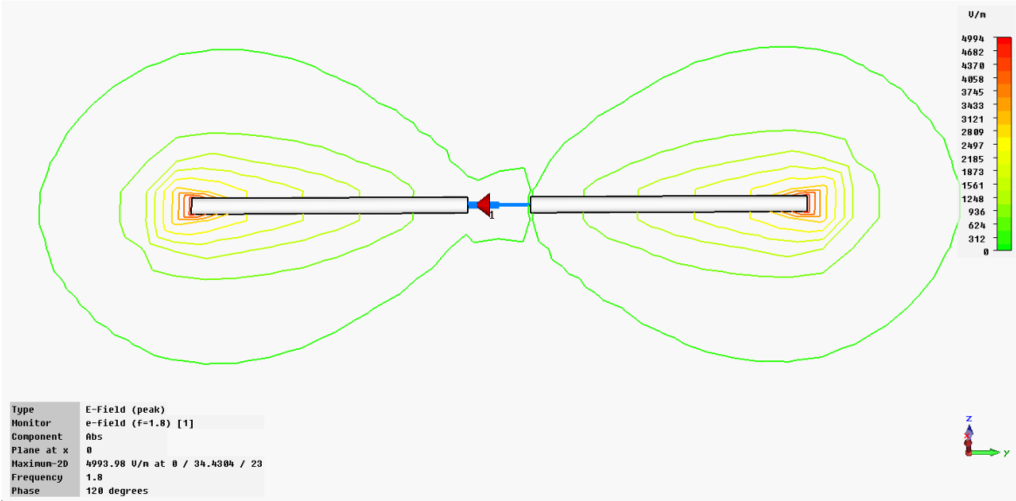

Figure 3.9: E-field Radiation of Dipole Antenna (without Incremental Gap)

The figure 3.6 shows the simulation diagram of dipole antenna without incremental gap and has an obvious difference between feed gap as compare to dipole with incremental gap. The figure 4.7 shows the reflection coefficient and it is -19.69 dB at a frequency of 1.8 GHz which shows the 98.92% matching and only 1.07% (small portion) signal is reflected back. In figure 3.8, the radiation pattern looks similar in both cases and total efficiency is improved by 0.9734 from 0.8811 because of good matching. And in figure 3.9, the e-field has wide signal strength as compare to case-1 because we have good matching at desired frequency.

3.3.3 Case – 3: Dipole Antenna with Insulator Cover:

The insulator cover is used to provide the proper structure to dipole. It improved a small amount of reflection coefficient and efficiency.

- **Simulation Diagram:**

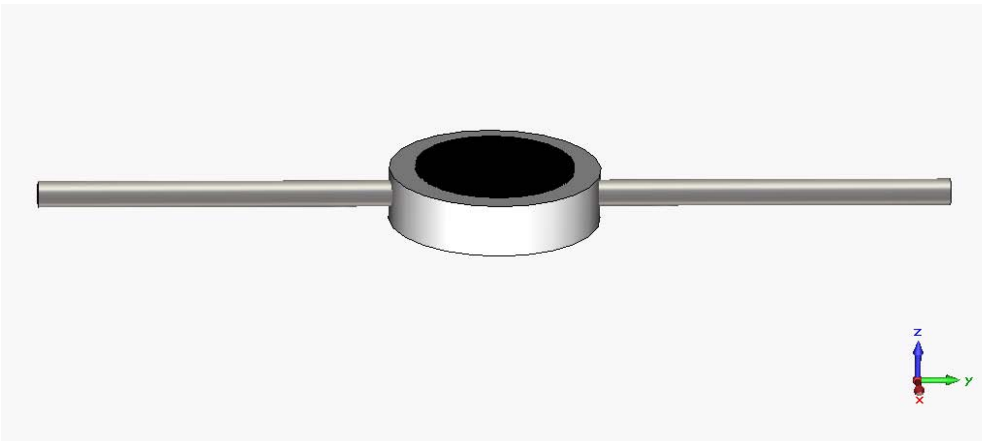

Figure 3.10: Dipole Antenna (with insulator cover)

- **Reflection Coefficient:**

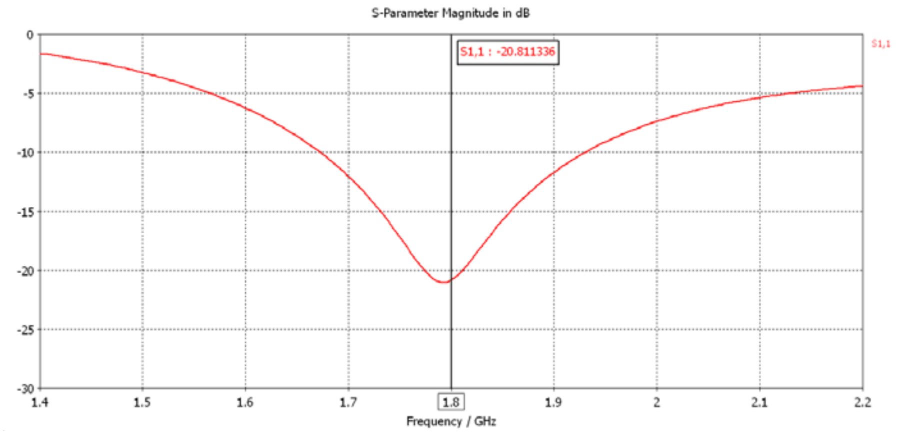

Figure 3.11: Reflection Coefficient of Dipole Antenna (with insulator cover)

- **3-D Radiation Pattern**

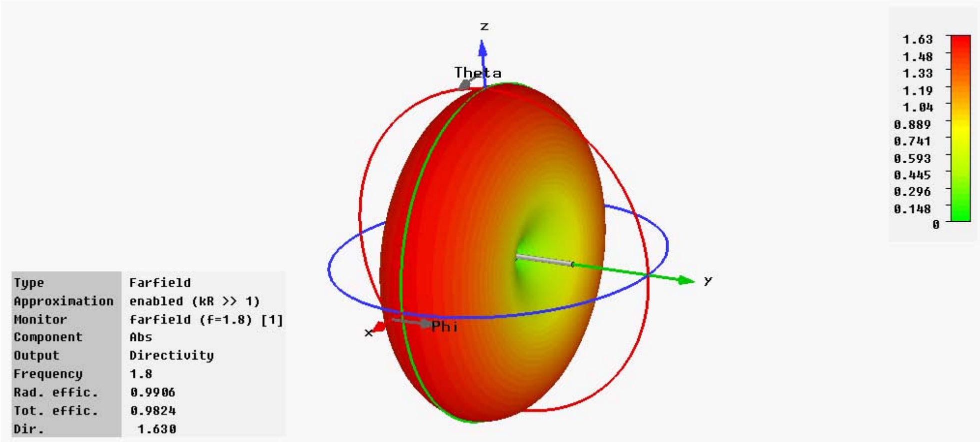

Figure 3.12: Radiation Pattern of Dipole Antenna (with insulator cover)

- **E-field Radiation:**

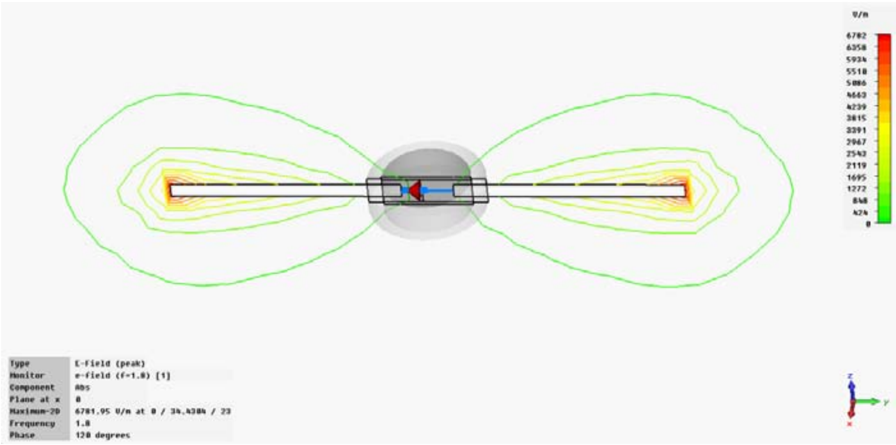

Figure 3.13: E-field Radiation of Dipole Antenna (with insulator cover)

The figure 3.10 shows the simulation diagram of dipole antenna with insulator cover. The insulator cover is used to provide protection from radiations coming from feed gap. In figure 3.11, the reflection coefficient (S11) is -20.81 dB at a frequency of 1.8 GHz which shows that 99.17% (Complete match) matching and only 0.82% (small portion) signal is reflect back. In figure 3.12, the radiation pattern is again similar but total efficiency is improved by 0.9824 from 0.9734 because of good matching. And in figure 3.13, the e-field has again wide signal strength as compare to case-2 and case-1 because we have again good matching at desired frequency.

3.3.4 Case – 4: Dipole Antenna with the Effect of Balun:

When a dipole has been fed by a coaxial cable (two parallel conductor lines), the inner and outer conductors are not coupled to the antenna (dipole) in the same way. This type of connection produces an unbalanced current flowing through the ground on the outside part of the conductor (coaxial cable). To compensate and balance the current flow, a quarter-wave section is attached and connected at the transmission line. This configuration is called “Balun” and it is shown in figure 3.14 [18].

A dipole antenna is design with the effect of Balun. Balun is an electrical transformer, which converts balance impedance to unbalance and vice versa. Balun can be use for impedance transformation; therefore it can be called as Balun transformers. There are many types of Balun but we used ‘Split Coax Balun’.

Coaxial Balun is a very cost effective method to remove cable radiations. It works on some small set of operating frequency. It can be made by adding one more coaxial quarter wave length cable called coax stub parallel to main feeder (Transmission line) as shown in the figure 3.14. Both core and shield of coax stub are short together. One end of coax stab is short with feeder shield at quarter wave length and other end is short with main feeder core.

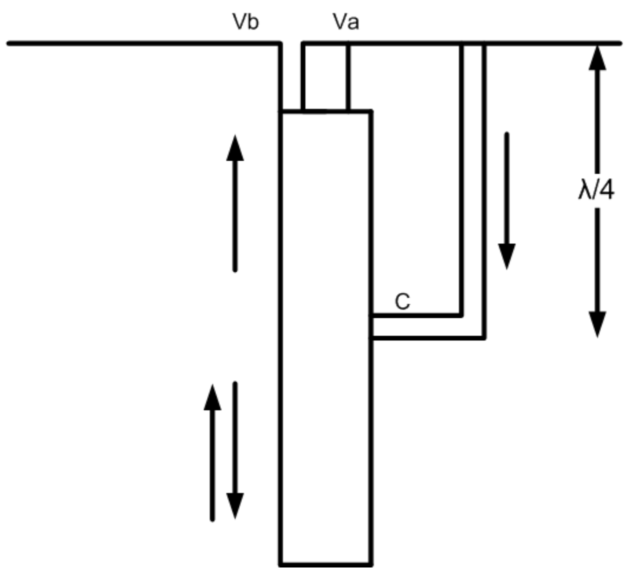

Figure 3.14: Split Coax Balun [18]

Consider figure 3.14, the core of coaxial cable at point V_A to the outer conductor of transmission line doesn't change the antenna impedance (Z_{ant}) at quarter wavelength. Another quarter wavelength coaxial cable joint with outer coaxial of the transmission line which makes an additional equivalent transmission line, quarter wavelength long shorted at point C as shown in figure 3.14. The short circuit at point C is transformed to infinite impedance at the antenna terminal, parallel with Z_{ant} leaving the input impedance unchanged. The quarter wavelength line induced a cancellation current outside the coaxial transmission line. Therefore, the net current on the outside of the main coaxial below the quarter wavelength is zero. [18]

A Balun that leaves the impedance unchanged is called 'One to one Balun' and a Balun which change the antenna impedance 72 ohm to 288 ohm is called 'Four to one Balun'.

- **Simulation Diagrams:**

Figure 3.15: Dipole Antenna (with the Effect of Balun)

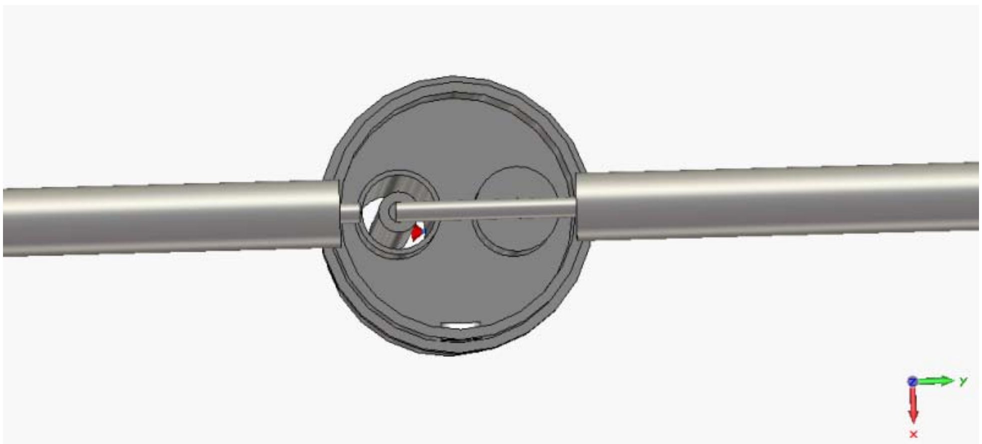

Figure 3.16: Dipole Antenna (with the Effect of Balun) from inside – 1

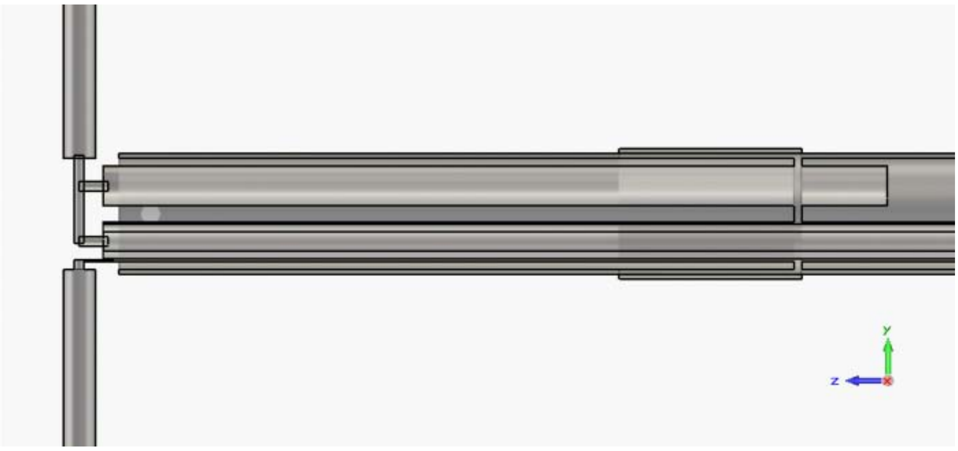

Figure 3.17: Dipole Antenna (with the Effect of Balun) from inside – 2

- **Reflection Coefficient:**

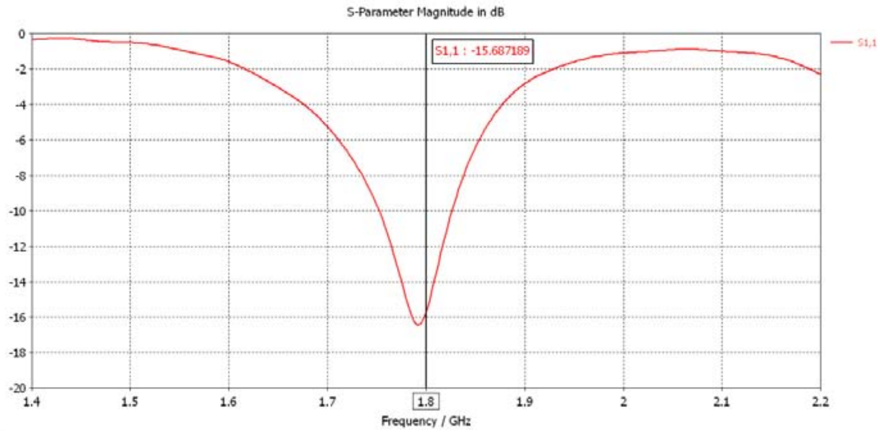

Figure 3.18: Reflection Coefficient of Dipole Antenna (with the Effect of Balun)

- **3-D Radiation Pattern:**

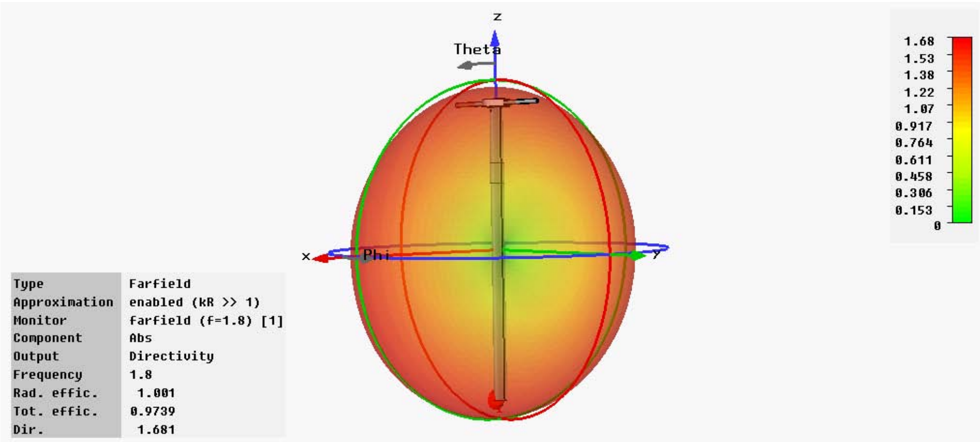

Figure 3.19: Radiation Pattern of Dipole Antenna (with the Effect of Balun)

- **E-field Radiation:**

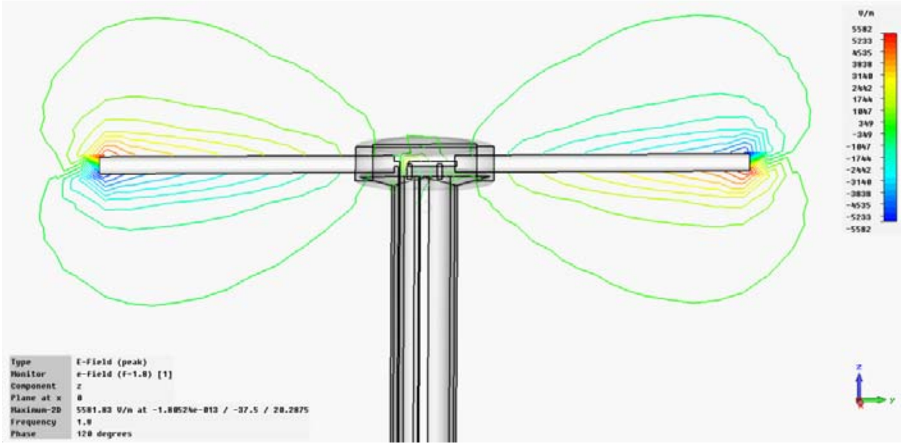

Figure 3.20: E-field Radiation of Dipole Antenna (with the Effect of Balun)

The figure 3.15 shows the simulation diagram of dipole antenna with the effect of Balun. And the figure 3.16 & 3.17 show the internal structure of dipole antenna. A discrete port (Red Color) is used for excitation which is connected at the end of antenna. In figure 3.18, the reflection coefficient (S11) is -15.68 dB at a frequency of 1.8 GHz which shows the 97.3% matching. The reflection coefficient of practical antenna is approximate -15 dB and we achieved -15.68 dB by simulation approach, it shows that, the antenna is perfectly design and has a perfect match. In figure 3.19, the radiation pattern is shown with the help of dipole antenna to understand how the radiation pattern is generated. The total efficiency is decreases by 0.9739 from 0.9824 because of matching. And in figure 3.20, the e-field has good signal strength as compare to previous case's. And we can also see that the e-filed is not radiate from insulator cover.

3.3.5 Case – 5: Dipole Antenna with Balun above an infinite Ground plane:

The dipole antenna is same as in case-4 but here, we used infinite ground plane (Dimension is taken from Bluetest are shown in table 3.1). The ground plane is used to increase the directivity of antenna as shown in figure 3.21.

- **Simulation Diagram:**

Figure 3.21: Dipole Antenna with Balun above an infinite Ground plane

- **Reflection Coefficient:**

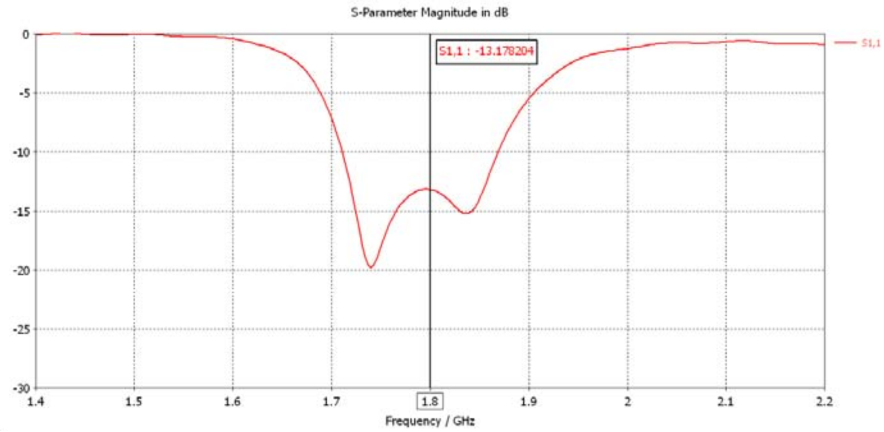

Figure 3.22: Reflection Coefficient of Dipole Antenna with Balun above an infinite Ground plane

- **3-D Radiation Pattern:**

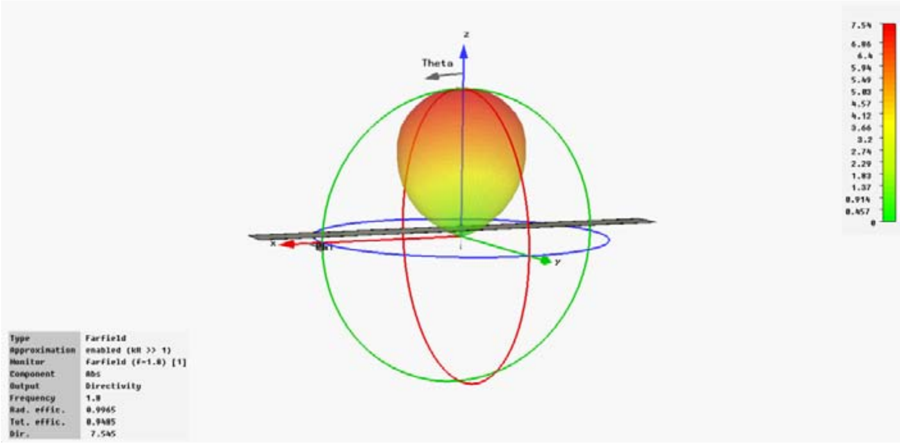

Figure 3.23: Radiation Pattern of Dipole Antenna with Balun above an infinite Ground plane

- **E-field Radiation:**

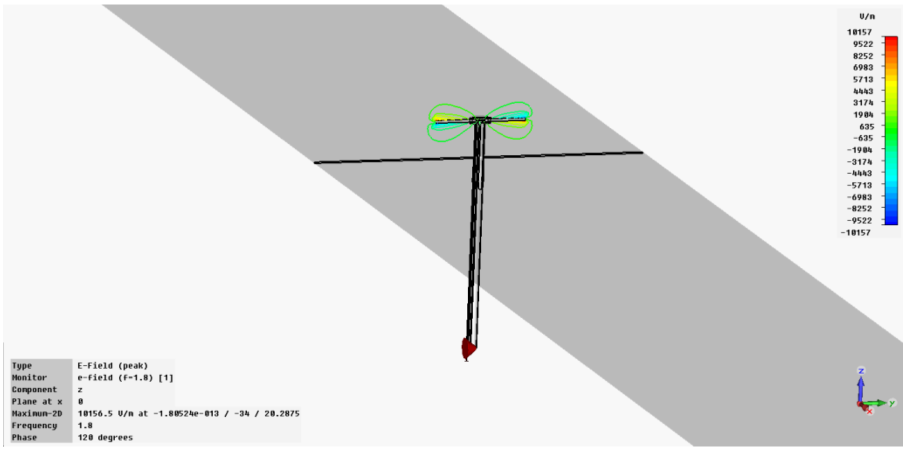

Figure 3.24: E-field Radiation of Dipole Antenna with Balun above an infinite Ground plane

- **Absolute Directivity (Polar):**

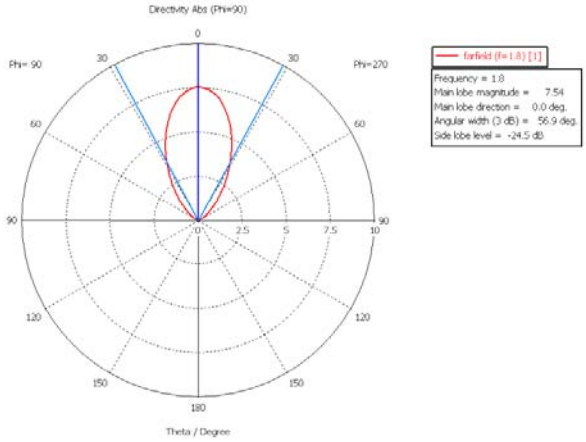

Figure 3.25: Absolute Directivity of Dipole Antenna with Balun above an infinite Ground plane

The figure 3.21 shows the simulation diagram of dipole antenna with the effect of Balun above an infinite ground plane. A ground plane is used to increase the directivity of antenna in particular direction. The ground plane has to be put at the right place because the electromagnetic waves like vectors needs to be sum in phase otherwise, out of phase they will cancel each other. In figure 3.22, the reflection coefficient (S11) is -13.17 dB at a frequency of 1.8 GHz which shows the 95.18% matching. In figure 3.23, the dipole antenna is radiating in only one direction because we used ground plane, and the total efficiency is 0.9485. In figure 3.24, the e-field has good signal strength as compare to previous case's. The figure 3.25 shows the absolute directivity in polar coordinates. The main lobe has a magnitude of 7.54 and angular width (3 dB) is 56.9°.

Table 3.3: Reflection Coefficient & Radiation Efficiency of Single Dipole			
No	**Cases**	**Reflection Coefficient (dB)**	**Total Efficiency (dB)**
1	Case - 1	-10.44	-0.55
2	Case - 2	-19.69	-0.12
3	Case - 3	-20.81	-0.08
4	Case - 4	-15.68	-0.11
5	Case - 5	-13.17	-0.23

The table 3.3 shows the complete comparison of above five different cases between reflection coefficient and total efficiency. And case-3 is the best one, because we got highest reflection coefficient and maximum total efficiency.

3.3.6 Case – 6: Four Dipole Antenna Array above a Ground Plane:

The geometric diagram of four dipoles antenna array is shown in figure 3.26. In four dipoles antenna array, the performance of first and last element is same because of symmetric property, similarly, the performance of second and third element are same. In top diagram, the arrangement of dipoles is shown from right to left. And in second diagram is shown the complete structure of antenna array. The length of monopole is λ/4; therefore the length of dipole is λ/2. The 'g' is a distance between monopoles which is called "feed gap". The distance between dipole antennas is "s" and it is very important factor in antenna array because the performance of antenna array is totally depend on it. We have analyzed the different distance between dipole because the correlation and efficiency is depend upon distance. There are three different distance selected on the basis of practical requirement which are (a) 0.5λ, (b) 0.2 λ, (c) 0.1 λ. We will study the results of all three configurations and analyze the effects when the distance between antennas is changed and also the effect on reflection coefficient, radiation pattern, correlation and efficiency. To obtain a good result, we have to maintain minimum 0.5λ distance between dipoles as discuss in previous chapter.

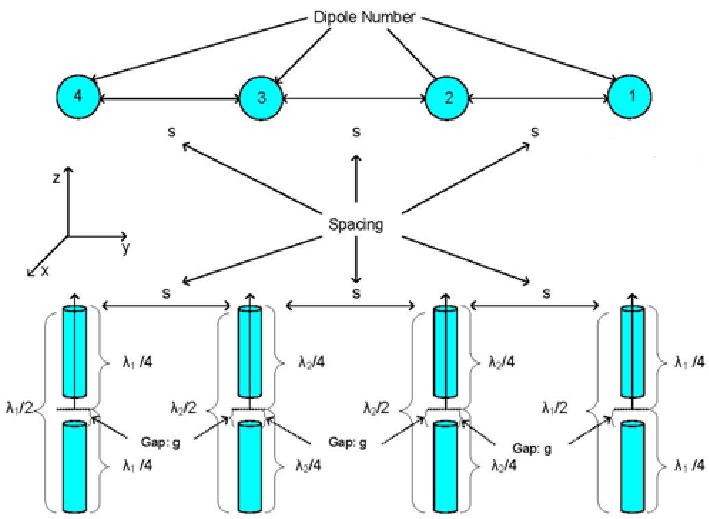

Figure 3.26: Four Dipole Antenna Array (Figure courtesy of Gizmo Antenna)

3.3.6.1 Case – 6.1: Four dipoles antenna array at a distance of 0.5 λ:

The antenna array is consisted of four dipoles with the 0.5 λ distance between them as shown in the figure 3.27.

- **Simulation Diagrams:**

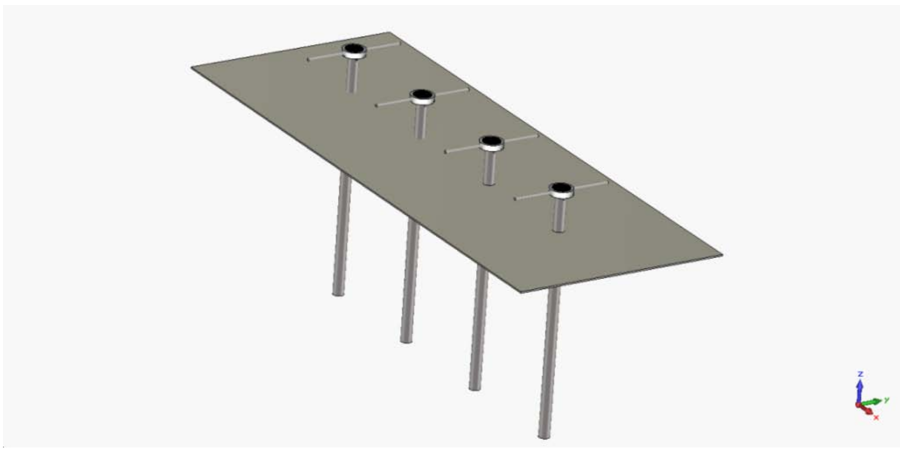

Figure 3.27: Dipole Antenna Array above a Ground Plane at a distance of 0.5 λ

➢ Reflection Coefficients:

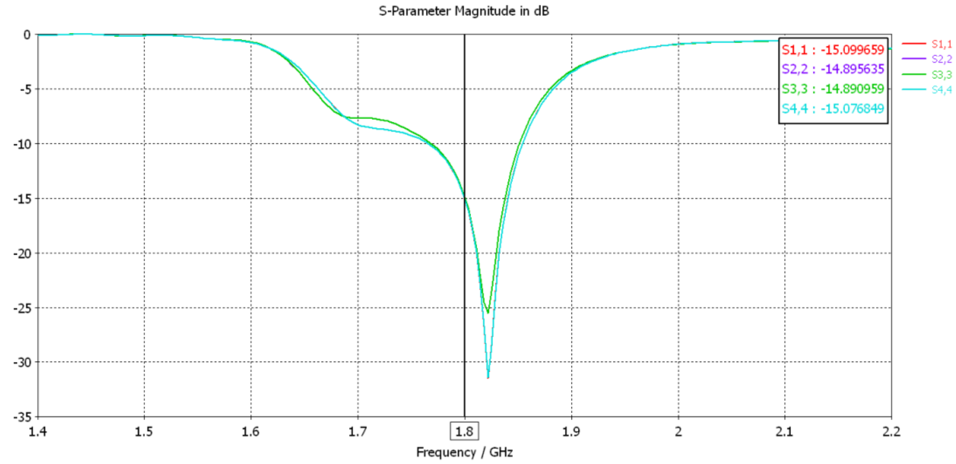

Figure 3.28: Reflection Coefficient of Dipole Antenna Array above a Ground Plane

- **Reflection Coefficient at Port 1:**

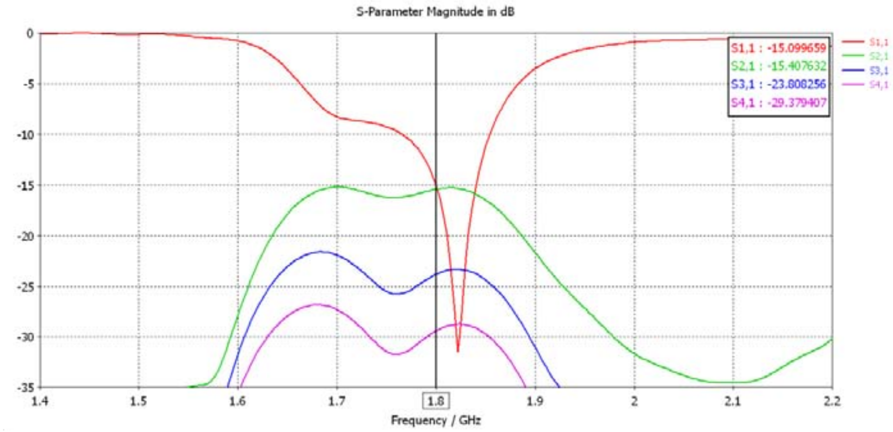

Figure 3.29: Reflection Coefficient of Dipole Antenna Array above a Ground Plane at Port 1

- **Reflection Coefficient at Port 2:**

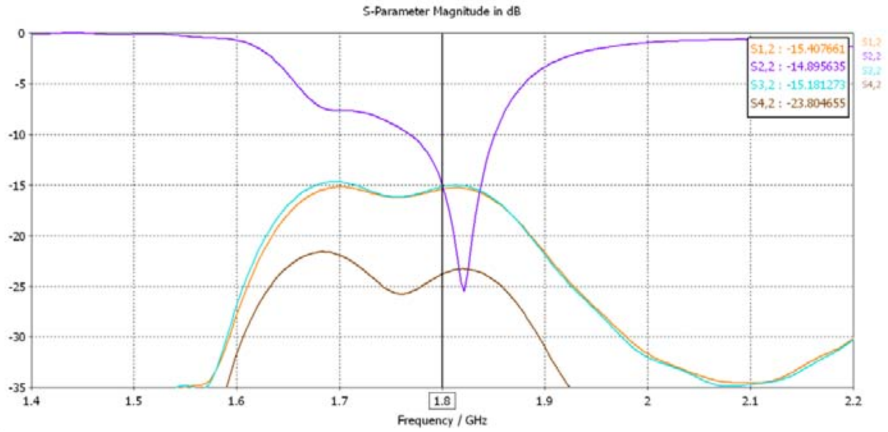

Figure 3.30: Reflection Coefficient of Dipole Antenna Array above a Ground Plane at Port 2

➢ 3 - D Radiation Patterns:

- ### 3 - D Radiation Pattern of 1st Element:

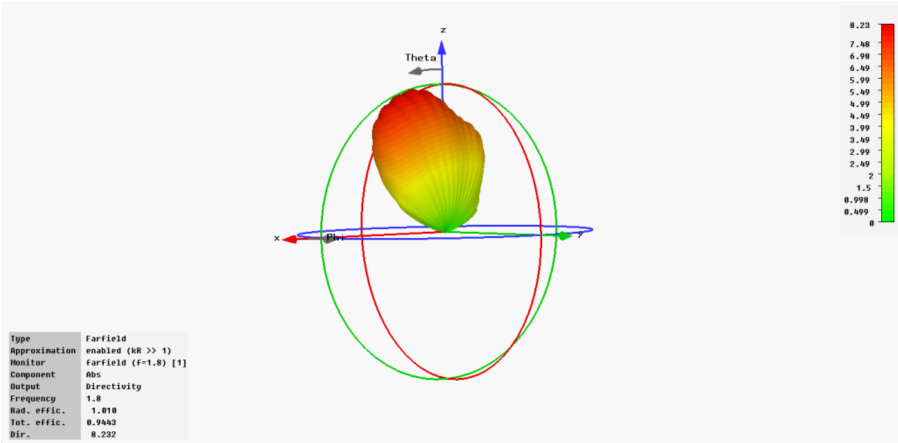

Figure 3.31: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 1st Element

- ### 3 - D Radiation Pattern of 2nd Element:

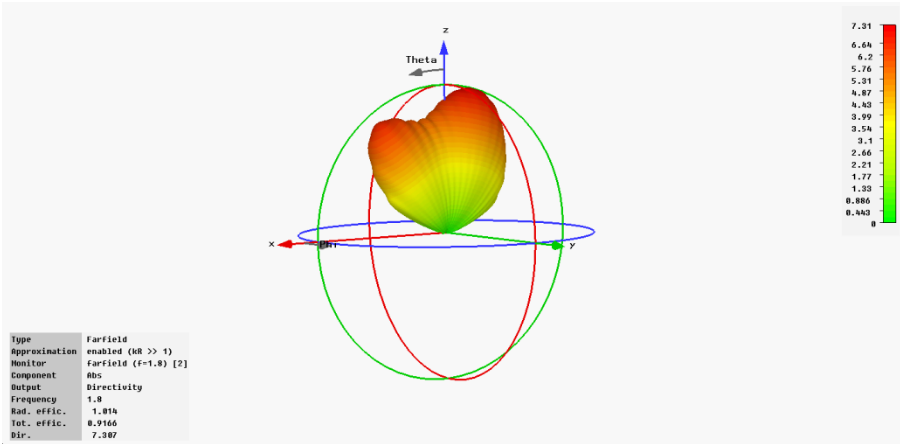

Figure 3.32: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 2nd Element

➢ Absolute Directivities (Polar):

- ### Absolute Directivity (Polar) of 1st Element:

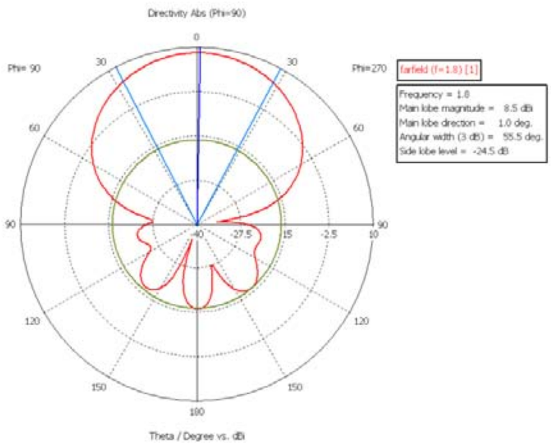

Figure 3.33: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 1st Element

- **Absolute Directivity (Polar) of 2nd Element:**

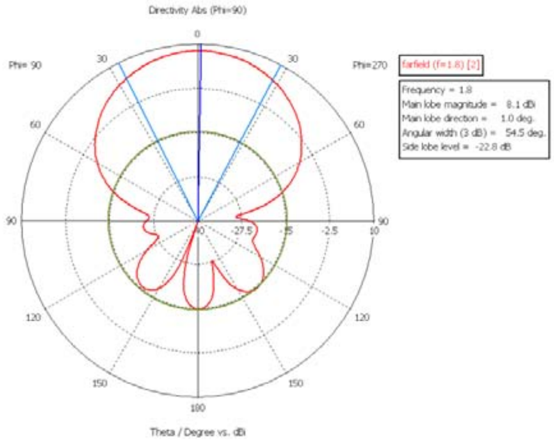

Figure 3.34: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 2nd Element

The simulation diagram of four dipole antenna array with the effect of Balun above an infinite ground plane at a distance of 0.5 λ is shown in figure 3.27. The table 3.4 shows the reflection coefficient of all four ports. The reflection coefficient of port 1 (S11) & port 4 (Both are same due to symmetric) is -15.1 dB at a frequency of 1.8 GHz which shows 96.90% matching and reflection due to other ports at port 1 is also shown in figure 3.29. Similarly, the reflection coefficient of port 2 (S22) & port 3 (Both are same due to symmetric) is -14.90 dB which shows the 96.76% matching is shown in figure 3.30. The figure 3.31 shows the radiation pattern of element 1 (dipole 1) and has a total efficiency of 0.9443, due to symmetric property, the radiation pattern of element 4 is the mirror image of element 1 and has a same total efficiency. Similarly, the radiation pattern of element 2 is shown in figure 3.32, due to symmetric property, the radiation pattern of element 3 is the mirror image of element 2 and both have a same total efficiency of 0.9166. The figure 3.33 shows the absolute directivity in polar coordinates of element 1. The main lobe has a magnitude of 8.5 dBi and angular width (3 dB) is 55.5°, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, in figure 3.34, the main lobe magnitude is 8.1 dBi and angular width (3 dB) is 54.5°, due to symmetric property, element 3 has a same main lobe magnitude and angular width (3 dB).

Table 3.4: Reflection Coefficient at a Distance of 0.5 λ

No	**Case 6.1**	**Reflection Coefficient (dB)**			
		1	**2**	**3**	**4**
1	S1	-15.09	-15.4	-23.8	-29.37
2	S2	-15.4	-14.89	-15.18	-23.8
3	S3	-23.8	-15.18	-14.89	-15.4
4	S4	-29.37	-23.8	-15.4	-15.07

3.3.6.2 Case – 6.2: Four dipoles antenna array at a distance of 0.2 λ

The antenna array is consisted of four dipoles with the 0.2 λ distance between them as shown in the figure 3.35.

