Department of Technology and Build Environment

Study of Multiport Antenna Systems on Terminals for WLAN

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Abstract

In the last decades, wireless services and mobile communication have great influence and effect growth and become the nerves of life. The desire to purchase goods and services of high capacity and performance of mobile communication has been increased. In the nearest past, one radio was connected to one antenna, but now days the situation is completely different, there are more than one radio used at the same time to improve the link budget between base station and mobile and also to increase the capacity of the channels following higher data transmission and low bit error probability such as Bluetooth, GPS and WLAN. For this reason Multi Input Multi Output (MIMO) systems have been introduced. In MIMO systems, antennas are planted in small confined volumes such as in e.g. mobile phones which causes high coupling between them, as a result of fact it leads to high correlation as well as low efficiency which leads to bad diversity gain and high return loss (RL). Diversity is one of the most important characteristics of MIMO antenna. Good diversity means that radio signal can be transmitted or received in any direction with any polarization and correlation is low of received signal therefore the channel capacity is increased. This thesis is purposed to study multiport antenna systems on terminals such as WLAN by using more than one antenna to speed up the data rate in wireless communication system and to study the power or capacity of causing an effect in intangible way of the radiation efficiency and the correlation on the effective diversity gain between the antennas by implementation components or networks between the ports of antennas. The thesis will result in a working methodology how to use Multi Port Analyzer (MPA) plus design, location and orientation rules for the standard antennas used in multi system. Simulation tools from CST Microwave Studio ©, time domain solver for electromagnetic structures will be used in combination with MPA developed in CHASE to generate results plus Matlab for figures and illustrations. Promising simulation outcomes will result in a mockup which will be built and measured using Vector Network Analyzer (VNA) and reverberation chamber. This thesis was proposed project on Multi Input Multi Output (MIMO) terminals for WLAN by Ethertronics Sweden AB in Kalmar within Chalmers Antenna Systems Excellence Center (CHASE).

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To Free Palestine…

To my Parents…

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1. Introduction

Previously in abstract, the demand of high capacity, good coverage, faster connection and high data rate is increased in the field of wireless communication; it was very noticeable in 3rd mobile generations. To achieve such kind of connection several points must be taken in consideration such as high efficiency, good gain, wide bandwidth, reduce losses and low coupling. In this thesis a study of multiport antenna systems on terminal of WLAN will be established using certain specification on the antennas. Several problems have been taken into account following by fading, multipath environment and coupling, since both antennas will be integrated near each other. We will see how the diversity is one of the solutions to avoid such problems and how it will affect our system. Furthermore the correlation between these antennas will be minimized. Antennas will be optimized for effective diversity gain. Optimization over different antenna locations and orientations plus source impedance. This procedure show us how changing the location or orientation of antennas influence the coupling, diversity gain, correlation and as well as the radiation efficiency. Also how this influence will take an action by adding components between the ports of antennas.

This thesis consists of 7 chapters, everyone is discussed independently. First chapter is general introduction relating to this project. Second chapter is dealing with facts of generic ideas and basic theoretical background belongs to this thesis. It handles diversity technique and the different types of diversity which gives practical effect to and ensure of actual fulfillment by concrete measure. It is explaining a set of observable manifestations of multipath environment and fading and how they can affect the system. Expressing types of wireless system such WLAN and WiMax. It is relating to MIMO system in general.

Third chapter is characterized by the software used in this thesis. Starting with general description of CST Microwave studio ©, Multiport Analyzer MPA which has been developed by Kristian karlsson and provided by CHASE, Circuit Simulator (CircSim) which developed by Jan Carlsson at SP technical research institute specially for MPS, LPFK protoMat which is a circuit board plotter that can be used to produce prototype PCB's.

Fourth chapter is relating to software simulations for our design using different techniques to increase the radiation efficiency.

Two parallel dipoles are used as process especially for the determination of the degree of validity of measuring software (MPA and CircSim). Simulations were made by CST Microwave studio ©, the results were imported to CircSim and MPA.

Fifth chapter is including measurements setups which belong to our design, such as efficiency measurements, RL, coupling, and diversity gain.

Sixth chapter is including conclusion and discussion of this project.

Seventh chapter is including suggestion of future work.

2. Theoretical description

Today's mobile wireless terminal has the ability to operate utilizing different frequency bands. However, the high demand on small terminal for mobile communication is increased as long as the demand on small antenna too because the reciprocal action and influence between antenna and terminal is getting valuable in relationship. As a result such demand is causing antenna design to be more challenge and more complex in order to achieve higher data transmission rate and low bit error. These new small antennas must prepare in advance large bandwidth and gain for such small dimensions, since the bandwidth performance of antenna is directly related to its dimensions in relation to wavelength, also to figure out the geometry and structure to solve a lot of problems specially when more than one antennas will be integrated in the same electronic device, such small distance will cause mutual coupling and interference, also must solve one of the most important problems that antennas can face which is multipath and fading environments. Therefore poor design of system components or incorrect assumptions about the channel could lead to drastic reduction in system performance [1].

2.1 Multi Input Multi Output (MIMO)

Telecommunication engineering admits that the capacity is limited by the bandwidth and transmission power [2]. This limitation has been expanded by introducing many antenna at both transmitter and receiver, so the number of channels can be increased. This system is called as MIMO. So MIMO systems use multiple inputs and multiple outputs at both transmitter and receiver to improve communication performance to minimize error and optimize data speed. It proposes significant increase in data and link range without changing either transmit power or bandwidth and it achieves this by reducing fading (diversity) and increasing signal-to-noise ratio (SNR), because of that MIMO becomes the dominant topic in mobile or wireless communication. As it is mentioned in [3], the quality of MIMO system in fading multipath environment is characterized by the maximum available capacity. The capacity of MIMO system strongly depends on the available channel state at transmitter or receiver, the channel SNR and correlation between the channel gains on each antenna elements. Therefore the instantaneous maximum capacity of MIMO system with no channel knowledge is:

$$C = log_2\left(\det\left((I_{MxN}) + \frac{SNR}{M} H_{MxN} H^*_{MxN}\right)\right) \quad [b/s/Hz] \qquad (2.1)$$

Where M is the number of transmitters and N is the number of receivers in the MIMO system. I_{MxN} Is a unit matrix, H_{MxN} is a normalized complex channel matrix and H^*_{MxN} is the complex conjugate transpose of H_{MxN}. [4].

2.2 Multipath and Fading

In wireless communication when radio signal is transmitted, as a result of fact this signal is spread out in space and developed wider. The RF signal engage in conflict with objects that reflect, diffract or interfere with it during its way to last destination, this technique is called Non Line of Sight (LOS) condition or Fading. There are two types of fading which are respectively long term fading occurs when the RF signal show sharp decrease in its strength due to large distance, and short term fading or known as Rayleigh fading occurs when RF signal show fast change due to short distance in very short time. Multiple path propagation occurs when RF signal takes different path from source to receiver, which can be defined as the combination of original pulse or signal and the duplicated one that result from the reflected of the waves between transmitter and receiver and characterized by different phase, amplitude and angle of arrival.

2.3 Diversity

Previously on multipath and fading, when RF signal is reflected along multipath and before being received, can lead time delay, phase shift, distortion and even attenuation. The performance of mobile and wireless terminal in multipath environment can be notably improved by using diversity. The idea of diversity is to receive the signal two or many times, and that the signal envelops are to some degree uncorrelated so that they can be combined into a new signal with shallower fading dips [5]. So the advantage of diversity effect involves the transmission and/or reception of multiple RF waves to increase data speed and decrease the error rate. The fundamental notion of diversity is to acquire an exact reproduction of independent signal when the signal is transmitted through several independent diversity branches by:

2.3.1 Frequency diversity

It depends on sending signal or message carrying same information on multiple carrier frequency, since we have different fading at different frequency, if one of these frequencies passes through deep fading, the rest can be used.

2.3.2 Time diversity

Transmit the message in different time slots, providing signal repetition after time delay [6].

2.3.3 Space diversity

Since the fading is different at different points, spatial diversity utilizes multiple antennas which are sufficiently separated from each other. Relies on the fact that correlation decreases with an increase in the distance of antennas or increase in the distance of scatterers.

2.3.4 Polarization diversity

Antennas transmit or receive multiple signals with different polarization.

2.3.5 Pattern diversity

It is called also angle diversity, when antenna collect signals from different angles then pattern diversity takes place.

Among these five diversity categories only space diversity, polarization diversity and pattern diversity will be used. Diversity is also utilizing combining technique on the signal of multiple antennas in order to give shape of the combined signal.

- Selection combining always chooses the strongest antenna branch at all time [7].
- Switch combining switches the active antenna to the other antenna when it drops under a threshold level.
- Passive combining. In this method an extra additional antenna is added, and the signals are summed together.
- Equal gain combining. In this method every signal is participating to a receiver where signal will be added constructively and co-phased since this method introduce the phase shift. Actually its very good method because it is used all valid branches.

- Maximal ration combining co-phases the signals and combined them [7]. It is similar to equal gain combining, that signals are co-phased, but it only differs in that each branch at the receiver is weighted.

Therefore after reviewing the process technique of diversity, only selection combining will be utilized by this thesis.

2.4 Diversity gain

In additional to what has been mentioned about diversity and diversity scheme, we should not ignore one of the most important parameter of diversity scheme which is diversity gain. When diversity scheme take an action, the majority role of diversity gain is increase in signal-to-interference ratio, or how much the transmission power can be reduced when diversity scheme is introduced without a performance loss [8]. As is remarked in [9], diversity gain is divided into three kinds as follows:

2.4.1 Apparent diversity

Only takes the correlation into account when determining the diversity gain.

2.4.2 Actual diversity

Gain is obtained by normalizing the combined signal to a reference antenna at the same location where the antenna diversity system is intended to be located. Both total radiation efficiency and correlation are used when determining the diversity gain.

2.4.3 Effective diversity

Gain is obtained by normalizing the combined signal to a reference antenna (e.g. a dipole with known radiation efficiency) located in free space. Both the total radiation efficiency and correlation are used when determining the diversity gain.

The apparent diversity gain is expressed in formula below

$$G_{div} = {}^{P_{div}}/_{P_{branch}} \qquad (2.2)$$

Where P_{div} the power level after diversity combining, and P_{branch} is the power level of the stronger antenna branch [10].