- **Simulation Diagram:**

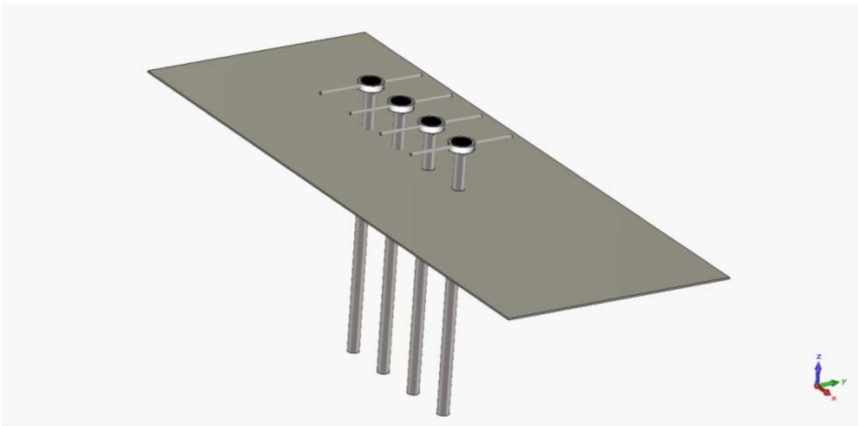

Figure 3.35: Dipole Antenna Array above a Ground Plane at a distance of 0.2 λ

➢ **Reflection Coefficients:**

- **Reflection Coefficient at Port 1:**

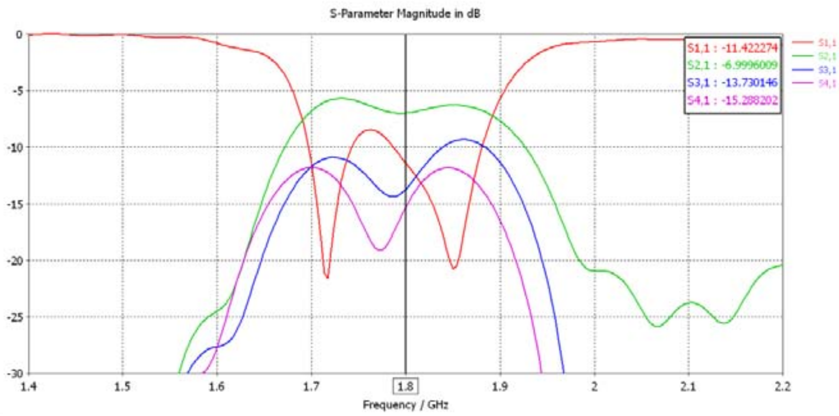

Figure 3.36: Reflection Coefficient of Dipole Antenna Array above a Ground Plane at Port 1

- **Reflection Coefficient at Port 2:**

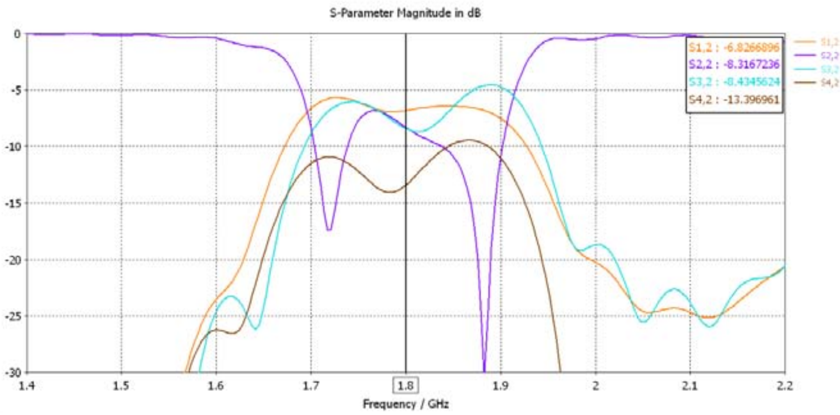

Figure 3.37: Reflection Coefficient of Dipole Antenna Array above a Ground Plane at Port 2

➢ 3 - D Radiation Patterns:

- **3 - D Radiation Pattern of 1st Element:**

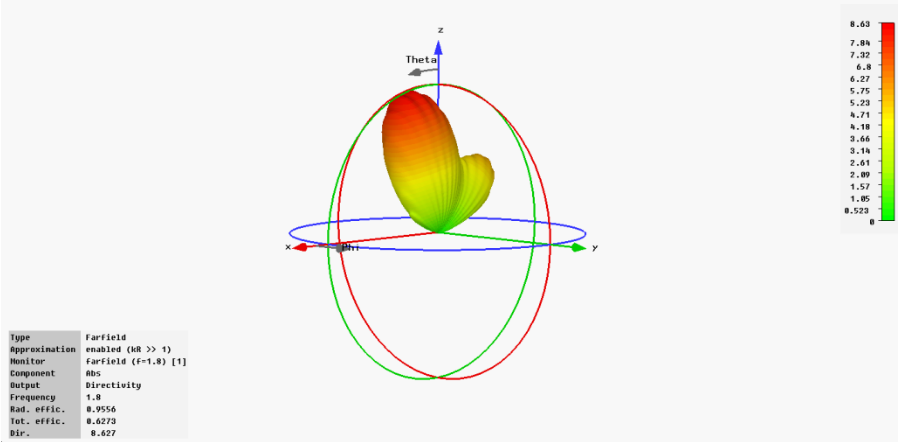

Figure 3.38: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 1st Element

- **3 - D Radiation Pattern of 2nd Element:**

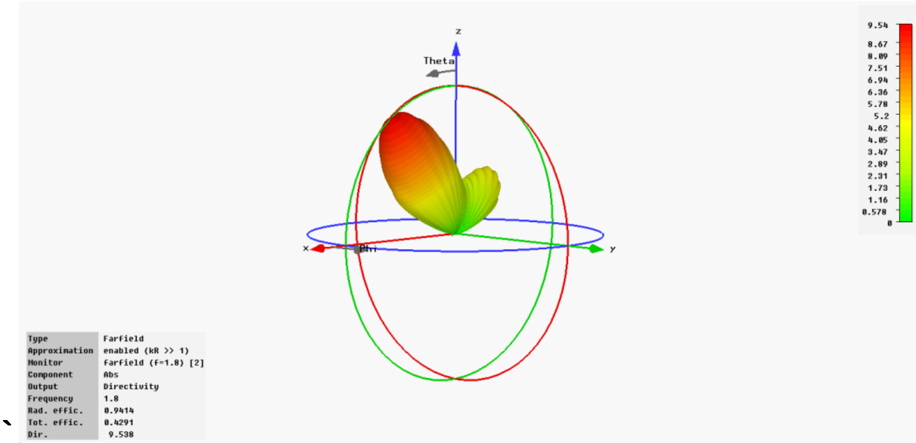

Figure 3.39: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 2nd Element

➢ Absolute Directivities:

- **Directivity Abs (Polar) of 1st Element:**

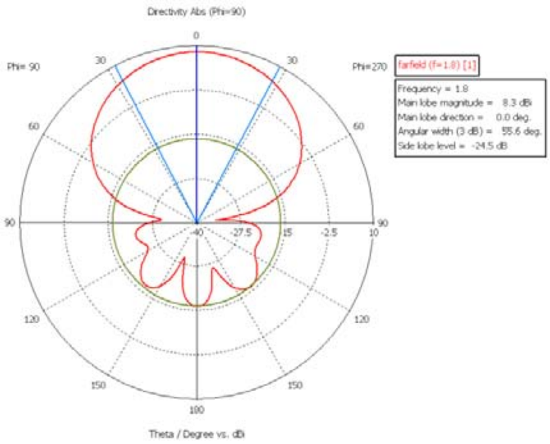

Figure 3.40: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 1st Element

- **Directivity Abs (Polar) of 2nd Element:**

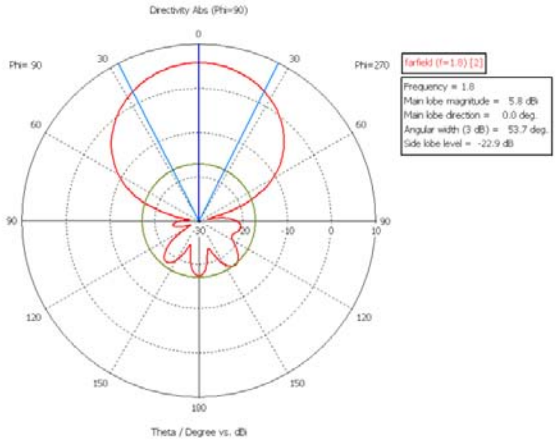

Figure 3.41: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 2nd Element

The simulation diagram of four dipole antenna array with the effect of Balun above an infinite ground plane at a distance of 0.2 λ is shown in figure 3.35. The table 3.5 shows the reflection coefficient of all four ports. The reflection coefficient of port 1 & port 4 is -11.42 dB at a frequency of 1.8 GHz which shows the 92.78% matching. It is decreased by decreasing the distance between dipoles from 0.5 λ to 0.2 λ; and reflection due to other ports at port 1 is also shown in figure 3.36. Similarly, the reflection coefficient of port 2 & port 3 is -8.31 dB which shows 85.24% matching, decreases due to distance between dipoles is shown in figure 3.37. The figure 3.38 shows the radiation pattern of element 1 and has a total efficiency of 0.6273. It is also decreased because of reflection from other ports. Similarly, the radiation pattern of element 2 is shown in figure 3.39 and has a total efficiency of 0.4291. Element 3 & 4 are not shown here because of symmetric. The figure 3.30 shows the absolute directivity in polar coordinates of element 1. The main lobe has a magnitude of 8.3 dBi and angular width (3 dB) is 55.6°, it is decreased because we have decreased the distance between dipoles from 0.5 λ to 0.2 λ, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, due to symmetric property of element 2 & 3, the main lobe magnitude is 5.8 dBi and angular width (3 dB) is 53.7°.

Table 3.5: Reflection Coefficient at a Distance of 0.2 λ

No	Case 6.2	Reflection Coefficient (dB)			
		1	2	3	4
1	S1	-11.42	-6.99	-13.73	-15.28
2	S2	-6.82	-8.31	-8.43	-13.39
3	S3	-13.38	-8.43	-8.3	-6.83
4	S4	-15.28	-13.74	-7	-11.43

3.3.6.3 Case – 6.3: Four dipoles antenna array at a distance of 0.1 λ

In this case, we have a very small distance between dipoles, which is 0.1 λ as shown in the figure 3.42.

- **Simulation Diagram - 1:**

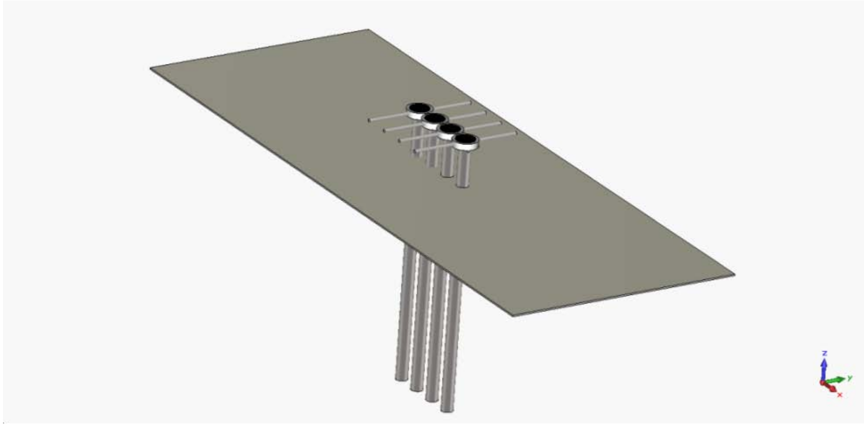

Figure 3.42: Dipole Antenna Array above a Ground Plane at a distance of 0.1 λ

➢ **Reflection Coefficients:**

- **Reflection Coefficient at Port 1:**

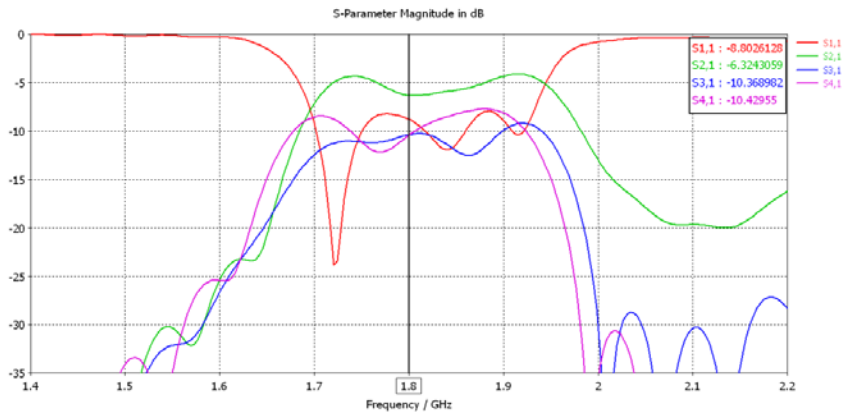

Figure 3.43: Reflection Coefficient of Dipole Antenna Array above a Ground Plane

- **Reflection Coefficient at Port 2:**

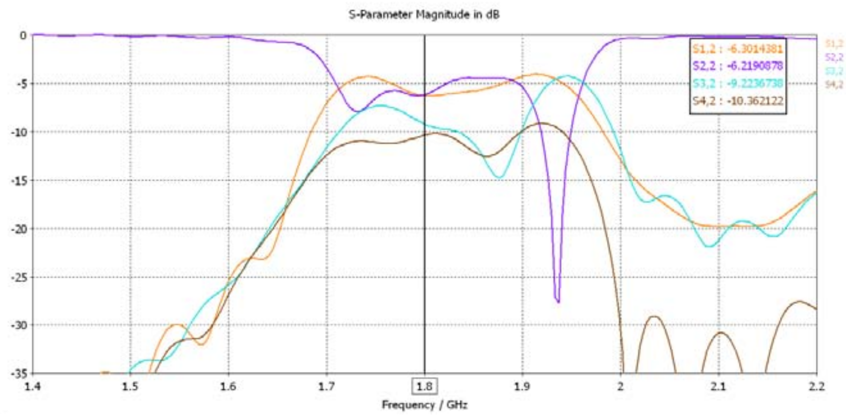

Figure 3.44: Reflection Coefficient of Dipole Antenna Array above a Ground Plane

➢ Radiation Patterns:

- **3 - D Radiation Pattern of 1st Element :**

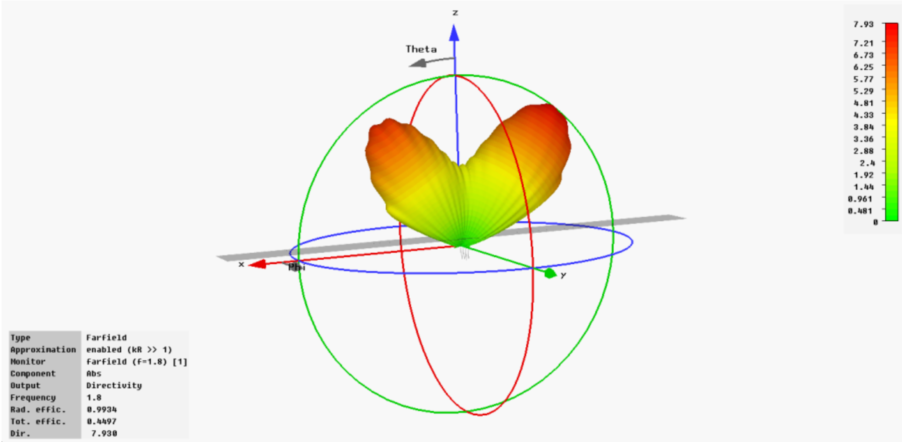

Figure 3.45: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 1st Element

- **3 - D Radiation Pattern of 2nd Element:**

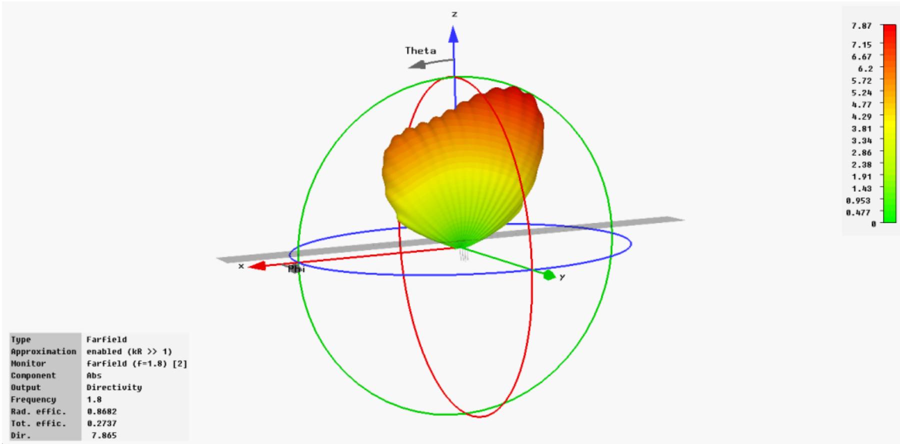

Figure 3.46: Radiation Pattern of Dipole Antenna Array above a Ground Plane of 2nd Element

➢ Absolute Directivities:

- **Directivity Abs (Polar) of 1st Element:**

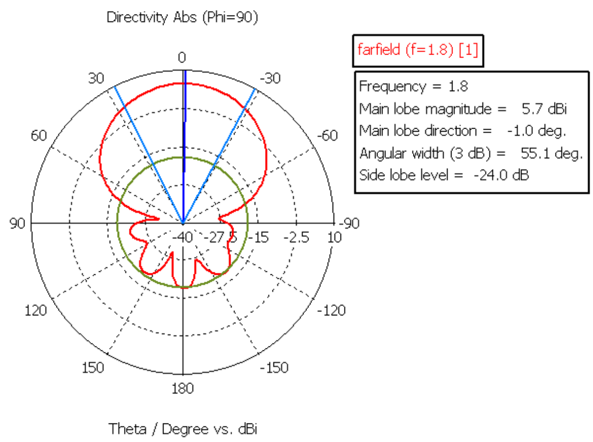

Figure 3.47: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 1st Element

- **Directivity Abs (Polar) of 2nd Element:**

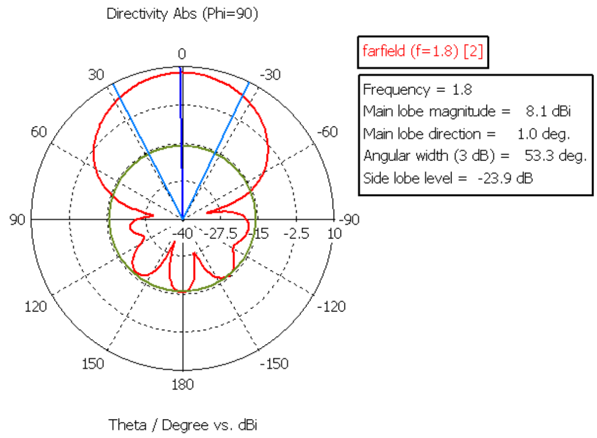

Figure 3.48: Absolute Directivity of Dipole Antenna Array above a Ground Plane of 2nd Element

The simulation diagram of four dipole antenna array with the effect of Balun above an infinite ground plane at a distance of 0.1 λ is shown in figure 3.42. We have already discussed in previous chapter that we want to analyze the results, when we have the maximum and minimum distance between dipoles. This is a worst case in our example because we have very small distance between antennas. The minimum distance between antennas is reducing the efficiency of overall system. The correlation is increased due to the disturbance from neighbor branches, and similarly efficiency is also decreased. Therefore, the performance of all branches goes down due to bad efficiency and correlation.

The table 3.6 shows the reflection coefficient of all four ports. The reflection coefficient of port 1 is -8.8 dB at a frequency of 1.8 GHz which shows 86.81% matching. It is further decreased because we have reduced the distance from 0.2 λ to 0.1 λ. The reflections due to other ports at port 1 are also shown in figure 3.43. Similarly, the reflection coefficient of port 2 is -6.21 dB, which shows only 76.06% match, and 23.93% signal is reflected back. It is a worst case of reflection coefficient. The reflections from other port at port 2 are shown in figure 3.44.

Table 3.6: Reflection Coefficient at a Distance of 0.1 λ

No	Case 6.3	Reflection Coefficient (dB)			
		1	2	3	4
1	S1	-8.8	-6.32	-10.36	-10.42
2	S2	-6.3	-6.21	-9.22	-10.36
3	S3	-10.37	-9.22	-6.21	-6.29
4	S4	-10.42	-10.35	-6.32	-8.8

The figure 3.45 shows the radiation pattern of element 1. The total efficiency of element 1 is 0.4497. It is also decreased because of reflection from other ports. Similarly, the radiation pattern of element 2 is shown in figure 3.46 and has a total efficiency of 0.2737.

The figure 3.47 shows the absolute directivity in polar coordinates. The main lobe has a magnitude of 5.7 dBi and angular width (3 dB) is 55.1°, it is further decreased because we have reduced the distance from

0.2 λ to 0.1 λ, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, due to symmetric property of element 2 & 3, the main lobe magnitude is 8.1 dBi and angular width (3 dB) is 53.3°.

3.3.6.4 Antenna Simulation Results for Element Port Excitation:

Table 3.7: Reflection Coefficient of Four Dipole Array for Element Port Excitation

No	Cases	Reflection Coefficient (dB)			
		S11	S22	S33	S44
1	Case – 6.1	-15.1	-14.9	-14.9	-15.1
2	Case – 6.2	-11.42	-8.31	-8.3	-11.43
3	Case – 6.3	-8.8	-6.21	-6.21	-8.8

Table 3.8: Total Efficiency of Four Dipole Array for Element Port Excitation

No	Cases	Total Efficiency (dB)			
		Element -1	Element -2	Element -3	Element -4
1	Case – 6.1	-0.25	-0.38	-0.38	-0.25
2	Case – 6.2	-2.02	-3.67	-3.67	-2.02
3	Case – 6.3	-3.47	-5.62	-5.62	-3.47

Table 3.9: Absolute Directivity of Four Dipole Array for Element Port Excitation

No	Cases	Main Lobe Magnitude (dBi)		Angular Width (3dB)	
		Element -1	Element -2	Element -1	Element -2
1	Case – 6.1	8.5	8.1	55.5°	54.5°
2	Case – 6.2	8.3	5.8	55.6°	53.7°
3	Case – 6.3	5.7	8.1	55.1°	53.3°

3.3.7 Case – 7: Excitation on Beam Ports versus Element Ports:

Beam forming is a signal processing technique and it is used in sensor array for direction signal transmission. Beam forming can be achieved by fixed transmit or receive beam patterns. Conventional beam formers use a fixed set of weights and phases to combine the signal from sensors in the array. Primarily, the only interested information is the position of sensors in space and the wave directions. In contrast, adaptive or fixed beam forming combines the information with the property of the signals received by an array. Beam forming can be used in both time and frequency domain [7].

An ideal butler matrix is a lossless & passive reciprocal network which when is excited by a signal at one port of its n port, transform the signal to the corresponding ones at all its output ports with uniform amplitude but specified phase progression among them. The butler matrix performs a fast Fourier transformation. This property when combined with multiple linear antennas can yield up to n orthogonal beams. The ports at the element terminals are referred as 'Element Ports' and the output port of the butler network are connected to these (element port) ports. The input port of butler matrix is called 'Beam Port' [8].

The reciprocal lossless 8-port circuit is considered that provide equal power division without attenuation between any of two input ports to output ports or vice versa. The amplitude of any output port is the half of its input port [7].

The butler matrix is constructed by the combination of hybrid coupler, phase shifter and crossover. The hybrid coupler is used to create 90° phase shift at output port. The crossover is too isolated the signal at the crossing point. It can be obtained by cascading of two hybrid coupler. And the phase shifter is used to add 45° delay in the signal. The block diagram of butler matrix is shown in figure 3.49 [7]:

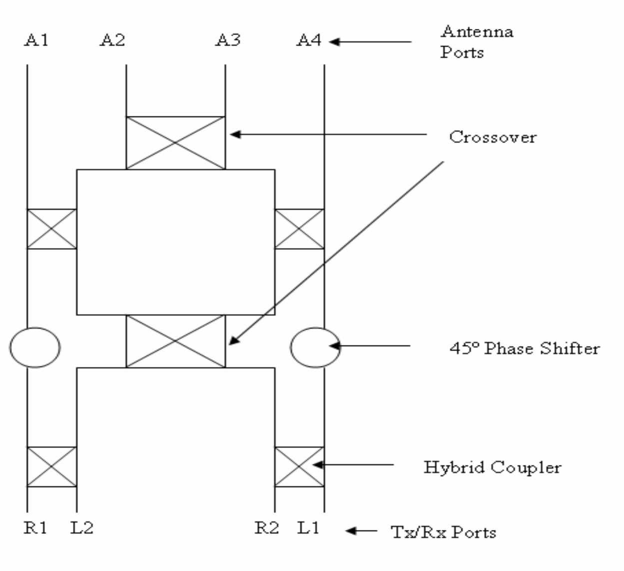

Figure 3.49: Butler Matrix Block Diagram [7]

The table 3.10 shows the input ports configuration of four dipole antenna array above an infinite ground plan for beam port. The amplitude of all ports is half of its input ports but with different phases.

Table 3.10: Design Specification of Butler Matrix						
No	**Tx & Rx / Antenna Port**	**A1**	**A2**	**A3**	**A4**	**β**
1	R1	0°	-45°	-90°	-135°	45°
2	L2	-90°	45°	180°	-45°	-135°
3	R2	-45°	-180°	45°	-90°	135°
4	L1	-135°	-90°	-45°	0°	-45°

3.3.7.1 Case – 7.1: Four dipoles antenna array at a distance of 0.5 λ:

The antenna array consists of four dipoles with the 0.5 λ distance between them same as case 6.1 but only the excitation process is changed.

- **Reflection Coefficients:**
  - **Reflection Coefficient at Port 1:**

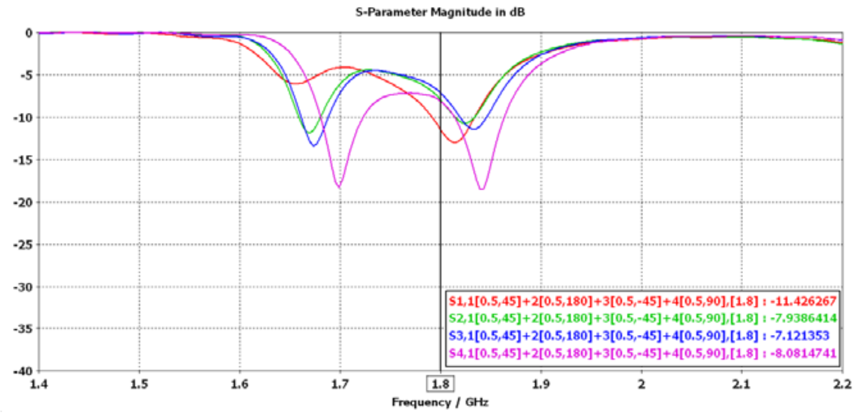

Figure 3.50: Reflection Coefficient of Dipole Antenna Array at Port 1 for beam port

  - **Reflection Coefficient at Port 2:**

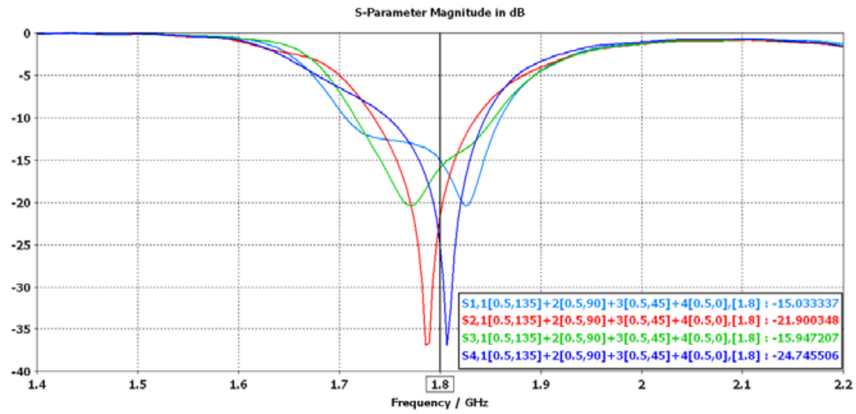

Figure 3.51: Reflection Coefficient of Dipole Antenna Array at Port 2 for beam port

- **3 - D Radiation Patterns:**
  - **3 - D Radiation Pattern of 1st Element:**

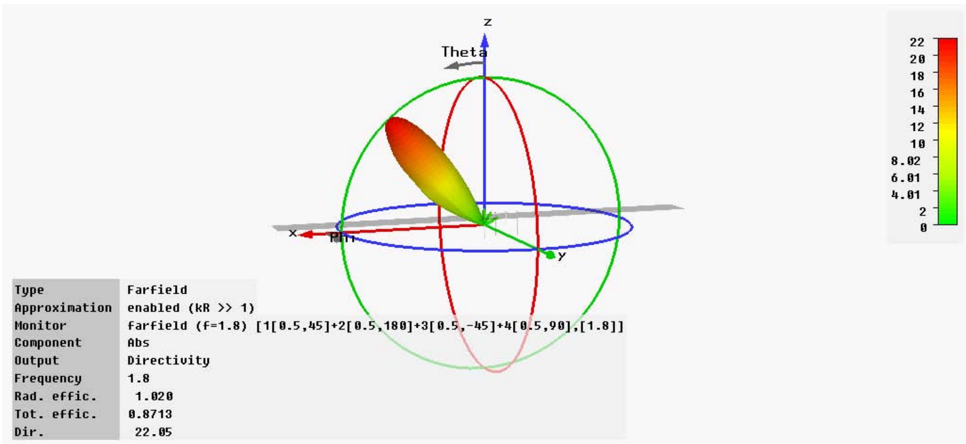

Figure 3.52: Radiation Pattern of Dipole Antenna Array of 1st Element for beam port

- **3 - D Radiation Pattern of 2nd Element:**

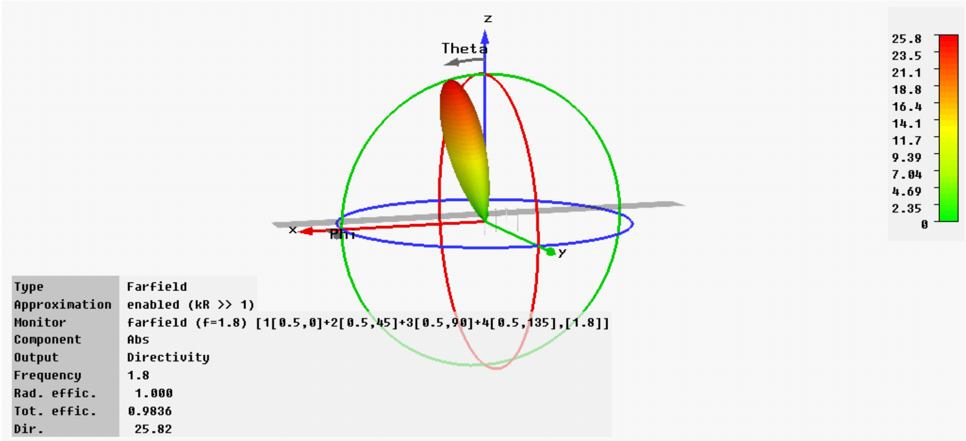

Figure 3.53: Radiation Pattern of Dipole Antenna Array of 2nd Element for beam port

➢ Absolute Directivities (Polar):

- **Absolute Directivity (Polar) of 1st Element:**

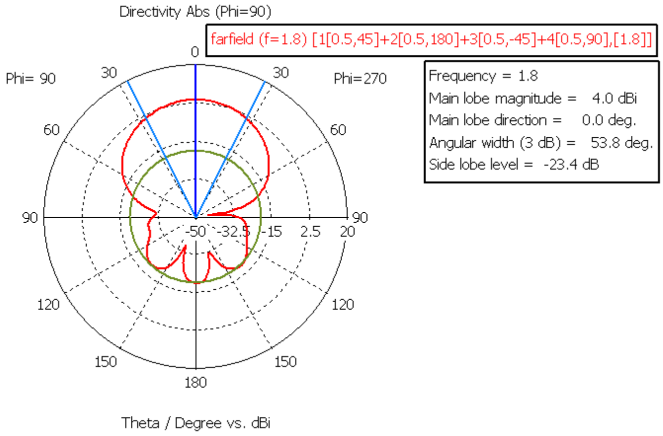

Figure 3.54: Absolute Directivity of Dipole Antenna Array of 1st Element for beam port

- **Absolute Directivity (Polar) of 2nd Element:**

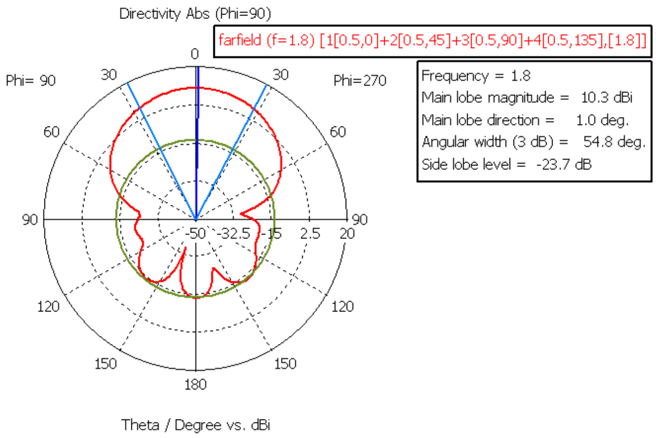

Figure 3.55: Absolute Directivity of Dipole Antenna Array of 2nd Element for beam port

The simulation diagram of four dipole antenna array with the effect of Balun above an infinite ground plane at a distance of 0.5 λ for beam port excitation is same as for element port excitation. The table 3.11 shows the reflection coefficient of all four ports. The reflection coefficients at port 1 & port 4 are same in magnitude but they are mirror image of each other (due to beam port excitation) and reflection due to other ports at port 1 is also shown in figure 3.50. Similarly, the reflection coefficient of port 2 (S22) is shown in figure 3.51. The figure 3.52 shows the radiation pattern of element 1 (dipole 1) and has a total efficiency of -0.5981 dB, due to symmetric property, the radiation pattern of element 4 is the mirror image of element 1 and has a same total efficiency. Similarly, the radiation pattern of element 2 is shown in figure 3.53 and has a total efficiency of -0.07184 dB. The figure 3.54 shows the absolute directivity in polar coordinates of element 1. The main lobe has a magnitude of 4 dBi and angular width (3 dB) is 53.8°, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, due to symmetric property of element 2 & 3, the main lobe magnitude is 10.3 dBi and angular width (3 dB) is 54.8°.

Table 3.11: Reflection Coefficient at a Distance of 0.5λ for beam port					
No	**Case 7.1**	**Reflection Coefficient (dB)**			
		1	**2**	**3**	**4**
1	S1	-11.42	-7.93	-7.12	-8.08
2	S2	-15.03	-21.90	-15.94	-24.75
3	S3	-24.78	-15.94	-21.90	-15.01
4	S4	-8.09	-7.13	-7.94	-11.41

3.3.7.2 Case – 7.2: Four dipoles antenna array at a distance of 0.2 λ

The antenna array is consists of four dipoles with the 0.2 λ distance between.

- **Reflection Coefficients:**

  - **Reflection Coefficient at Port 1:**

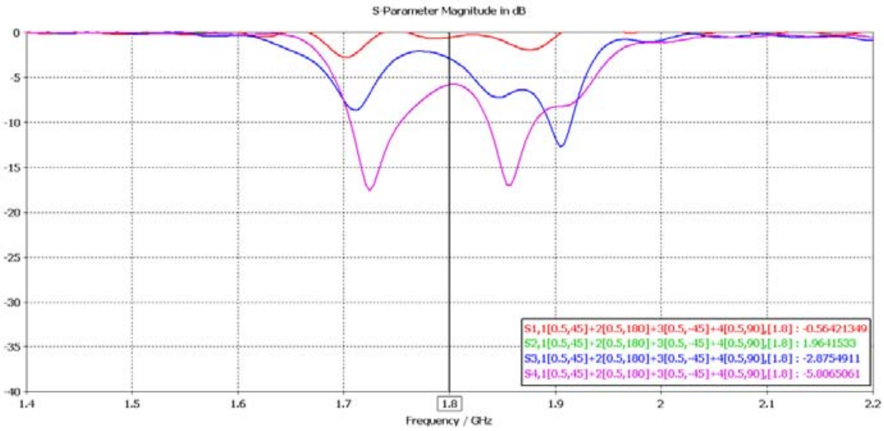

Figure 3.56: Reflection Coefficient of Dipole Antenna Array at Port 1 for beam port

- **Reflection Coefficient at Port 2:**

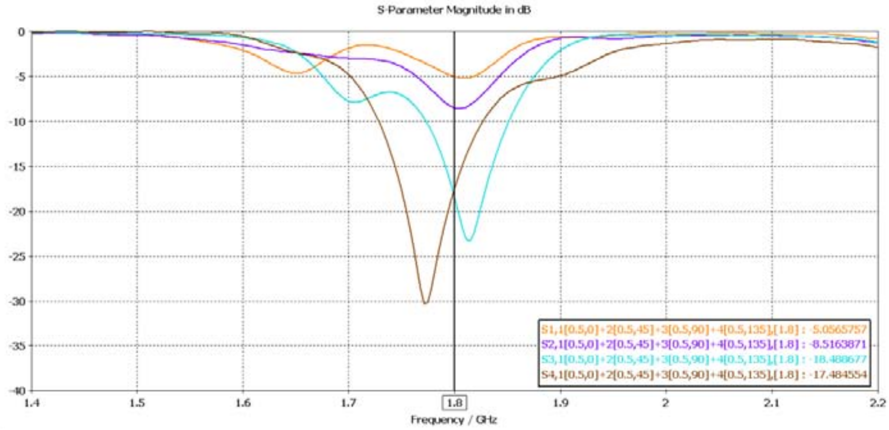

Figure 3.57: Reflection Coefficient of Dipole Antenna Array at Port 2 for beam port

➢ 3 - D Radiation Patterns:

- **3 - D Radiation Pattern of 1st Element:**

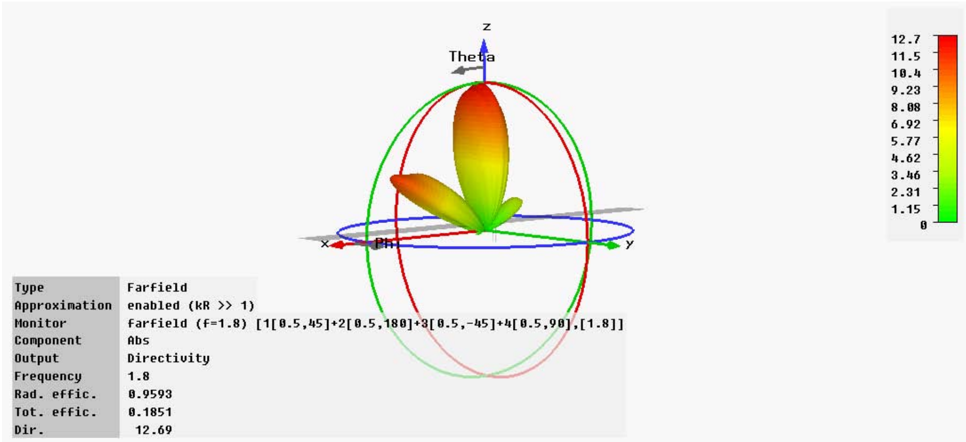

Figure 3.58: Radiation Pattern of Dipole Antenna Array of 1st Element for beam port

- **3 - D Radiation Pattern of 2nd Element:**

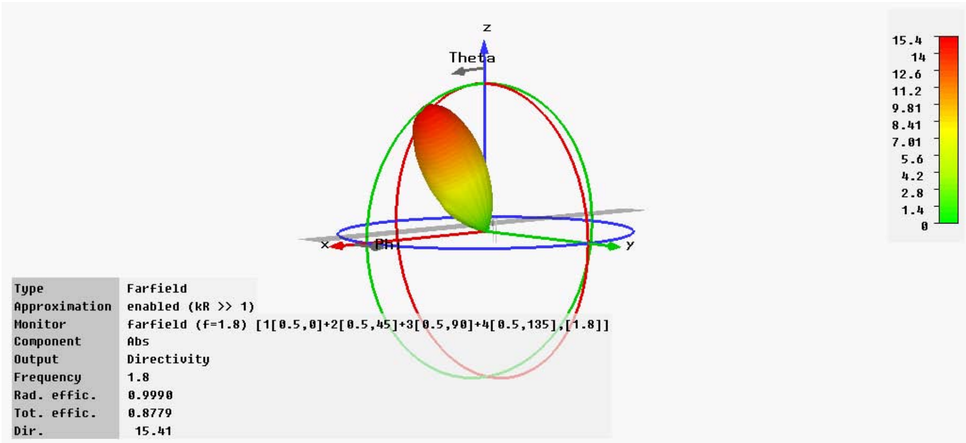

Figure 3.59: Radiation Pattern of Dipole Antenna Array of 2nd Element for beam port

➢ Absolute Directivities:

- **Directivity Abs (Polar) of 1st Element:**

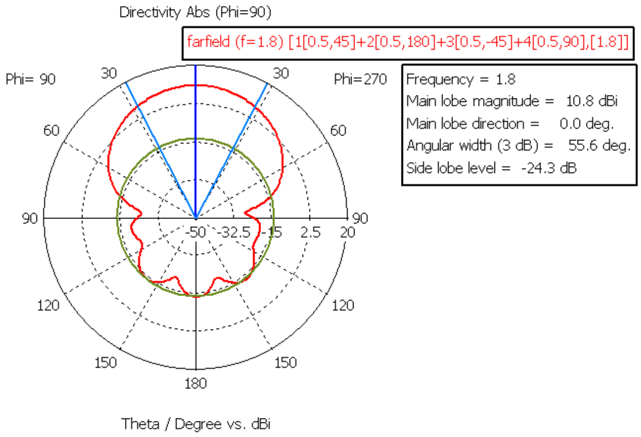

Figure 3.60: Absolute Directivity of Dipole Antenna Array of 1st Element for beam port

- **Directivity Abs (Polar) of 2nd Element:**

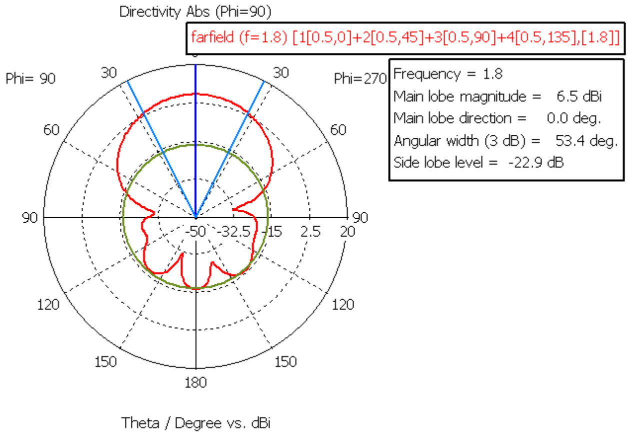

Figure 3.61: Absolute Directivity of Dipole Antenna Array of 2nd Element for beam port

The simulation diagram of four dipole antenna with the effect of Balun above an infinite ground plane at a distance of 0.2 λ for beam port excitation is same as element port excitation. The table 3.12 shows the reflection coefficient of all four ports. The reflection coefficients at port 1 & port 4 are same in magnitude but they are mirror image of each other (due to beam port excitation). It is decreased because we have decreased the distance between dipoles from 0.5 λ to 0.2 λ and reflection due to other ports at port 1 is shown in figure 3.56. Similarly, the reflection coefficient of port 2 is also decreased is shown in figure 3.57. The figure 3.58 shows the radiation pattern of element 1 and has a total efficiency of 0.1851. It is also decreased because of reflection from other ports. Similarly, the radiation pattern of element 2 is shown in figure 3.59 and has a total efficiency of 0.8782. The figure 3.60 shows the absolute directivity in polar coordinates of element 1. The main lobe has a magnitude of 10.8 dBi and angular width (3 dB) is 55.6°, it is decreased because we have decreased the distance between dipoles from 0.5 λ to 0.2 λ, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, due to symmetric property of element 2 & 3, the main lobe magnitude is 6.5 dBi and angular width (3 dB) is 53.4°.