The relation between the correlations coefficient ρ and the apparent diversity gain G_{app} of two antenna systems is expressed [11]:

$$G_{app} = 10e_{\rho} \text{ with } e_{\rho} = \sqrt{1 - |\rho|^2} \quad (2.3)$$

Where 10 is the maximum apparent diversity gain at the 1% probability level with selection combining, and e_{ρ} is the reduction in diversity gain due to the correlation coefficient. Furthermore the effective diversity gain can be expressed as:

$$G_{effdiv} = \frac{P_{div}}{P_{branch}} \cdot \left(e_{radeff}\right)_{branch} \text{ or } G_{effdiv} = {}^{P_{div}}/_{P_{ideal}} \quad (2.4)$$

Where $\left(e_{radeff}\right)_{branch}$ is the radiation efficiency of the stronger antenna branch, and P_{ideal} is the received power level of a single antenna with unit radiation efficiency and located in the same environment. The maximum effective diversity gain is 10dB at 1% probability level and with 100% efficient antenna when using selection combining [10]. A diversity measurement is done in a reverberation chamber is shown below:

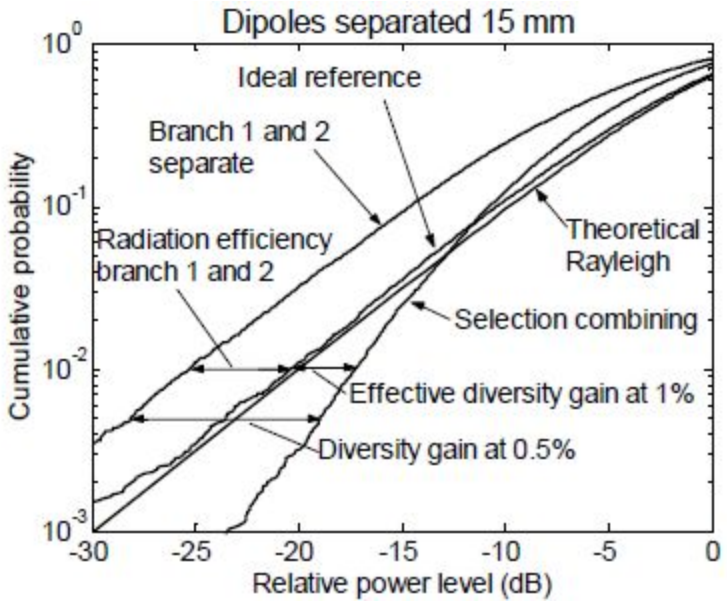

Figure 2.1 *Cumulative density function of two parallel dipoles separated 0.045λ*

2.5 Correlation coefficient

To achieve good diversity we have to take in consideration low correlation. The correlation coefficient between two ports can be calculated from the coupling the corresponding embedded elements radiation field functions [11]:

$$\rho = \frac{\int_{4\pi}\int G_{emb.}^{(1)} G_{emb}^{(2)*} d\Omega}{\sqrt{\int_{4\pi}\int G_{emb.}^{(1)} G_{emb}^{(2)*} d\Omega \int_{4\pi}\int G_{emb.}^{(2)} G_{emb}^{(2)*} d\Omega}} \qquad (2.5)$$

The higher diversity gain means the lower correlation coefficient. This can be brought out into perfect state by adding and optimizing components between the ports of antennas.

2.6 Dipoles

Two horizontal rods in line with each other and $\lambda/4$ in length for each build up a dipole antenna, so the total length of dipole is $\lambda/2$. Dipole is balance antenna because of equal length, dipole antenna feeds from its center as shown:

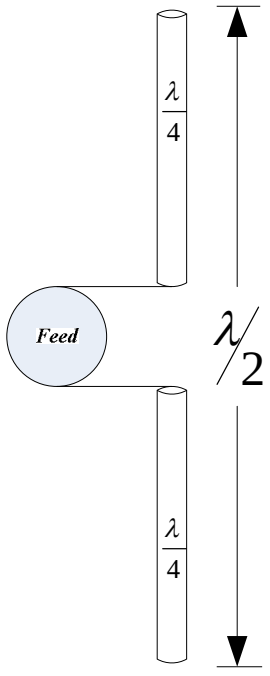

Figure 2.2 *Dipole antennas.*

2.7 WLAN and WiMAX

The high demand in digital wireless systems and mobile communication to transmit video and voice communication without any difficulties, characterized by high speed and to operate at high frequency radio waves leads to develop Wireless Local Area Network (WLAN) which has just appeared and IEEE 802.11 committee handled that to develop standard wireless LANs. Furthermore WLAN has made a great jump in wireless communication by developing WiFi (wireless Fidelity), that allows broadcast media and wireless connection. In the nearest past we touch a strong revolution in digital wireless system aims to provide high speed wireless connection over long distances so WiMAX (Worldwide Interoperability for Microwave access) is born and become the wireless technology.

3. Software

Previously on abstract, it has mentioned that several software programs will be used in this thesis such as:

- CST microwave studio © 2008.
- Multi-Port antenna evaluator (MPA).
- Circuit simulator (CircSim).
- Circuit CAM
- MATLAB.

3.1 CST microwave studio

This software is used to design all components which belong to our antenna system. It is a specialist tool for the 3D Electromagnetic (EM) simulations of high frequency components [12]. It includes multi signal functionality to simulate various excitations. Has the ability to calculate E-field patterns, far field, S-parameters, radiation efficiency and total radiation efficiency besides many antenna parameters by using powerful different kind of solvers such as Time domain solver, Frequency domain solver, and Transient solver. It allows mesh generation that divided the system to small cells in order to get accurate results.

3.2 MPA

Multi-Port Antenna evaluator is new and young program which is developed by Kristian Karlsson at SP Technical Research Institute of Sweden [13]. MPA has the ability to compute and analyze a multi port antenna system in very short time in combination with a full wave EM simulator and circuit simulator. It has the power to perform a way for optimizing process to improve the performance of antenna. It calculates the total radiation from the multi port antenna from the current calculated in CircSim (will be explained later on) and by weighting the embedded element patterns which has been imported from resulting of s-parameters from EM simulator program. Besides, it has the ability to compute different antenna parameters like diversity gain, correlation, etc. any feeding networks and networks connected to antenna can be defined also able to optimize any component connecting to antenna ports. MPA is compatible with different kind of full wave simulators, WSAP, CST, EMDS and IE3D. More details will be found out in Appendix [3].

3.3 Circuit Simulator

CircSim software utilizes the idea of modified nodal sequences. It requires little skill to acquire probe files for MPA besides the ability to solve in Time or Frequency domain. It is developed by Jan Carlsson. More details will be found in Appendix [3].

3.4 Circuit CAM

Circuit CAM (LPFK) proto Mat is a circuit board plotter which can be used to produce prototype PCB's and gravure, films and for engraving aluminum or plastic.

3.6 MATLAB

MATLAB is a programming language. It is allowing plotting of functions and data, matrix manipulation, etc…

3.7 Reciprocal actions of software's

As it is mentioned before about each software, here we focus about the interaction between CST microwave studio ©, CircSim and MPA. Several steps will be taken before start MPA simulation for calculating total radiation efficiency, correlation and diversity gain; figure 3.1 shows the interaction between this software's.

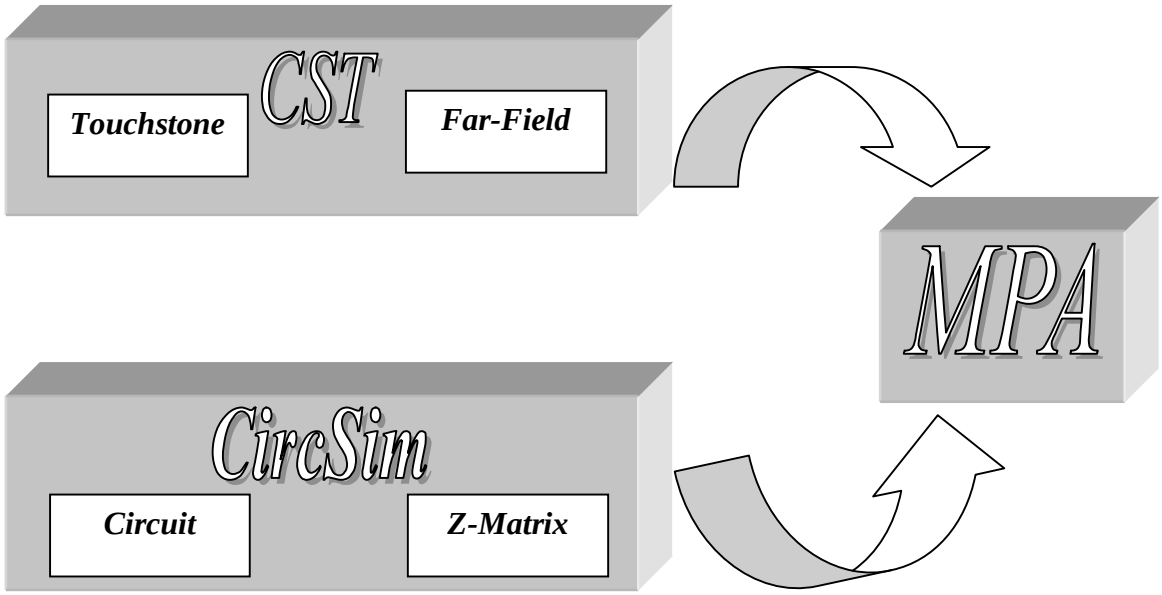

Figure 3.1 *Block diagram between software interactions.*

Starting with CST microwave studio © since we need to get far-field patterns keeping in mind that ports in the design must have S-parameters source type and reference impedance of 50Ω as following:

- Define frequency range for F-min and F-max for the design to be simulated
- Define far-field monitor at our central frequency and at the frequency band limits.
- Start transient solver parameter for simulation, recommended to be 60 dB for more accuracy.
- Plot far-field as E-fields in linear scaling with reference distance of 1m and by using far-field approximation.
- The angle step width to represent far-field patterns is set to be 15 for accuracy results and for more accuracy just increase it more.
- Export S-parameters as Touchstone file.
- Export far-field files for each port and save it as ASCII.

Following using CircSim:

- Draw circuit of two ports antenna

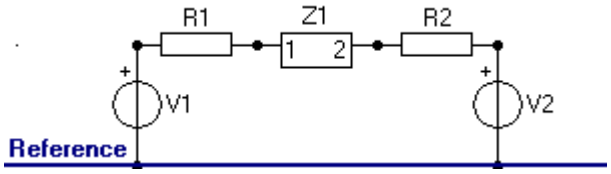

Figure 3.2 *CircSim circuit belongs to 50 Ω system.*

- To compute response the circuit utilizes Z-parameters.
- Convert S-parameters in the format of Touchstones file then to Z-matrix.
- Interpolate Z-matrix, to select the desire frequencies which lead to modify the Z-matrix.
- Create probe files for MPA in order to identify the circuit in MPA.

Now MPA is ready to simulate all parameters belonging to these antennas and to calculate them.

4. Simulation

4.1 Two parallel dipoles

Two lossless parallel dipoles are designed and simulated using CST microwave studio as a first step and also simulated via MPA for comparison purposes by getting radiation patterns. Each port of antennas transmits through their embedded elements pattern. The radiation efficiency at each port as well as the correlation between signals at both ports are determined by the embedded elements [11] and keeping in mind the mutual coupling between antennas because it will influence radiation efficiency and correlation as well. Follow same example in [14, 15] the only difference is that our dipoles is simulated by CST microwave studio and not using analytical dipole equation. As it is seen in [14, 15] two source voltages V_1 and V_2 corresponds to these two parallel dipoles having source impedances Z_{S1} and Z_{S2}; separating distance d in our case $d = 19\,mm$. Since the two dipoles are identical and having independent transmitter or receiver this implies that source impedances are equal and the input impedances Z_{in} also are equal as shown in figure 4.1

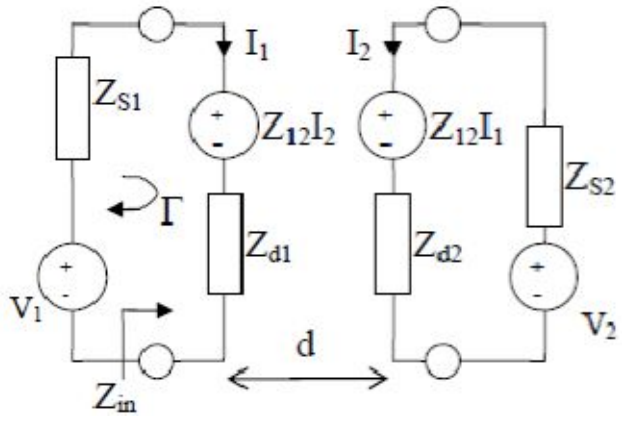

Figure 4.1 *Equivalent circuits for classical analysis having independent source voltages.*

The length of the dipoles is 160 mm which is the half wave length, radius of 2 mm and separation distance is 19 mm, while the resonance frequency is 900MHz. The gap between each dipole arms is 2 mm. More over the system is simulated at different frequencies in the interval 800-1000MHz; discrete ports are used for these two dipoles for an excitation. We set up the frequency range setting 0-3GHz, far-field monitors are defined at our central frequency and in the interval 800-1000MHz.

The design is seen in figure 4.2

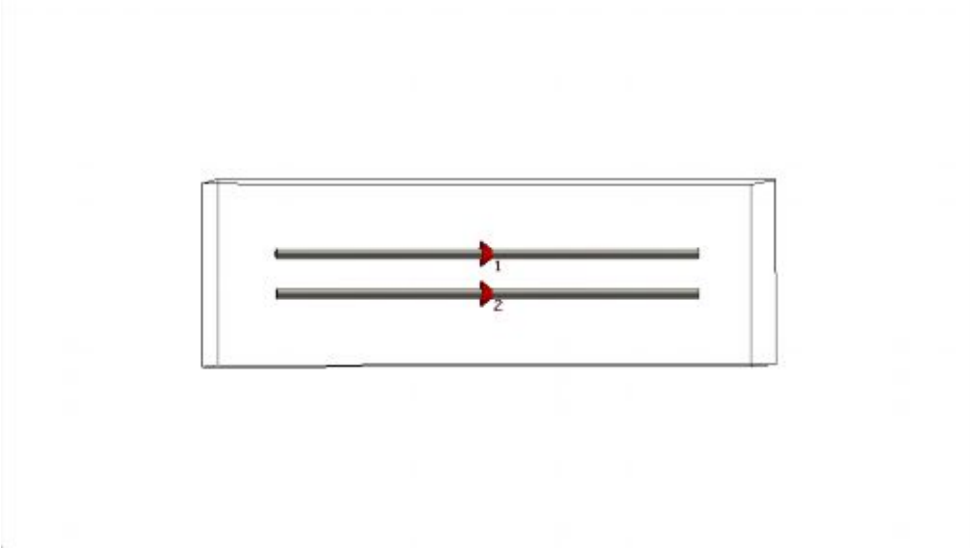

Figure 4.2 *Two parallel dipoles of separation 19 mm.*

After computation, embedded far-field patterns have been exported and ready to be imported to MPA in order to evaluate the validity of MPA in this example. Following what have been mentioned in chapter 3 sections 3.7, from S-parameters file in CST microwave studio shown in figure 4.3

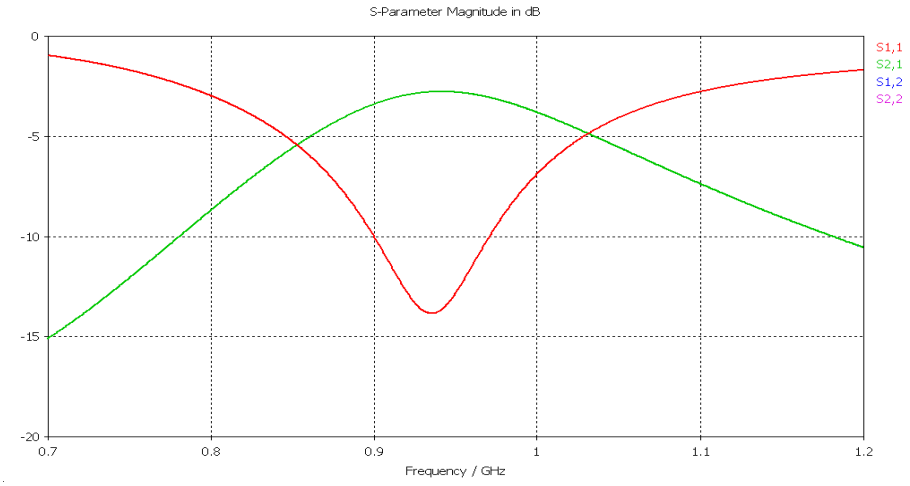

Figure 4.3 *S-parameters for two parallel dipoles.*

The touchstone files are exported and used in CircSim circuit after have been converted to Z-parameters.

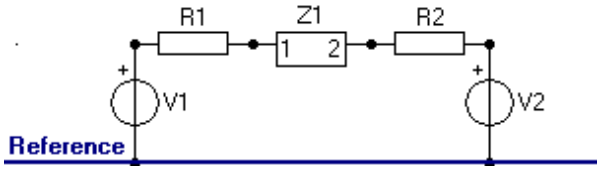

Figure 4.4 *Feeding networks of two parallel dipoles.*

Z_1 represents the multiport antenna, V_1 represents the source at port one and V_2 the source at port 2. In a like style R_1 and R_2 typifies the generator impedances or the termination of the ports. The values of V_1 and V_2 are 14.14 V to imitate the value of 1 W passing through each port in CST microwave studio. Since the ports in CST microwave studio will be terminated to 50Ω, R_1 and R_2 having values of 50Ω both. Two cases will be followed with respect to source impedances first case represented to 50Ω system where imaginary parts equal to zero, and the second case represented by varying the source impedance to $R \pm jX$. Table 4.1 shows the result simulations of total radiation efficiencies from CST microwave studio and MPA for 50Ω system.

	Total rad. Eff.				***Total rad. Eff.***		
Freq.[MHz]	**CST**	**MPA P1**	**MPA P2**	**Freq.[MHz]**	**CST**	**MPA P1**	**MPA P2**
800	*0.3572*	*0.3530*	*0.3554*	***900***	***0.4403***	***0.4322***	***0.4366***
810	*0.3738*	*0.3690*	*0.3718*	*910*	*0.4398*	*0.4316*	*0.4357*
820	*0.3886*	*0.3834*	*0.3865*	*920*	*0.4379*	*0.4297*	*0.4335*
830	*0.4015*	*0.3958*	*0.3993*	*930*	*0.4347*	*0.4266*	*0.4299*
840	*0.4124*	*0.4063*	*0.4100*	*940*	*0.4302*	*0.4223*	*0.4250*
850	*0.4213*	*0.4148*	*0.4188*	*950*	*0.4244*	*0.4168*	*0.4189*
860	*0.4284*	*0.4214*	*0.4257*	*960*	*0.4175*	*0.4101*	*0.4115*
870	*0.4337*	*0.4263*	*0.4307*	*970*	*0.4095*	*0.4024*	*0.4032*
880	*0.4373*	*0.4296*	*0.4342*	*980*	*0.4006*	*0.3939*	*0.3941*
890	*0.4395*	*0.4316*	*0.4361*	*990*	0.3912	0.3848	0.3845
				1000	0.3814	0.3753	0.3744

Table 4.1 *Total radiation efficiency computed in CST and MPA for 50Ω system.*

As we see in the table of results, MPA has closer answers comparing to that in CST microwave studio. This slight difference in computed results is related to the fact that CST microwave studio reckons the efficiency from losses while MPA reckons the efficiency as integration of the far-field pattern more over it is due to mesh system in CST since we can increase the number of cells to be simulated which gives more accuracy but it utilize long time simulation.

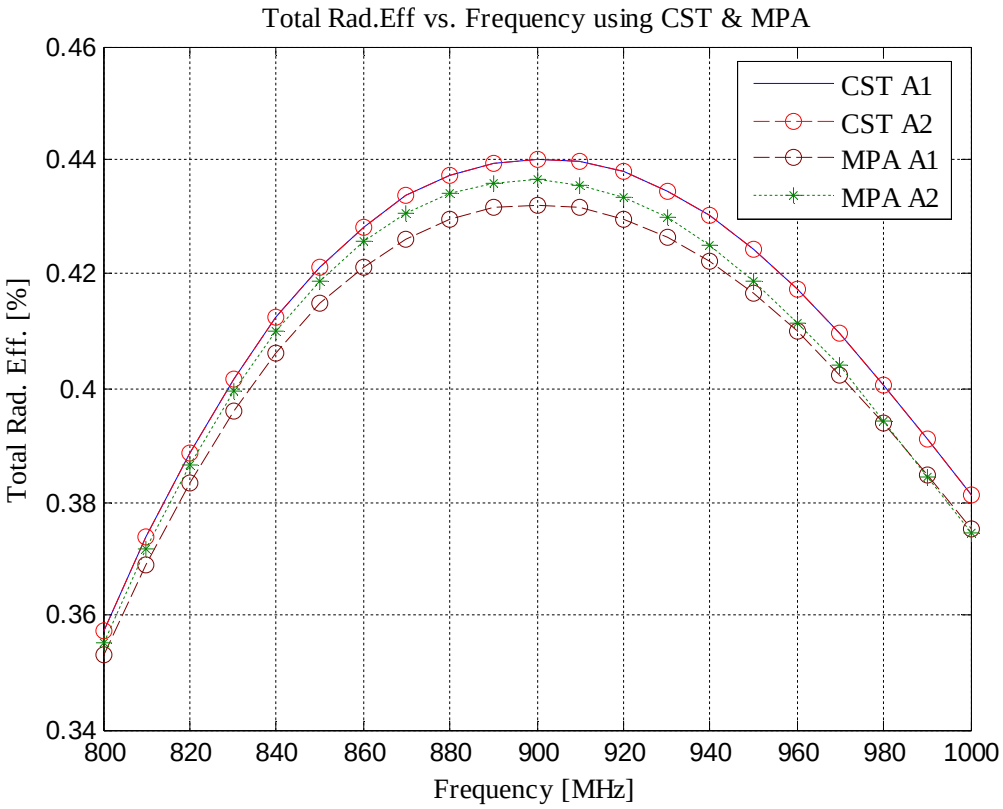

Figure 4.5 *Total rad. Eff. Calculated for the parallel dipoles at 19 mm separation. CST A1 is dipole 1 calculated with CST and CST A2 the same for dipole 2. MPA A1 is dipole 1 calculated with MPA and MPA A2 the same for dipole 2.*

As we can see in figure 4.5 the total radiation efficiency which has been calculated using CST (CST A1, CST A2) corresponds to -3.56 dB and MPA (MPA A1, MPA A2) corresponds to -3.66 dB at 900 MHz. It is clear that both antennas A1 and A2 computed in MPA having same results as CST.