Table 3.12: Reflection Coefficient at a Distance of 0.2 λ for beam port					
No	**Case 7.2**	**Reflection Coefficient (dB)**			
		1	**2**	**3**	**4**
1	S1	-0.56	-1.96	-2.875	-5.80
2	S2	-5.05	-8.51	-18.48	-17.48
3	S3	-17.47	-18.41	-8.52	-5.07
4	S4	-5.79	-2.87	-1.96	-0.57

3.3.7.3 Case – 7.3: Four dipoles antenna array at a distance of 0.1 λ

The antenna array is consists of four dipoles with the 0.1 λ distance between.

- **Reflection Coefficients:**

  - **Reflection Coefficient at Port 1:**

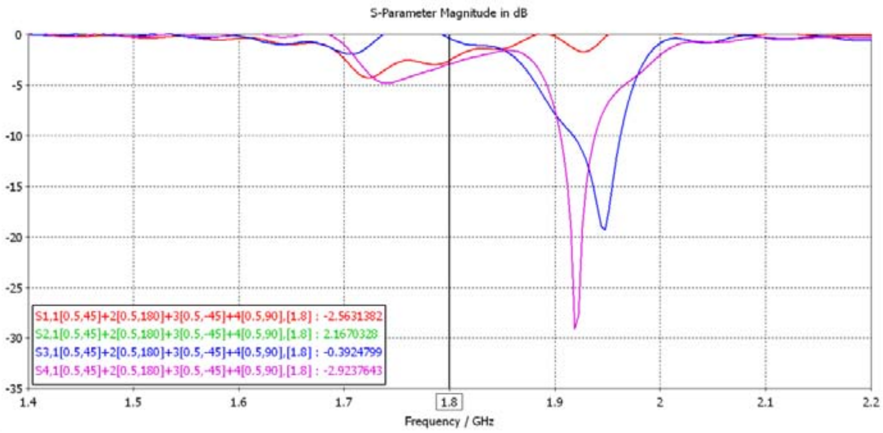

Figure 3.62: Reflection Coefficient of Dipole Antenna Array at Port 1 for beam port

  - **Reflection Coefficient at Port 2:**

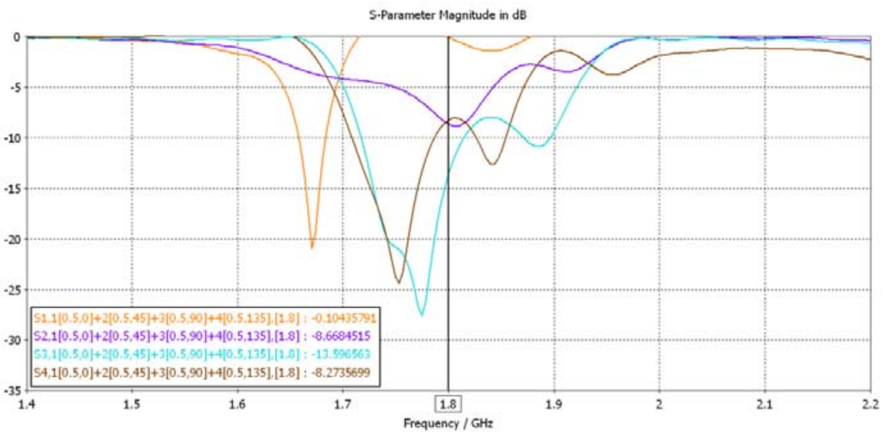

Figure 3.63: Reflection Coefficient of Dipole Antenna Array at Port 2 for beam port

➢ Radiation Patterns:

- **3 - D Radiation Pattern of 1st Element :**

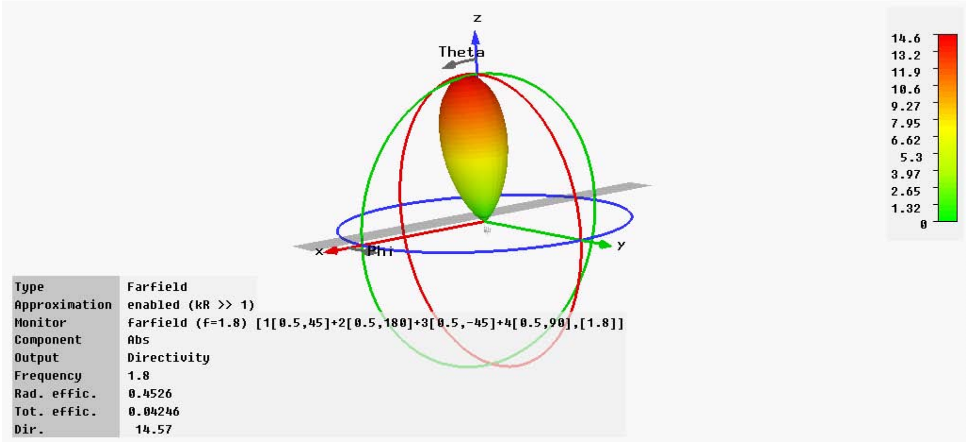

Figure 3.64: Radiation Pattern of Dipole Antenna Array of 1st Element for beam port

- **3 - D Radiation Pattern of 2nd Element:**

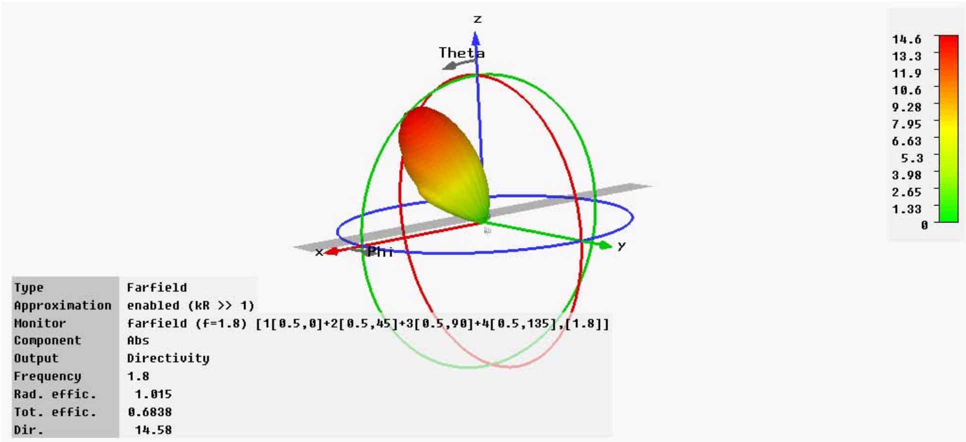

Figure 3.65: Radiation Pattern of Dipole Antenna Array of 2nd Element for beam port

➢ Absolute Directivities:

- **Directivity Abs (Polar) of 1st Element:**

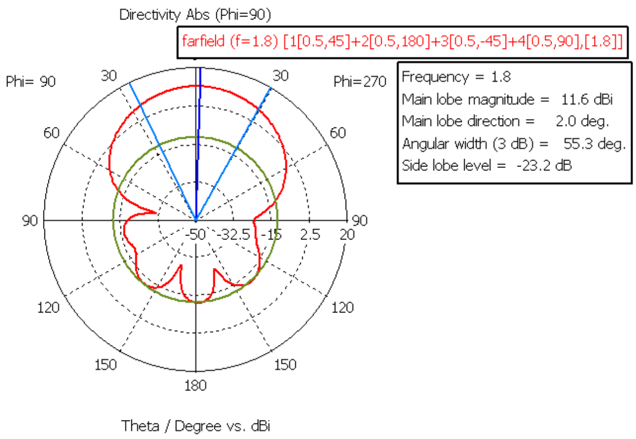

Figure 3.66: Absolute Directivity of Dipole Antenna Array of 1st Element for beam port

- **Directivity Abs (Polar) of 2nd Element:**

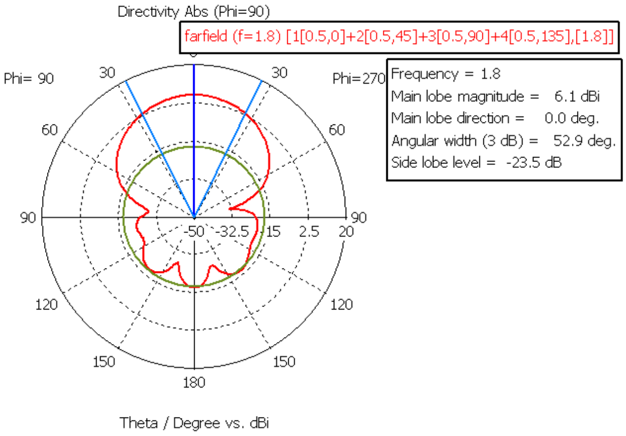

Figure 3.67: Absolute Directivity of Dipole Antenna Array of 2nd Element for beam port

The simulation diagram of four dipole antenna array with the effect of Balun above an infinite ground plane at a distance of 0.1 λ is shown in figure 3.42. This is a worst case in over example for beam port excitation, because we have very small distance between antennas. The minimum distance between antennas is reduced the efficiency of overall system. The correlation is increased due to the disturbance from neighbor branches, and similarly efficiency is also decreases. Therefore, the performance of all branches goes down due to bad efficiency and correlation.

The table 3.13 shows the reflection coefficient of all four ports. The reflection coefficient of port 1 is further decreased because we have reduced the distance from 0.2 λ to 0.1 λ. The reflection due to other ports at port 1 is shown in figure 3.62. Similarly, the reflection coefficient of port 2 is shown in figure 3.63. It is a worst case of reflection coefficient. The reflections from other ports at port 2 are shown in figure 3.63.

Table 3.13: Reflection Coefficient at a Distance of 0.1 λ for beam port

No	Case 7.3	Reflection Coefficient (dB)			
		1	2	3	4
1	S1	-2.563	-2.16	-0.392	-2.92
2	S2	-0.104	-8.66	-13.59	-8.27
3	S3	-8.29	-13.58	-8.69	-0.104
4	S4	-2.92	-0.393	-2.167	-2.56

The figure 3.64 shows the radiation pattern of element 1. The total efficiency of element 1 is 0.04246. It is decreased further because of reflection from other ports. Similarly, the radiation pattern of element 2 is shown in the figure 3.65 and has a total efficiency of 0.6839.

The figure 3.66 shows the absolute directivity in polar coordinates. The main lobe has a magnitude of 11.6 dBi and angular width (3 dB) is 55.3°, due to symmetric property, element 4 has a same main lobe magnitude and angular width (3 dB). Similarly, due to symmetric property of element 2 & 3, the main lobe magnitude is 6.1 dBi and angular width (3 dB) is 52.9°.

3.3.7.4 Antenna Simulation Results for Beam Port Excitation:

Table 3.14: Reflection Coefficient of Four Dipole Array for Beam Port Excitation

No	Cases	Reflection Coefficient (dB)			
		S11	S22	S33	S44
1	Case – 7.1	-11.42	-21.90	-21.90	-11.41
2	Case – 7.2	-0.56	-8.51	-8.52	-0.57
3	Case – 7.3	-2.563	-8.66	-8.66	-2.56

Table 3.15: Total Efficiency of Four Dipole Array for Beam Port Excitation

No	Cases	Total Efficiency (dB)			
		Element -1	Element -2	Element -3	Element -4
1	Case – 7.1	-0.60	-0.07	-0.07	-0.60
2	Case – 7.2	-7.32	-0.57	-0.56	-7.32
3	Case – 7.3	-13.72	-1.65	-1.65	-13.72

Table 3.16: Absolute Directivity of Four Dipole Array for Beam Port Excitation

No	Cases	Main Lobe Magnitude (dBi)		Angular Width (3dB)	
		Element -1	Element -2	Element -1	Element -2
1	Case – 7.1	4.0	10.3	53.8	54.8
2	Case – 7.2	10.3	6.5	55.6	53.4
3	Case – 7.3	11.6	6.1	55.3	52.9

Chapter 4

Simulation Results

The Matlab is used to calculate all the simulation results with the help of touchstone and far-filed files imported from CST. The Multipath Environment Emulator for Simulation of MIMO Terminals (MEST) codes written in matlab for both environments, isotropic and non-uniform, has been created in Antenna Group at Chalmers. As we discussed earlier, there are two main files imported from CST which has all the information about s-parameters (Touchstone) and e-field (Far-field). The touchstone file contains s-parameter information of all frequencies and far-filed contains complex e-field of θ and φ components for all frequencies. The chosen resolutions during the simulations were Δθ = 5° in elevation angle and Δφ = 5° in azimuth angle, in both polarizations. A resolution of 1° instead of 5° for both of the angles would have generated more than eight times as much data. We have used Matlab 7.6 version for all calculation and simulation.

4.1 Calculation of Received Power & Voltage from Far-field function:

There are two types of environments used in this project isotropic and non-uniform environment. We have to calculate received power and voltage in both environments.

4.1.1 Isotropic Environment:

In isotropic environment, waves are coming uniformly over the sphere encircling the terminal. The elevation plane (theta) and azimuth plane (phi) have sinus and uniform distribution to bestow a uniform AOA. The waves received at antenna are scatter from different objects. These objects are randomly distributed in our environment.

- **Generate Random θ & φ Components:**

The theta and phi which show their coordinates have sinus and uniform distribution to bestow a uniform AOA in the whole sphere. In order to have Rayleigh distribution, the coming waves in each polarization shall be complex Gaussians of unit variance.

Suppose we have 20 different scatters in our environment. These scatters are generated randomly for both theta (θ) and phi (φ). For theta angle, 20 different angles are randomly generated from 0 to 180°. Similarly, for phi, 20 different angles are randomly generated from 0 to 359°. These scatters are generating with the help of ‘rand’ command.

- **Random Signal Calculation at Antenna**

The received signal at antenna has random amplitude in both θ & ϕ directions. Therefore, the received signal is generated from 'rand' command. The received signal is a complex signal, so after using 'rand' then we will convert it into complex value by using the 'complex' function.

- **Far-filed Calculation from Random θ & ϕ Components**

The format of far-field file is shown in appendix A.2. The first and second column contains ϕ and θ values, and remaining four columns contain complex value of e-filed for θ and ϕ directions. Each ϕ value contains 180 values of θ; it means we have total 65341 (181 x 361) radiation pattern values in dB. We take the 1st value of angle form Theta Scatters & Phi Scatters and then, find these angles in far field file (1st & 2nd column). We know that, each value of ϕ and θ contains complex e-field values, therefore, we takes the complex e-field θ and ϕ value from far-field. Similarly for 2nd and so on or depend upon total number of scatters.

The row 3 & 4 of far-field file contains real and imaginary value of e-field in θ directions; similarly, the row 5 & 6 of far-field file contains real and imaginary value of e-field in ϕ directions.

- **Combine E-filed from Random θ & ϕ Components**

Now, we have two different values of e-field in θ & ϕ directions. The first value is the complex e-field value of received signal at antenna (generated by complex command of matlab). And the second value is the complex e-field value taking from far-field file. If the signal is received at first random θ and ϕ angle, it will be multiply by the e-filed at first random angle from far-field file. The θ component of e-field from received signal is multiplied with the θ component of e-field from far-field, similarly, for ϕ component.

- **Received Signal at Antenna Port**

The received signal at antenna port is the sum of θ and ϕ components. We have 20 random scatters in over environment. So, this process will repeat 20 times. The sum of all 20 received signals is called 1 Realization.

We have total 1×10^5 realizations. It means that the above process will repeat 1×10^5 times, similarly for four dipole antennas. The same process will follow for each antenna.

- **Antenna Received Power**

The maximum received power by any antenna depends upon the far-field function as well as the stimulated power; it can be defined as [5]

$$P_L = \frac{\lambda^2}{4\eta^2 P_{stimulated}} \left| \sum_{K=1}^{N} \overrightarrow{G_r}(\theta_K, \psi_K) * \overrightarrow{E_o}^K \right|^2$$

Where,

$P_{stimulated} \ = Stimulated\ power$

$\eta \ = Antenna\ efficiency$

- **Received Voltage at Antenna Port**

The Calculation of Received Voltage Vectors at the Ports of the multi-element antennas in multipath environments can be calculated from the sum of received signal and it can be defined as [5]

$$V_L = \frac{-2j\lambda}{\eta} \sqrt{\frac{R_{ant}}{2P_{Accepted}}} \frac{R_L}{Z_{ant} + R_L} \sum_{K=1}^{N} \overrightarrow{G_r}(\theta_K, \psi_K) * \overrightarrow{E_o}^K$$

Where,

$R_{ant} \ = Antenna\ input\ resistance, and\ it\ is\ real\ part\ of\ Z$

$R_L = Load\ resistance, and\ it\ is\ 50\ \Omega$

$Z_{ant} \ = Antenna\ input\ impedance$

$P_{Accepted} \ = Accepted\ power$

$\eta \ = Antenna\ efficiency$

$\overrightarrow{G_r}(\theta_K, \psi_K) * \overrightarrow{E_o}^K \ = Multiplication\ of\ far - field\ function\ with\ e - field$

4.1.2 Non-uniform Environment

The above process of isotropic environment will follow the same as for angle 'Ꝋ' but 'θ' angle will be changed. In non-uniform environment, the azimuth plane 'Ꝋ' is uniformly distributed and elevation plane 'θ' is Gaussian distributed (discussed in previous chapter). For Ꝋ components, we have generated the same angles as we generated in isotropic environment. But θ is Gaussian distributed so, it has some mean and variance. The mean and variance is shown in the matlab code by 'Theta mean' and 'Sigma'. The received signal has particular angle in any direction.

The difference between isotropic and non-uniform environment is that, all the wave are coming uniformly in equal numbers from all directions, while in the non-uniform environment the signal often come from reflection building, and seldom from the sky. In this master thesis, the value of Theta mean (mean) & Sigma (variance) are 32 & 64, measured by Ningyo-cho route in Tokyo Taga [9].

4.2 Influences on distance between elements

The influence on distance between elements is very important factor because it is affected by reflection coefficient, correlation, efficiency, diversity gain and input impedance. As we discuss in previous chapters, reflection coefficient, correlation and efficiency depends on distance between antennas. We have plotted all these quantities with respect to distance between elements. And the distance is changed from 0.1 λ to 1.0 λ.

4.2.1 Influence of Distance between Dipoles on Reflection Coefficient

The figure 4.1 shows the relation between reflection coefficient and distance between dipoles of element 1 & 2. And, element 3 and 4 are not shown here because they are symmetric. It is clear from the figure that, S11 has a red curve and S22 has black. The reflection is maximum at 0.1 λ because we have maximum mutual coupling and correlation due to small distance between elements. As we changed the distance from 0.1 to 0.5 λ, reflection coefficient increases very fast. The reflection coefficient is minimum at 0.5 λ and after that it remains constant because both correlation and mutual coupling are not affective after 0.5 λ. The format of touchstone file is shown in appendix A.1, it can be seen from the file that we have four different value of radius (r) and angle (θ) at each frequency, each value of r and θ represent the S-parameter, therefore we can calculate S-parameter using equation 5.1.

$$SP = rCos(\theta) + jrSin(\theta) \tag{5.1}$$

The eq. 5.1 is called Euler's Identity and it is used to calculate scattering parameters.

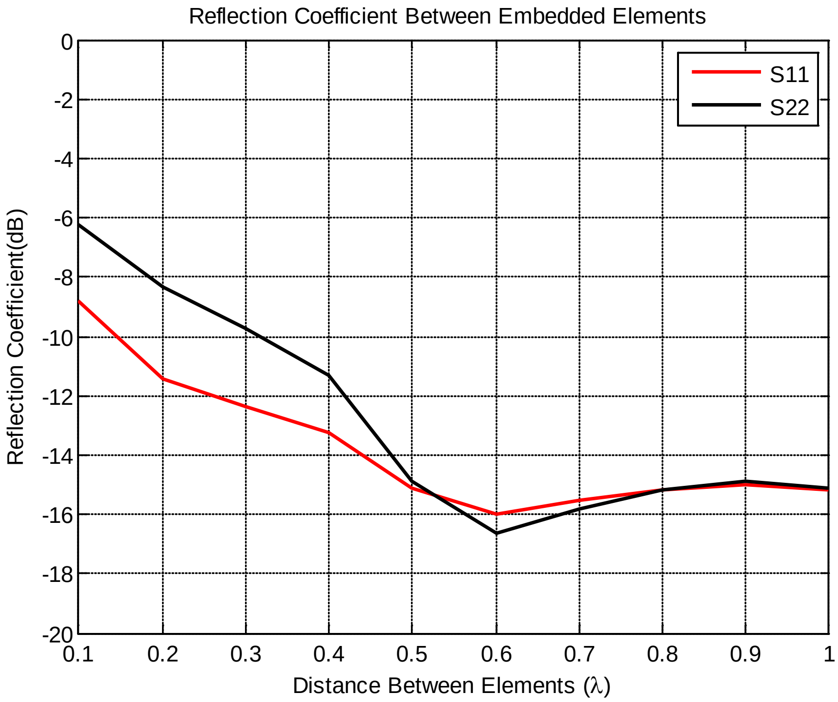

Figure 4.1: Influence of Distance between Dipoles on Reflection Coefficient

4.2.2 Influence of Distance between Dipoles on Correlation

The figure 4.2 shows the correlation between different elements. The 'Cor12' is the correlation between element 1 & 2. Similarly 'Cor13' is the correlation between element 1 & 3, and 'Cor14' between element 1 & 4. It is cleared from the figure that, the correlation is maximum at 0 λ and minimum at 0.5 λ. From 0.1 to 0.5 λ, the correlation is decreasing very fast because mutual coupling is decreased as we increase the distance between dipoles, and after 0.5 λ, it remains constant. The correlation between 'Cor12' and 'Cor23' is same because of same distance between both couple of antennas. Similarly, the correlation between 'Cor13' and 'Cor23' is also same.

The Correlation is calculated by the received voltages at each antenna port. Each antenna port contains different voltages. By using the matlab command 'corrcoef', we have calculated the correlation between each couple of elements.

```
Cor12 = corrcoef(Voltage1, Voltage2);
```

The above command is used in matlab to calculate correlation between two antennas.

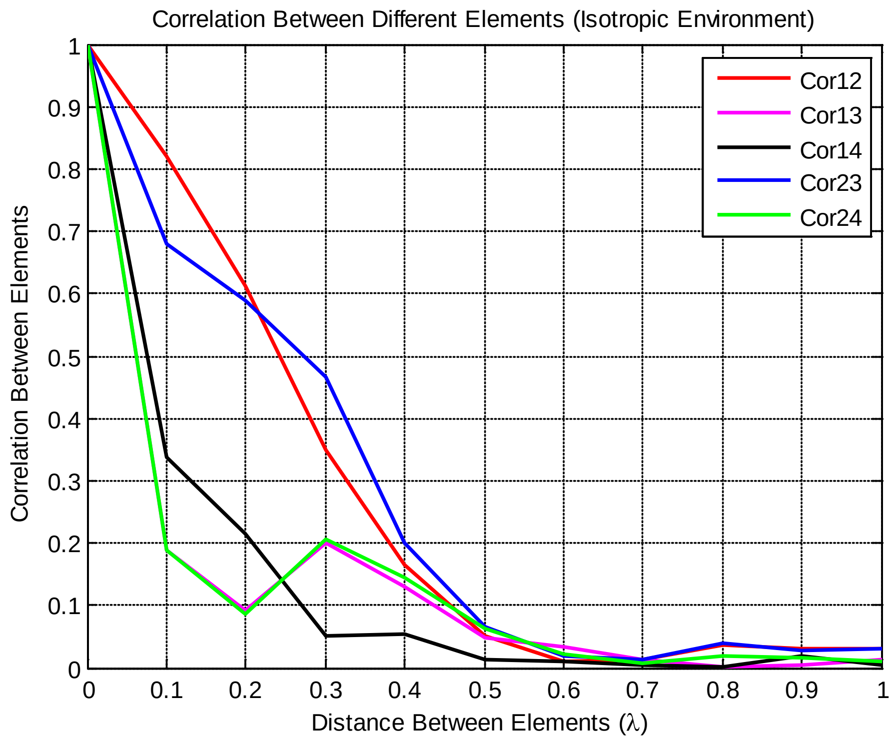

Figure 4.2: Influence of Distance between Dipoles on Correlation

4.2.3 Influence of Distance between Dipoles on Efficiency

The figure 4.3 shows the efficiency of different elements. The total embedded efficiency is calculated using equation 5.2, reflection efficiency using equation 5.3 and decupling efficiency using equation 5.4 on matlab. The efficiency is depending upon the reflection coefficient, so if we have small reflection then it gives the good efficiency or vice versa. The efficiency at 0.1 λ is minimum because of high mutual coupling and correlation, and it is increasing from 0.1 to 0.5 λ as we increased the distance between elements. And after 0.5 λ, it is remain constant or approximate 0.99. The efficiency of element 2 is less as compare to element 1 because element 2 has two neighbor antenna's, and it is affected more as compare to element 1. The efficiency of element 3 & 4 are not shown here because they are symmetric.

$$e_{rad} = 1 - \sum_{i=1}^{n} \left|S_{ij}\right|^2 \quad (5.2)$$

$$e_{ref} = 1 - \sum_{i=1}^{n} |S_{ii}|^2 \quad (5.3)$$

$$e_{decoupling} = \frac{e_{tot}}{e_{matc\ hing}} \quad (5.4)$$

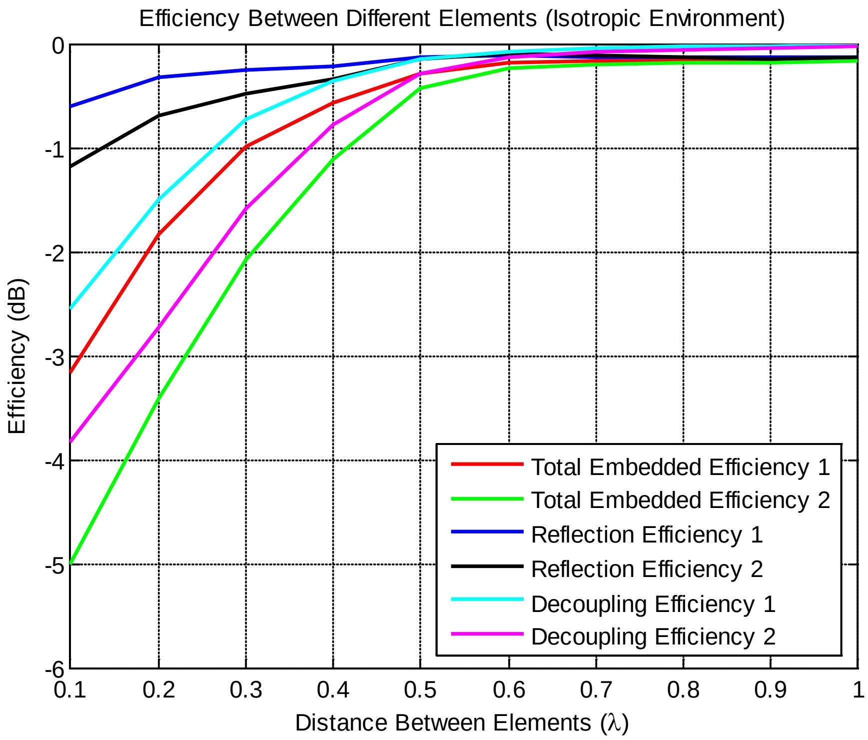

Figure 4.3: Influence of Distance between Dipoles on Efficiency

4.2.4 Influence of Distance between Dipoles on Diversity Gain

The figure 4.4 shows the apparent & effective diversity gain. We know that the apparent diversity gain is always greater then effective diversity gain. In figure 4.4, effective diversity gain is very less at 0.1 λ, as we discussed earlier that this high reduction in value is due to mutual coupling and antenna correlation. As we increased the distance between antenna's, it increased rapidly and after 0.5 λ, it is remain constant up to 1.0λ but there is some high peaks between 0.5 to 0.1 λ because it could be attributed to the numerical error involved in our simulations.

The apparent diversity gain is calculated by using matlab. Similarly, the effective diversity gain is calculated using equation 5.6 as shown in figure 4.4.

$$Effective\ Diversity\ Gain = e_{max} \times ADG \qquad (5.6)$$

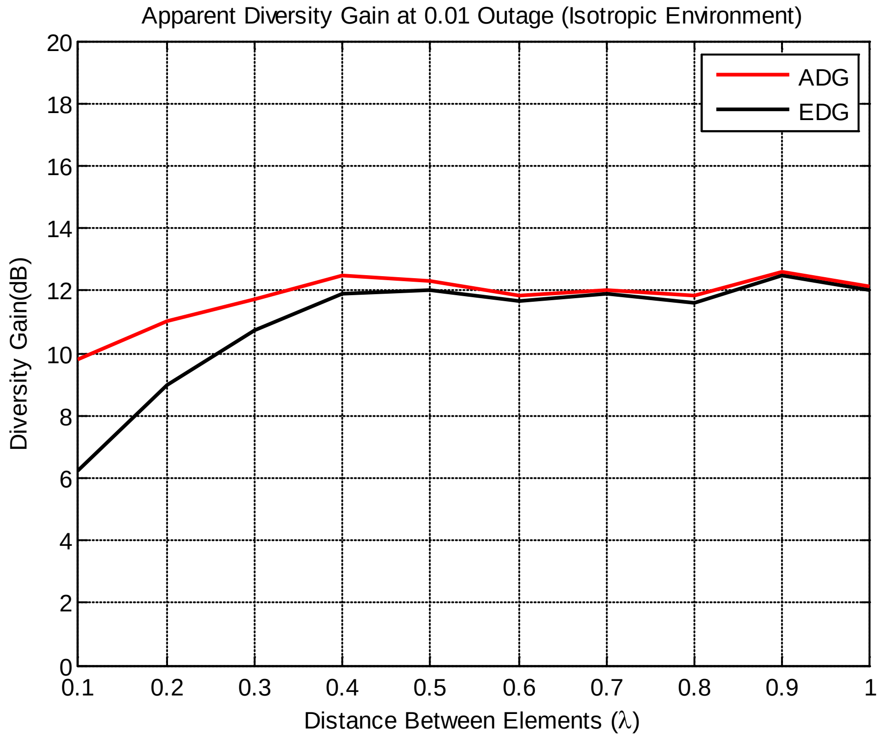

Figure 4.4: Influence of Distance between Dipoles on Diversity Gain

4.2.5 Influence of Distance between Dipoles on Input Impedance

The figure 4.5 shows the complex input impedance between dipoles antennas. The input impedance is also affected by mutual coupling and correlation. The characteristic impedance of transmission line is 50Ω. It is clear from the figure 4.5 that, the real part of impedance is minimum at 0.1λ, and increasing with changing the distance between antennas. And, it is maximum at 0.5λ; at after 0.5 to 1.0λ it is remain constant. Similarly, imaginary part is also increased by changing the distance between elements. The input impedance of Z3 and Z4 is not shown here because of symmetric.

The input impedance (Z) is calculated by using the scattering parameters. Each antenna has different input impedance because of different reflection coefficient. We have calculated it by the help of equation 5.7 on matlab as shown in the figure 4.5.

$$Z = 50 \times \frac{(1+SP)}{(1-SP)} \quad (5.7)$$

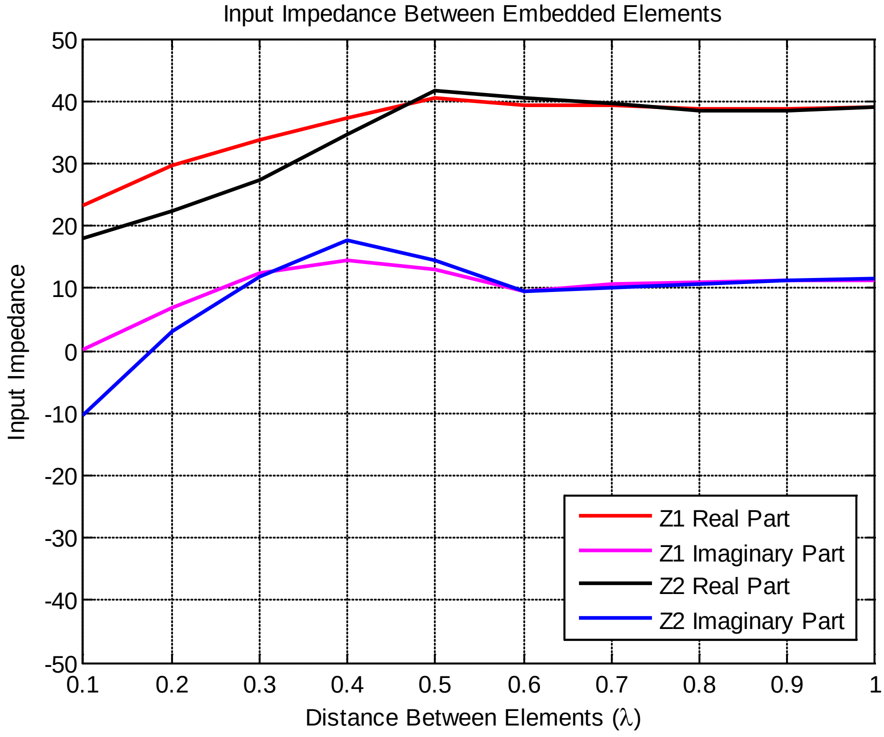

Figure 4.5: Influence of Distance between Dipoles on Input Impedance

4.3 Influences on Number of Realizations

The received voltage at antenna port is depended upon the number of incident waves from different scatters. In isotropic environment, the signal can be received by different scattering environments. These environments can be urban, suburban and rural. The input waves are coming uniformly in equal number from all directions (already discussed in previous chapter). The signal received at antenna depends on the number of scatters. So we have to suppose enough number of scatters to get good signal strength.

Suppose we have four antenna array and we are taking randomly 100 scatters in our environment. Each time these scatters will be generated randomly. For 1st time, we received 100 waves at antenna, similarly 2nd and so on; the repetition of this process is called 'Number of Realizations'. Similarly, for the number of scatters, we have to suppose a number of realizations.

When the distance between elements is 0.5 λ (discussed in chapter 3), we are going to study that, what will be the effect on diversity gain and capacity when we are changing the number of realizations from 1×10^4 to 1×10^5 but the number of scatters will be constant and we are taking 100 scatters. The calculation time will increase, if we increase the number of realizations. If above number of realizations and scatters is used then total $1 \times 10^5 \times 100 = 10 \times 10^6$ times calculation runs and it will take more time.

4.3.1 Influence of Number of realization on Diversity Gain

The figure 4.6 shows the relationship between apparent & effective diversity gain and number of realizations when the distance between dipole antennas is 0.5 λ. We can see from the figure that, if we change the number of realizations, there is no effect on diversity gain. Diversity gain is same at both realizations 1×10^4 and 1×10^5. Diversity gain does not depend upon the realizations but it depends upon mutual coupling and correlation. If we increase the number of realizations from 1×10^4 to 1×10^5, there is no effect on diversity gain.

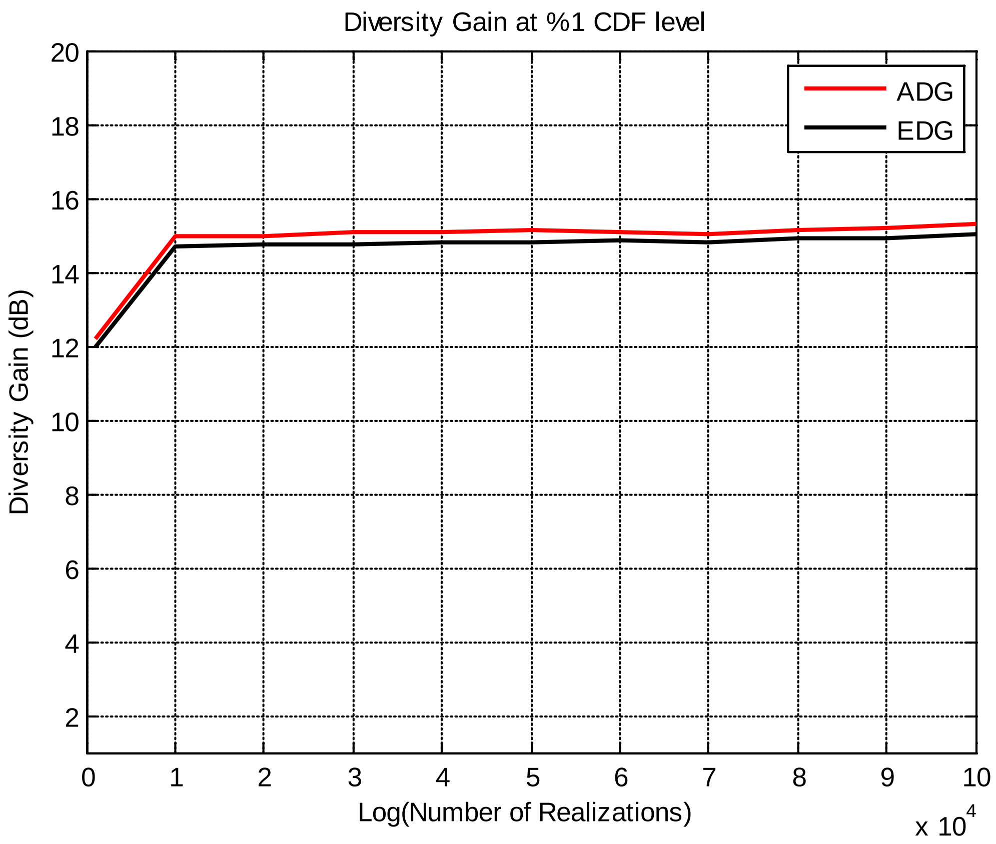

Figure 4.6: Influence of Number of realization on Diversity Gain

4.3.2 Influence of Number of realization on Capacity

The figure 4.7 shows the relationship between capacity of multi-element antennas at 15 dB SNR and number of realizations when the distance between dipole antennas is 0.5 λ. It is clear from the figure that, if we change the number of realizations, there is no effect on capacity. Capacity is same for both realizations 1×10^4 and 1×10^5. It does not depend upon the number of realizations. If we increase the number of realizations from 1×10^4 to 1×10^5, there is no effect on Ergodic capacity.

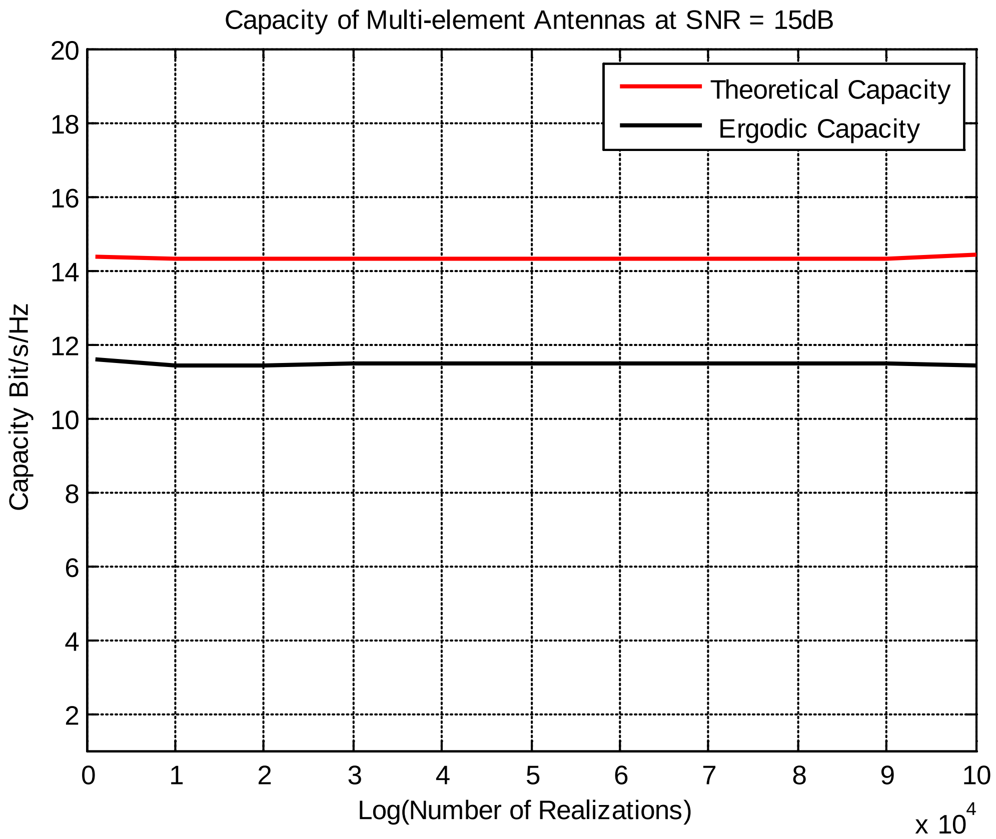

Figure 4.7: Influence of Number of realization on Capacity

4.4 Influence on Number of Scatters (Number of Incident waves)

As we discussed earlier that, the signals received at antenna is coming from different scatters. There are two types of environments used in this project, isotropic and non-uniform environment. In isotropic environment, the waves are coming uniformly in equal numbers from all directions. And in non-uniform environment, the objects are uniformly distributed in azimuth plane and Gaussian distributed in elevation plane.

We are going to study the effect on diversity gain, correlation and Mean Effective Gain (MEG) when we are changing the number of scatters from 10 to 100 but the number of realizations will be constant and it is 1×10^5. We are comparing three different cases (distance between elements) here which are 0.1 λ, 0.2 λ and 0.5 λ (discussed in previous chapter). The effects on diversity gain, correlation and MEG on different environments are listed below.

- **Isotropic Environment**
  - Influence of Number of Scatters on Diversity Gain & Correlation for Element port.
  - Influence of Number of Scatters on Diversity Gain & Correlation for Beam Port
- **Non-uniform Environment:**
  - Influence of Number of Scatters on Diversity Gain, Correlation & MEG for Element Port
  - Influence of Number of Scatters on Diversity Gain, Correlation & MEG for Beam Port.

4.4.1 Isotropic Environment

4.4.1.1 Influence of Number of Scatters on Diversity Gain for Element Port

The figure 4.8 shows the apparent and effective diversity gain of selection combining (SC) and maximum ratio combining (MRC) at 1% CDF level. It is shown from the figure 4.8 that, the difference between apparent and effective diversity gain is very large because the distance between elements is very less (0.1 λ). And small distance between elements creates the mutual coupling and correlation. The curve of apparent diversity gain of selection combining is exactly follow the curve of effect diversity gain of MRC. It just happened that the two curves of ADG-SC & EDG-MRC coincide here. The diversity gain is small at Scatter 10 and from Scatter 10 to 20 it is increasing, after that, it remains constant. It means that, we need minimum 20 scatters to receive the good signal quality. The figure 5.9 & 5.10 is also shows the diversity gain at 1% CDF level. In figure 4.9, the diversity gain is improved and difference between ADG & EDG is also decreases because of increased distance between elements. In figure 4.10, the ADG and EDG are very close to each other because the distance between elements is now 0.5 λ, and at this distance, there is very less mutual coupling and correlation.

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ**

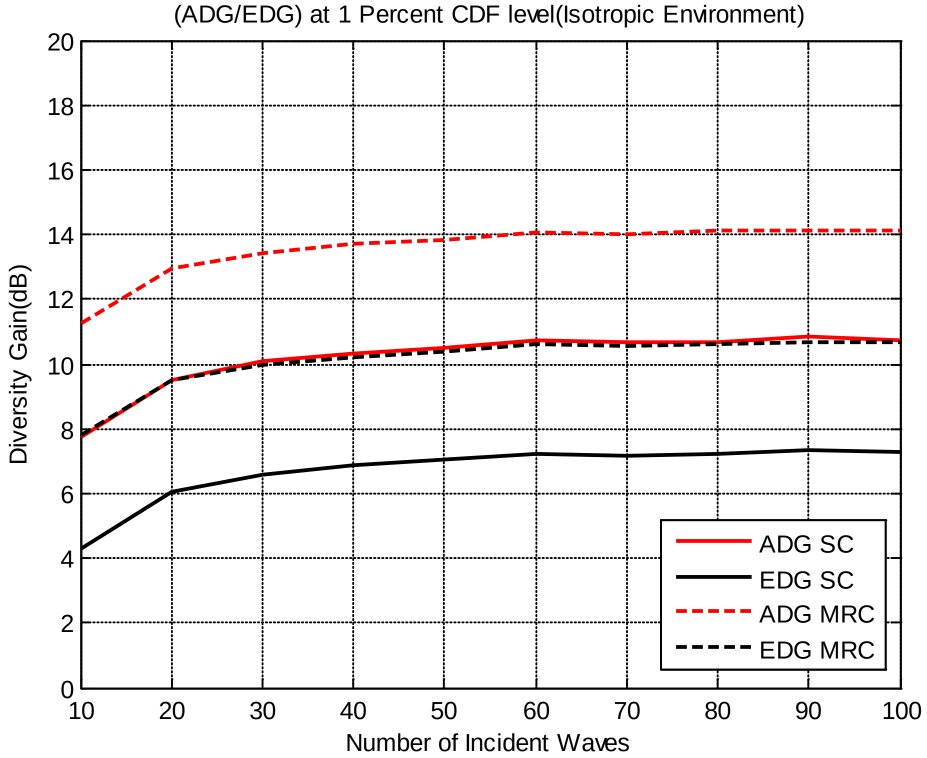

Figure 4.8: Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ for Element Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ**

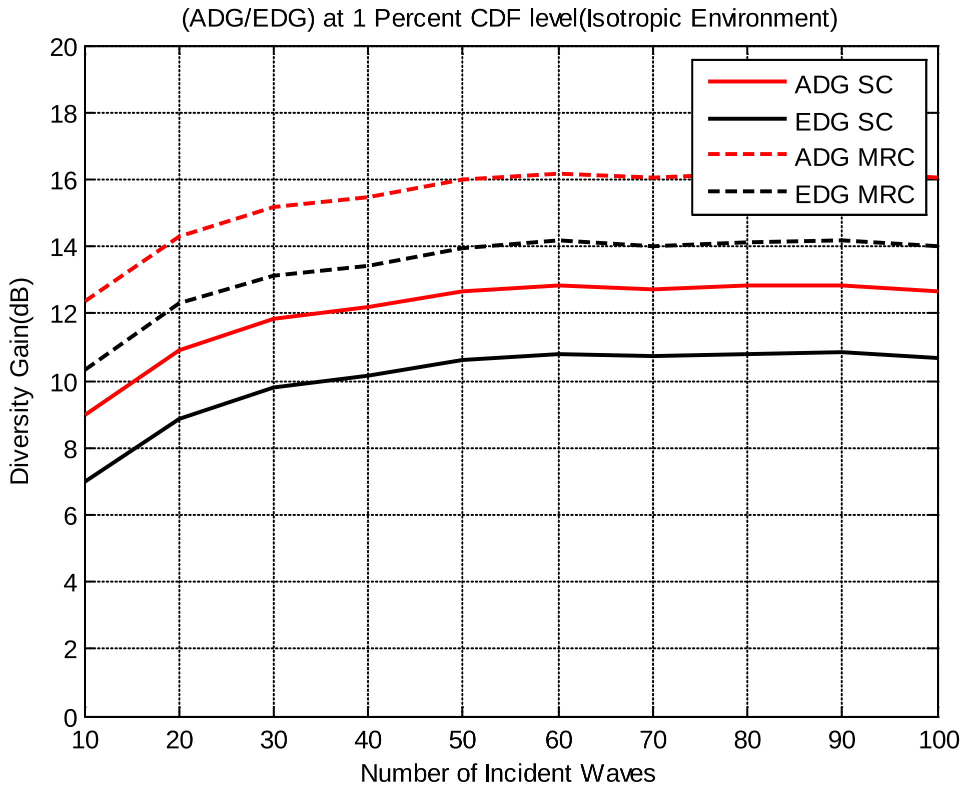

Figure 4.9: Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ for Element Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ**

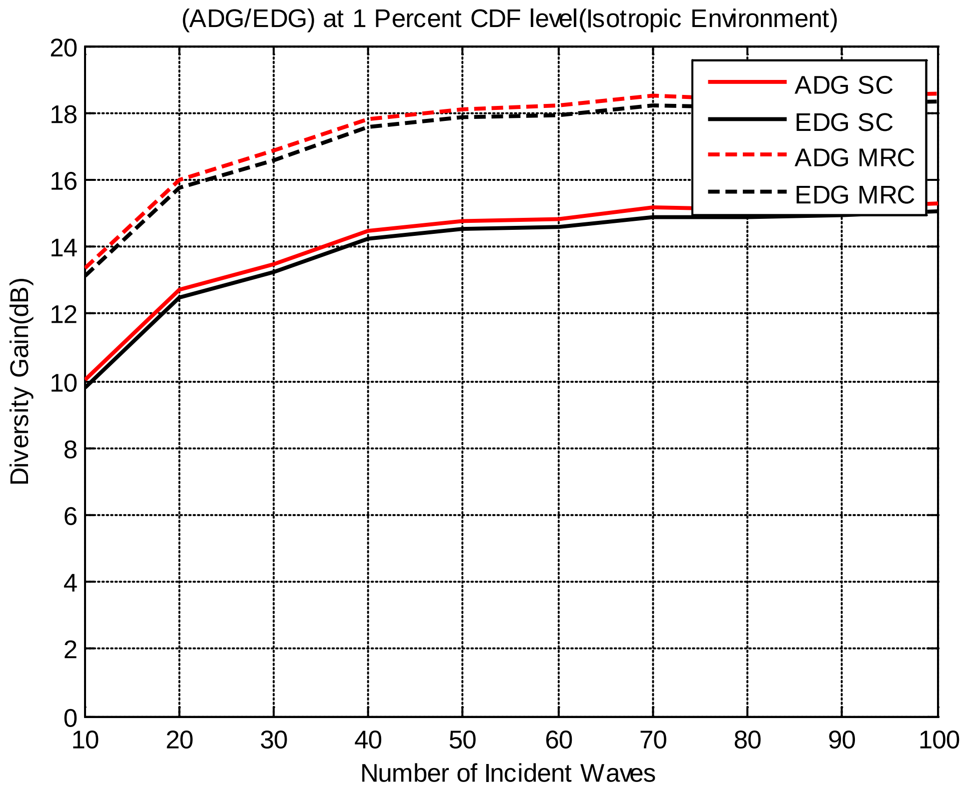

Figure 4.10: Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ for Element Port

4.4.1.2 Influence of Number of Scatters on Correlation for Element Port

The figure 4.11 shows the correlation between elements at a distance of 0.1 λ. It is shown from the figure 4.11 that, the number of scatters does not create any effect on correlation. Form Scatter 0 to 100, the curve of correlation remains constant. The correlation between element 1 & 2 'Cor12' is very high because of small distance (0.1 λ). Similarly, the Cor23 is also high. The curve of Cor12 & Cor23 both are approximate equal to each other, and the curve of Cor13 and Cor24 both are equal because both element have equal distance between elements. In figure 4.12, the correlation is decreased as we increase the distance between elements. And the curve of Cor12 & Cor23 gets close to each other. In figure 4.13, the correlation between 'Cor12' and 'Cor23' are equal because both elements have equal distance between elements. Similarly, correlation between 'Cor13' and 'Cor24' are also equal. And, the correlation between element 1 & 4 'Cor14' is very less because both of these element are far in antenna array. A little bouncing in each correlations curve could be probably attributed to numerical inaccuracy inherent in our simulations. Its mean that, in element port excitation, there is no effect of correlation as we change the scatters in isotropic environment and the curve of two neighbor elements gets closer if we increase the distance between elements.

- **Influence of Number of Scatters on Correlation at Distance of 0.1 λ**

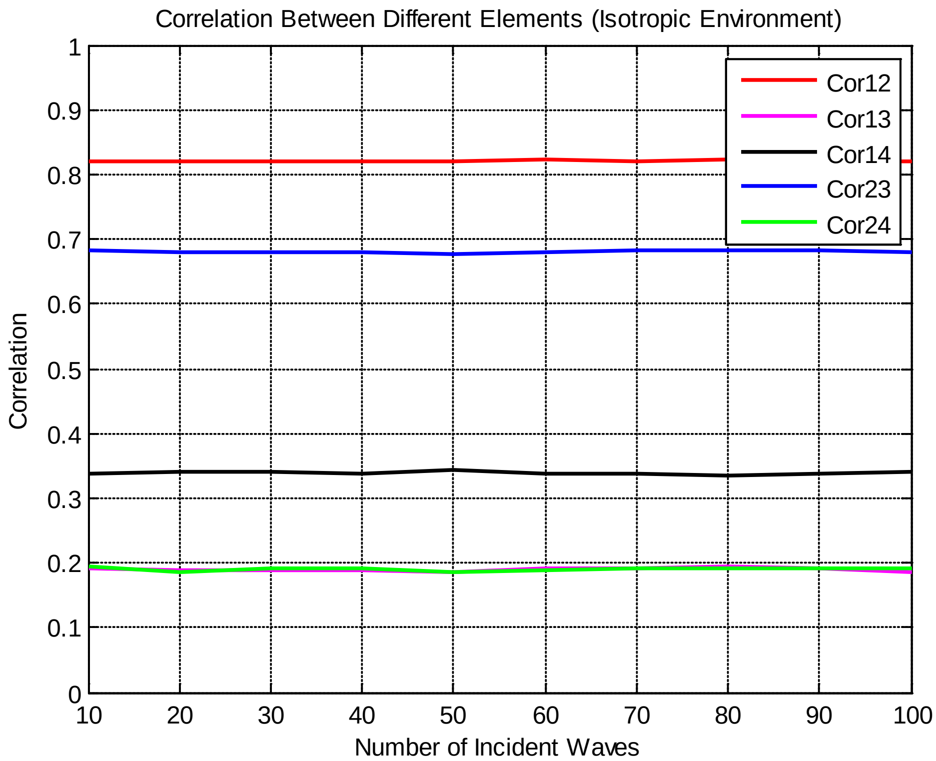

Figure 4.11: Influence of Number of Scatters on Correlation at Distance of 0.1 λ for Element Port

- **Influence of Number of Scatters on Correlation at Distance of 0.2 λ**

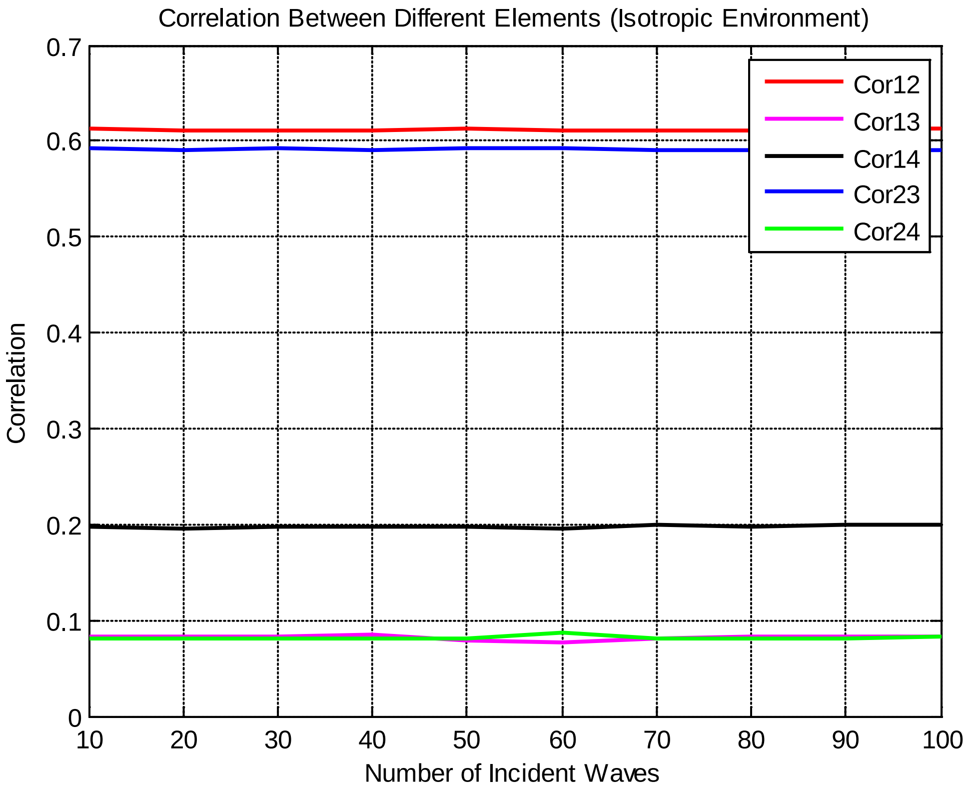

Figure 4.12: Influence of Number of Scatters on Correlation at Distance of 0.2λ for Element Port

- **Influence of Number of Scatters on Correlation at Distance of 0.5 λ**

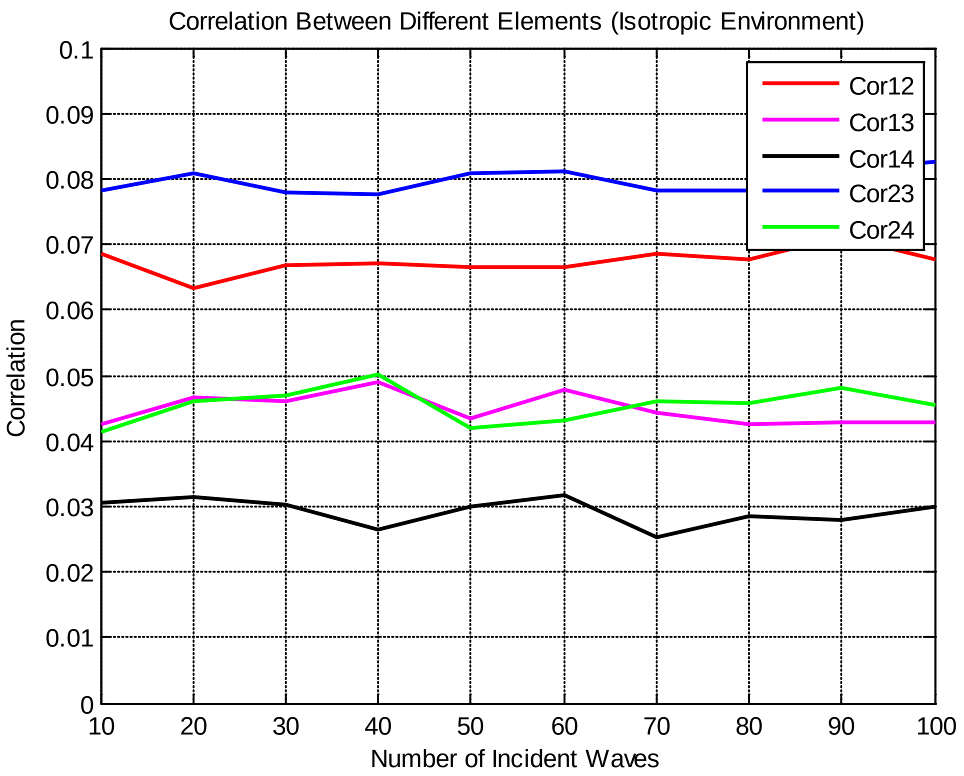

Figure 4.13: Influence of Number of Scatters on Correlation at Distance of 0.5 λ for Element Port

4.4.1.3 Influence of Number of Scatters on Diversity Gain for Beam Port

The figure 4.14 shows the apparent and effective diversity gain of selection combining (SC) and maximum ratio combining (MRC) at 1% CDF level for beam port excitation. It is shown from the figure 4.14 that, the difference between apparent and effective diversity gain of SC and MRC is very close. The diversity gain is small at Scatter 10 and from Scatter 10 to 20 it is increasing, after that, it remains constant. It means that, we need minimum 20 scatter to receive the good signal strength. The figure 4.15 & 4.16 also shows the diversity gain at 1% CDF level. In figure 4.15, the diversity gain is increased but the difference between ADG & EDG is less increased. In figure 4.16, the ADG and EDG are very close to each other because the distance between elements is now 0.5 λ, and at this distance, there is a very less mutual coupling and correlation. The ADG of MRC is also improved. The MRC is the best case because it has the high gain. In MRC, we took the ratio of all received signals but in SC, we took the strongest signals from all received signals.

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ**

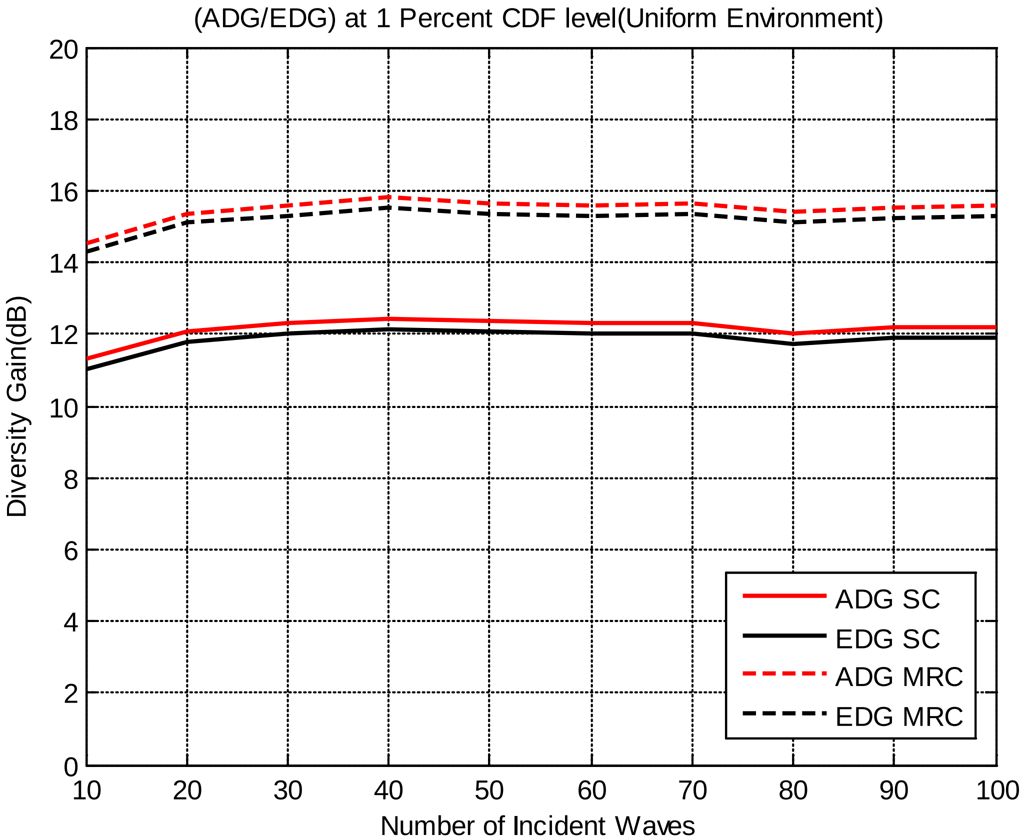

Figure 4.14: Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ for Beam Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ**

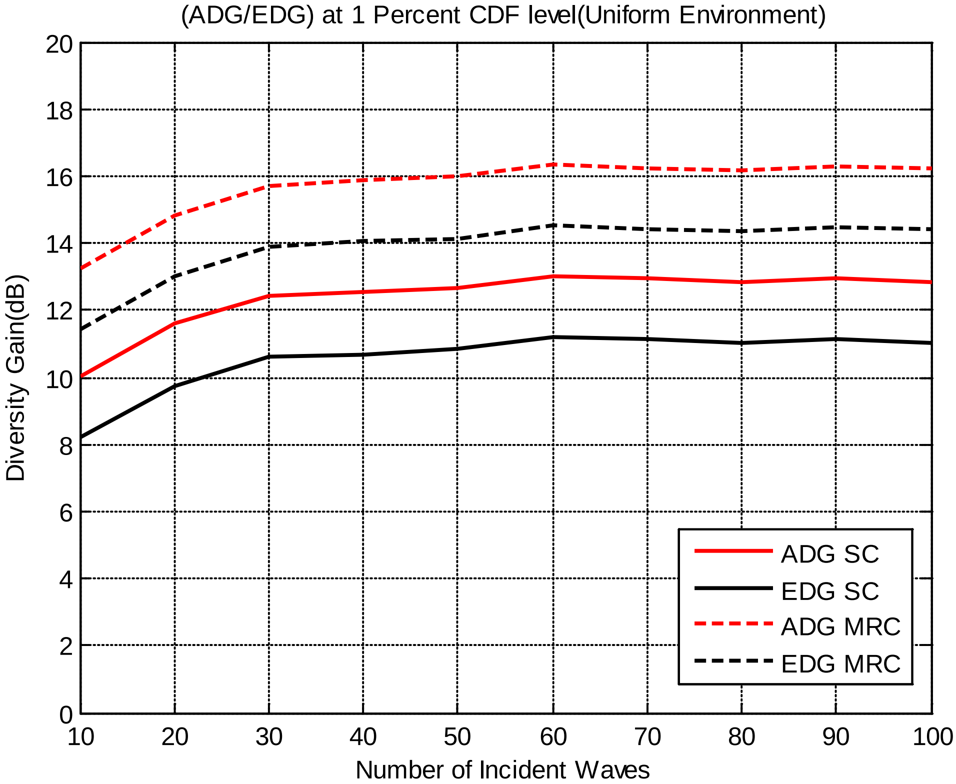

Figure 4.15: Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ for Beam Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ**

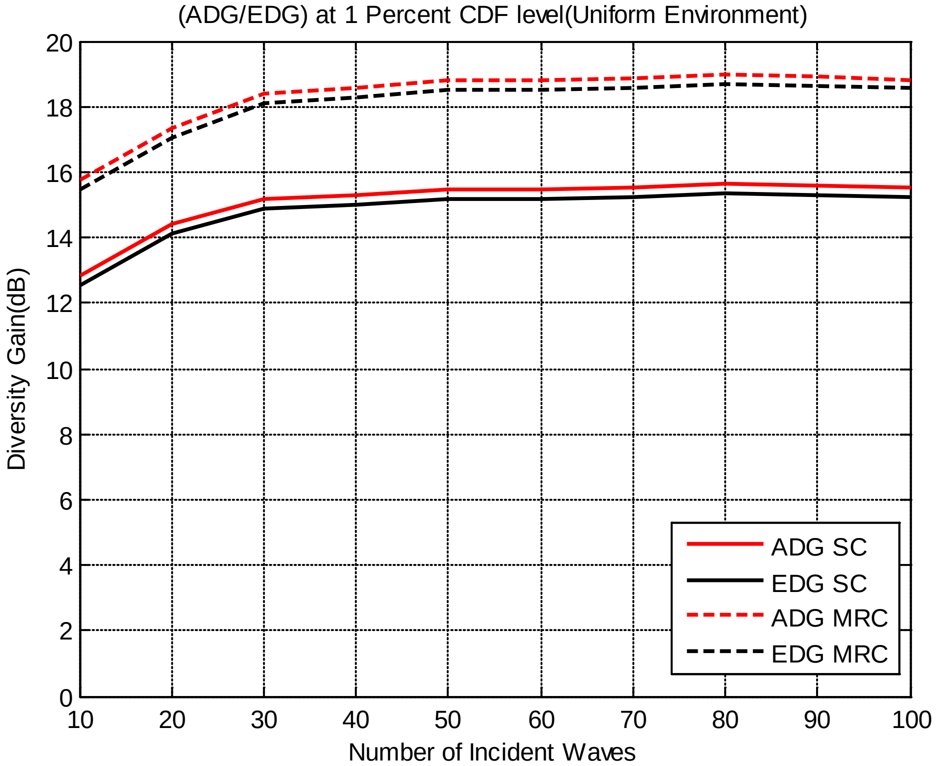

Figure 4.16: Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ for Beam Port

4.4.1.4 Influence of Number of Scatters on Correlation for Beam Port

The figure 4.17 shows the correlation between elements at a distance of 0.1 λ. It is shown from the figure 4.17 that, the number of scatters does not create any effect on correlation. Form Scatter 0 to 100, the curve of correlation remains constant. The correlation between element 1 & 2 'Cor12' is very high because of small distance (0.1 λ). The curve of Cor12 & Cor23 both should be equal to each other but due to very high mutual coupling they are not equal, and the curve of Cor13 and Cor24 both are equal because both elements have equal distance between elements. In figure 4.18, the correlation decreased as we increase the distance between elements. And the Cor12 & Cor23 gets close to each other. In figure 4.19, the correlation between 'Cor12' and 'Cor23' are equal because both elements have equal distance between them. Similarly, correlation between 'Cor13' and 'Cor24' are also equal. It means that, in beam port excitation, there is no effect of correlation as we change the scatters in isotropic environment and the curve of two neighbor elements gets close if we increase the distance between elements.

- **Influence of Number of Scatters on Correlation at Distance of 0.1 λ**

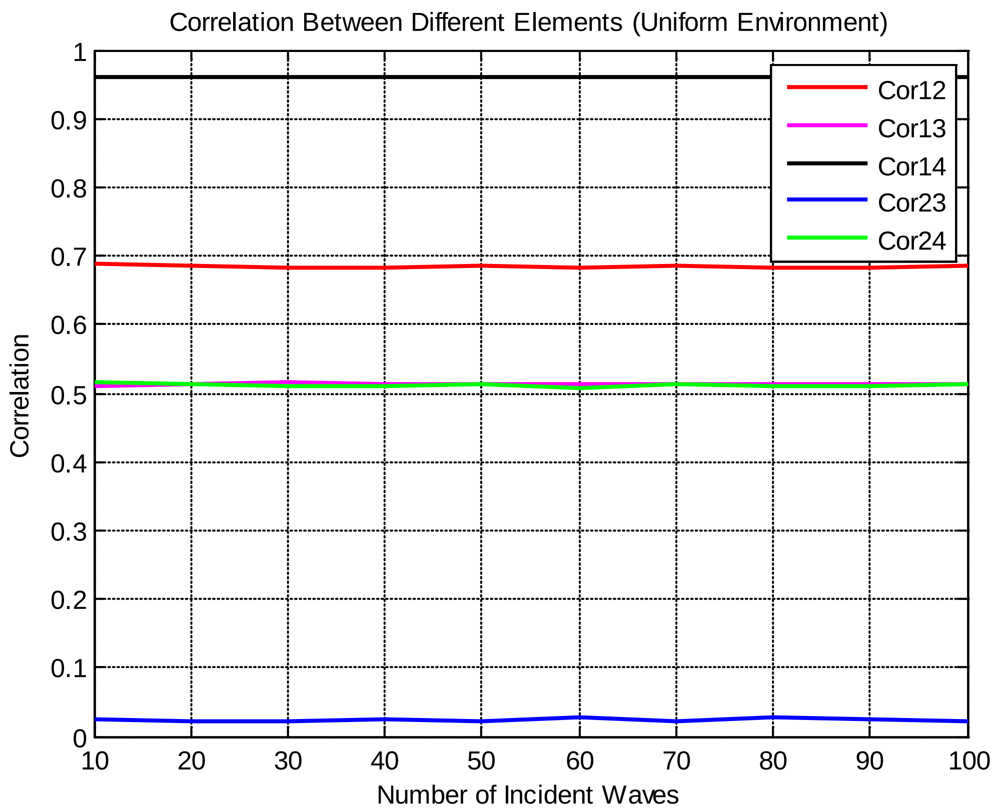

Figure 4.17: Influence of Number of Scatters on Correlation at Distance of 0.1 λ for Beam Port

- **Influence of Number of Scatters on Correlation at Distance of 0.2 λ**

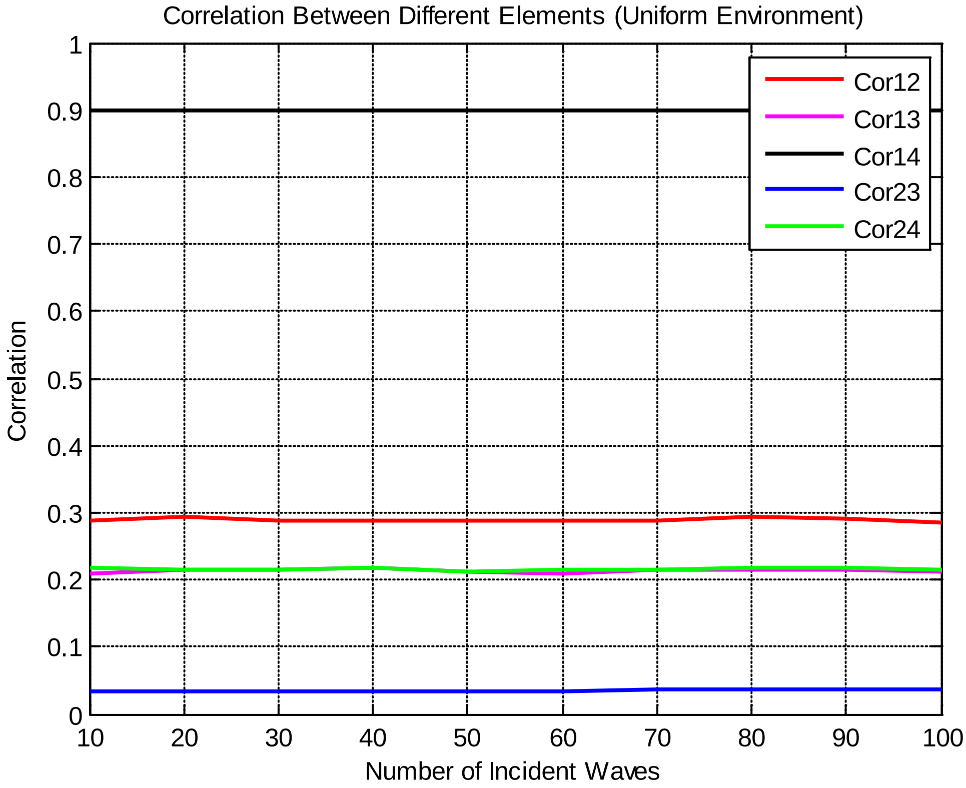

Figure 4.18: Influence of Number of Scatters on Correlation at Distance of 0.2 λ for Beam Port

- **Influence of Number of Scatters on Correlation at Distance of 0.5 λ**

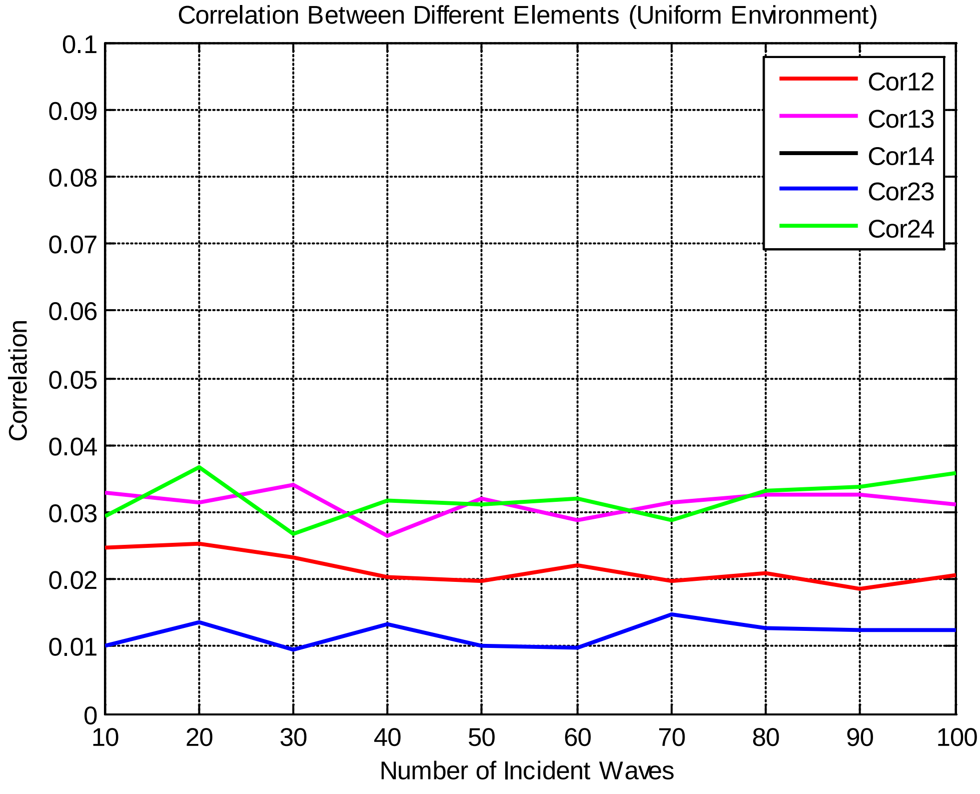

Figure 4.19: Influence of Number of Scatters on Correlation at Distance of 0.5 λ for Beam Port

4.4.1.5 Comparative study of Apparent and Effective Diversity Gain

The figure 4.19(a) shows the diversity gains for element and beam ports versus number of incident waves in isotropic environment. Since the received signals at each beam port has contributions from signals received by all element ports, the diversity curve corresponding to beam ports can also be referred to as hybrid selection combined. It is shown from the figure 4.19(a) that, from Scatter 10 to 30, the diversity gain of the beam port has a bit better performance in comparison with element port, and after that the apparent and effective diversity gain at element port and beam port are very close to each other [11]

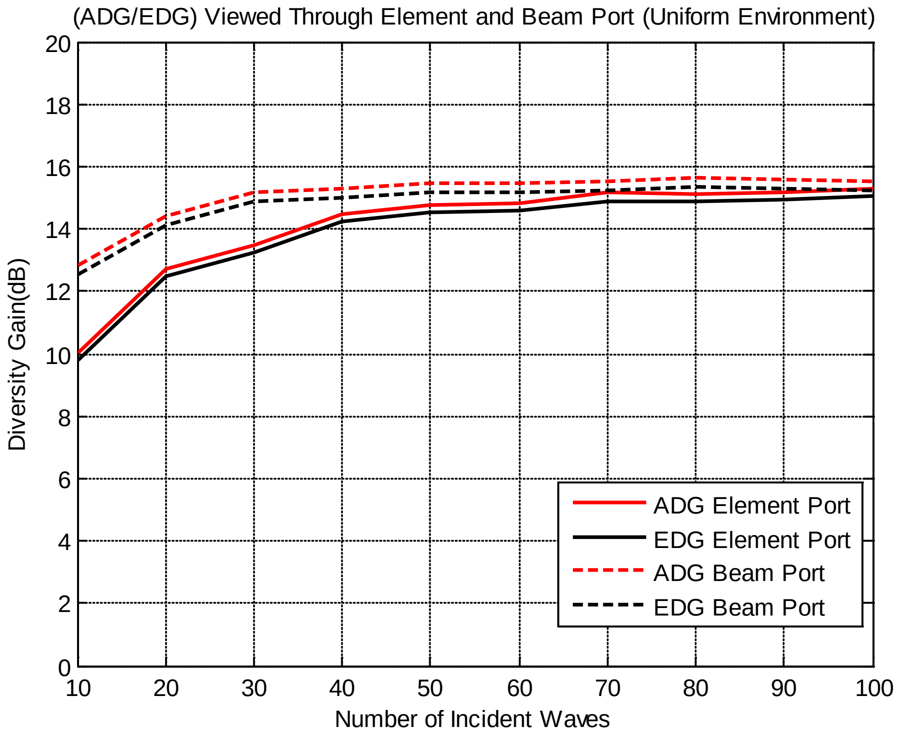

Figure 4.19(a): DG at Element port and Beam ports versus No of Incident wave for isotropic

4.4.2 Non-uniform Environment

The value of Theta mean (mean) & Sigma (variance) are 32 & 64, measured by Ningyo-cho route in Tokyo Taga [9].

4.4.2.1 Influence of Number of Scatters on Diversity Gain for Element Port

The figure 4.20 shows the apparent and effective diversity gain of selection combining (SC) and maximum ratio combining (MRC) at 1% CDF level for element port excitation. It is clear from the figure that, the difference between apparent and effective diversity gain is very large because we have very small distance between elements (0.1 λ) which eventually leads to reduced total radiation efficiency. The curve of apparent diversity gain of selection combining (ADG – SC) is exactly following the curve of effect diversity gain of MRC. It just happened that the two curves of ADG-SC & EDG-MRC coincide here. The diversity gain is small at Scatter 10 and from Scatter 10 to 20 it is increasing, after that, it remains constant. It means that, we need minimum 20 scatter to receive the good signal. The figure 4.21 & 4.22 also shows the diversity gain at 1% CDF level. In figure 4.21, the diversity gain is improved and difference between ADG & EDG is also decreased. In figure 4.22, the ADG and EDG are very close to each other because the distance between elements is now 0.5 λ, The ADG of MRC is also improved by 18.6 dB and it is same in isotropic. Therefore, there is very less effect of environment on diversity gain. Diversity gain is approximating same in both environment but non-uniform environment has a little bit more gain.