Not only total radiation efficiency will be calculated and compared with MPA, CST has the ability to calculate correlation and diversity gain for the far field patterns of the system. As

shown in table 4.2 and 4.6. However, CST uses the S-parameters to determine the correlation and this work when we have lossless system. CST also calculates correlation from the far-field patterns but we did not have the latest version of CST, including this calculation, when we performed our simulations.

The performance of correlation and effective diversity gain are shown in the following

	Correlation			***Correlation***	
Freq.[MHz]	**CST**	**MPA**	**Freq.[MHz]**	**CST**	**MPA**
800	*0.9211*	*0.9211*	***900***	***0.7550***	***0.7550***
810	*0.9126*	*0.9126*	*910*	*0.7307*	*0.7307*
820	*0.9026*	*0.9026*	*920*	*0.7072*	*0.7072*
830	*0.8909*	*0.8909*	*930*	*0.6853*	*0.6853*
840	*0.8773*	*0.8773*	*940*	*0.6658*	*0.6658*
850	*0.8617*	*0.8617*	*950*	*0.6493*	*0.6493*
860	*0.844*	*0.844*	*960*	*0.6362*	*0.6362*
870	*0.8241*	*0.8241*	*970*	*0.6264*	*0.6264*
880	*0.8024*	*0.8024*	*980*	*0.6197*	*0.6197*
890	*0.7792*	*0.7792*	*990*	*0.616*	*0.616*
			1000	*0.6145*	*0.6145*

Table 4.2 *Correlation between antenna ports using CST & MPA for 50Ω system.*

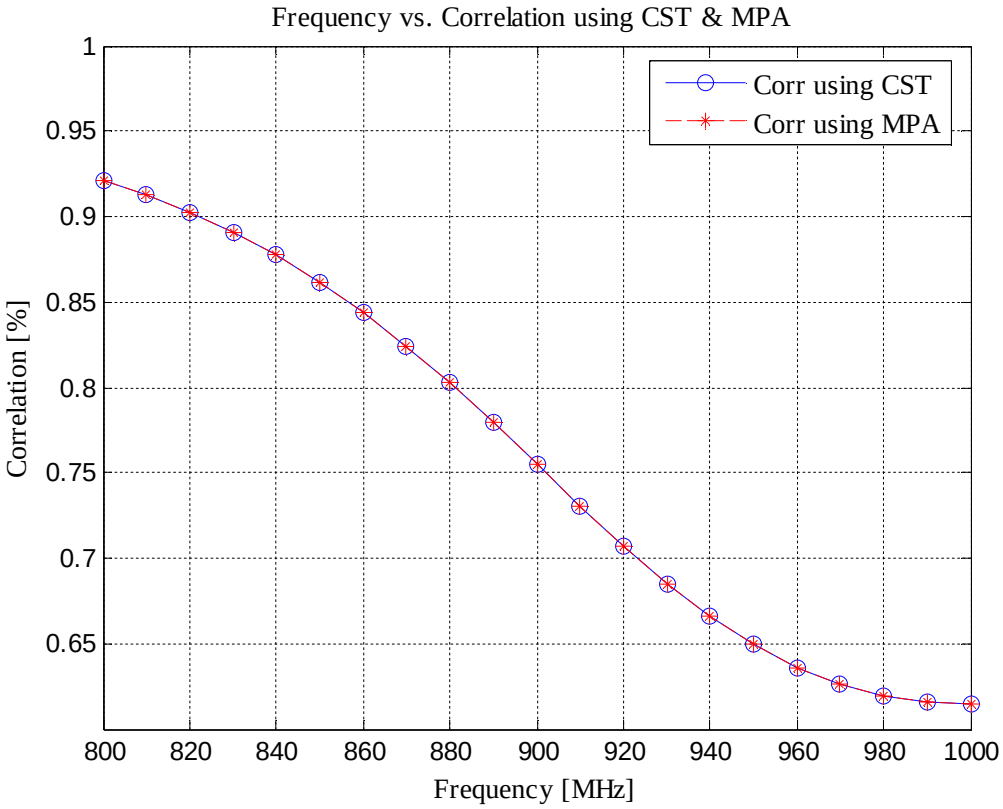

Figure 4.6 *Frequency vs. Correlation computed by CST & MPA.*

The diversity gain is shown in the following table 4.3 and figure 4.7

	Diversity Gain [dB]			***Diversity Gain [dB]***	
Freq.[MHz]	**CST**	**MPA**	**Freq.[MHz]**	**CST**	**MPA**
800	*3.8928*	*6.021*	***900***	***6.5566***	***8.1954***
810	*4.0883*	*6.2211*	*910*	*6.8262*	*8.3666*
820	*4.3047*	*6.4329*	*920*	*7.0697*	*8.5157*
830	*4.5419*	*6.6544*	*930*	*7.2821*	*8.6417*
840	*4.7988*	*6.8828*	*940*	*7.4606*	*8.745*
850	*5.0737*	*7.115*	*950*	*7.6046*	*8.8265*
860	*5.3634*	*7.3476*	*960*	*7.7152*	*8.8882*
870	*5.6633*	*7.5762*	*970*	*7.7950*	*8.9322*
880	*5.9671*	*7.7966*	*980*	*7.8477*	*8.961*
890	*6.2676*	*8.0044*	*990*	*7.8774*	*8.9771*
			1000	*7.8884*	*8.9831*

Table 4.3 *Diversity gain simulated using CST & MPA.*

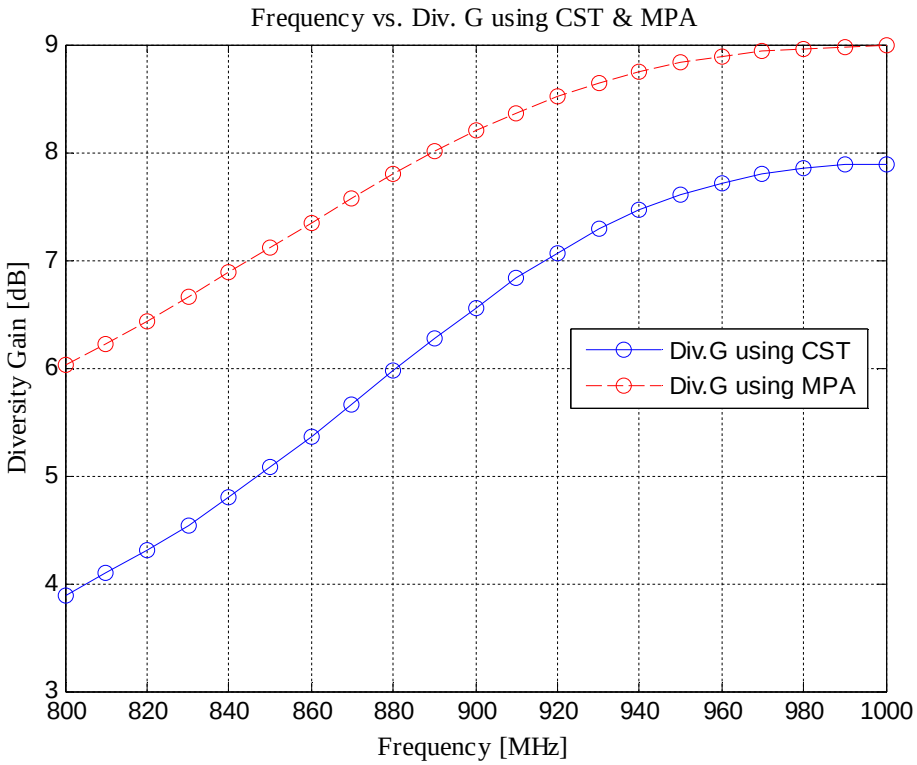

Figure 4.7 *Frequency vs. Diversity gain computed in CST & MPA.*

In the second case we will change the source impedances of two parallel dipoles to $R \pm jX$ and study the performance to these dipoles and how it will affect not only the radiation efficiency but also correlation and effective diversity gain. Previously in [15], shows how to optimize source impedances of two parallel dipoles at distance 19mm and resonant frequency 900 MHz where the source impedances for real and imaginary parts are equal $Z_{S1} = Z_{S2}$

Plot of the total radiation efficiency as shown below in figure 4.8

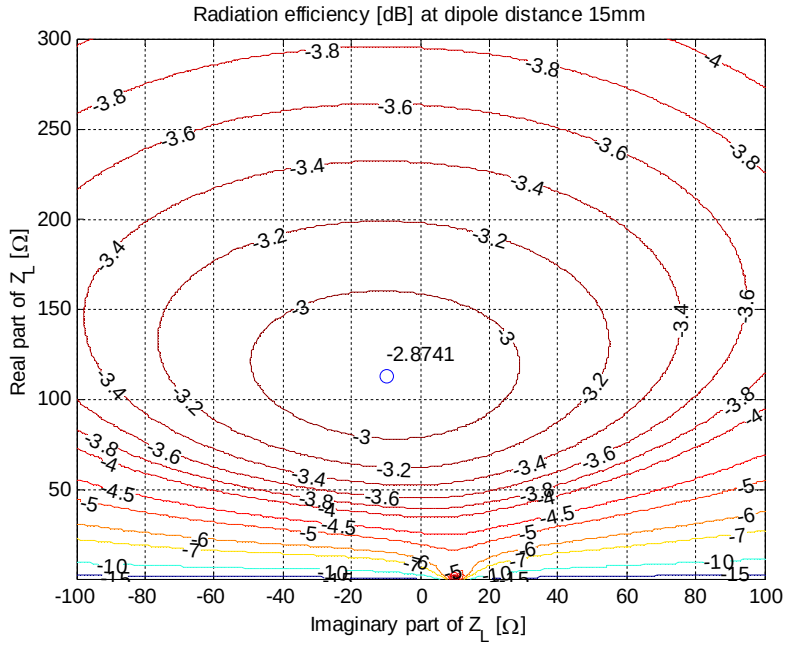

Figure 4.8 *Total radiation efficiency calculated by analytical equations as a function of source impedances.*

In our case we will optimize the sources impedances via MPA and choose the value which belongs to the highest radiation efficiency. Real part R_e will be computed and optimized to range belong to {0: 200} and Imaginary part $I_m$to range belong to {-200: 200}. After simulation it seems that the highest radiation efficiency belongs to $Z_s = 120 - j10$. Keep in mind that also correlation and effective diversity gain will be calculated at the same Z_S

Now the simulations will be performed and compared by varying the source impedances to $Z_s = 120 - j10$ between CST microwave studio and MPA as shown in the table 4.4 below