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ**

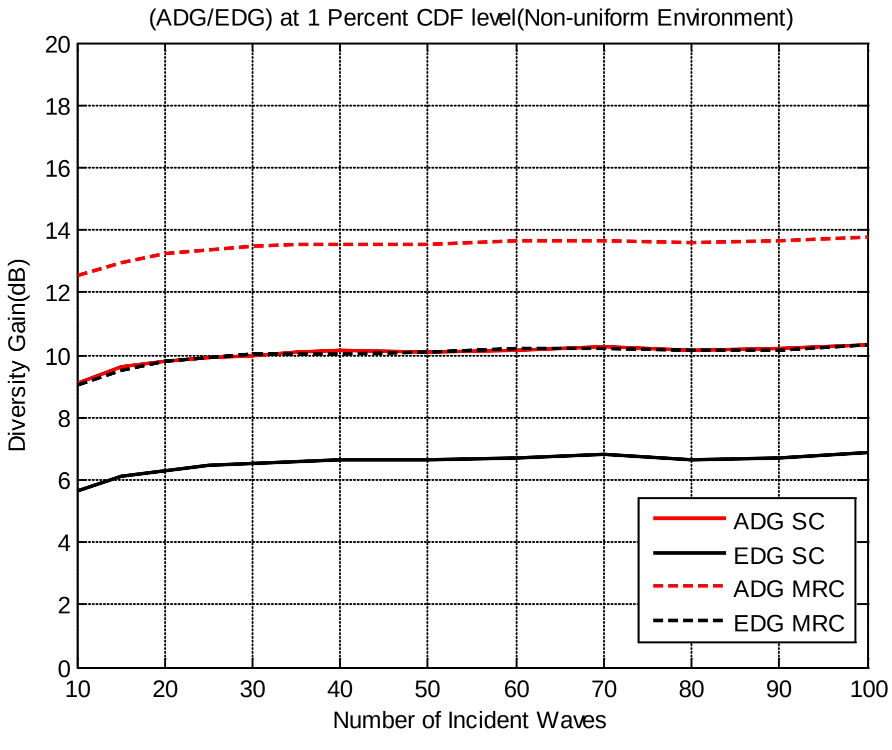

Figure 4.20: Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ for Element Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ**

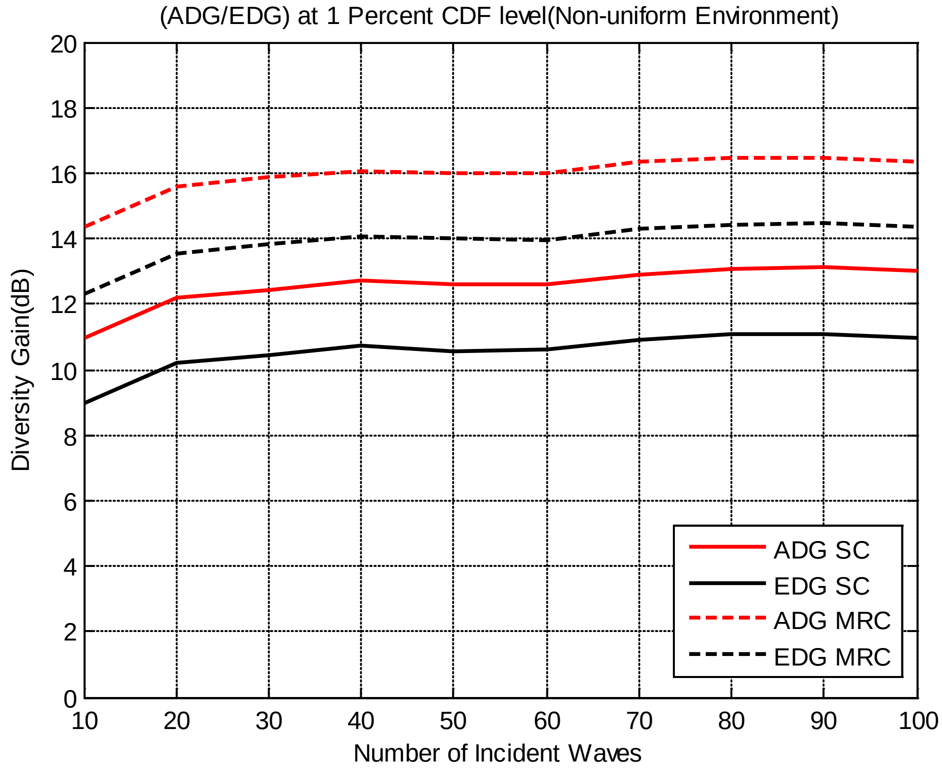

Figure 4.21: Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ for Element Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ**

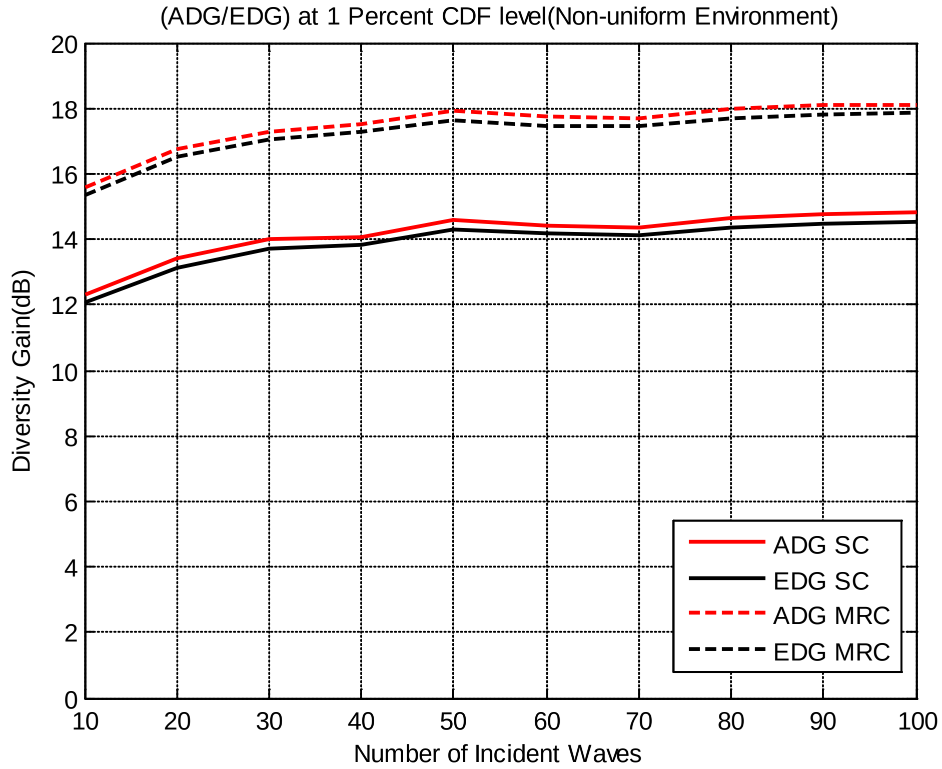

Figure 4.22: Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ for Element Port

4.4.2.2 Influence of Number of Scatters on Correlation for Element Port

The figure 4.23 shows the correlation between elements at a distance of 0.1 λ**.** The value of Theta mean (mean) & angle of spread (variance) are 32 & 64. It is shown from the figure that, the number of scatters does not create any effect on correlation. Form Scatter 0 to 100, the curve of all correlations remains constant. The correlation between element 1 & 2 ‘Cor12’ is very high because non-uniform environment plays a significant role. Similarly, the Cor23 is also high. The curve of Cor12 & Cor23 both should be equal to each other but they are not equal due to mutual coupling and the curve of Cor13 and Cor24 both are equal because both elements have equal distance between them. In figure 4.24, the correlation decreased as we increase the distance between elements. And the curve of Cor12 & Cor23 gets close to each other. In figure 4.25, the correlation between ‘Cor12’ and ‘Cor23’ are equal because both elements have equal distance between them. Similarly, correlation between ‘Cor13’ and ‘Cor24’ are also equal. It just happened that the correlation between two different curves (Cor13 & Cor24) coincides. The correlation between element 1 & 4 ‘Cor14’ is also less. It means that, there is no effect of correlation as we change the scatters in non-uniform environment. Both environments have equal correlations but ‘cor12’ & ‘Cor23’ of 0.5λ distance between elements has a bit more in non-uniform environment.

- **Influence of Number of Scatters on Correlation at Distance of 0.1 λ**

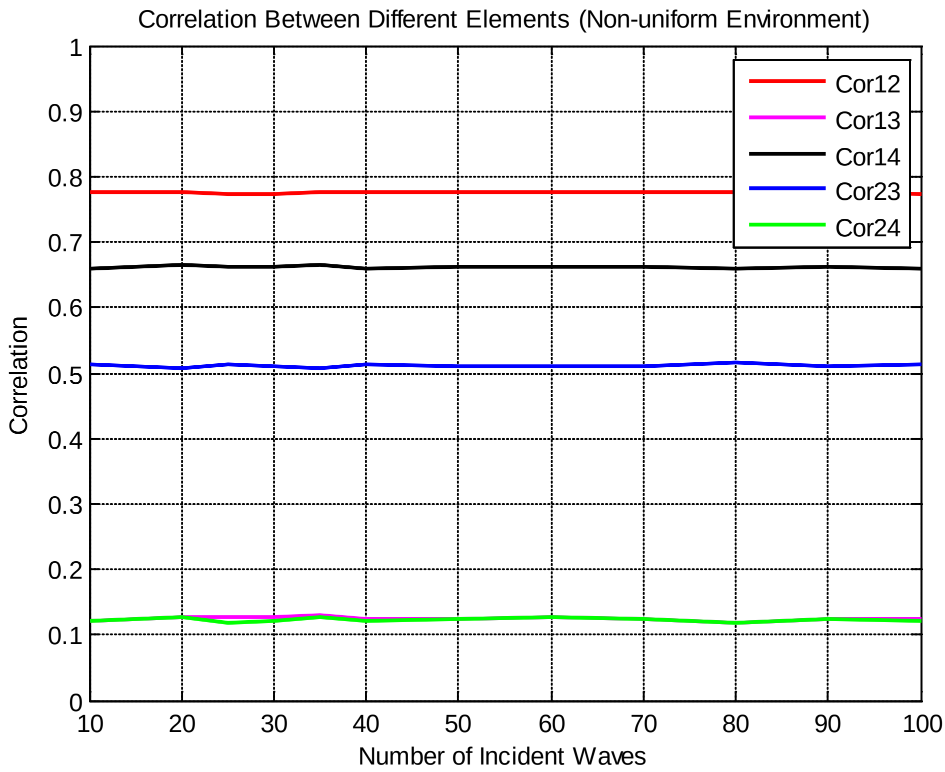

Figure 4.23: Influence of Number of Scatters on Correlation at Distance of 0.1 λ for Element Port

- **Influence of Number of Scatters on Correlation at Distance of 0.2 λ**

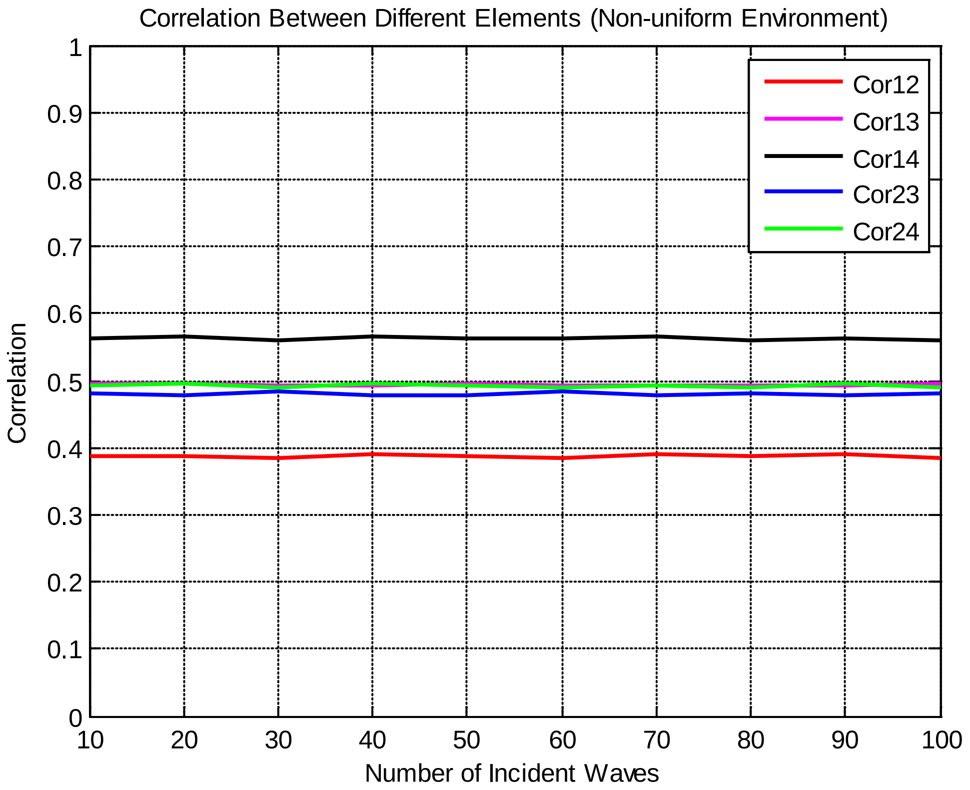

Figure 4.24: Influence of Number of Scatters on Correlation at Distance of 0.2 λ for Element Port

- **Influence of Number of Scatters on Correlation at Distance of 0.5 λ**

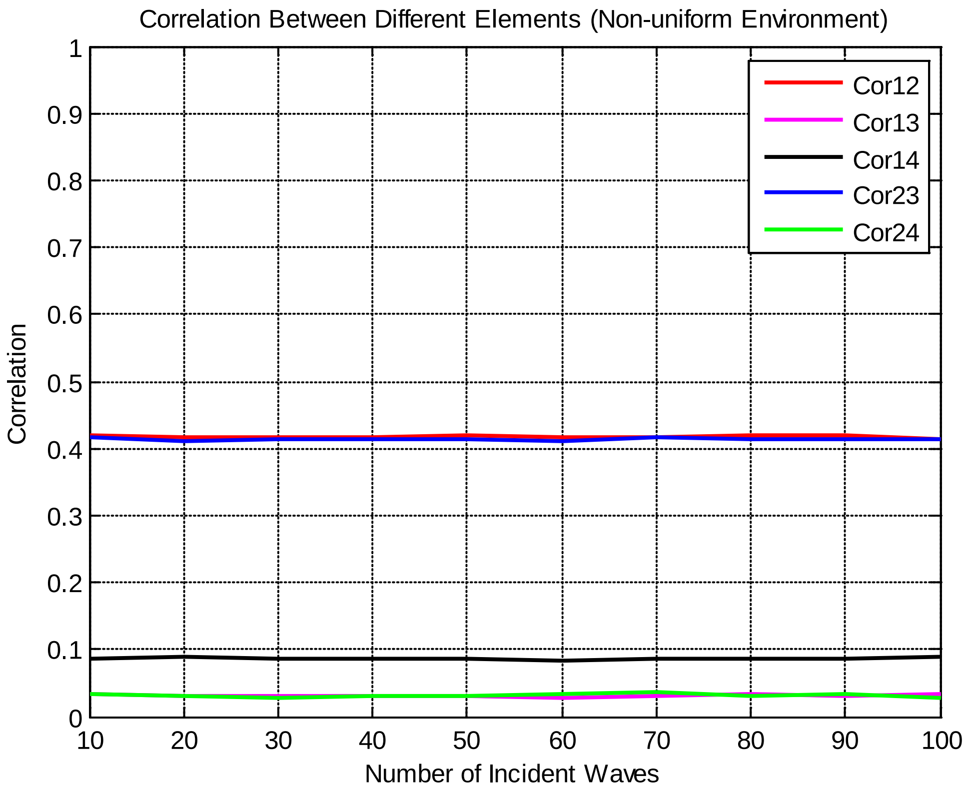

Figure 4.25: Influence of Number of Scatters on Correlation at Distance of 0.5 λ for Element Port.

4.4.2.3 Influence of Number of Scatters on MEG for Element Port

The figure 4.26 shows the Mean Effective Gain (MEG) of all elements for dual-polarized isotropic antenna. The value of Theta mean (mean) & angle of spread (variance) are 32 & 64. It is clear from the figure that, the MEG of element 1 & 4 both are equal because of symmetric property. Similarly, the MEG of element 2 & 3 are also equal. The curve of MEG is constant from Scatter 0 to 100. It means that number of scatters does not create any effect on MEG. The difference between MEG 1 & MEG 2 is very large because we have very small distance between elements (0.1 λ). The figure 4.27 & 4.28 also shows the MEG. In figure 4.27, the mean effective gain is improved and difference between MEG 1 & MEG 2 is also decreased. In figure 4.28, the MEG 1 and MEG 2 are very close to each other because the distance between elements is now 0.5 λ. There is no effect of MEG as we change the scatters in non-uniform environment and the curve of two neighbor elements gets close if we increase the distance between elements.

- **Influence of Number of Scatters on MEG at Distance of 0.1 λ**

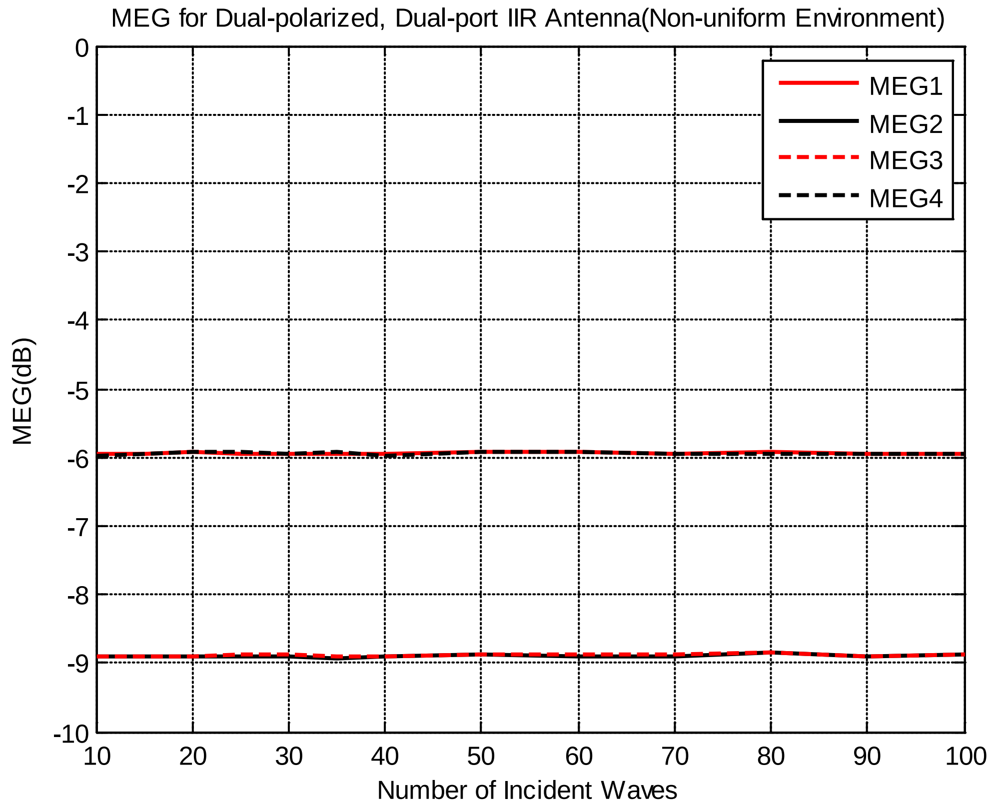

Figure 4.26: Influence of Number of Scatters on MEG at Distance of 0.1 λ for Element Port

- **Influence of Number of Scatters on MEG at Distance of 0.2 λ**

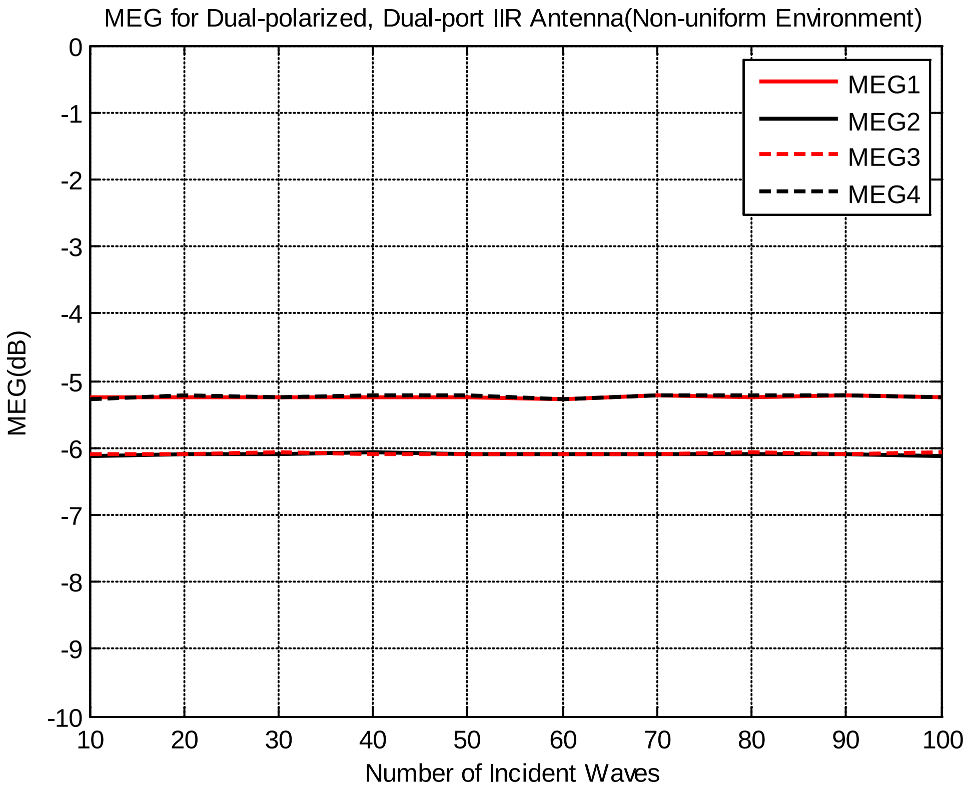

Figure 4.27: Influence of Number of Scatters on MEG at Distance of 0.2 λ for Element Port

- **Influence of Number of Scatters on MEG at Distance of 0.5 λ**

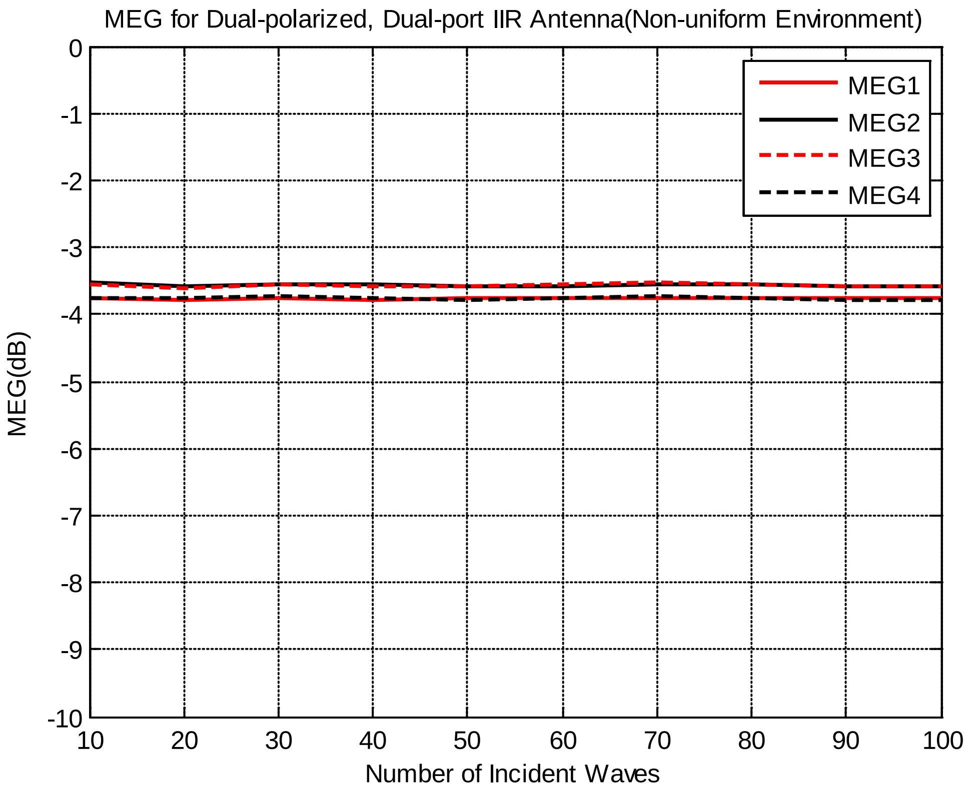

Figure 4.28: Influence of Number of Scatters on MEG at Distance of 0.5 λ for Element Port

4.4.2.4 Influence of Number of Scatters on Diversity Gain for Beam Port

The figure 4.29 shows the apparent and effective diversity gain of selection combining (SC) and maximum ratio combining (MRC) at 1% CDF level for beam port excitation. The value of Theta mean (mean) & angle of spread (variance) are 32 & 64. It is shown from the figure that, the difference between the apparent and effective diversity gain of SC and MRC is very close. The diversity gain is small at Scatter 10 and from Scatter 10 to 20 it is increasing, after that, it remains constant. It means that, we need minimum 20 scatters to receive the good signal quality. The figure 4.30 & 4.31 also shows the diversity gain at 1% CDF level. In figure 4.30, the diversity gain is increased but the difference between the ADG & EDG is a bit increased. In figure 4.31, the curves of ADG and EDG are very close to each other because the distance between elements is now 0.5 λ, and at this distance, there is a very less mutual coupling and correlation. After 20 scatters, there is no effect of number of scatters on diversity gain in both environments. But in non-uniform environment we have a little bit more gain as compare to isotropic environment. And the MRC has a maximum gain in both environments.

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ**

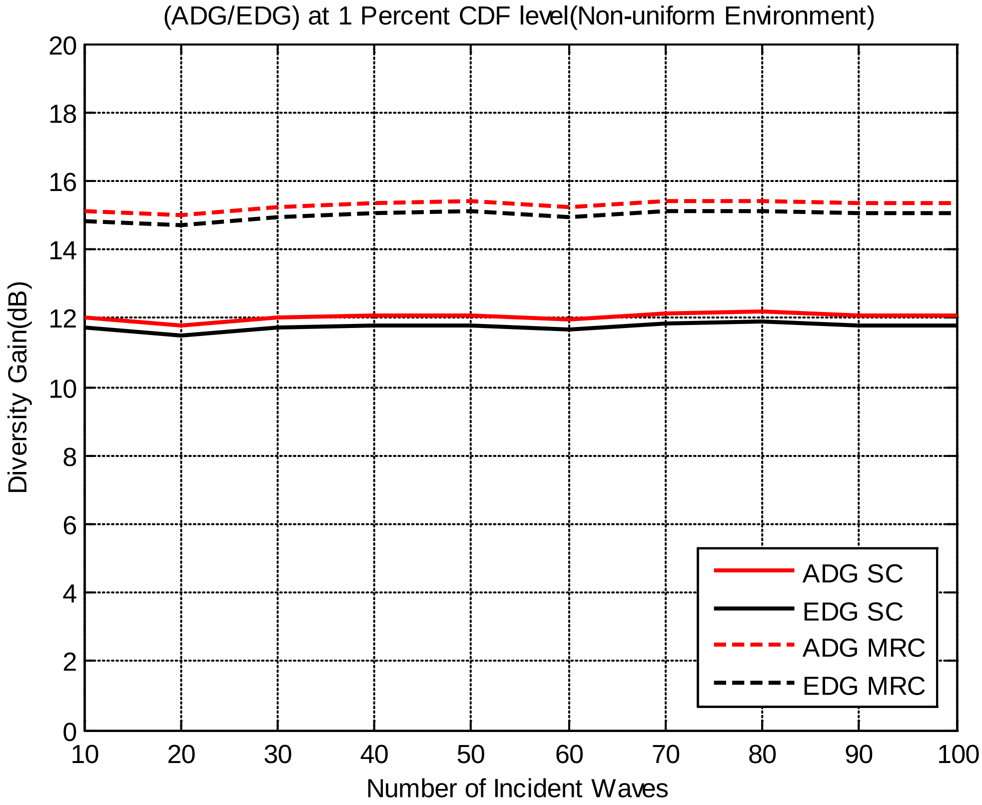

Figure 4.29: Influence of Number of Scatters on Diversity Gain at Distance of 0.1 λ for Beam Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ**

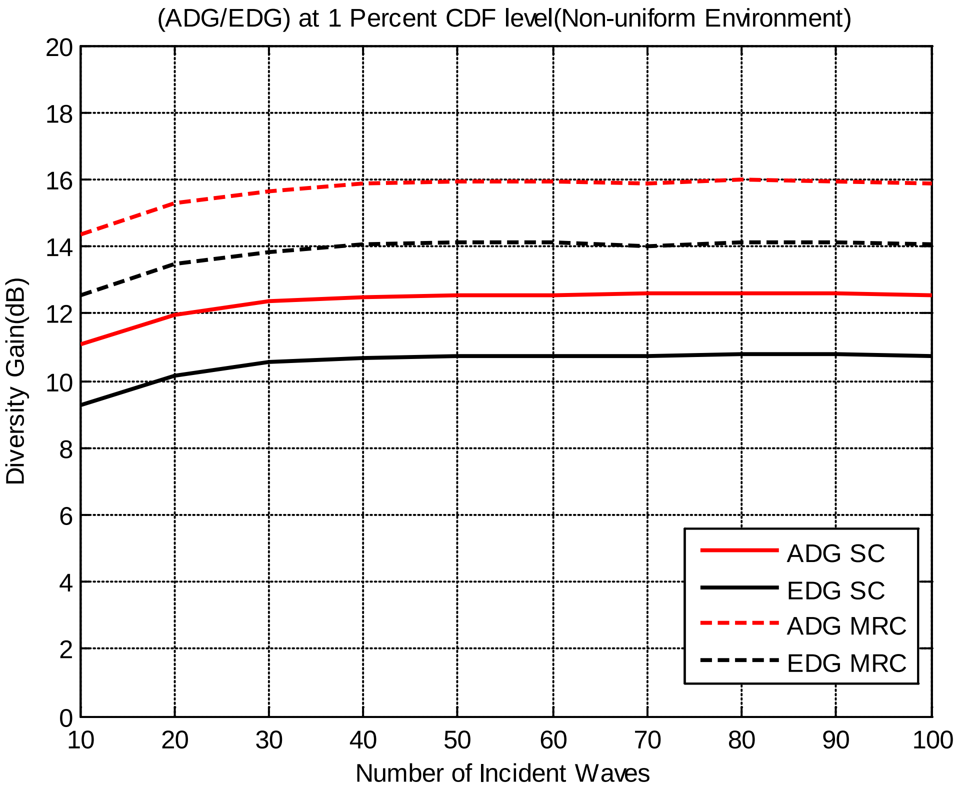

Figure 4.30: Influence of Number of Scatters on Diversity Gain at Distance of 0.2 λ for Beam Port

- **Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ**

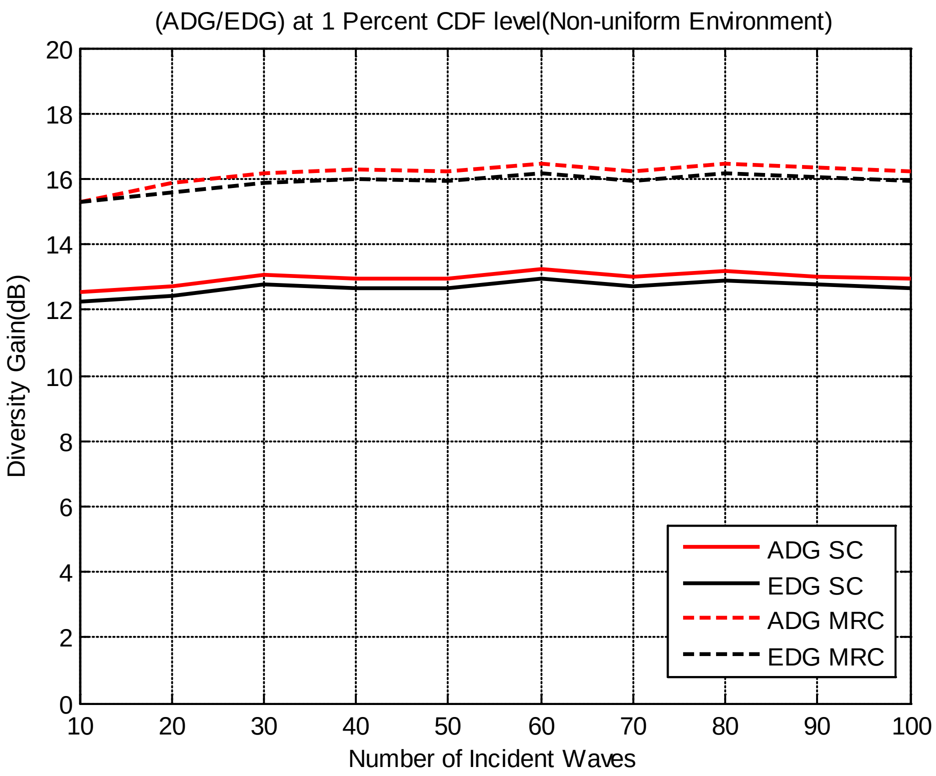

Figure 4.31: Influence of Number of Scatters on Diversity Gain at Distance of 0.5 λ for Beam Port

4.4.2.5 Influence of Number of Scatters on Correlation for Beam Port

The figure 4.32 shows the correlation between elements at a distance of 0.1 λ for beam port excitation. The value of Theta mean (mean) & angle of spread (variance) are 32 & 64. It is clear from the figure that, the number of scatters does not create any effect on correlation. Form Scatters 0 to 100 the correlation remains constant. The correlation between element 1 & 2 'Cor12' is very high because non-uniform environment plays a significant role. The Cor12 & Cor23 both should be equal to each other but due to very high mutual they are not equal, and the Cor13 and Cor24 both are equal because both elements have equal distance between them. In figure 4.33, the correlation decreased as we increase the distance between elements. And the curve of Cor12 & Cor23 gets close to each other. In figure 4.34, the correlation between 'Cor12' and 'Cor23' are not very close to each other, but correlation between 'Cor13', 'Cor23' and 'Cor14' is equal. It means that, in beam port excitation, there is no effect of correlation as we change the scatters in non-uniform environment. But the correlation between 'Cor12' & 'Cor23' was equal in isotropic environment for beam port but these correlations are not equal in non-uniform environment for beam port. And the curve of two neighbor elements gets close if we increase the distance between elements.

- **Influence of Number of Scatters on Correlation at Distance of 0.1 λ**

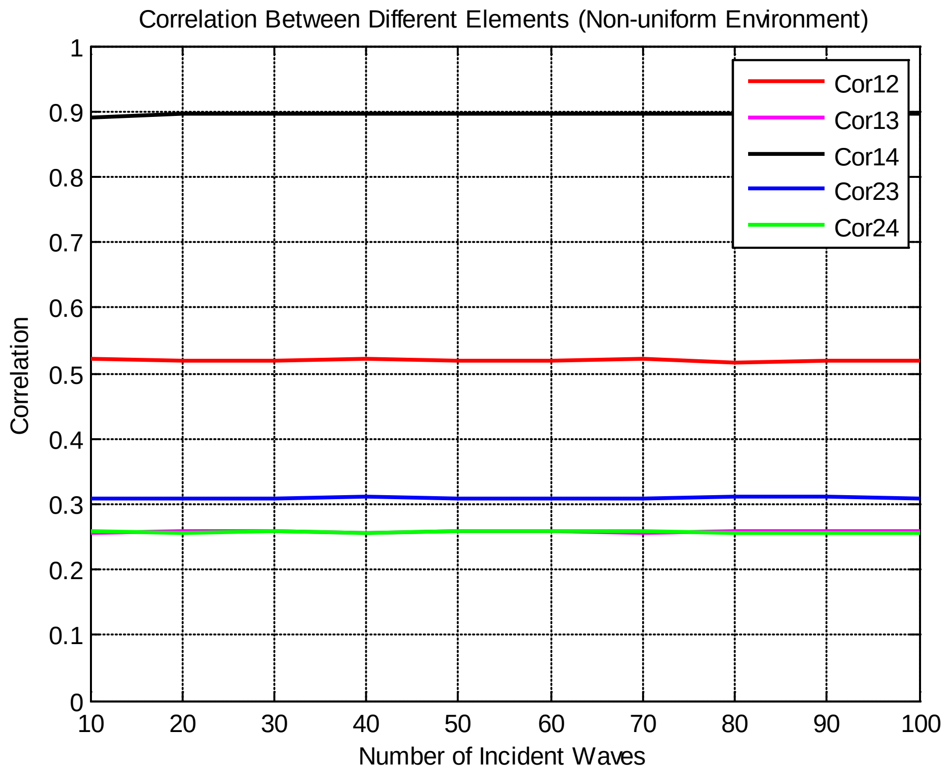

Figure 4.32: Influence of Number of Scatters on Correlation at Distance of 0.1 λ for Beam Port

5.3.9.2 Influence of Number of Scatters on Correlation at Distance of 0.2 λ

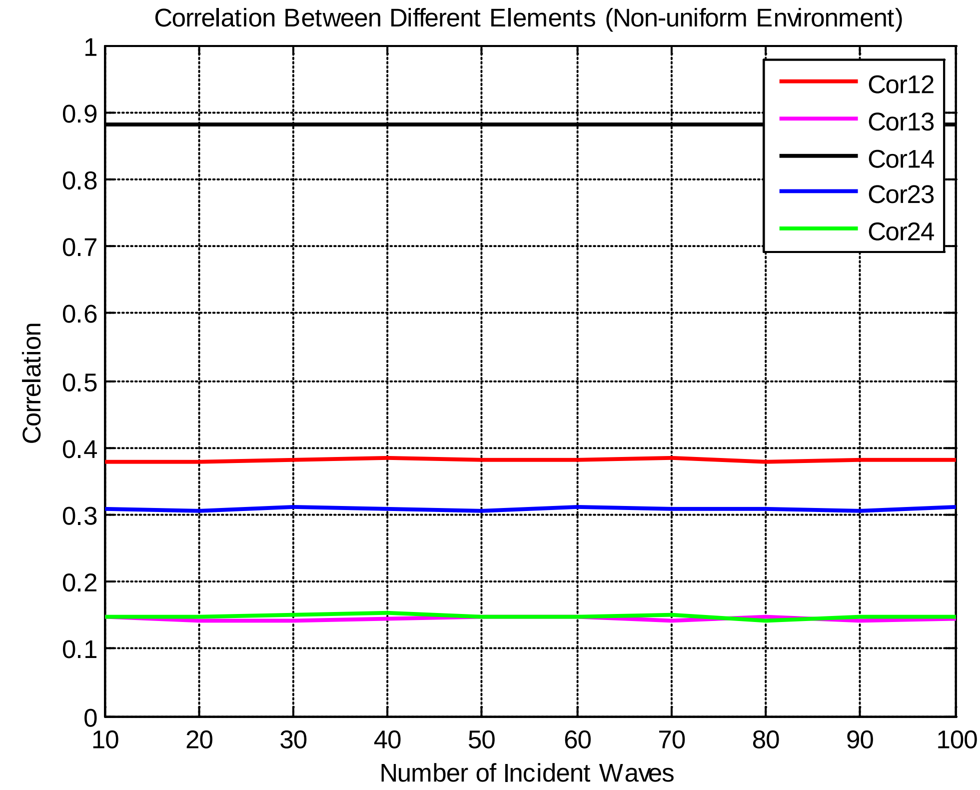

Figure 4.33: Influence of Number of Scatters on Correlation at Distance of 0.2 λ for Beam Port

5.3.9.3 Influence of Number of Scatters on Correlation at Distance of 0.5 λ

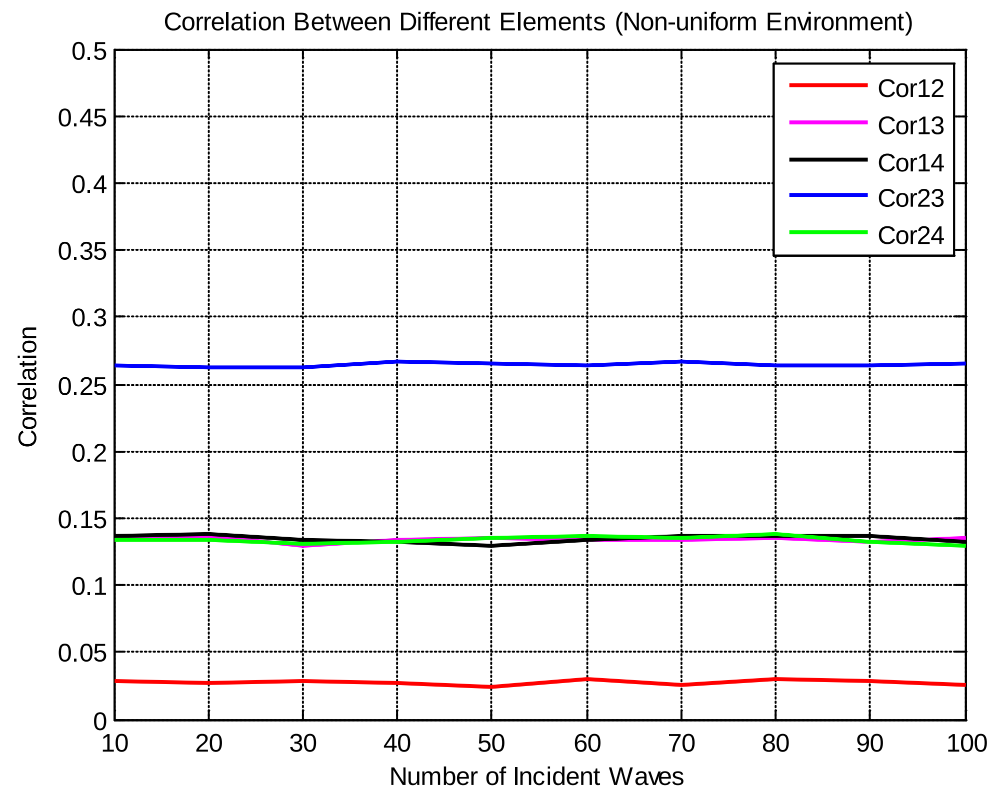

Figure 4.34: Influence of Number of Scatters on Correlation at Distance of 0.5 λ for Beam Port

4.4.2.6 Influence of Number of Scatters on MEG for Beam Port

The figure 4.35 shows the Mean Effective Gain (MEG) of all elements for dual-polarized, dual port isotropic antenna. The value of Theta mean (mean) & angle of spread (variance) are 32 & 64. It is clear from the figure 4.35 that, the MEG of element 1 & 4 both are equal because of symmetric property. Similarly, the MEG of element 2 & 3 are also equal. The MEG is constant from Scatter 0 to 100. It means that number of scatters does not create any effect on MEG. The difference between MEG 1 & MEG 2 is very large because of very small distance between elements (0.1 λ). The figure 4.36 & 4.37 also shows the MEG. In figure 4.36, as we increase the distance between elements, the MEG 1 is improved but MEG 2 is decreased. In figure 4.37, the MEG 1 and MEG 2 are not close to each other. As we increasing the distance, MEG 1 is improved but MEG 2 is decreased. There is no effect of MEG as we change the scatters in non-uniform environment. Both environments have different MEG. In isotropic, MEG of all elements is improved as we increase the distance between elements, but in non-uniform environment, the MEG 1 & 4 is improved, while the MEG 2 & 3 is decreased by increasing the distance between elements.