	Total rad. Eff.				***Total rad. Eff.***		
Freq.[MHz]	**CST**	**MPA P1**	**MPA P2**	**Freq.[MHz]**	**CST**	**MPA P1**	**MPA P2**
800	*0.4299*	*0.4087*	*0.41*	***900***	***0.51***	***0.5038***	***0.5067***
810	*0.4421*	*0.4240*	*0.4255*	*910*	*0.5068*	*0.5063*	*0.5093*
820	*0.4535*	*0.4381*	*0.4398*	*920*	*0.5068*	*0.5078*	*0.5109*
830	*0.4640*	*0.4511*	*0.4529*	*930*	*0.5058*	*0.5085*	*0.5116*
840	*0.4735*	*0.4627*	*0.4646*	*940*	*0.5039*	*0.5082*	*0.5114*
850	*0.4820*	*0.4729*	*0.4750*	*950*	*0.5012*	*0.5073*	*0.5105*
860	*0.4893*	*0.4817*	*0.4840*	*960*	*0.4978*	*0.5053*	*0.5090*
870	*0.4953*	*0.4892*	*0.4917*	*970*	*0.4938*	*0.5037*	*0.5069*
880	*0.50*	*0.4953*	*0.4979*	*980*	*0.4892*	*0.5012*	*0.5043*
890	*0.5035*	*0.5003*	*0.5029*	*990*	*0.4842*	*0.4983*	*0.5014*
				1000	*0.4788*	*0.4951*	*0.4981*

Table 4.4 *Total radiation efficiency computed in CST and MPA for 120-j10 source impedances.*

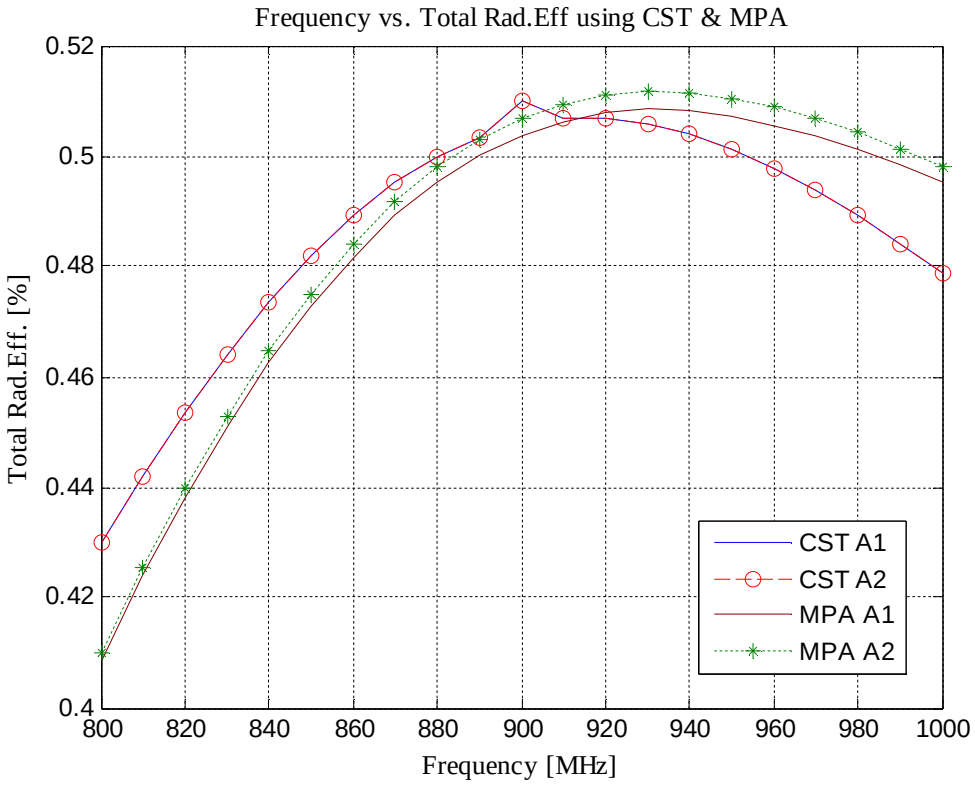

Figure 4.9 *Total radiation efficiency computed in CST and MPA for 120-j10 source impedances.*

The performance of correlation and diversity gain calculated in MPA are shown in table 4.5

Freq. [MHz]	Corr. MPA	Div.G [dB]MPA	Freq. [MHz]	Corr. MPA	Div.G [dB] MPA
800	*0.9531*	*5.0123*	***900***	***0.8957***	***6.5667***
810	*0.9491*	*5.1693*	*910*	*0.8880*	*6.7055*
820	*0.9447*	*5.3285*	*920*	*0.8801*	*6.8375*
830	*0.94*	*5.4887*	*930*	*0.8722*	*6.962*
840	*0.9348*	*5.6487*	*940*	*0.8643*	*7.0782*
850	*0.9292*	*5.8079*	*950*	*0.8565*	*7.1861*
860	*0.9233*	*5.9654*	*960*	*0.8489*	*7.2861*
870	*0.9169*	*6.1208*	*970*	*0.8414*	*7.3787*
880	*0.9102*	*6.2734*	*980*	*0.8341*	*7.4647*
890	*0.9031*	*6.4224*	*990*	*0.8270*	*7.5445*
			1000	*0.8177*	*7.6445*

Table 4.5 *Correlation and Diversity gain computed in MPA for 120-j10 source impedances.*

This process takes action when we connect two ports to our design in CST design studio, change the ports impedances to $Z_s = 120 - j10$ which gives total radiation efficiency of 0.51, -2.91 dB. Transforming the 50 ohm systems to $120 - j10$ by using lumped components as seen in the figure below

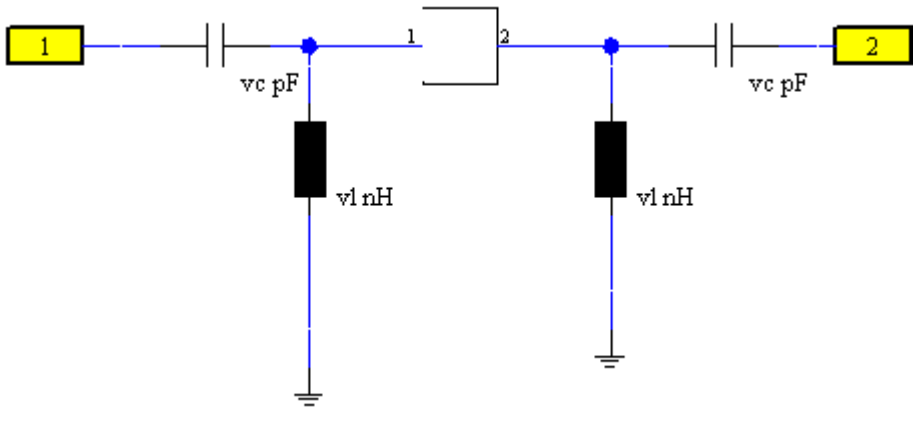

Figure 4.10 *Transforming the 50ohm port 1 and port 2 to 120-j10.*

Where two capacitors are using in series of values *3.3 pF* and two parallel inductance of values *20 nH*.

As we see in figure 4.11 the correlation is changing with frequency since it depends on it.

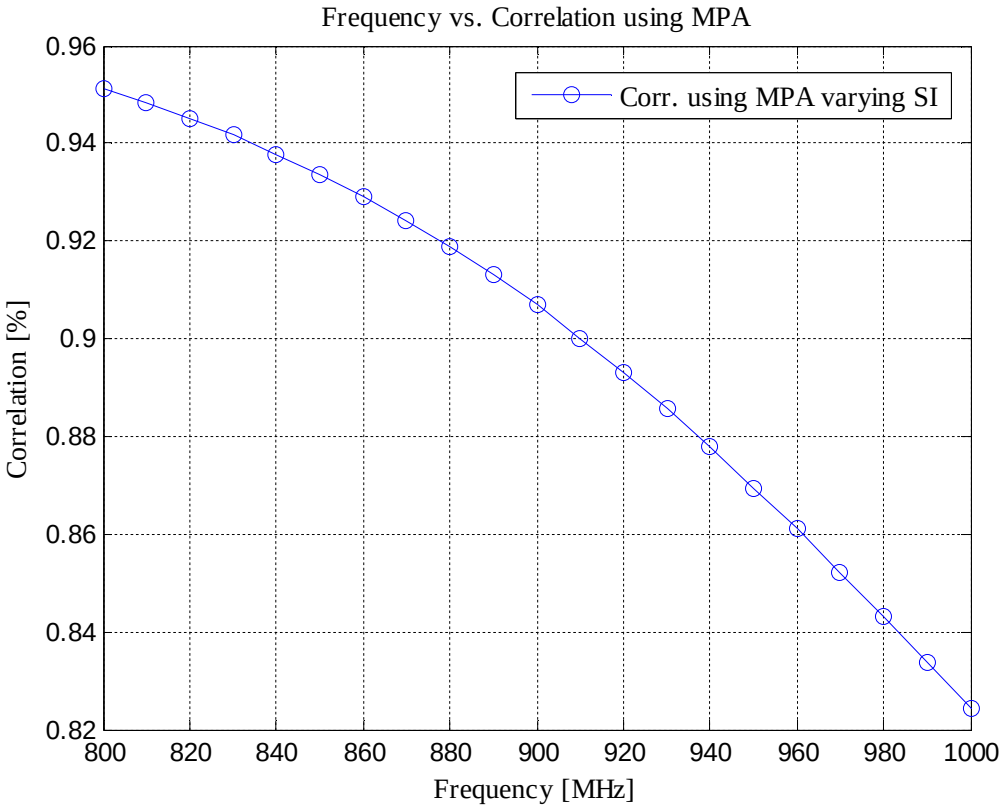

Figure 4.11 *Frequency vs. Correlation using MPA for changing source impedances.*

The values of radiation efficiency, correlation and effective diversity gain have been studied and showed for both 50 Ω system and for $R \pm jX$ system by using matching networks; as a result the maximization of radiation efficiency leads to increasing the from approximately 0.82 to 0.91 correlation and degrading in the effective diversity gain for two parallel dipoles.

4.2 Goal antenna requirements

The terminal on WiMAX will use antenna elements that shall be produced, and having same electrical characteristics and requirements explained below in table 4.6

ITEM	NEEDED
Frequency range (GHz)	2.5-2.7
Return Loss (dB)	≥-10
Efficiency (%)	50%
Height (mm)	1
Length (mm)	5
Width	3
Material	Ceramic

Table 4.6 *Antenna characteristics*

The MIMO system is tested by mounting the antenna elements on PCB, two antennas will be designed, manufactured and mounted on PCB for WiMAX according the specification in table 4.6. The ceramic antenna using dielectric material in order to reduce the physical size and to have better performance matching for 50Ω since we need input of 50Ω and to increase the radiation efficiency. Keep in mind it is dielectric loaded antenna because conducting element is the radiator and the dielectric is used to reduce the physical size.

4.2.1 Single antenna element design and simulation

Incipient work using simulation tools to develop antenna which is CST microwave studio©. The ceramic antenna has 5 mm long, 3 mm width and 1mm height. The substrate has thickness of 0.8mm. To guarantee strong connect between ceramic antenna and PCB besides good electrical junction, a micro-strip move forward on the lower face which works as feed to the ceramic antenna. The micro-strip line has 1.5 mm width. PCB has dimensions of *76.4 mm x 44 mm*. This design is to bring out into a perfected state 200 MHz bandwidth and RL ≥ -10 dB. Total radiation efficiency, coupling and RL will be simulated in this designed. Since we are using more than one antenna on the terminal of WiMAX another ceramic antenna followed by same specification will be also designed.

4.2.2 Two antennas element design and simulation

4.2.2.1 50Ω source impedance

Now both antennas are separated i.e. 14 mm air between the antennas see figure 4.12 and 4.13 respectively; to be simulated to study the performance of them at frequency range 2.5-2.7 GHz where different frequencies are monitored to calculate the far-field patterns as well as efficiency, coupling and RL.

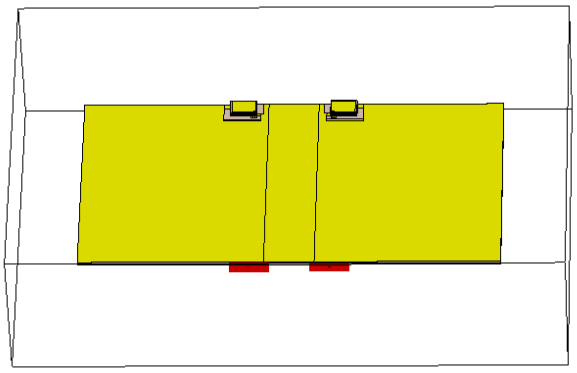

Figure 4.12 *Front view of two ceramic antennas design in CST microwave studio.*

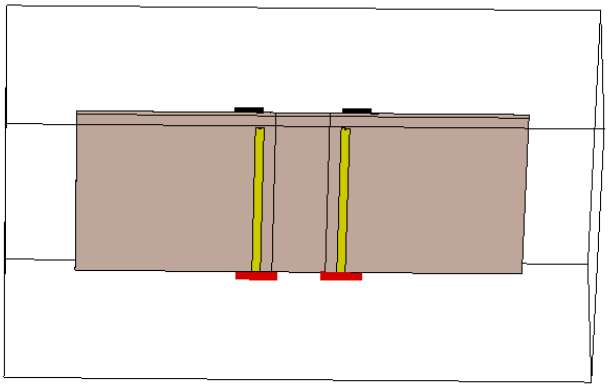

Figure 4.13 *Back view of two ceramic antennas design in CST microwave studio.*

Simulation results from CST microwave studio are available in the appendix [1] more over radiation patterns and RL still acceptable with the coupling between elements. All results related to single and multi antennas such as RL, coupling and gain are included in the appendix. Never forget that MPA is a part of this project, following same steps mentioned previously in chapter 3 section 3.7 for comparison purposes. Keep in mind the first simulations belong to 50 Ω system. Compared results between CST microwave studio and MPA are shown in the following table 4.7 with respect to total radiation efficiency.

	Total rad. Eff. A1		***Total rad. Eff. A2***	
Frequency [GHz]	***CST***	***MPA***	***CST***	***MPA***
2.5	*0.3078*	*0.3077*	*0.3609*	*0.3623*
2.52	*0.3703*	*0.3711*	*0.4248*	*0.4262*
2.54	*0.4369*	*0.4366*	*0.4846*	*0.4861*
2.56	*0.5007*	*0.5008*	*0.5324*	*0.5344*
2.58	*0.5545*	*0.5556*	*0.5630*	*0.5658*
2.6	***0.5926***	***0.5951***	***0.5752***	***0.5791***
2.62	*0.6124*	*0.6163*	*0.5718*	*0.5768*
2.64	*0.6141*	*0.6193*	*0.5574*	*0.5633*
2.66	*0.6002*	*0.6062*	*0.5359*	*0.5425*
2.68	*0.5740*	*0.5804*	*0.5094*	*0.5164*
2.7	*0.5387*	*0.5453*	*0.4787*	*0.4859*

Table 4.7 *Total radiation efficiency computed in CST and MPA for 50Ω system.*

It is clear that both CST and MPA give the same results which mean the validation of MPA is achieved and proved of our goal in terms of total radiation efficiency. The graphical representation of total radiation efficiency is shown in figure 4.14 where A1 simulations belong to (CST A1, MPA A1) and A2 simulations belong to (CST A2, MPA A2). According to table 4.7 the total radiation efficiency computed in CST and MPA for first antenna A1 at 2.6 GHz corresponds to -2.27 dB, and for the second antenna A2 it corresponds to -2.40 dB.

As we can see the similarity between CST and MPA in figure 4.14

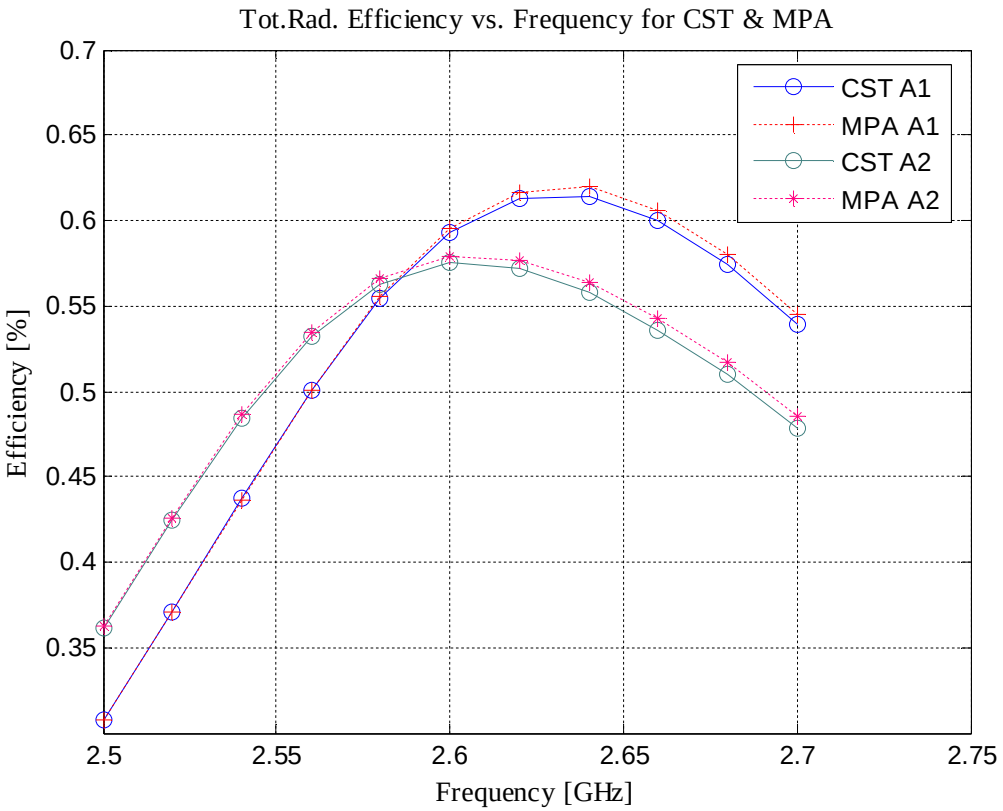

Figure 4.14 *Total rad. Eff. Computed by CST & MPA for 50Ω system.*

The correlation and apparent diversity gain were also studied using MPA and shown in table 4.8

	Correlation	
Freq. [GHz]	**CST**	**MPA**
2.5	*0.1931*	*0.1925*
2.52	*0.1615*	*0.1610*
2.54	*0.1546*	*0.1541*
2.56	*0.1738*	*0.1732*
2.58	*0.2186*	*0.2181*
2.6	***0.2857***	***0.2851***
2.62	*0.3662*	*0.3657*
2.64	*0.4482*	*0.4478*
2.66	*0.5198*	*0.5194*
2.68	*0.5735*	*0.5731*
2.7	*0.6081*	*0.6077*

Table 4.8 *Correlation between antennas port using CST & MPA for 50Ω system.*

Graphical representation for correlation and diversity gain are shown below.

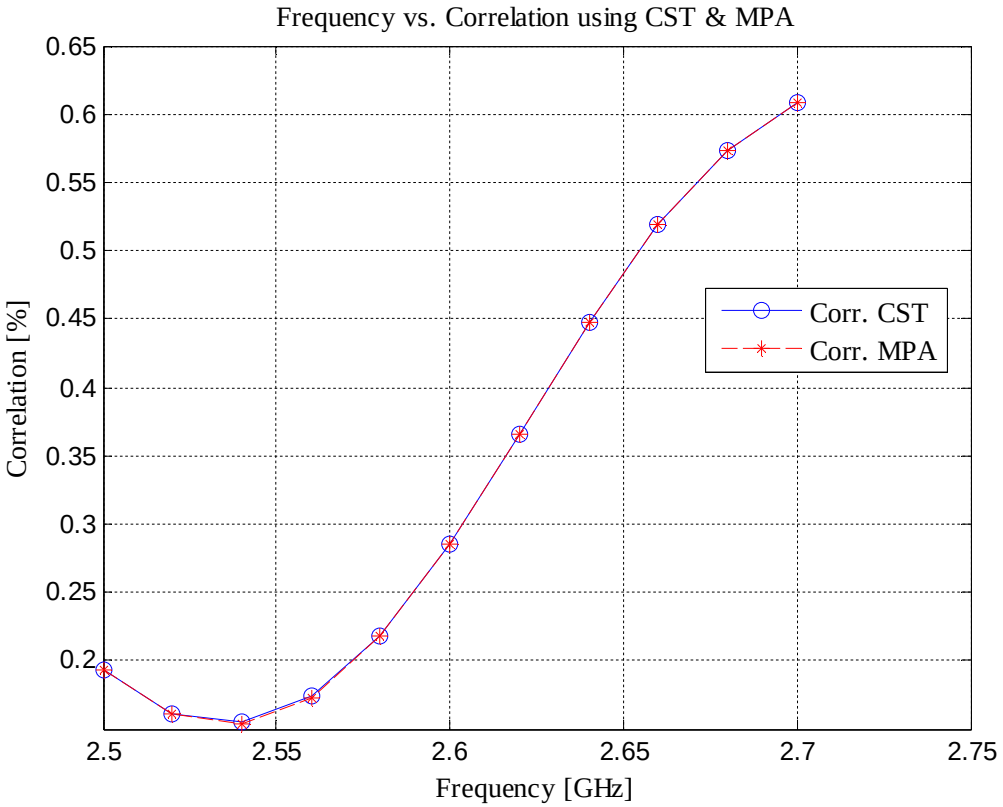

Figure 4.15 *Frequency vs. Correlation computed by CST & MPA for 50Ω system.*

	Diversity gain [dB]	
Freq. [GHz]	**CST**	**MPA**
2.5	*9.8116*	*9.9215*
2.52	*9.8685*	*9.9457*
2.54	*9.8796*	*9.9504*
2.56	*9.8477*	*9.9368*
2.58	*9.7579*	*9.8982*
2.6	***9.5831***	***9.8217***
2.62	*9.3050*	*9.6965*
2.64	*8.9389*	*9.5256*
2.66	*8.5425*	*9.3323*
2.68	*8.1920*	*9.1538*
2.7	*7.9383*	*9.0197*