- **Influence of Number of Scatters on MEG at Distance of 0.1 λ**

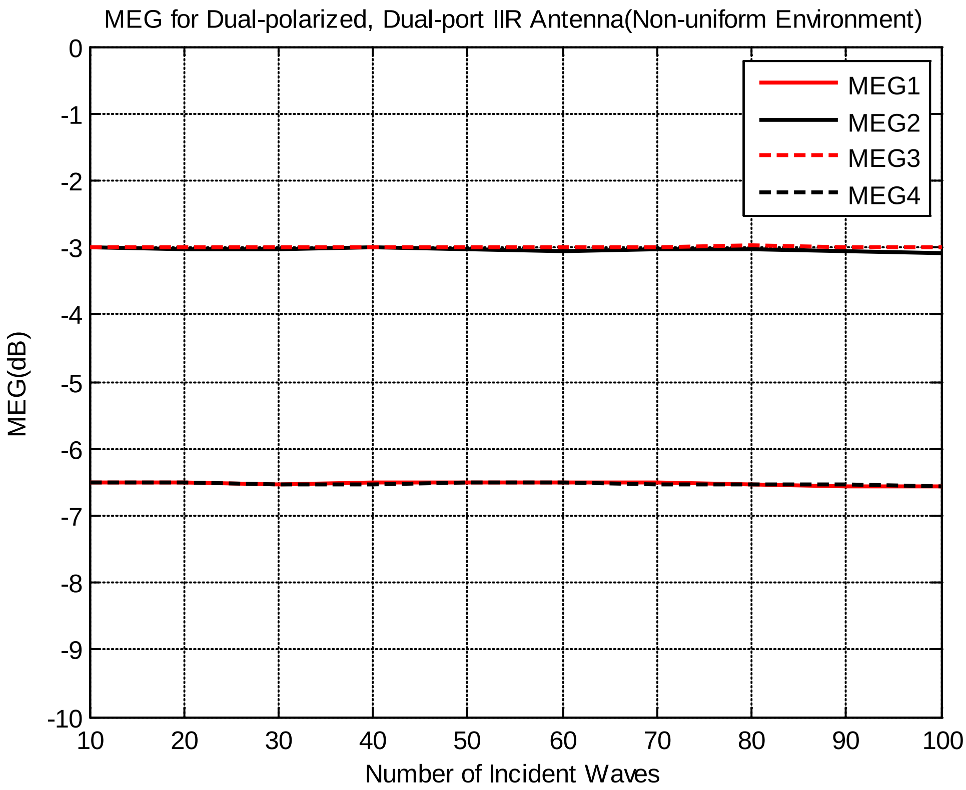

Figure 4.35: Influence of Number of Scatters on MEG at Distance of 0.1 λ for Beam Port

- **Influence of Number of Scatters on MEG at Distance of 0.2 λ**

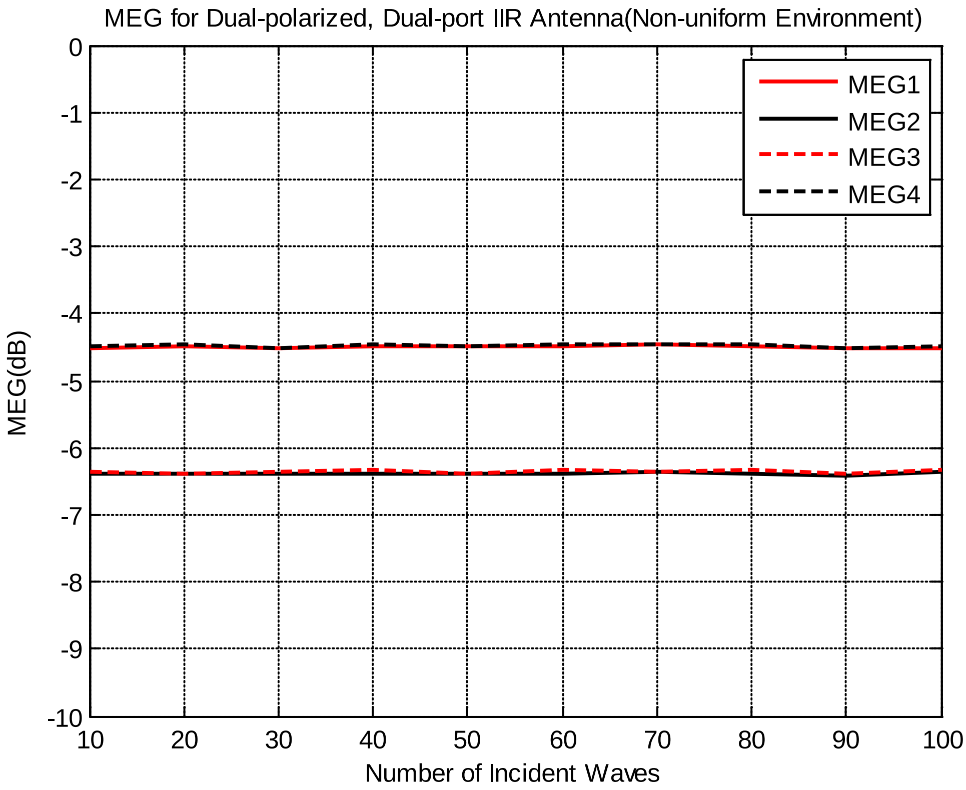

Figure 4.35: Influence of Number of Scatters on MEG at Distance of 0.1 λ for Beam Port

- **Influence of Number of Scatters on MEG at Distance of 0.5 λ**

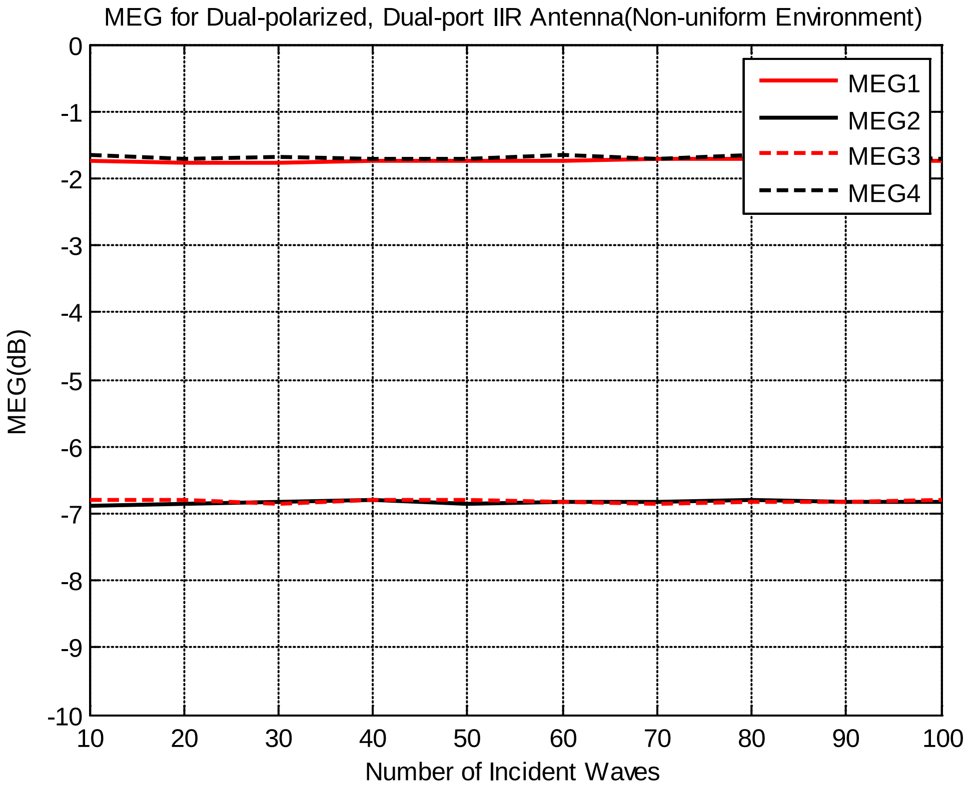

Figure 4.37: Influence of Number of Scatters on MEG at Distance of 0.5 λ for Beam Port

4.4.2.7 Comparative study of Apparent and Effective Diversity Gain

The figure 4.38 shows the apparent and effective diversity gains for element port and beam ports excitation versus number of incident waves in non-uniform environment. The diversity gain of element port and beam port both have the same gain at scatter 10, after that both curves are separate but they are close to each other. The diversity gain is independent from the number of scatters. The both curves of diversity gain will not be converging. In both environments (isotropic and non-uniform), the diversity gain is independent from the number of scatters. In isotropic environment, the curve of both diversity gains is converged but in non-uniform, both curves are diverged after 20 scatters.

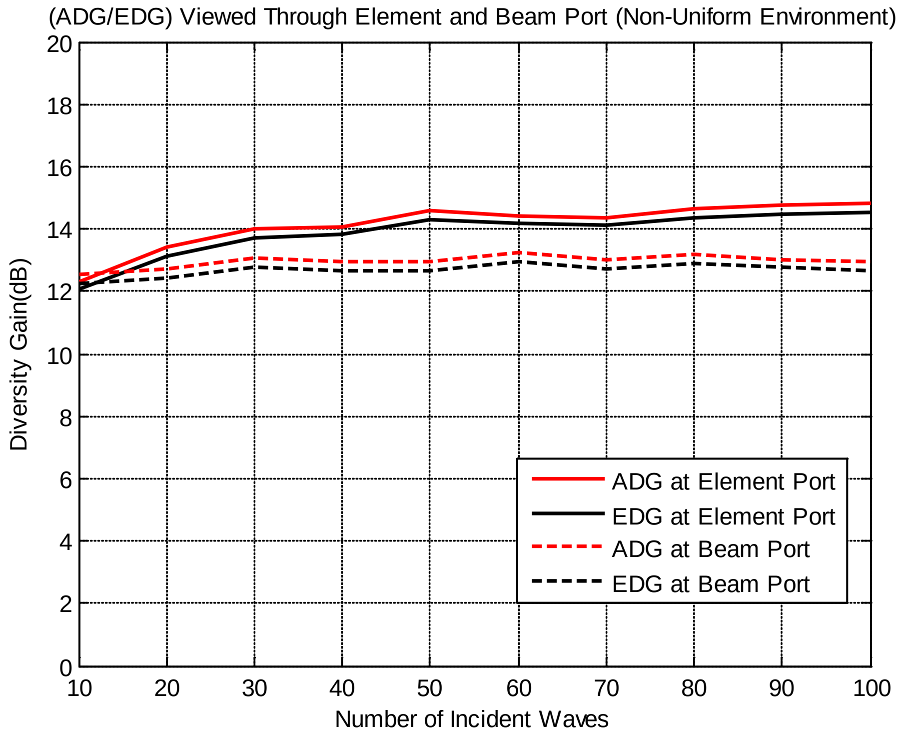

Figure 4.38: DG at Element port and Beam ports versus No of Incident wave for non-uniform

4.5 Comparison between Isotropic & Non-uniform Environment for Element Port:

The table 4.1 shows the results of isotropic and non-uniform environment for element port excitation. The correlation has decreased by the increase of the distance between dipoles. The non-uniform environment has less correlation & diversity gain as compare to isotropic.

Table 4.1: Comparison b/w Isotropic & Non-uniform Environment for Element Port

No	Elements	0.1 λ		0.2 λ		0.5 λ	
		Isotropic	Non-uniform	Isotropic	Non-uniform	Isotropic	Non-uniform
Correlation Between Elements							
1	Element 1 & 2	0.82	0.77	0.61	0.38	0.06	0.41
2	Element 1 & 3	0.19	0.12	0.08	0.49	0.04	0.03
3	Element 1 & 4	0.34	0.66	0.20	0.56	0.03	0.09
4	Element 2 & 3	0.68	0.51	0.59	0.48	0.08	0.41
5	Element 2 & 4	0.19	0.12	0.08	0.49	0.04	0.02
Diversity Gain (dB)							
1	ADG - MRC	14.12	13.78	16.03	16.37	18.59	18.11
2	EDG - MRC	10.65	10.31	14.01	14.35	18.34	17.86
3	ADG - SC	10.75	10.35	12.67	12.99	15.29	14.8
4	EDG - SC	7.28	6.883	10.65	10.97	15.04	14.55
Capacity at SNR 15 dB (bit/s/Hz)							
1	Capacity	6.48	6.51	8.30	8.17	11.20	10.41

4.6 Comparison between Isotropic & Non-uniform Environment for Beam Port:

The table 4.2 shows the results of isotropic and non-uniform environment for beam port excitation which shows that the correlation is very less in non uniform for 0.1 λ, but by the increase of the distance between dipoles, the correlation in non-uniform environment is also increased for both 0.2 λ & 0.5 λ. The diversity gain is also good for isotropic environment for all cases (0.1 λ, 0.2 λ, & 0.5 λ).

Table 4.2: Comparison b/w Isotropic & Non-uniform Environment for Beam Port

No	Elements	0.1 λ		0.2 λ		0.5 λ	
		Isotropic	Non-uniform	Isotropic	Non-uniform	Isotropic	Non-uniform
Correlation Between Elements							
1	Element 1 & 2	0.69	0.16	0.29	0.38	0.02	0.03
2	Element 1 & 3	0.51	0.26	0.21	0.14	0.03	0.13
3	Element 1 & 4	0.96	0.90	0.90	0.89	0.11	0.13
4	Element 2 & 3	0.02	0.30	0.04	0.31	0.01	0.27
5	Element 2 & 4	0.51	0.25	0.21	0.15	0.04	0.13
Diversity Gain (dB)							
1	ADG - MRC	15.61	15.33	16.24	15.89	18.83	16.25
2	EDG - MRC	15.32	15.04	14.41	14.07	18.54	15.96
3	ADG - SC	12.21	12.08	12.82	12.55	15.52	12.93
4	EDG - SC	11.92	11.79	11.13	10.73	15.23	12.64
Capacity at SNR 15 dB (bit/s/Hz)							
1	Capacity	6.56	9.98	8.44	9.18	11.15	11.78

4.7 Comparison between Correlation by MEST & Pattern Multiplication in Non-uniform Environment:

The table 4.3 & 4.4 show that comparison between correlation by MEST code and pattern multiplication for element port excitation & beam port excitation. The results shows that the correlation for all cases (0.1 λ, 0.2 λ, & 0.5 λ) in non uniform environment is approximate same.

4.7.1 Element Port Excitation (EPE):

Table 4.3: Comparison b/w Correlation by MEST & Pattern Multiplication for (EPE)

Spacing	MEST					Pattern Multiplication				
	Cor12	Cor13	Cor14	Cor23	Cor24	Cor12	Cor13	Cor14	Cor23	Cor24
0.1 λ	0.77	0.12	0.66	0.51	0.12	0.77	0.13	0.67	0.51	0.13
0.2 λ	0.38	0.49	0.56	0.48	0.49	0.38	0.50	0.56	0.48	0.50
0.5 λ	0.41	0.03	0.09	0.41	0.03	0.43	0.04	0.08	0.42	0.04

4.7.2 Beam Port Excitation (BPE):

Table 4.4: Comparison b/w Correlation by MEST & Pattern Multiplication for (BPE)

Spacing	MEST					Pattern Multiplication				
	Cor12	Cor13	Cor14	Cor23	Cor24	Cor12	Cor13	Cor14	Cor23	Cor24
0.1 λ	0.52	0.26	0.90	0.31	0.25	0.51	0.25	0.89	0.31	0.25
0.2 λ	0.38	0.14	0.88	0.31	0.15	0.39	0.15	0.88	0.31	0.16
0.5 λ	0.03	0.13	0.13	0.27	0.13	0.03	0.14	0.14	0.27	0.14

Chapter 5

Measurement Result

The four-element dipole antenna array above a finite ground plan MIMO array is measured in the Reverberation Chamber (RC) at Chalmers Antenna Group [2]. The chamber has a dimension of 1.2 m x 1.8 m x 1.05 m with shielding effect over 100dB as shown in figure 5.1. It uses platform stirring, polarization stirring, and frequency stirring to improve accuracy. In all measurements, we used 50 platform and mechanical stirring position. Each platform stirring contain 2 mechanical stirrer positions. The reverberation chamber corresponds to a uniform multipath propagation environment in which all the wave comes uniformly in equal number from all directions [9].

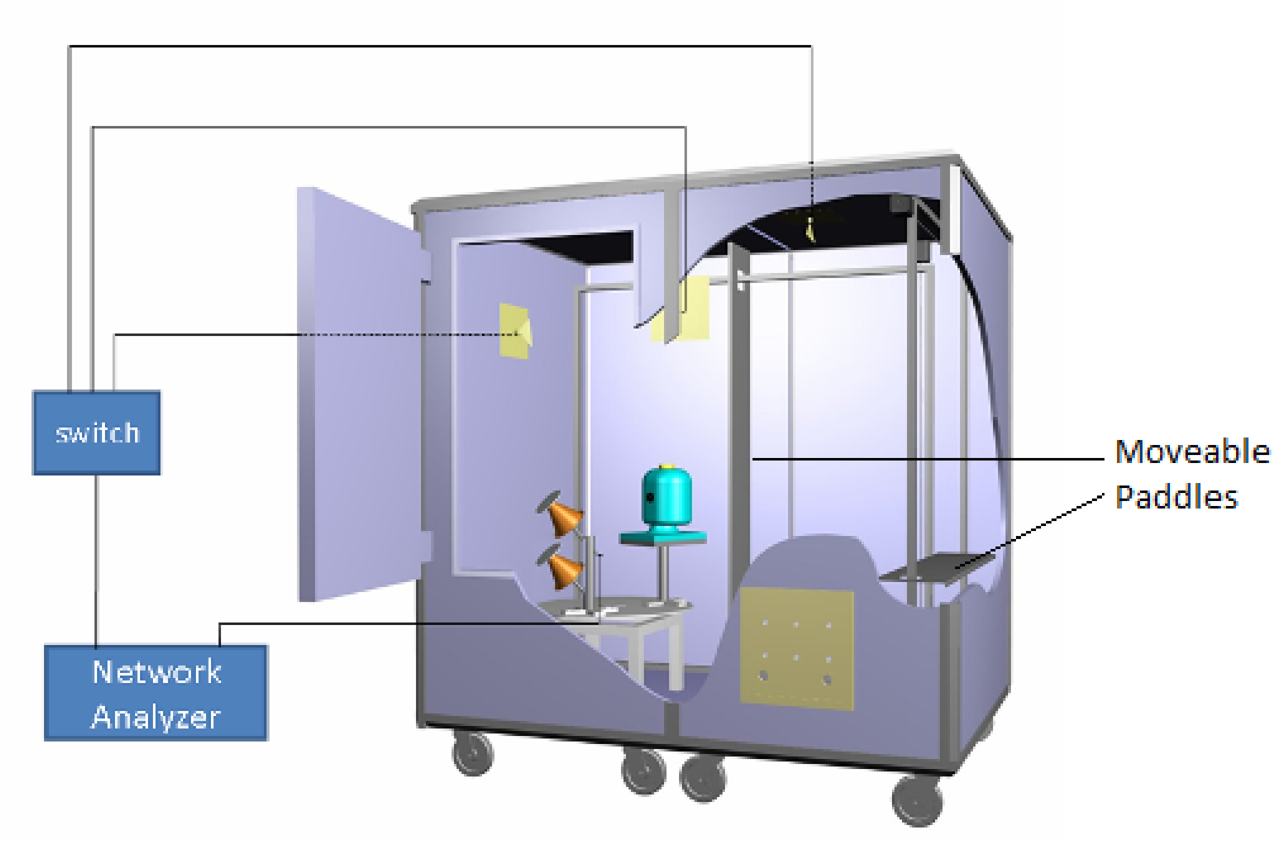

Figure 5.1: Bluetest RC800 reverberation chamber and setup for diversity measurements [13].

We can measure diversity gain relative to different single antenna references. The ADG is measured relative to one of the branches. A more practical effective diversity gain is measured relative to an ideal reference antenna, which is lossless and matched to 50 Ohms. The actual diversity gain is measured relative to an existing single-antenna solution, with certain radiation efficiency [13]. There are different stirrings used to improve the accuracy of the chamber.

✓ **Mechanical Stirrer:**

The RC contains 2 moveable paddles that cause different reflection patterns depending on their positions. These 2 moveable paddles are called mechanical stirrer as shown in figure 5.1. These 2 paddles can be moved along a complete wall and along the ceiling. A good set of data contains a large amount of independent samples.

✓ **Polarization Stirrer:**

There are three orthogonal antennas at the walls inside the chamber connected with the switch as shown in figure 5.1. Just like the paddles, their task is to multiply the number of samples.

✓ **Platform Stirrer:**

Antenna under test (AUT) is located on a rotatable platform which moves the antenna to different positions in the chamber. This stirring method is very effective in small chambers.

When measuring a diversity antenna system, first dipole antenna is fed and all other are terminated by 50 Ω load, similarly, for 2nd and so on. The combining method used in the reverberation chamber is selection combining (SC).

There are three different configurations are measured in reverberation Chamber. These configurations are shown in table 5.1 & 5.2. The length of dipoles is approximate same but with different distances and height above ground plane. These three distances are 0.1 λ, 0.2 λ and 0.5 λ.

Table 5.1: Length of Dipoles

No	Distance between Elements	Length of Dipole (mm)			
		Dipole - 1	Dipole - 2	Dipole - 3	Dipole - 4
1	Case-1 (0.5 λ)	72.8	79.3	74.6	73.4
2	Case-2 (0.2 λ)	72.8	79.3	74.6	73.4
3	Case-3 (0.1 λ)	72.8	79.3	74.6	73.4

Table 5.2: Length of Dipoles

No	Distance between Elements	Dipole arm length (mm)			
		Dipole-1	Dipole-2	Dipole-3	Dipole-4
1	Case-1 (0.5 λ)	34	34	35	35
2	Case-2 (0.2 λ)	36	35	36.7	36.8
3	Case-3 (0.1 λ)	33.72	33	33.8	35

5.1 Case –1: Four dipoles antenna array at a distance of 0.5 λ

The measurement diagram of four horizontal dipole antenna array with 0.5 λ distance between them is shown in figure 5.2. The dipole array is placed inside the RC with reference antenna (dual polarized isotropic antenna) and phantom.

5.1.1 Measurement Setup:

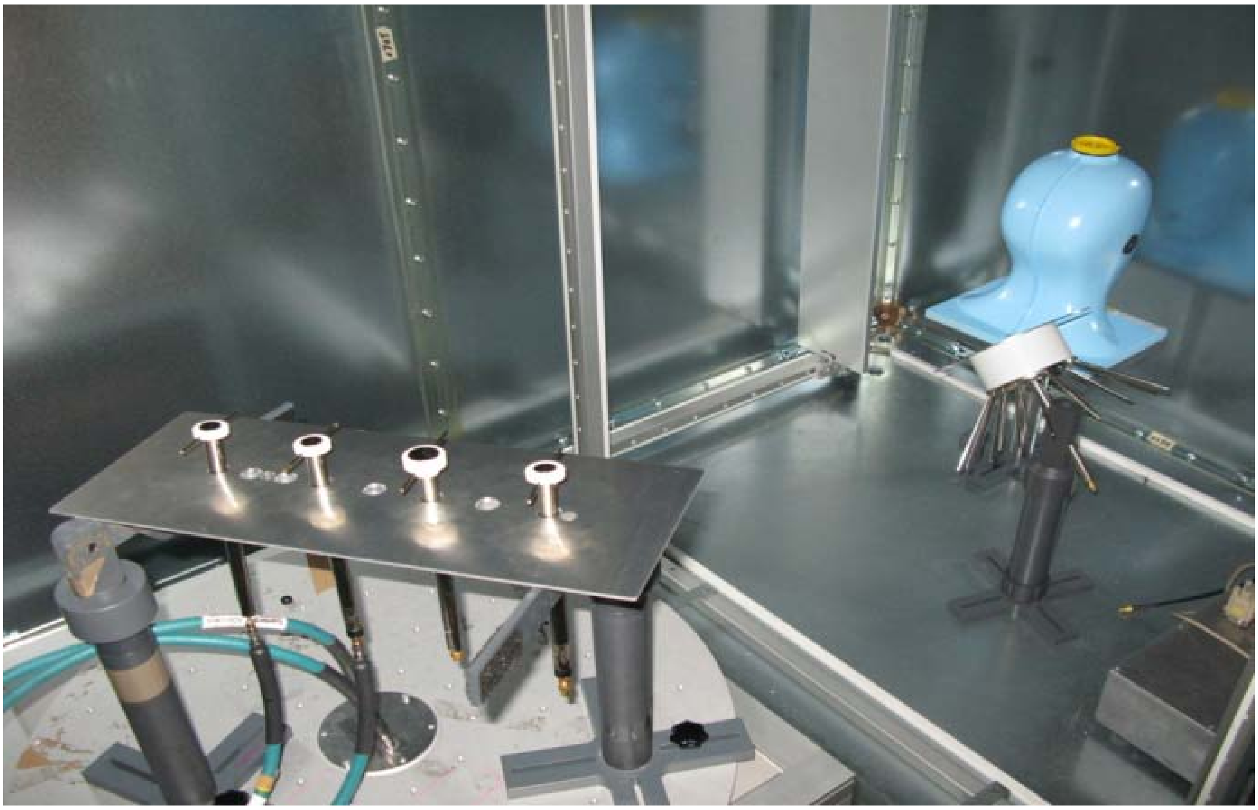

Figure 5.2: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.5 λ

5.1.2 Measurement Results

The figure 5.3 shows the CDF of the diversity antenna at 1.8 GHz, measured in a RC when the distance between dipoles is 0.5 λ. It is clear from the figure 5.3 that the curve of branch 1 and 4 are same. Similarly the curve of branch 2 & 3 are same. The radiation efficiency is approximate 94%. The curves of all braches followed the curve of theoretical Rayleigh. The apparent diversity gain is 15.17 dB and effective diversity gain is 14.84 dB. In figure 5.4 shows the capacity of 3 x 4 MIMO systems. The capacity at SNR 15 dB is 12.37 bit/s/Hz.

5.1.2.1 Diversity Gain:

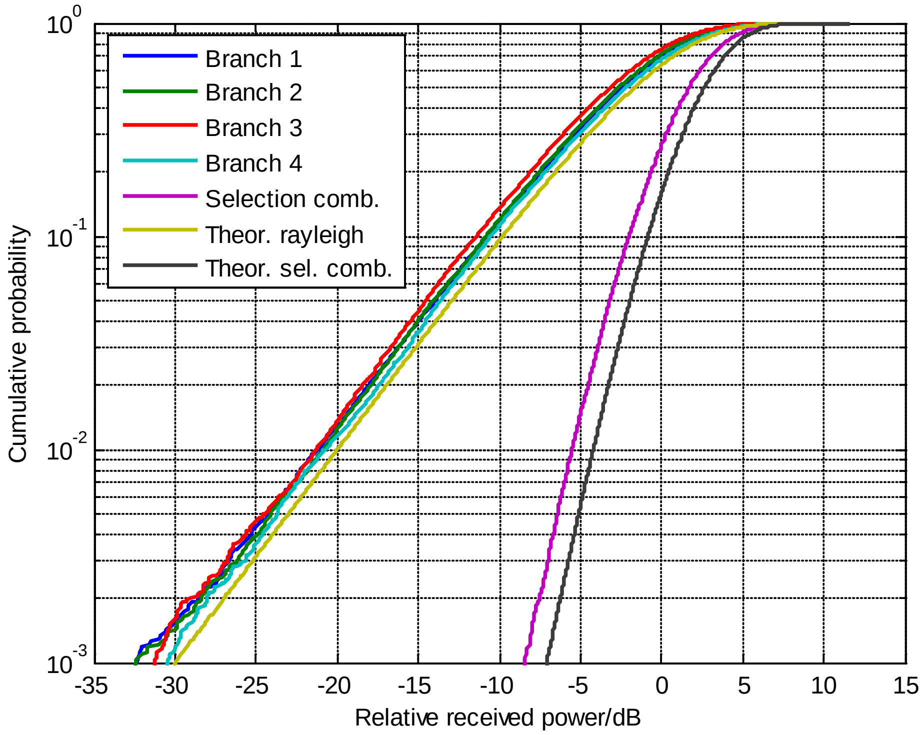

Figure 5.3: CDF of the diversity antenna, measured in a RC (Distance between dipole is 0.5 λ)

5.1.2.2 Capacity:

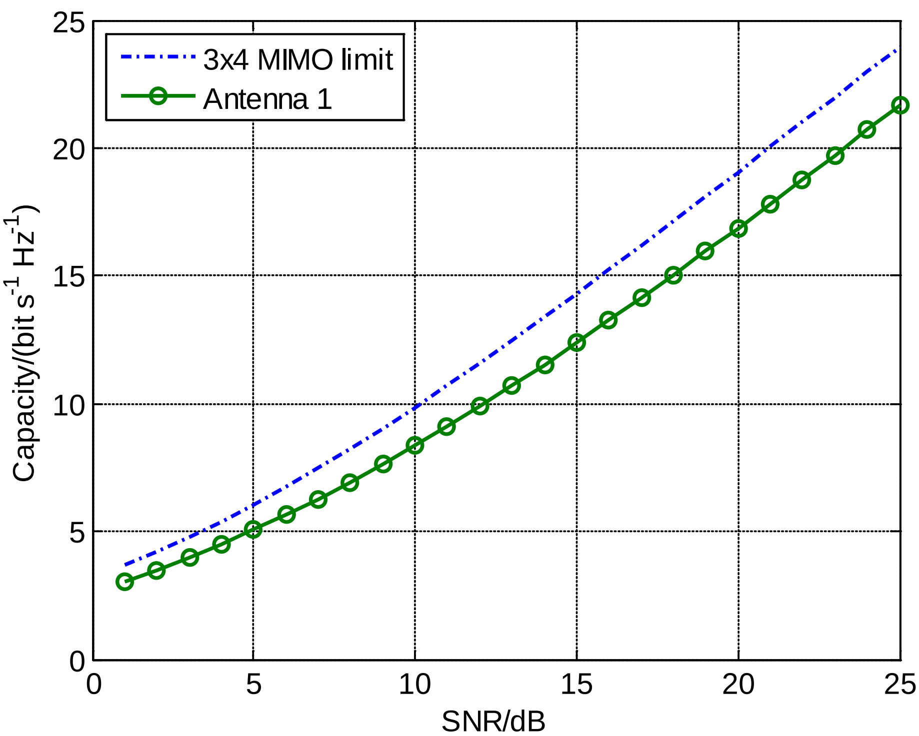

Figure 5.4: Capacity of 3 x 4 MIMO systems, measured in a RC (Distance between dipole is 0.5 λ)

5.2 Case – 2: Four dipoles antenna array at a distance of 0.2 λ

The measurement Setup of four dipoles antenna array with 0.2 λ distance between them is shown in figure 5.5.

5.2.1 Measurement Setup:

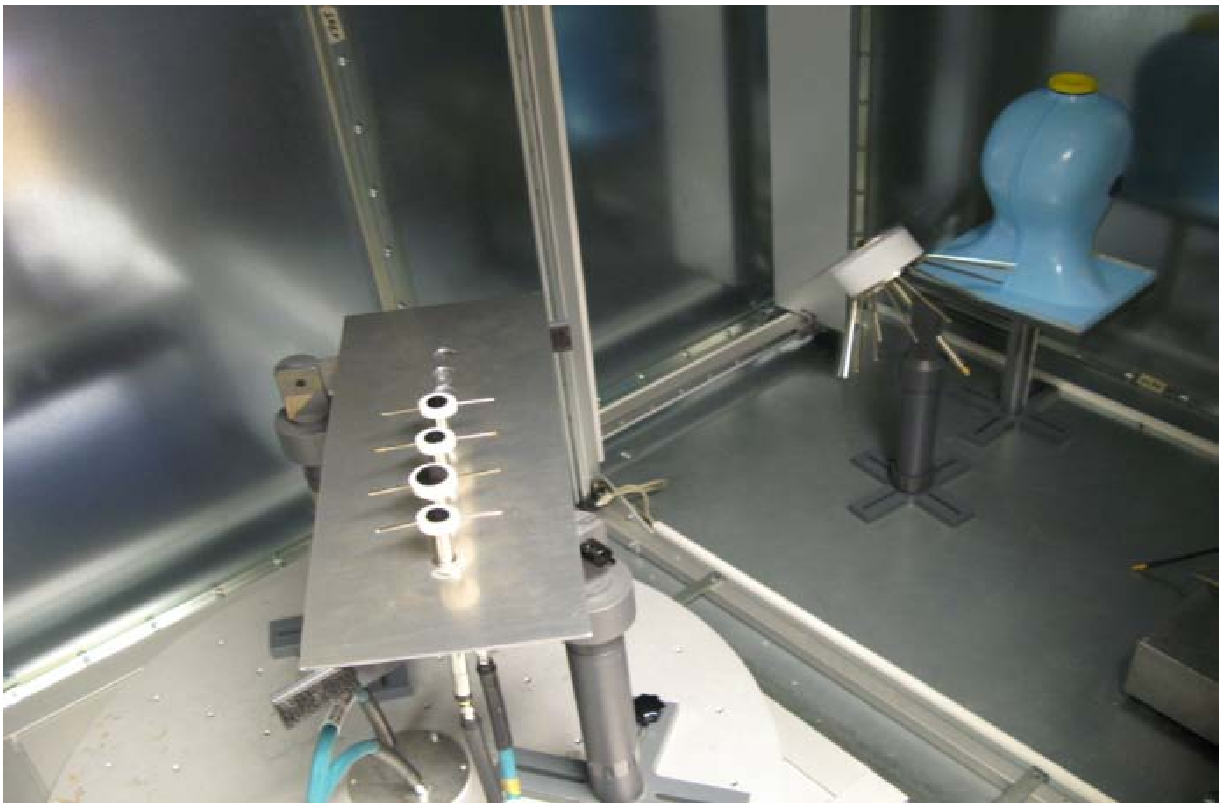

Figure 5.5: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.2 λ

5.1.2 Measurement Results

The figure 5.6 show the CDF of the diversity antenna at a distance of 0.2 λ measured in a RC. It is clear from the figure 5.6 that the curve of branch 1 and 4 are same. Similarly the curve of branch 2 & 3 are same. The radiation efficiency is decreased due to decreasing the distance between dipoles. The curve of branch 1 is shifted towards left which shows that the correlation between element 1 & 2 is increased. Similarly, branch 2 & 3 is shifted. The diversity gain is also decreased. The apparent diversity gain is now 13.74 dB from 15.17 dB and effective diversity gain is now 12.1 dB from 14.84 dB. In figure 5.7 shows the capacity of 3 x 4 MIMO systems. The capacity is decreased due to decreasing the distance between elements. The capacity at SNR 15 dB is now 10.38 bit/s/Hz from 12.37 bit/s/Hz.

5.2.3.1 Diversity Gain:

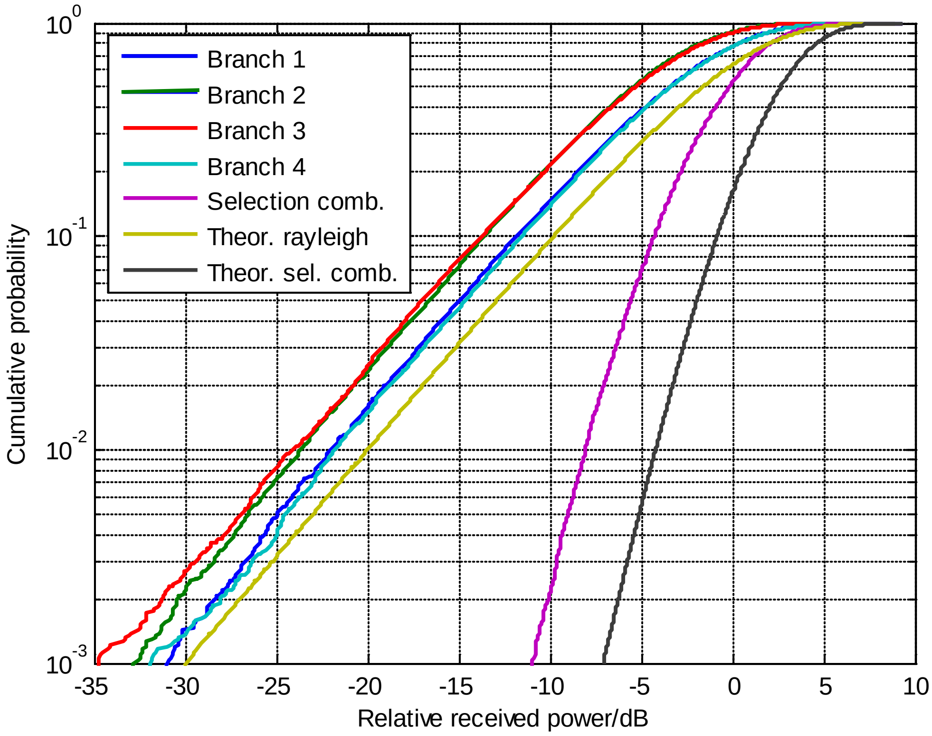

Figure 5.6: CDF of the diversity antenna, measured in a RC (Distance between dipole is 0.2 λ)

5.2.3.2 Capacity:

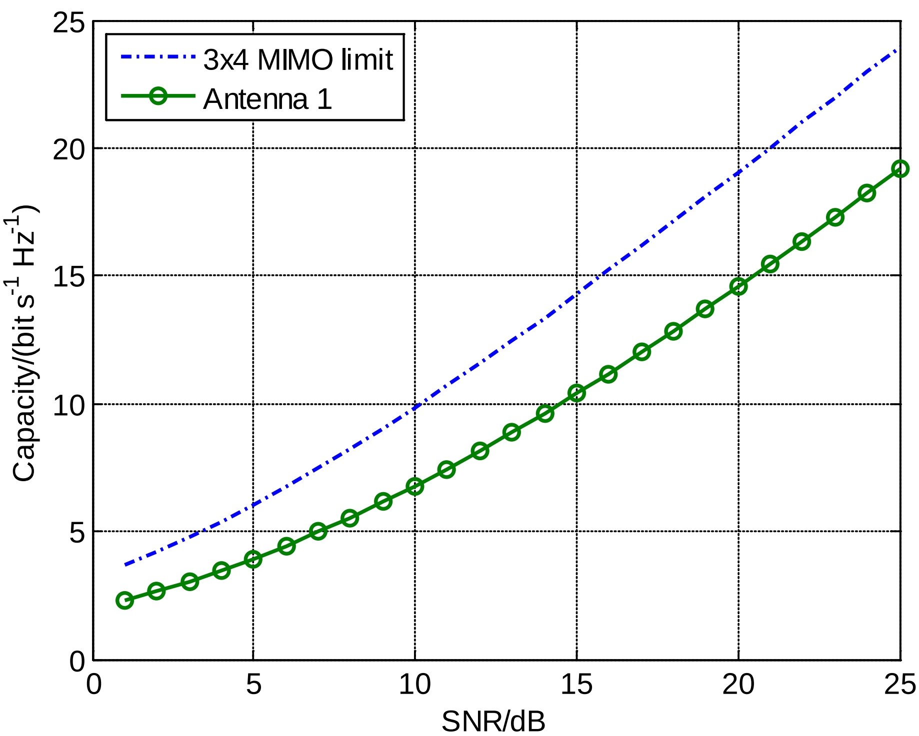

Figure 5.7: Capacity of 3 x 4 MIMO systems, measured in a RC (Distance between dipole is 0.2 λ)

5.3 Case – 3: Four dipoles antenna array at a distance of 0.1 λ

The measurement Setup of four dipoles antenna array with 0.1 λ distance between them is shown in figure 5.8.