Table 4.9 *Diversity gain simulated using CST & MPA.*

Diversity gain can be seen in figure 4.16

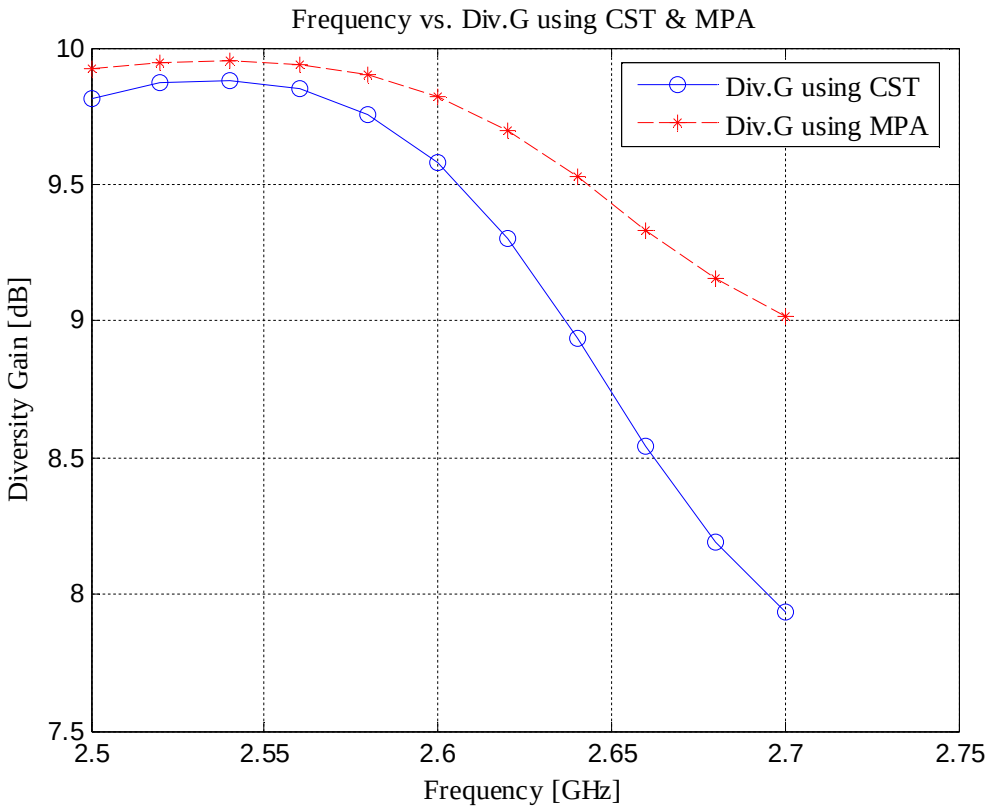

Figure 4.16 *Frequency vs. Diversity gain computed in CST & MPA.*

Increase efficiency of both antennas can be achieved by either adding components between their ports or changing source impedances. In our case which belongs to 14 mm between antennas and having several simulations and MPA optimizing the lumped network in figure 4.17 gives us a solution of not adding any components at all.

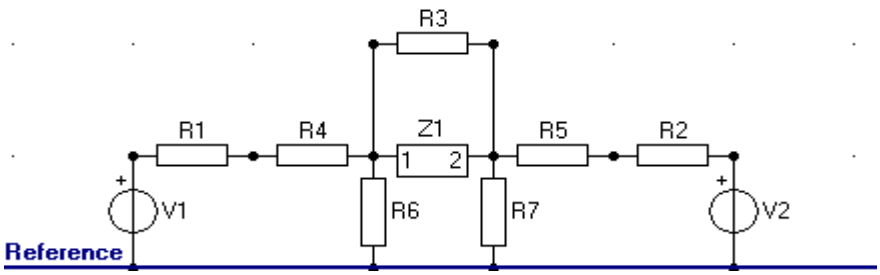

Figure 4.17 *Extra components between antennas port.*

The optimal solution seems to be that no extra components are suitable to be added, in other word the efficiency and correlation cannot be improved by matching circuits, since both antennas are already very good at distance of 14 mm, the idea of my supervisor lead us to another approach to decrease distance between antennas e.g. 11 mm.

4.2.2.2 50 Ω source impedance at 11 mm

Same steps of simulation will take an action under distance of 11 mm starting with CST microwave studio and comparing results to MPA ones.

	Total rad. Eff. A1		***Total rad. Eff. A2***	
Frequency [GHz]	***CST***	***MPA***	***CST***	***MPA***
2.5	*0.2723*	*0.2640*	*0.3230*	*0.3211*
2.52	*0.3264*	*0.3162*	*0.3781*	*0.3762*
2.54	*0.3861*	*0.3739*	*0.4307*	*0.4288*
2.56	*0.4461*	*0.4320*	*0.4742*	*0.4725*
2.58	*0.4997*	*0.4845*	*0.5039*	*0.5026*
2.6	***0.5411***	***0.5256***	***0.5186***	***0.5178***
2.62	*0.5664*	*0.5513*	*0.5202*	*0.5199*
2.64	*0.5745*	*0.5602*	*0.5122*	*0.5121*
2.66	*0.5668*	*0.5536*	*0.4975*	*0.4976*
2.68	*0.5462*	*0.5342*	*0.4775*	*0.4778*
2.7	*0.5159*	*0.5051*	*0.4527*	*0.4533*

Table 4.10 *Total radiation efficiency computed in CST and MPA for 50Ω system.*

	Correlation	
Freq. [GHz]	**CST**	**MPA**
2.5	*0.3455*	*0.3421*
2.52	*0.3094*	*0.3059*
2.54	*0.2958*	*0.2924*
2.56	*0.3084*	*0.3050*
2.58	*0.3462*	*0.3429*
2.6	***0.4051***	***0.4020***
2.62	*0.4772*	*0.4743*
2.64	*0.5515*	*0.5491*
2.66	*0.6171*	*0.6150*
2.68	*0.6670*	*0.6652*
2.7	*0.6998*	*0.6981*

Table 4.11 *Correlation between antennas port using CST & MPA for 50Ω system.*

Table 4.10 and 4.11 represents total radiation efficiency and correlation respectively for CST microwave studio and MPA simulations at our new distance between both antennas (11 mm) for 50Ω system.

It is noticeable that total radiation efficiency has decreased while the correlation has increased, this is due to fact when distance between antennas become smaller the mutual coupling will increase. Representation graphs of total radiation efficiency and correlation depending on frequency are shown in figures 4.18 and 4.19 respectively.

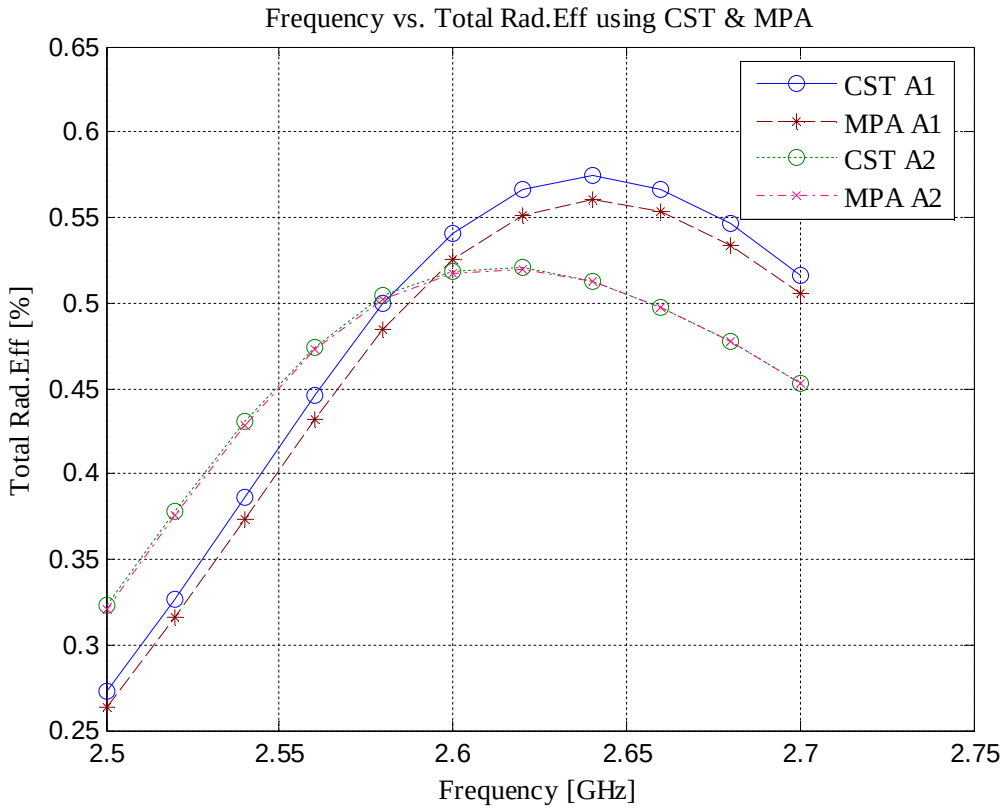

Figure 4.18 *Total rad. Eff. Computed by CST & MPA for 50Ω system.*

While A1 simulated in CST and MPA belongs to -2.7 dB, and A2 belongs to -2.9 dB at our central frequency 2.6 GHz.