5.3.1 Measurement Setup:

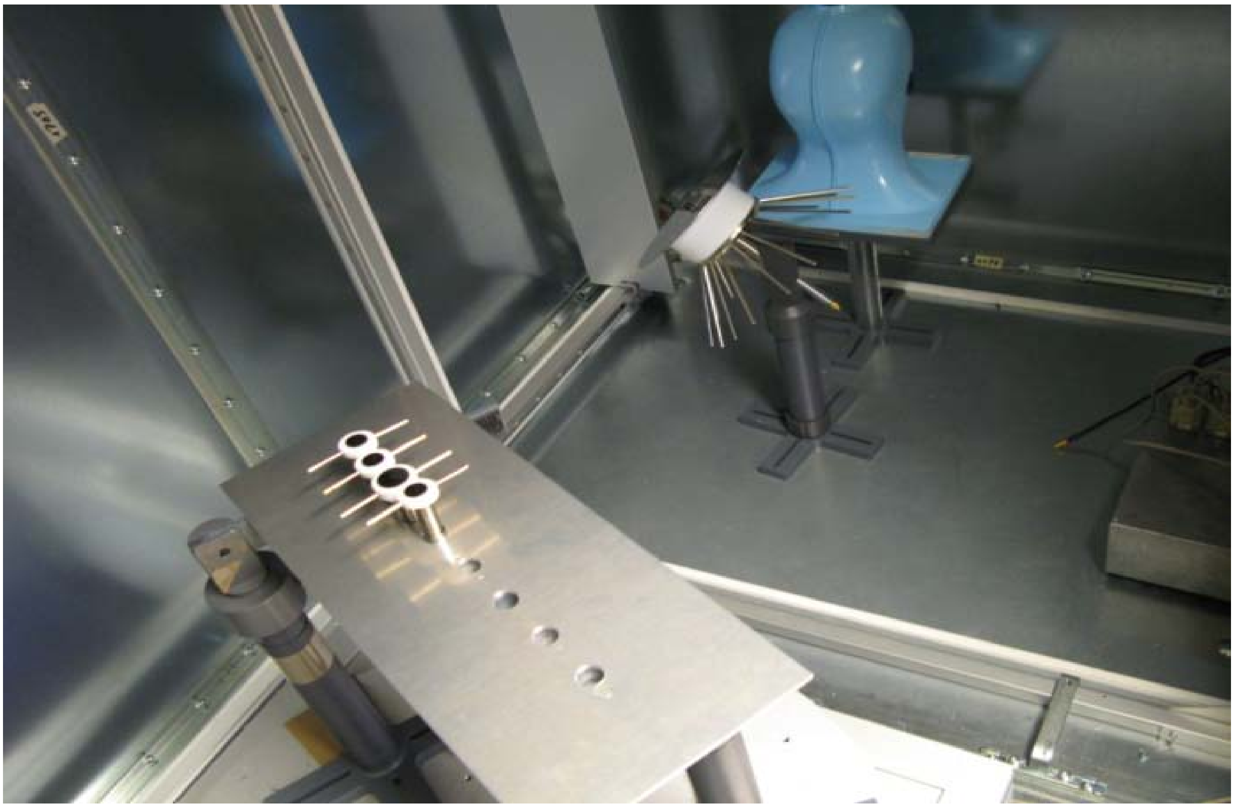

Figure 5.8: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.1 λ

5.3.2 Measurement Results

The figure 5.9 show the CDF of the diversity antenna at a distance of 0.1 λ measured in a RC. It is clear from the figure 5.9 that the curve of branch 1 and 4 are same. Similarly the curve of branch 2 & 3 are same. The radiation efficiency is further decreased due to decrease in the distance from 0.2 to 0.1 λ. The curve of all branches is shifted towards left which shows that the correlation between elements is increased. The diversity gain is also further decreased. The apparent diversity gain is now 12.53 dB from 13.74 dB and effective diversity gain is now 9.757 dB from 12.1 dB. In figure 5.10 shows the capacity of 3 x 4 MIMO systems. The capacity is also further decreased due to decrease in the distance between elements. The capacity at SNR 15 dB is now 8.977 bit/s/Hz from 10.38 bit/s/Hz.

5.3.3.1 Diversity Gain:

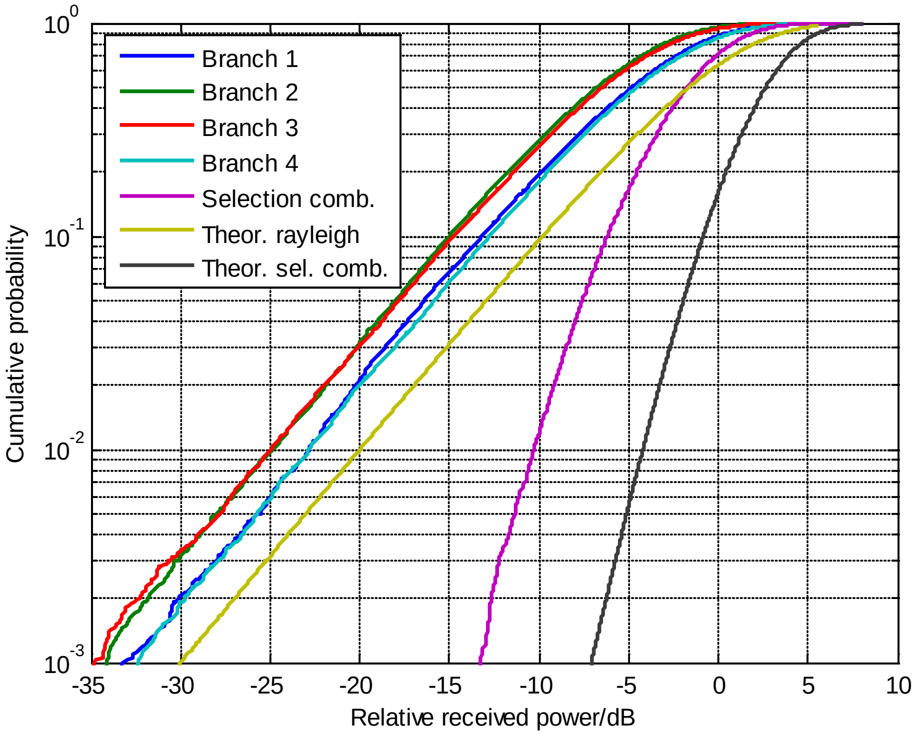

Figure 5.9: CDF of the diversity antenna, measured in a RC (Distance between dipoles is 0.1 λ)

5.3.3.2 Capacity:

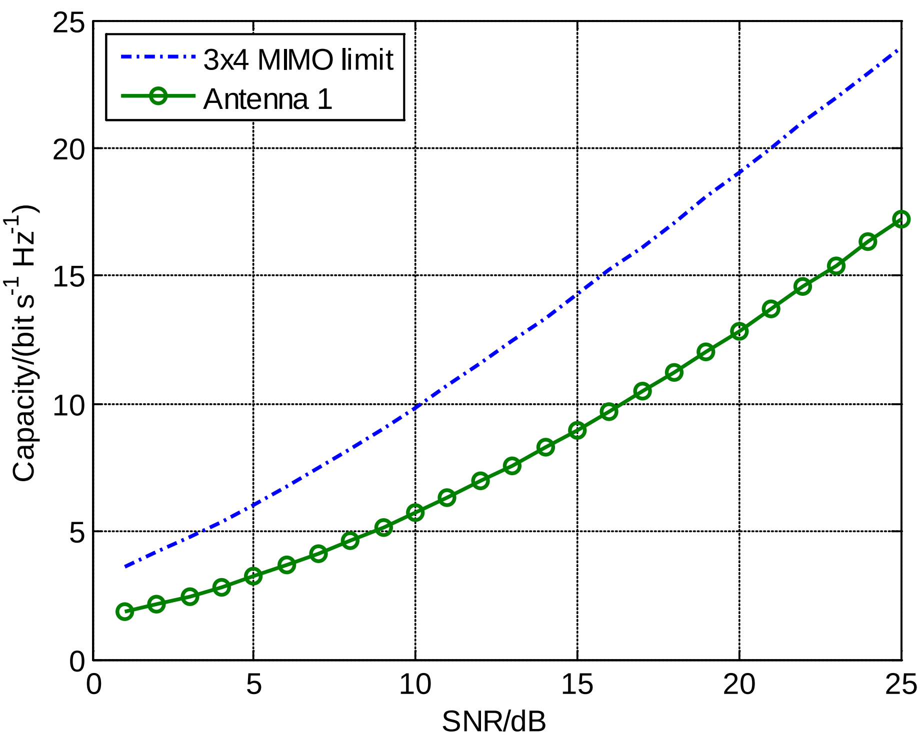

Figure 5.10: Capacity of 3 x 4 MIMO systems, measured in a RC (Distance between dipoles is 0.1 λ)

Chapter 6

Comparison between Simulated & Measured Results

The simulated and measured results are compared in this section. We have simulated and measured three different cases of dipole antenna array. Each case has different capacity & diversity gain in isotropic environment and correlation, diversity gain & MEG in non-uniform environment. The result of isotropic environment is compared here. Three different configurations of dipole antenna array are shown below.

6.1 Case – 1: Simulated and Measured Result at a distance of 0.5 λ

6.1.1 Simulation & Measurement Setup:

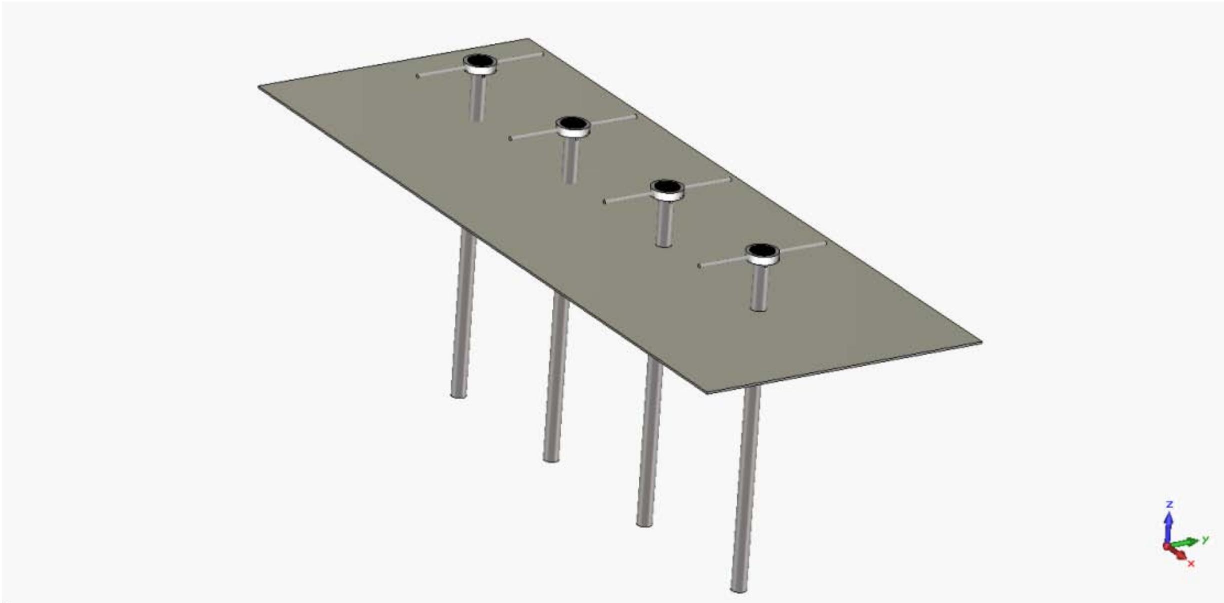

Figure 6.1: Simulation Setup of Antenna Array above a Ground Plane at a distance of 0.5 λ in CST

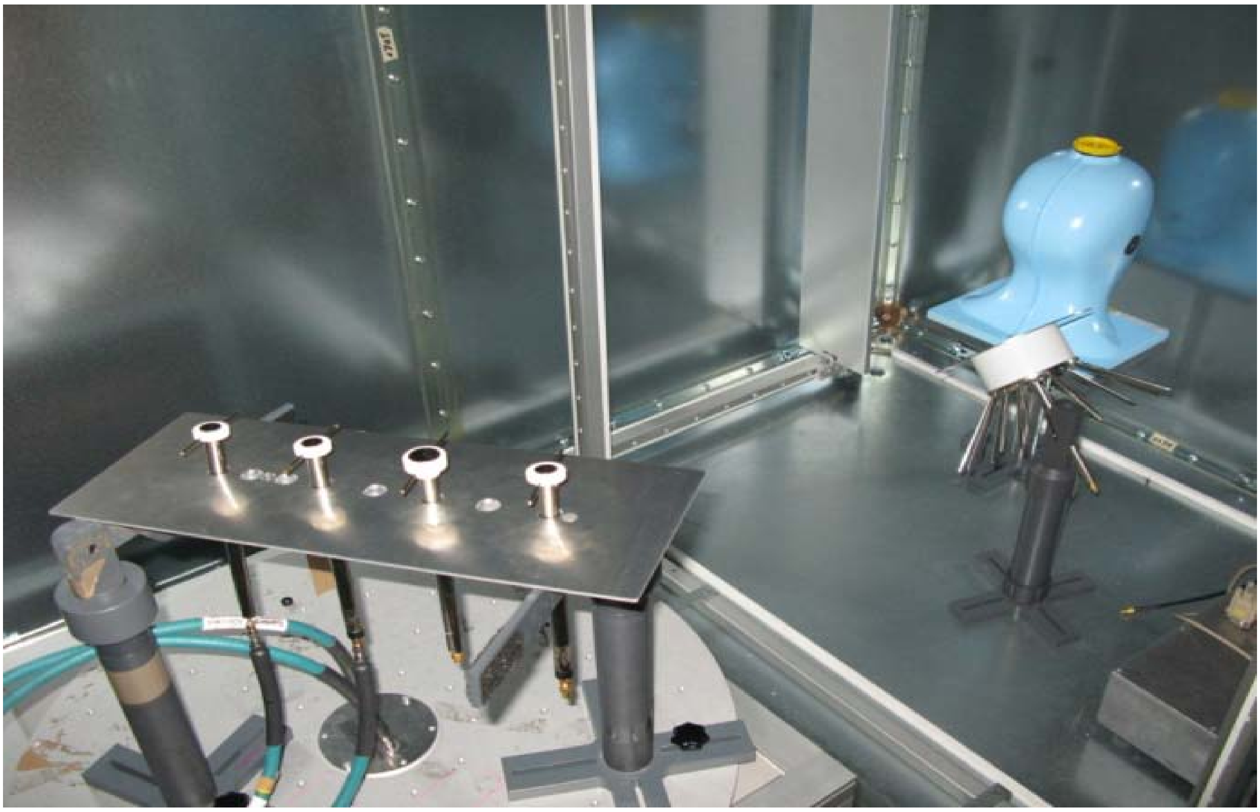

Figure 6.2: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.5 λ in RC

6.1.2 Simulated & Measured Diversity Gain:

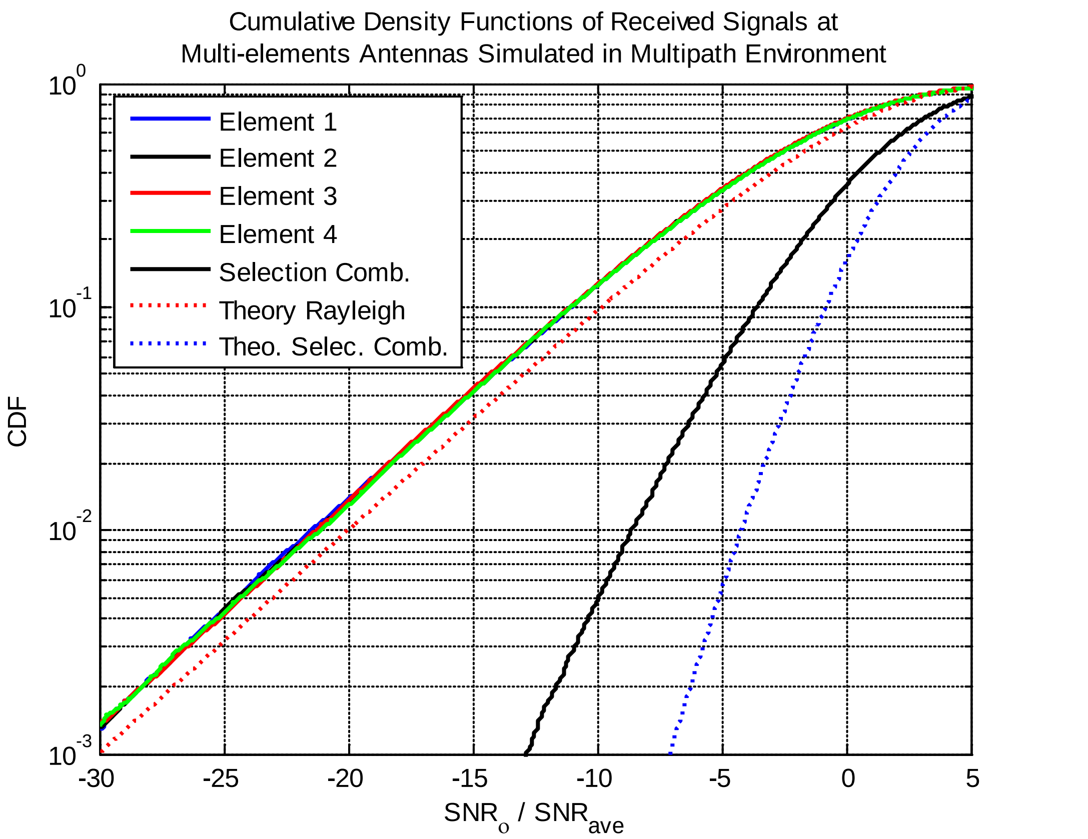

Figure 6.3: CDF of the diversity antenna, simulated in matlab (Distance between dipoles is 0.5 λ)

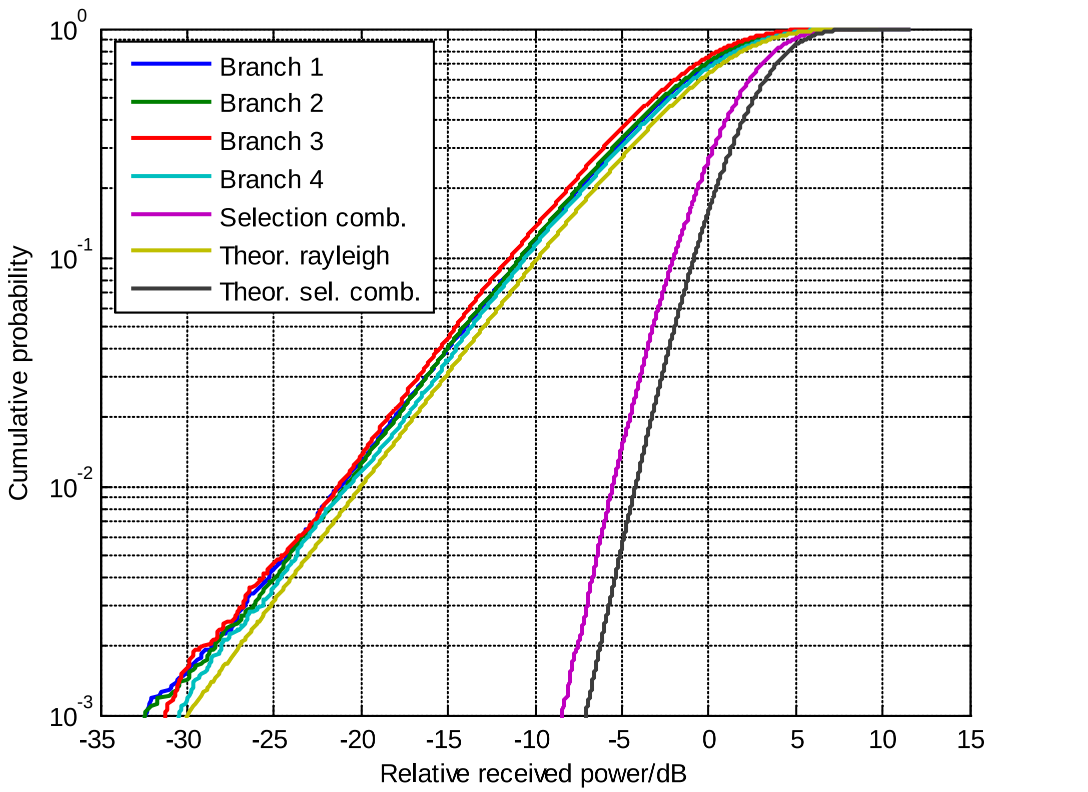

Figure 6.4: CDF of the diversity antenna, measured in RC (Distance between dipoles is 0.5 λ)

6.1.3 Simulated & Measured Capacity:

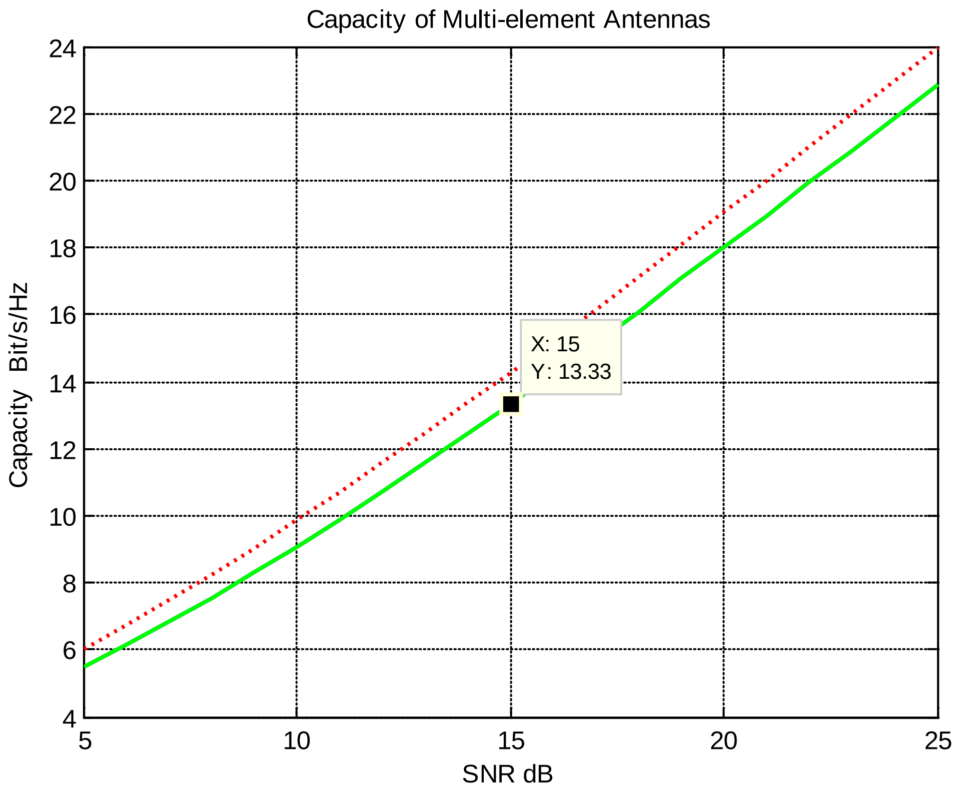

Figure 6.5: Capacity of 3 x 4 MIMO systems, simulated in matlab (Distance between dipoles is 0.5 λ)

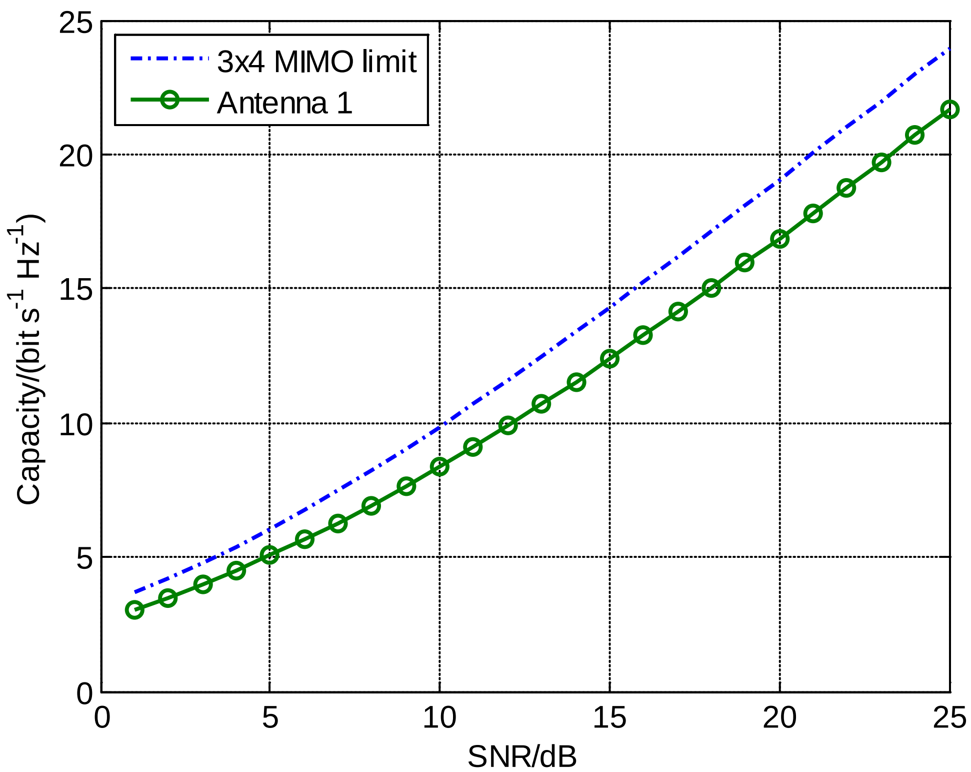

Figure 6.6: Capacity of 3 x 4 MIMO systems, measured in RC (Distance between dipoles is 0.5 λ)

6.1.3 Comparison between Simulated & Measured Results for case-1:

Table 6.1: Comparison b/w Simulated & Measured Results for Case-1			
No	**Elements**	**Simulated**	**Measured**
	Correlation Between Elements		
1	Element 1 & 2	0.05	0.06
2	Element 1 & 3	0.05	0.05
3	Element 1 & 4	0.01	0.04
4	Element 2 & 3	0.07	0.09
	Total Radiation Efficiency (dB)		
1	Total Radiation Efficiency of 1st Element	-0.29	-0.72
2	Total Radiation Efficiency of 2nd Element	-0.36	-0.90
3	Total Radiation Efficiency of 3rd Element	-0.40	-1.26
4	Total Radiation Efficiency of 4th Element	-0.27	-0.31
	Diversity Gain (dB)		
1	Apparent Diversity Gain	15.13	15.17
2	Effective Diversity Gain	14.88	14.48
	Capacity at SNR 15 dB (bit/s/Hz)		
1	Capacity	13.33	12.37

6.2 Case – 2: Simulated and Measured Result at a distance of 0.2 λ

6.2.1 Simulation & Measurement Setup:

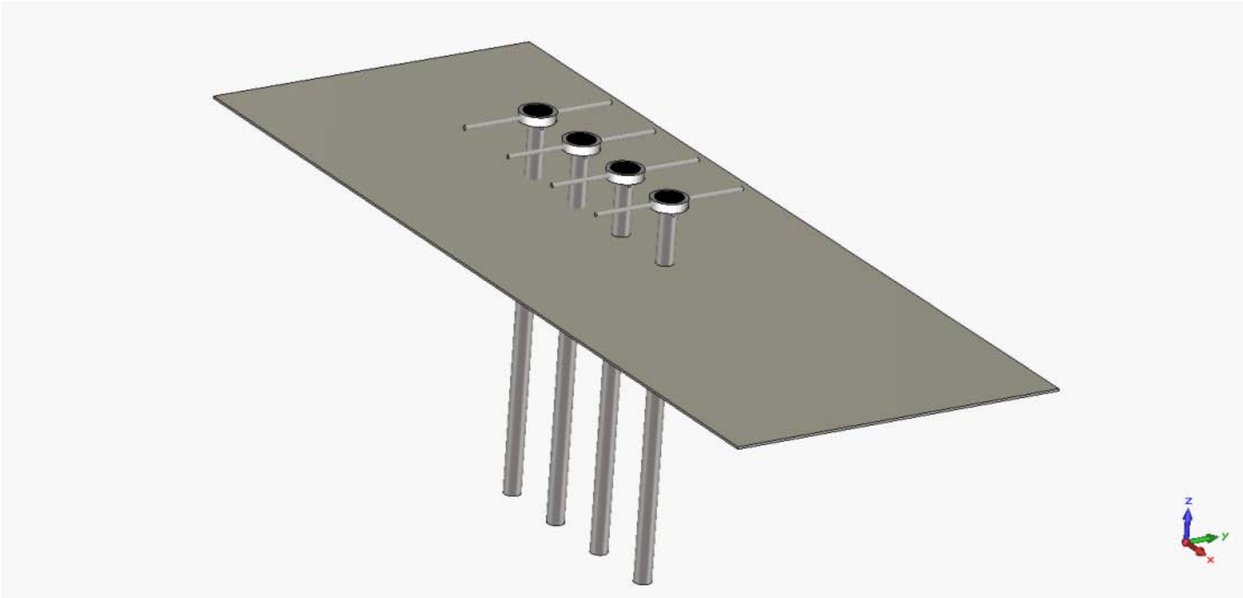

Figure 6.7: Simulation Setup of Antenna Array above a Ground Plane at a distance of 0.2 λ in CST

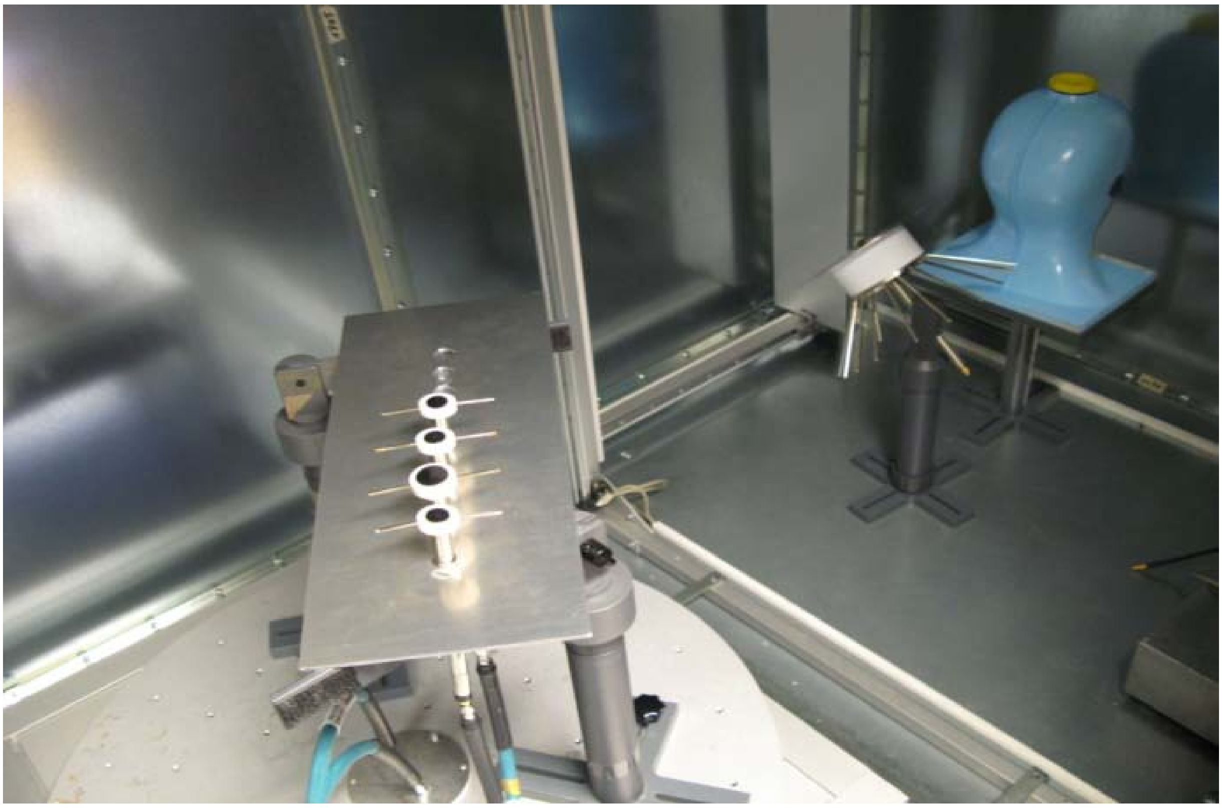

Figure 6.8: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.2 λ in RC

6.2.2 Simulated & Measured Diversity Gain:

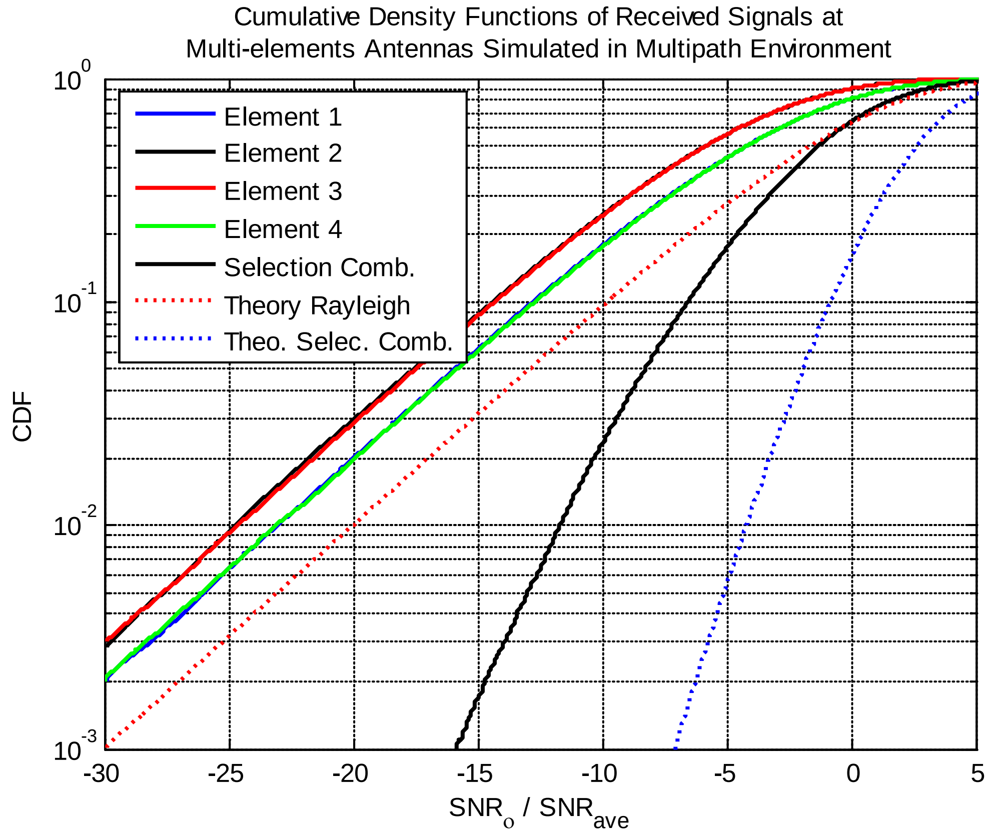

Figure 6.9: CDF of the diversity antenna, simulated in matlab (Distance between dipoles is 0.2 λ)

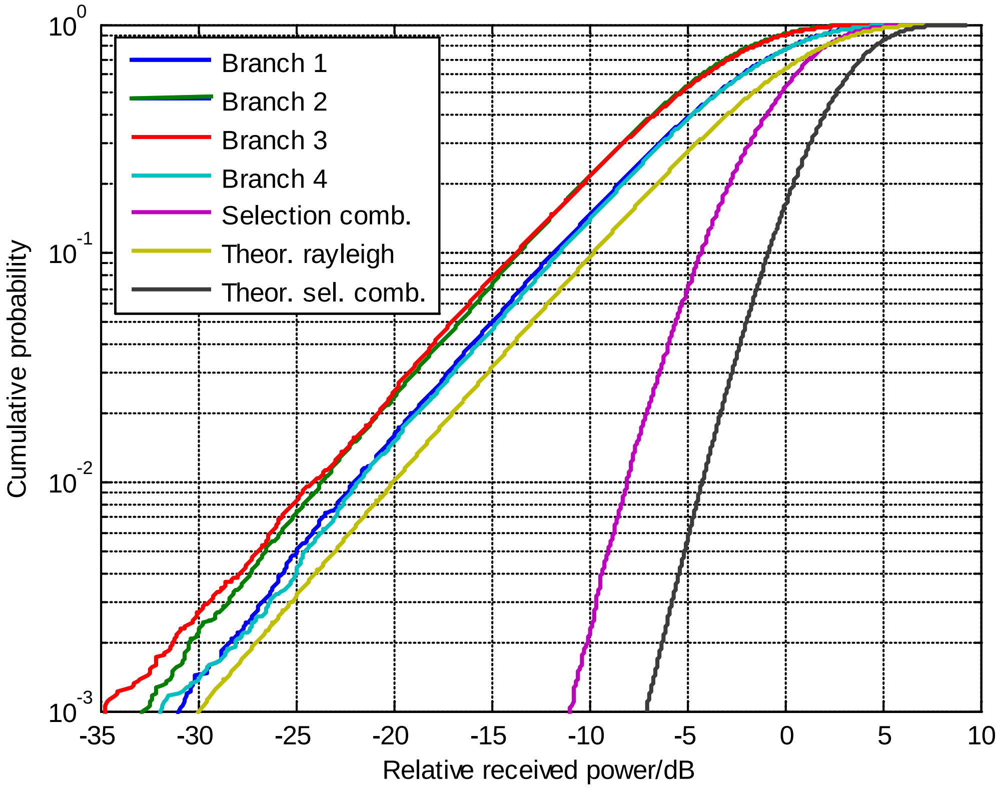

Figure 6.10: CDF of the diversity antenna, measured in RC (Distance between dipoles is 0.2 λ)

6.2.3 Simulated & Measured Capacity:

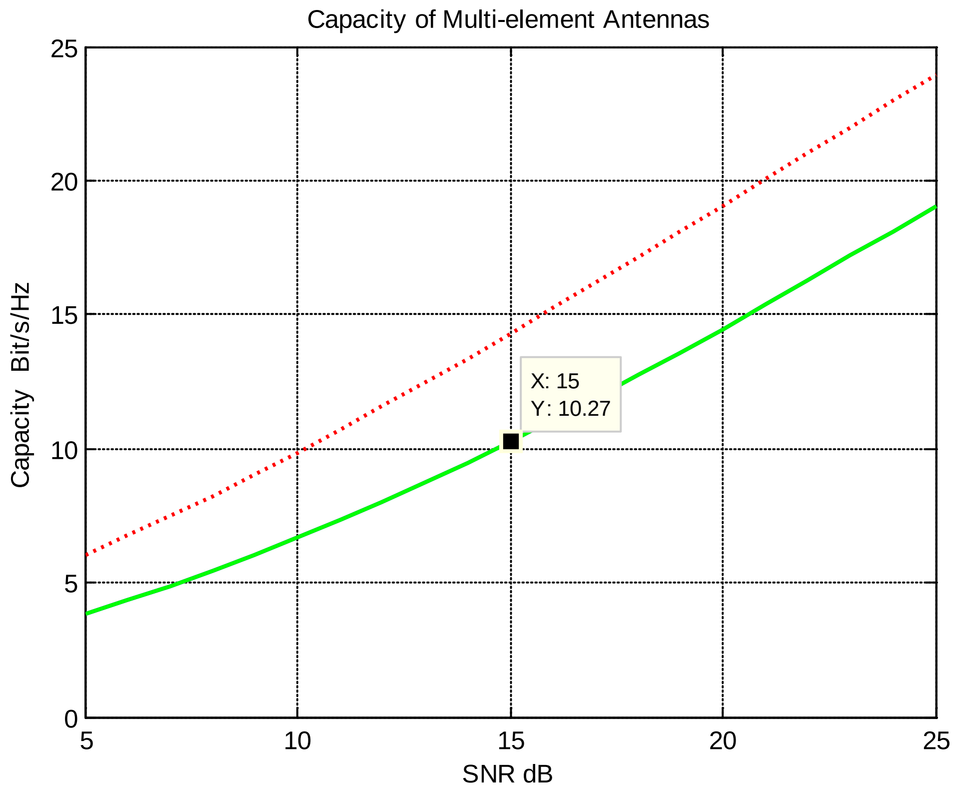

Figure 6.11: Capacity of 3 x 4 MIMO systems, simulated in matlab (Distance between dipoles is 0.2 λ)

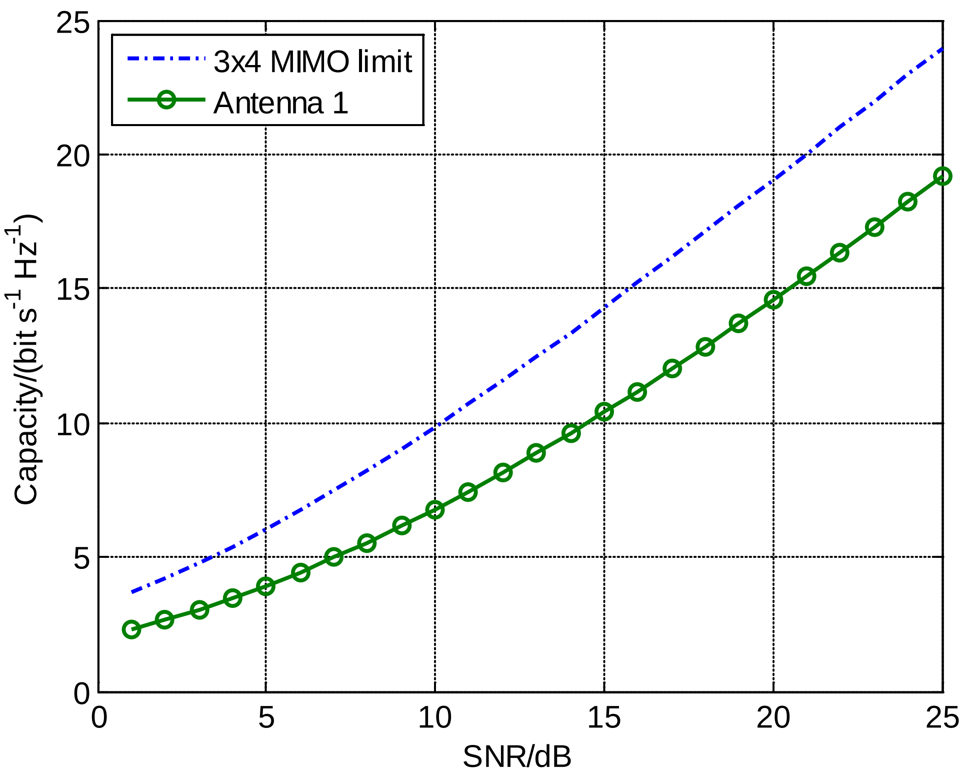

Figure 6.12: Capacity of 3 x 4 MIMO systems, measured in RC (Distance between dipoles is 0.2 λ)

6.2.3 Comparison between Simulated & Measured Results for case-2:

Table 6.2: Comparison b/w Simulated & Measured Results for Case-2			
No	**Elements**	**Simulated**	**Measured**
Correlation Between Elements			
1	Element 1 & 2	0.61	0.49
2	Element 1 & 3	0.09	0.16
3	Element 1 & 4	0.22	0.03
4	Element 2 & 3	0.59	0.46
Total Radiation Efficiency (dB)			
1	Total Radiation Efficiency of 1st Element	-2.05	-1.85
2	Total Radiation Efficiency of 2nd Element	-3.69	-3.74
3	Total Radiation Efficiency of 3rd Element	-3.71	-3.6
4	Total Radiation Efficiency of 4th Element	-2.09	-1.76
Diversity Gain (dB)			
1	Apparent Diversity Gain	12.89	13.86
2	Effective Diversity Gain	10.87	12.22
Capacity at SNR 15 dB (bit/s/Hz)			
1	Capacity	10.27	10.38

6.3 Case – 3: Simulated and Measured Result at a distance of 0.1 λ

6.3.1 Simulation & Measurement Setup:

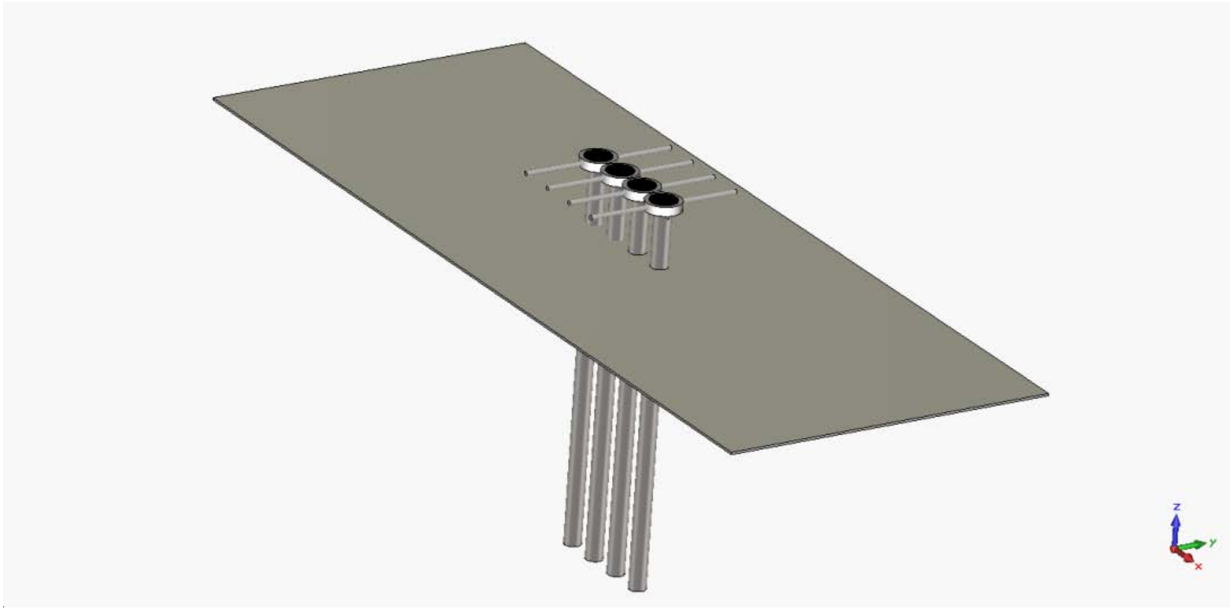

Figure 6.13: Simulation Setup of Antenna Array above a Ground Plane at a distance of 0.1 λ in CST

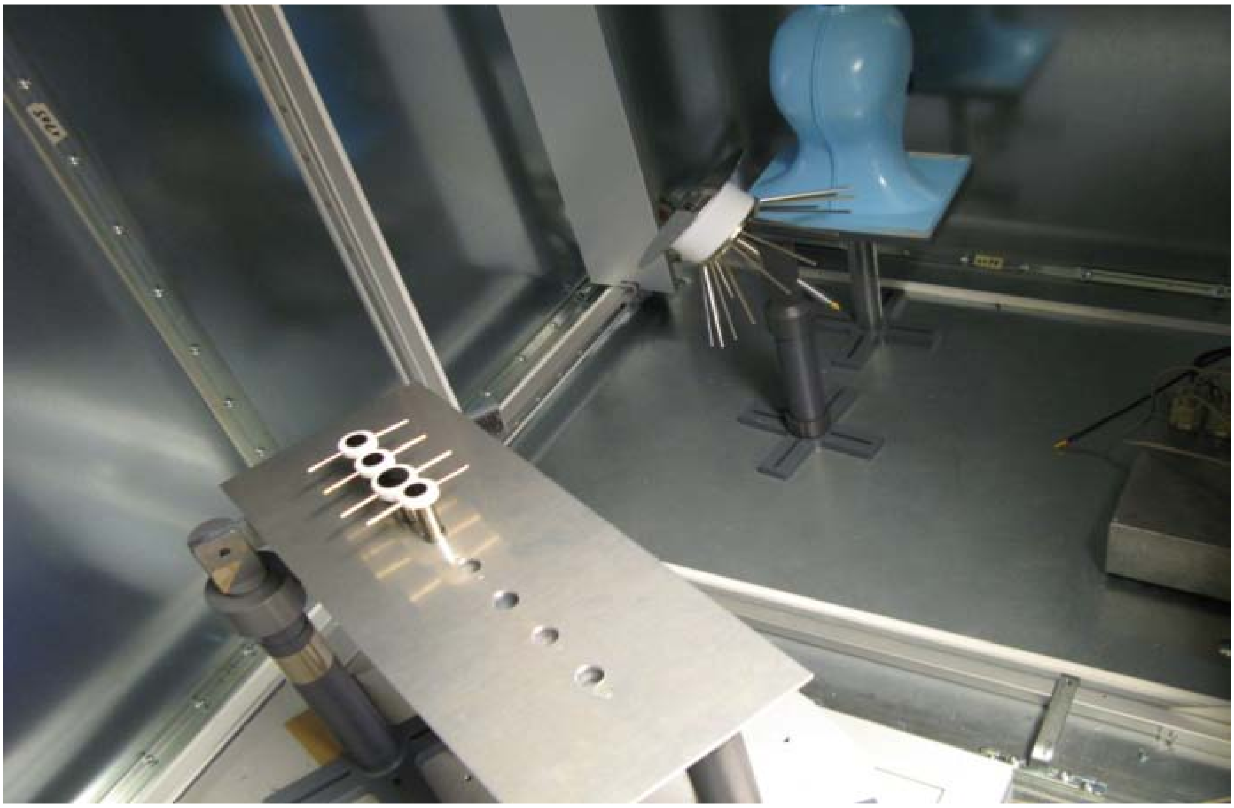

Figure 6.14: Measurement Setup of Antenna Array above a Ground Plane at a distance of 0.1 λ in RC

6.3.2 Simulated & Measured Diversity Gain:

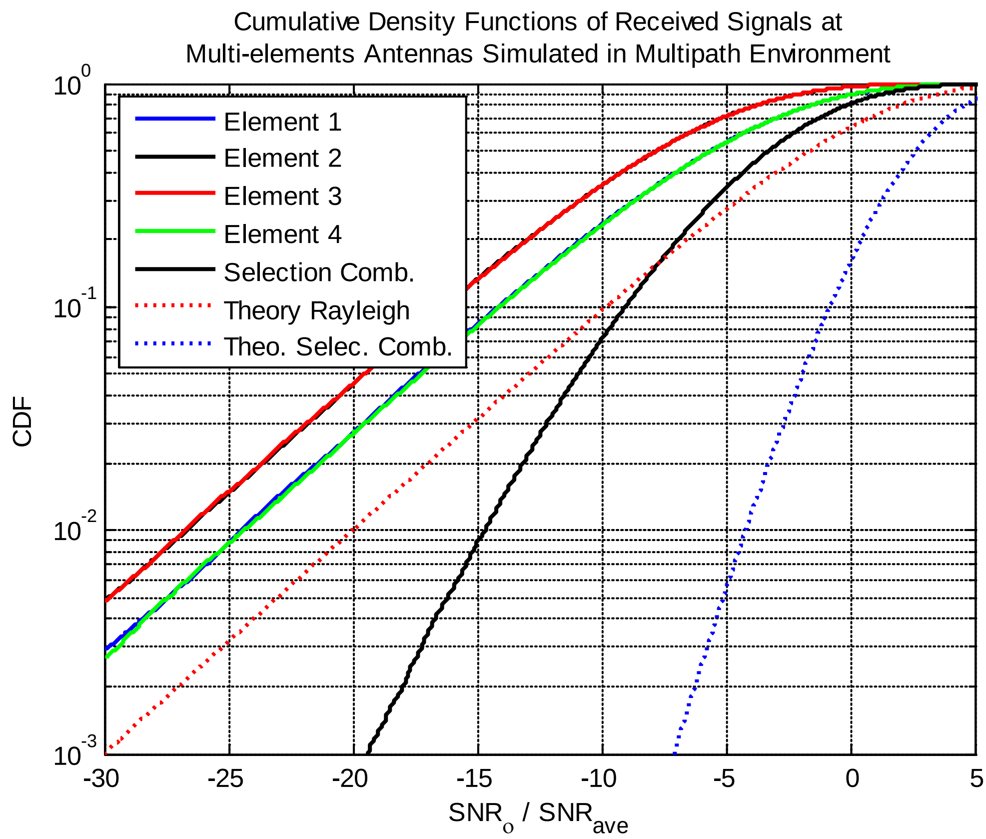

Figure 6.15: CDF of the diversity antenna, simulated in matlab (Distance between dipoles is 0.1 λ)

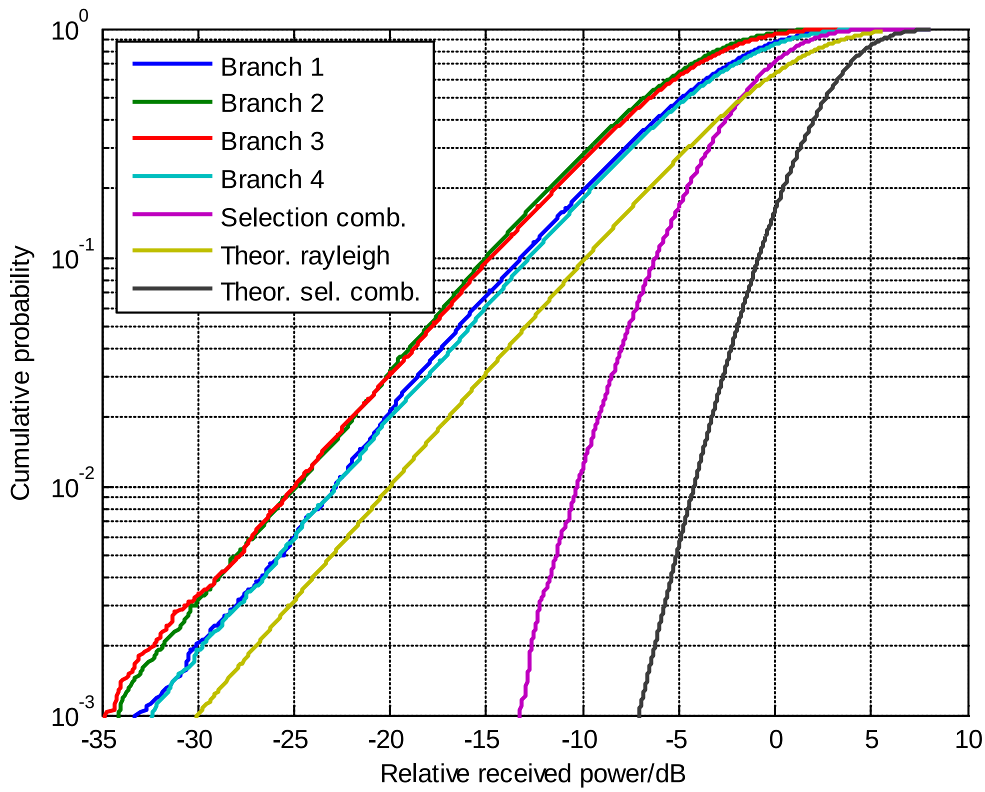

Figure 6.16: CDF of the diversity antenna, measured in RC (Distance between dipoles is 0.1 λ)

6.3.3 Simulated & Measured Capacity:

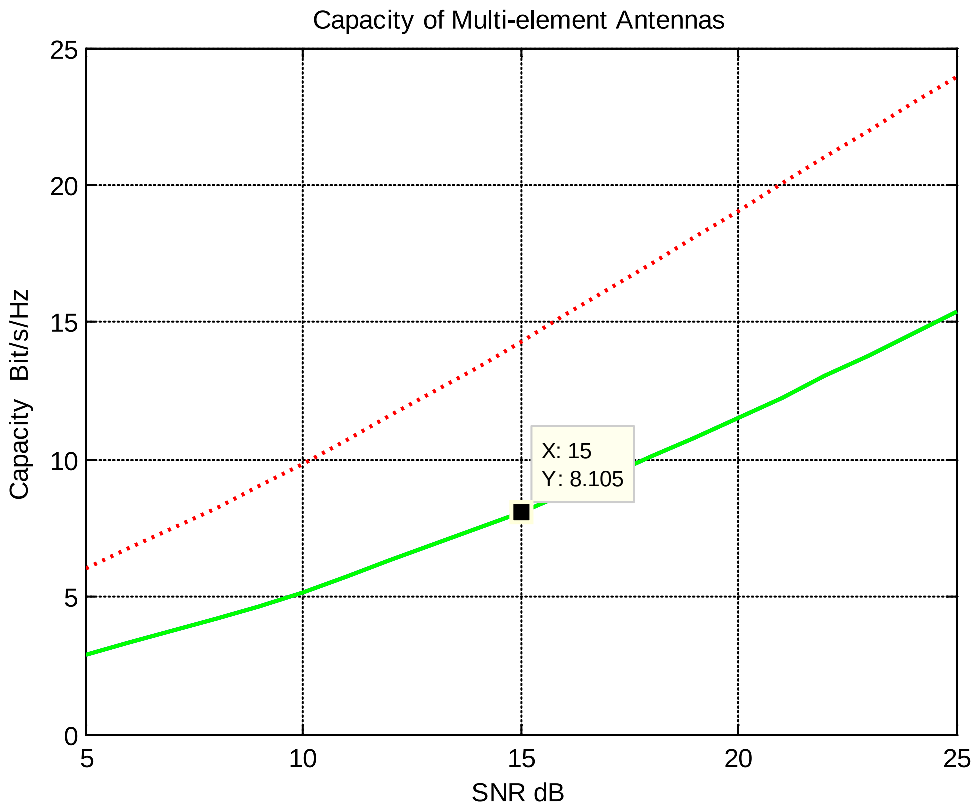

Figure 6.17: Capacity of 3 x 4 MIMO systems, simulated in matlab (Distance between dipoles is 0.1 λ)

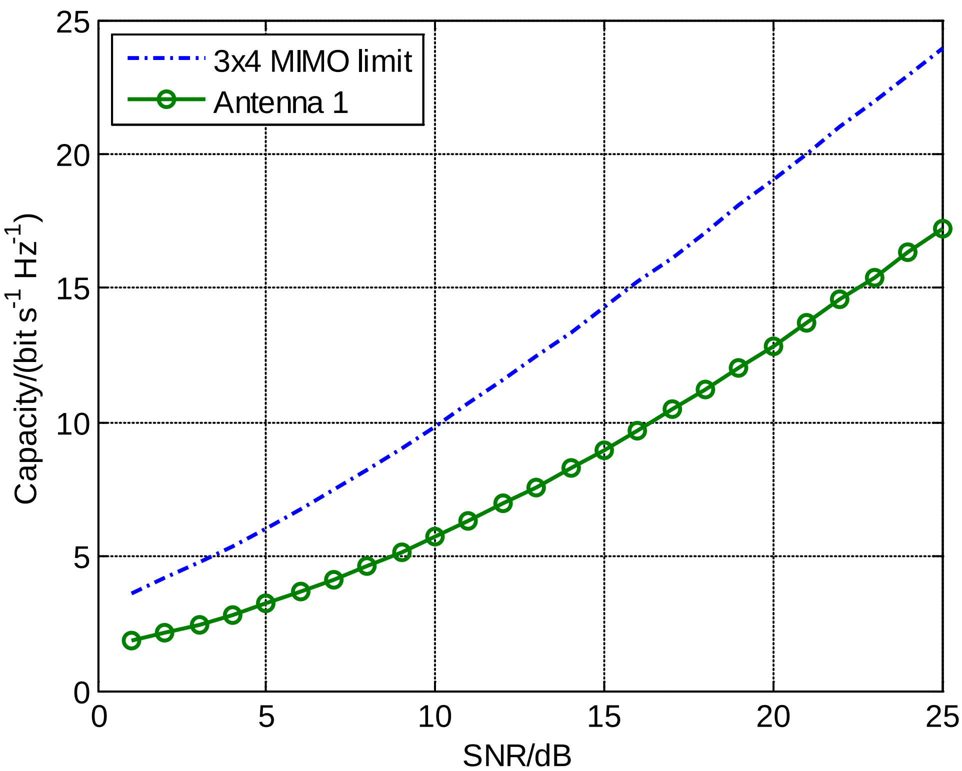

Figure 6.18: Capacity of 3 x 4 MIMO systems, measured in RC (Distance between dipoles is 0.1 λ)

6.3.3 Comparison between Simulated & Measured Results for case-3:

Table 6.3: Comparison b/w Simulated & Measured Results for Case-3			
No	**Elements**	**Simulated**	**Measured**
Correlation Between Elements			
1	Element 1 & 2	0.82	0.73
2	Element 1 & 3	0.19	0.14
3	Element 1 & 4	0.33	0.28
4	Element 2 & 3	0.68	0.47
Total Radiation Efficiency (dB)			
1	Total Radiation Efficiency of 1st Element	-3.58	-3.12
2	Total Radiation Efficiency of 2nd Element	-5.75	-5.06
3	Total Radiation Efficiency of 3rd Element	-5.74	-4.76
4	Total Radiation Efficiency of 4th Element	-3.59	-2.94
Diversity Gain (dB)			
1	Apparent Diversity Gain	10.69	12.53
2	Effective Diversity Gain	7.22	9.76
Capacity at SNR 15 dB (bit/s/Hz)			
1	Capacity	8.11	8.87

Chapter 7

Conclusion & Future work

- **Conclusion:**

In this master thesis, four horizontals dipole antenna array with the effect of Balun above an infinite ground plane is simulated by using a commercial full-wave simulator (CST). It gives the embedded element pattern, which has been used to calculate the radiation efficiency, correlation, diversity gain, and capacity of a MIMO antenna in both environments, isotropic and non-uniform environments. Finally, the MIMO antenna has been measured in a reverberation chamber which provides the rich scattering environment.

The simulated results of diversity gain and capacity of MIMO system antenna is highly dependent to the characteristics of non-uniform environment when dipoles are not located close to each other and excited by using element port (table 4.1). In beam port excitation, the diversity gain is reduced in non-uniform environment (table 4.2). When the dipoles are located close to each other, both environments have approximate same result for both excitations. The correlation calculated by using multipath environment emulator for simulation of MIMO terminals (MEST) and pattern multiplication in non-uniform environment both have approximate same correlation for element and beam port excitations (table 4.3 & table 4.4). The mutual coupling between the individual antennas of the MIMO array must be accounted for in the design of MIMO system. The coupling reduces the correlation between the signals (figure 4.2), which is desirable, but it also reduces the radiation efficiency (figure 4.3), which is undesirable. It also reduces the diversity gain (figure 4.4) and input impedance (figure 4.5). The combine effect is a significant reduction in capacity (figure 6.5, figure 6.11 & figure 6.17)

The CDF of the diversity antenna & the capacity of MIMO antenna for isotropic environment have measured in reverberation chamber. The measurement results show a clear reduction in diversity gain and capacity when the dipoles are located close to each other (table 6.1, table 6.2 & table 6.3). The radiation efficiency is also reduced and the correlation plays a smaller role.

- **Future work:**

The PIFAs and two cross dipole antenna can be simulated on CST and can check the environment effects (isotropic & non-uniform). It is also possible to change the distribution of elevation plane in non-uniform environment to Laplacian and double exponential. Furthermore, it is also possible to verify the Effect of double Rayleigh.

Appendix A

A.1 Touchstone File Format:

```
! TOUCHSTONE file generated by CST MICROWAVE STUDIO
! Date and time: Sun May 23 18:38:48 2010
! Project name: Case(0.1).cst
# GHZ S MA R 50
0        0.996118      -180          0.000767382   1.43148e-030  0.000755845   -9.37291e-031  4.89471e-005  -8.80635e-031
         0.000243521   -180          0.994017      -180          0.000978943   -180           0.000282808   -180
         0.000278112   -180          0.000978952   -180          0.994018      -180           0.000249578   -180
         4.89399e-005  -6.60574e-031 0.000757382   6.8295e-031   0.000769091   -6.72554e-031  0.996121      -180
0.0036   0.996403      179.104       0.000766069   -19.1287      0.000755697   -19.4145       4.90219e-005  -15.1904
         0.00024485    160.171       0.99441       179.143       0.000980287   160.314        0.000282964   161.014
         0.000278268   161.016       0.000980295   160.314       0.994411      179.143        0.000250906   160.189
         4.90147e-005  -15.1915      0.000757234   -19.4153      0.000767778   -19.1305       0.996406      179.104
0.0072   0.99722       178.196       0.000762383   -38.3469      0.000755282   -38.8398       4.9249e-005   -30.4502
         0.000248558   140.638       0.995539      178.268       0.000984044   140.701        0.000283404   142.056
         0.000278708   142.061       0.000984052   140.701       0.995539      178.268        0.000254611   140.665
         4.92419e-005  -30.4525      0.00075682    -38.8414      0.000764093   -38.3503       0.997223      178.195
0.0108   0.998459      177.262       0.000757053   -57.7324      0.000754689   -58.2849       4.96366e-005  -45.8434
         0.000253882   121.62        0.997261      177.361       0.000989441   121.221        0.000284047   123.147
         0.000279351   123.157       0.000989447   121.221       0.997261      177.361        0.000259932   121.646
         4.96296e-005  -45.8469      0.000756227   -58.2873      0.000758764   -57.737        0.998461      177.262
0.0144   0.999952      176.294       0.000751201   -77.3385      0.00075405    -77.7556       5.01982e-005  -61.4232
         0.000259746   103.227       0.999356      176.409       0.000995336   101.909        0.000284771   104.304
         0.000280075   104.318       0.000995342   101.909       0.999357      176.409        0.000265793   103.235
         5.01914e-005  -61.4278      0.000755588   -77.7587      0.000752913   -77.3438       0.999953      176.294
0.018    1.00149       175.287       0.000746197   -97.1821      0.00075352    -97.2533       5.09523e-005  -77.2275
         0.000264967   85.4539       1.00156       175.407       0.00100041    82.7703        0.000285431   85.5298
         0.000280736   85.5499       0.00100041    82.7707       1.00156       175.407        0.000271009   85.4314
         5.09457e-005  -77.2332      0.000755058   -97.257       0.00074791    -97.1874       1.00149       175.287
0.0216   1.00287       174.242       0.000743453   -117.234      0.000753256   -116.774       5.19207e-005  -93.276
         0.000268418   68.2124       1.00359       174.354       0.00100335    63.7799        0.000285881   66.8165
         0.000281186   66.8436       0.00100335    63.7803       1.00359       174.354        0.000274451   68.1481
         5.19146e-005  -93.2828      0.000754795   -116.778      0.000745167   -117.238       1.00287       174.242
0.0252   1.0039        173.161       0.000744173   -137.415      0.000753393   -136.31        5.3127e-005   -109.568
         0.000269149   51.3564       1.0052        173.255       0.00100306    44.8863        0.000285993   48.1454
         0.000281298   48.1803       0.00100306    44.8868       1.0052        173.255        0.000275163   51.2418
         5.31213e-005  -109.576      0.000754931   -136.315      0.000745886   -137.419       1.00389       173.161
0.0288   1.00441       172.052       0.000749102   -157.606      0.000754014   -155.848       5.45925e-005  -126.085
         0.000266463   34.6987       1.00616       172.118       0.000998833   26.0169        0.000285677   29.4886
         0.000280983   29.5317       0.000998831   26.0173       1.00616       172.118        0.000272449   34.5275
         5.45876e-005  -126.093      0.000755551   -155.853      0.000750812   -157.609       1.0044        172.052
0.0324   1.00432       170.925       0.00075834    -177.67       0.000755136   -175.373       5.63333e-005  -142.791
         0.000259969   18.0137       1.00634       170.957       0.000990431   7.08362        0.000284899   10.8121
         0.000280206   10.863        0.000990427   7.08405       1.00634       170.957        0.000265917   17.7823
         5.63292e-005  -142.8        0.000756674   -175.379      0.000760047   -177.673       1.00431       170.925
0.036    1.00361       169.791       0.000771275   162.523       0.000756704   165.129        5.83552e-005  -159.64
         0.000249638   1.02734       1.00571       169.785       0.000978221   -12.0092       0.000283687   -7.92117
         0.000278994   -7.86331      0.000978215   -12.0089      1.00571       169.785        0.000255546   0.73584
         5.83521e-005  -159.65       0.00075824    165.122       0.000772978   162.52         1.00361       169.791
0.0396   1.00236       168.66        0.000786648   143.072       0.000758583   145.671        6.06506e-005  -176.583
         0.000235872   -16.6037      1.00432       168.617       0.000963195   -31.3564       0.000282137   -26.7469
         0.000277444   -26.6836      0.000963188   -31.3561      1.00432       168.617        0.000241751   -16.9493
         6.06486e-005  -176.593      0.000760118   145.664       0.000788346   143.067        1.00235       168.66
0.0432   1.00069       167.541       0.000802728   124.027       0.000760578   126.263        6.31962e-005  166.425
         0.000219626   -35.3174      1.00232       167.465       0.000946964   -51.0387       0.000280412   -45.6946

1.8      0.1758        118.139       0.169675      -91.3579      0.0645038     85.1519        0.0339648     -93.8945
         0.169675      -91.3579      0.179978      110.527       0.174155      -93.3945       0.064531      85.2671
         0.0645041     85.1514       0.174155      -93.3945      0.180075      110.561        0.16978       -91.2559
         0.0339648     -93.8945      0.0645308     85.2676       0.169779      -91.2559       0.176262      118.253
```

A.2 Far-field File Format:

```
// CST Farfield Source File

// Version:
1.1

// Radiated Power
4.721538e-001

// Accepted Power
4.674953e-001

// Stimulated Power
5.000000e-001

// Frequency
1.800000e+009

// >> Total #phi samples, total #theta samples
361 181

// >> Phi, Theta, Re(E_Theta), Im(E_Theta), Re(E_Phi), Im(E_Phi):
   0.000     0.000   3.34569686e-004  -1.44766410e-003 -4.34979715e+000   1.34472094e+001
   0.000     1.000   5.56557064e-004   4.22961894e-003 -4.40294941e+000   1.35597726e+001
   0.000     2.000   4.64493338e-003   3.97907805e-003 -4.42756649e+000   1.37109632e+001
   0.000     3.000   1.31590098e-002  -2.39927491e-003 -4.44549436e+000   1.38381586e+001
   0.000     4.000   2.25759263e-002  -9.38467165e-003 -4.47097097e+000   1.39066092e+001
   0.000     5.000   2.85125708e-002  -1.10165311e-002 -4.49752058e+000   1.39406305e+001
   0.000     6.000   2.97148924e-002  -6.49463486e-003 -4.50339641e+000   1.39989787e+001
   0.000     7.000   2.91552200e-002  -9.10491146e-004 -4.46974877e+000   1.41170293e+001
   0.000     8.000   3.12901425e-002  -4.76389020e-004 -4.39730809e+000   1.42732386e+001
   0.000     9.000   3.80169443e-002  -6.74793670e-003 -4.30599440e+000   1.44072014e+001
   0.000    10.000   4.70120656e-002  -1.52061692e-002 -4.21927610e+000   1.44765475e+001
   0.000    11.000   5.38650788e-002  -1.94439993e-002 -4.14515953e+000   1.44942325e+001
   0.000    12.000   5.60037700e-002  -1.70233316e-002 -4.07043145e+000   1.45154961e+001
   0.000    13.000   5.48989663e-002  -1.16452927e-002 -3.97291534e+000   1.45859657e+001
   0.000    14.000   5.46715221e-002  -9.74252922e-003 -3.84076526e+000   1.46992940e+001
   0.000    15.000   5.84893840e-002  -1.46883202e-002 -3.68393638e+000   1.48044465e+001
   0.000    16.000   6.58959839e-002  -2.38299671e-002 -3.52648221e+000   1.48509621e+001
   0.000    17.000   7.33420329e-002  -3.08940202e-002 -3.38833222e+000   1.48354343e+001
   0.000    18.000   7.72556530e-002  -3.14954391e-002 -3.26976368e+000   1.48024806e+001
   0.000    19.000   7.69789498e-002  -2.68844636e-002 -3.15224831e+000   1.48062609e+001
   0.000    20.000   7.51846919e-002  -2.27895269e-002 -3.01408263e+000   1.48633569e+001
   0.000    21.000   7.55874751e-002  -2.45151055e-002 -2.84762746e+000   1.49406578e+001
   0.000    22.000   7.99868686e-002  -3.25486256e-002 -2.66507134e+000   1.49851987e+001
   0.000    23.000   8.69786773e-002  -4.22743637e-002 -2.48781353e+000   1.49690800e+001
   0.000    24.000   9.32214938e-002  -4.78413853e-002 -2.32992454e+000   1.49122336e+001
   0.000    25.000   9.60484079e-002  -4.68678168e-002 -2.18701153e+000   1.48639389e+001
   0.000    26.000   9.53902643e-002  -4.22277309e-002 -2.04049741e+000   1.48632602e+001
   0.000    27.000   9.36291656e-002  -3.96871499e-002 -1.87047953e+000   1.49076278e+001
   0.000    28.000   9.37375992e-002  -4.34638355e-002 -1.66957848e+000   1.49578310e+001
   0.000    29.000   9.71209238e-002  -5.31689430e-002 -1.44505417e+000   1.49679005e+001
   0.000    30.000   1.02763387e-001  -6.43076326e-002 -1.21183394e+000   1.49208543e+001
   0.000    31.000   1.08024392e-001  -7.16801828e-002 -9.79886048e-001   1.48370972e+001
   0.000    32.000   1.10468540e-001  -7.30383119e-002 -7.48246854e-001   1.47580349e+001
   0.000    33.000   1.09362217e-001  -7.03962571e-002 -5.05958955e-001   1.47124863e+001
   0.000    34.000   1.06009808e-001  -6.83149578e-002 -2.40919056e-001   1.46976756e+001
   0.000    35.000   1.02801592e-001  -7.05987560e-002  5.33559820e-002   1.46807235e+001
   0.000    36.000   1.01759923e-001  -7.77800101e-002  3.74741775e-001   1.46231741e+001
   0.000    37.000   1.03402615e-001  -8.69490867e-002  7.16393293e-001   1.45048716e+001
   0.000    38.000   1.06583517e-001  -9.38391436e-002  1.07153646e+000   1.43357460e+001
   0.000    39.000   1.09202739e-001  -9.56247927e-002  1.43722091e+000   1.41458064e+001
   0.000    40.000   1.09355465e-001  -9.26495203e-002  1.81319287e+000   1.39643382e+001
   0.000    41.000   1.06254720e-001  -8.81488708e-002  2.19945722e+000   1.38011502e+001
   0.000    42.000   1.00537911e-001  -8.63179352e-002  2.59329173e+000   1.36409439e+001
   0.000    43.000   9.38916434e-002  -8.99781032e-002  2.99014878e+000   1.34541630e+001
   0.000    44.000   8.82463935e-002  -9.91298789e-002  3.38531351e+000   1.32133648e+001
   0.000    45.000   8.49663520e-002  -1.11093951e-001  3.77721778e+000   1.29094515e+001
   0.000    46.000   8.43232897e-002  -1.21939065e-001  4.16799501e+000   1.25546067e+001
   0.000    47.000   8.54871026e-002  -1.28377652e-001  4.56090288e+000   1.21754911e+001
   0.000    48.000   8.69087239e-002  -1.29172859e-001  4.95710430e+000   1.17994347e+001
   0.000    49.000   8.69460759e-002  -1.25477375e-001  5.35162660e+000   1.14410499e+001
   0.000    50.000   8.44595899e-002  -1.20130787e-001  5.73345284e+000   1.10975887e+001
   0.000    51.000   7.91717203e-002  -1.16362745e-001  6.08822799e+000   1.07510829e+001
   0.000    52.000   7.17162857e-002  -1.16513095e-001  6.40275156e+000   1.03780489e+001
   0.000    53.000   6.33869526e-002  -1.21286852e-001  6.67012600e+000   9.96063807e+000
   0.000    54.000   5.56864349e-002  -1.29685794e-001  6.89252088e+000   9.49339303e+000
   0.000    55.000   4.98871941e-002  -1.39560715e-001  7.07993184e+000   8.98631036e+000
```

Appendix B

B.1 Matlab Codes:

1. **MEST – Isotropic (Multipath Environment Emulator for Simulation of MIMO Terminals in Isotropic Environment)**

   This code is used to calculate the correlation between different elements, apparent and effective diversity gain for selection combining and maximum ratio combining, and total embedded efficiency of each element. The inputs of this code are touchstone file, far-field files, number of scatters, and number of realizations. Furthermore, it also plots the figures of CDF of the diversity antenna and capacity of 3x4 MIMO systems.

2. **MEST – Non-uniform (Multipath Environment Emulator for Simulation of MIMO Terminals in Non-uniform Environment)**

   This code is used to calculate the correlation between different elements, apparent and effective diversity gain for selection combining and maximum ratio combining, and Mean effective gain. The inputs of this code are touchstone file, far-field files, number of scatters, number of realizations, and elevation angle (mean and variance). The elevation plane is Gaussian distributed. Furthermore, it also plots the figures of CDF of the diversity antenna and capacity of 3x4 MIMO systems.

B.2 Matlab code for plotting different figures:

```
%% ===== Plotting Diversity Gain & Correlation at 0.1λ (Isotropic) =======
% ======================================================================
% ======================================================================
clc
clear all;
close all;

Sc = [10 20 30 40 50 60 70 80 90 100];

%%  ------- Correlation Between Different Elements -------
%  -----------------------------------------------------
Cor12 = [0.82 0.8216 0.8206 0.8206 0.8202 0.8219 0.8214 0.823 0.8215 0.8203]
Cor13 = [0.1902 0.1899 0.1882 0.1891 0.1859 0.1914 0.1918 0.195 0.1922 0.185]
Cor14 = [0.3363 0.3411 0.34 0.3391 0.3448 0.3387 0.3376 0.3355 0.3365 0.3414]
Cor23 = [0.6822 0.6793 0.6803 0.681 0.6769 0.6804 0.6815 0.6823 0.6813
0.6796]
Cor24 = [0.1951 0.1867 0.1906 0.1918 0.1848 0.1888 0.1913 0.1905 0.1917
0.1922]

figure;
hold on;
plot(Sc,Cor12,'-r', 'LineWidth', 2)
plot(Sc,Cor13,'-m', 'LineWidth', 2)
plot(Sc,Cor14,'-k', 'LineWidth', 2)
plot(Sc,Cor23,'-b', 'LineWidth', 2)
plot(Sc,Cor24,'-g', 'LineWidth', 2)
set(gca,'XTick',10:10:100);
xlabel('Number of Incident Waves');
ylabel('Correlation');
title('Correlation Between Different Elements (Isotropic Environment)');
grid on, box on; legend('Cor12', 'Cor13', 'Cor14', 'Cor23', 'Cor24');
xlim([10 100])
ylim([0 1])

%%  ------- (ADG/EDG) at 1 Percent CDF level -------------
%  -----------------------------------------------------
AppDG_SC = [7.751 9.528 10.06 10.32 10.5 10.71 10.65 10.69 10.82 10.75]
EffDG_SC = [4.28 6.057 6.591 6.848 7.031 7.235 7.175 7.218 7.354 7.28]
AppDG_MRC= [11.26 12.97 13.45 13.69  13.85 14.07 14.03 14.1 14.15 14.12]
EffDG_MRC= [7.791 9.501 9.982 10.22 10.38 10.6 10.56 10.63 10.68 10.65]

figure;
hold on;
plot(Sc,AppDG_SC,'-r', 'LineWidth', 2)
plot(Sc,EffDG_SC,'-k', 'LineWidth', 2)
plot(Sc,AppDG_MRC,'--r', 'LineWidth', 2)
plot(Sc,EffDG_MRC,'--k', 'LineWidth', 2)
set(gca,'XTick',10:10:100);
xlabel('Number of Incident Waves');
ylabel('Diversity Gain(dB)');
title('(ADG/EDG) at 1 Percent CDF level(Isotropic Environment)');
grid on, box on; legend('ADG SC', 'EDG SC', 'ADG MRC', 'EDG MRC');
xlim([10 100])
ylim([0 20])
```

```
%% === Plotting MEG, Diversity Gain & Correlation at 0.1λ (Non-uniform) ===
% ========================================================================
% ========================================================================
clc
clear all;
close all;

Sc = [5 10 15 20 25 30 35 40 50 60 70 80 90 100];

%%  -------------- Mean Effective Gain (MED)--------------
%  -------------------------------------------------------
MEG1 = [-5.943 -5.964 -5.94 -5.918 -5.953 -5.952 -5.938 -5.957 -5.912 -5.93 -
5.948 -5.91 -5.95 -5.947]
MEG2 = [-8.881 -8.897 -8.891 -8.892 -8.895 -8.908 -8.919 -8.904 -8.865 -8.891
-8.895 -8.837 -8.892 -8.885]
MEG3 = [-8.86 -8.905 -8.889 -8.893 -8.861 -8.881 -8.898 -8.897 -8.861 -8.883
-8.887 -8.849 -8.892 -8.87]
MEG4 = [-5.939 -5.97 -5.938 -5.924 -5.932 -5.943 -5.922 -5.965 -5.909 -5.924
-5.941 -5.94 -5.944 -5.951]

figure;
hold on;
plot(Sc,MEG1,'-r', 'LineWidth', 2)
plot(Sc,MEG2,'-k', 'LineWidth', 2)
plot(Sc,MEG3,'--r', 'LineWidth', 2)
plot(Sc,MEG4,'--k', 'LineWidth', 2)
set(gca,'XTick',10:10:100);
xlabel('Number of Incident Waves');
ylabel('MEG(dB)');
title('MEG for Dual-polarized, Dual-port IIR Antenna(Non-uniform
Environment)');
grid on, box on; legend('MEG1', 'MEG2', 'MEG3', 'MEG4');
xlim([10 100])
ylim([-10 0])

%%  ------- Correlation Between Different Elements -------
%  -------------------------------------------------------
Cor12 = [0.7743 0.7761 0.7755 0.7757 0.7734 0.774 0.7749 0.7749 0.7754 0.7751
0.775 0.7756 0.7752 0.7742]
Cor13 = [0.1229 0.1211 0.1246 0.1285 0.126 0.1267 0.1305 0.1237 0.1256 0.1271
0.1245 0.1194 0.1244 0.1237]
Cor14 = [0.6602 0.6598 0.662 0.6644 0.6613 0.6617 0.6648 0.6607 0.6629 0.6637
0.6615 0.6585 0.6623 0.6606]
Cor23 = [0.5139 0.5133 0.5109 0.5074 0.5129 0.5111 0.5069 0.5126 0.5101
0.5091 0.5114 0.5156 0.5112 0.5137]
Cor24 = [0.1195 0.1222 0.1243 0.1277 0.1195 0.1216 0.1266 0.1215 0.125 0.126
0.1232 0.1194 0.1248 0.1203]

figure;
hold on;
plot(Sc,Cor12,'-r', 'LineWidth', 2)
plot(Sc,Cor13,'-m', 'LineWidth', 2)
plot(Sc,Cor14,'-k', 'LineWidth', 2)
plot(Sc,Cor23,'-b', 'LineWidth', 2)
plot(Sc,Cor24,'-g', 'LineWidth', 2)
set(gca,'XTick',10:10:100);
xlabel('Number of Incident Waves');
ylabel('Correlation');
title('Correlation Between Different Elements (Non-uniform Environment)');
grid on, box on; legend('Cor12', 'Cor13', 'Cor14', 'Cor23', 'Cor24');
xlim([10 100])
```

```
ylim([0 1])

%%  ------- (ADG/EDG) at 1 Percent CDF level -------------
%  -------------------------------------------------------
AppDG_SC = [7.563 9.121 9.592 9.769 9.933 10 10.07 10.14 10.1 10.14 10.28
10.13 10.19 10.35]
EffDG_SC = [4.092 5.65 6.121 6.298 6.462 6.531 6.595 6.665 6.625 6.672 6.806
6.655 6.717 6.883]
AppDG_MRC= [10.92 12.52 12.97 13.24 13.37 13.48 13.52 13.51 13.54 13.65 13.67
13.6 13.63 13.78]
EffDG_MRC= [7.445 9.054 9.502 9.767 9.9 10.01 10.05 10.04 10.07 10.18 10.2
10.13 10.16  10.31]

figure;
hold on;
plot(Sc,AppDG_SC,'-r', 'LineWidth', 2)
plot(Sc,EffDG_SC,'-k', 'LineWidth', 2)
plot(Sc,AppDG_MRC,'--r', 'LineWidth', 2)
plot(Sc,EffDG_MRC,'--k', 'LineWidth', 2)
set(gca,'XTick',10:10:100);
xlabel('Number of Incident Waves');
ylabel('Diversity Gain(dB)');
title('(ADG/EDG) at 1 Percent CDF level(Non-uniform Environment)');
grid on, box on; legend('ADG SC', 'EDG SC', 'ADG MRC', 'EDG MRC');
xlim([10 100])
ylim([0 20])
```

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