Correlation graph representation can be seen in figure 4.19

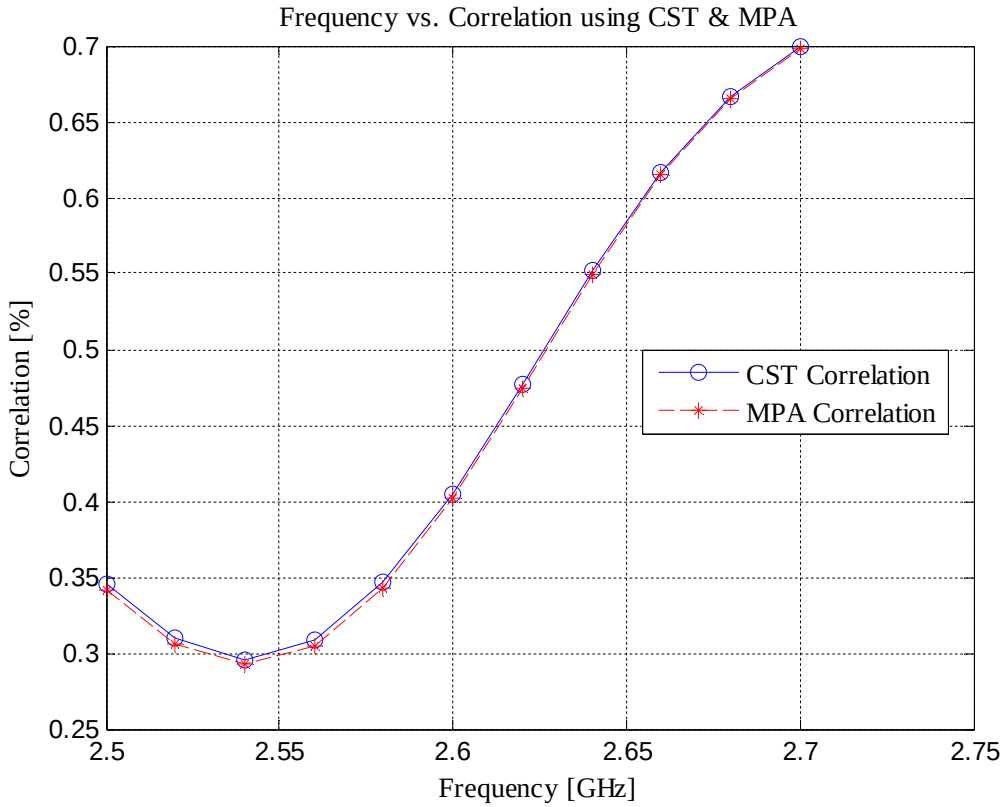

Figure 4.19 *Frequency vs. Correlation computed by CST & MPA for 50Ω system.*

While diversity gain is shown in table 4.12 and figure 4.20 in the following

	Diversity Gain [dB]	
Freq. [GHz]	**CST**	**MPA**
2.5	*9.3841*	*9.7325*
2.52	*9.5092*	*9.7888*
2.54	*9.5522*	*9.8079*
2.56	*9.5124*	*9.7902*
2.58	*9.3814*	*9.7312*
2.6	***9.1423***	***9.6213***
2.62	*8.7876*	*9.4528*
2.64	*8.3415*	*9.2302*
2.66	*7.8680*	*8.9811*
2.68	*7.4497*	*8.7484*
2.7	*7.1425*	*8.5693*

Table 4.12 *Diversity gain between antennas port using CST & MPA for 50Ω system.*

Representation of diversity gain depending on frequency is shown below

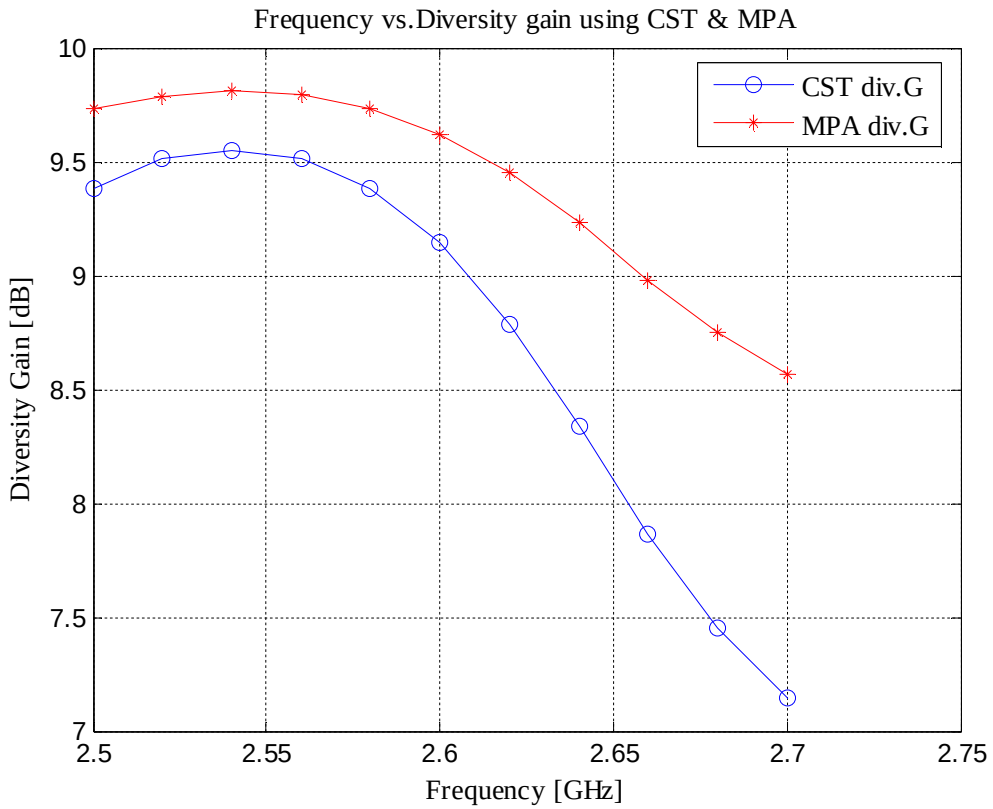

Figure 4.20 *Frequency vs. Diversity gain computed by CST & MPA for 50Ω system.*

4.2.2.3 Varying source impedance

It is obvious the influence of source impedances on antenna performance with respect to correlation, efficiency and diversity gain. Follow the dipoles example which has been published in [17] and has proved the idea of changing source impedances to $R \pm jX$. We have all results belong to 50 Ω systems; no need to simulate our system again just keeping the same files which have been used in MPA and CircSim and only change the values of the generator impedances R_1 and R_2 in CircSim besides source voltages and currents must be defined in MPA in this case. Since both antennas are the same and the total radiation efficiencies of both ports are quite similar, the effective diversity gain will be calculated at 1% probability level using equations

(2.3) and (2.4). Procedures related to changing source impedances and optimization which belongs to MPA to get the optimum values are available in Appendix [2].

Table 4.13 shows how the total radiation efficiency at 2.6 GHz is increase by varying the source impedances below using MPA optimization process.

Case no.	R_1	R_2	Eff.A1	Eff.A2	Correlation
1	***35+j8***	***35-j7***	***0.713***	***0.711***	***0.402***
2	***34+j8***	***34-j7***	***0.732***	***0.730***	***0.402***
3	***33+j8***	***33-j6.9***	***0.752***	***0.751***	***0.402***
4	***32+j8***	***32-j6.9***	***0.772***	***0.773***	***0.402***
5	***32+j7***	***31.5-j6.75***	***0.783***	***0.785***	***0.402***
6	***31+j7***	***31-j6***	***0.806***	***0.805***	***0.402***
7	***30+j7***	***30.2-j5***	***0.830***	***0.834***	***0.402***
8	***29+j6***	***29-j4.7***	***0.869***	***0.869***	***0.402***
9	***28+j5***	***28-j4***	***0.909***	***0.906***	***0.402***
10	***27+j4.5***	***27-j3.5***	***0.947***	***0.943***	***0.402***

Table 4.13 *Varying source impedances using MPA.*

In order to prove that using CST microwave studio we have to convert source impedances to lumped elements which are easier to implement them between the ports of both antennas. After several simulations using CST microwave studio by adding components belong to all 10 cases between antennas port, we find out that case no. 10 gives the best result for total radiation efficiency Take in consideration not only varying the source impedances will increase total radiation efficiency but also adding components or TL between antenna ports increase total radiation efficiency as well. In our case I choose lumped elements since are more easy to implement on PCB than TL.

Let's take a closer view to the network that has been added between antenna ports which belong to case no. 10 in table 4.13 using CST microwave studio, graphical representation for lumped elements in figure 4.21

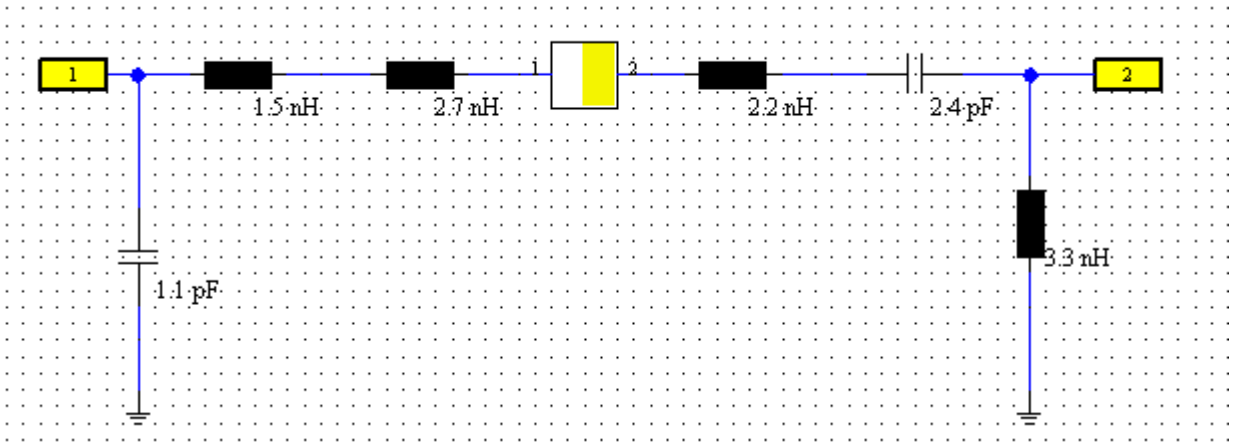

Figure 4.21 *Circuit schematic for adding components between antenna ports.*

Following table 4.14 including simulation results to lumped elements to increase total radiation efficiency using CST microwave studio belong to case no. 10

	Total rad. Eff. A1		Total rad. Eff. A2	
Frequency [GHz]	*CST*50 Ω	*CST*$R \pm jX$	*CST*50 Ω	*CST*$R \pm jX$
2.5	*0.2723*	*0.1178*	*0.3230*	*0.1470*
2.52	*0.3264*	*0.1246*	*0.3781*	*0.1554*
2.54	*0.3861*	*0.1304*	*0.4307*	*0.1607*
2.56	*0.4461*	*0.4085*	*0.4742*	*0.4458*
2.58	*0.4997*	*0.5514*	*0.5039*	*0.5930*
2.6	***0.5411***	***0.7542***	***0.5186***	***0.8150***
2.62	*0.5664*	*1.022*	*0.5202*	*1.143*
2.64	*0.5745*	*0.3646*	*0.5122*	*0.3515*
2.66	*0.5668*	*0.3892*	*0.4975*	*0.3754*
2.68	*0.5462*	*0.4055*	*0.4775*	*0.3971*
2.7	*0.5159*	*0.4142*	*0.4527*	*0.4153*

Table 4.14 *Total radiation efficiency computed using CST for lumped elements.*

At last final comparison between what have been done for 50Ω system and varying source impedances for WiMAX at 2.6 GHz and 11 mm apart shown in table 4.15

ITEM	***CST*50 Ω *System***		***CST*R ± *jX* System**	
Antenna	**A_1**	**A_2**	**A_1**	**A_2**
Efficiency [%]	***0.5411***	***0.5186***	***0.7542***	***0.8150***
RL [dB]	***-16.47***		***-12.262***	
Coupling [dB]	***-6.43***		***-7.330***	

Table 4.15 *Comparison results between 50Ω system and varying source impedances.*

According to our antenna design requirements these results are good and acceptable.

4.2.2.4 50 Ω source impedance at 5 mm

Previously on section 4.2.2.1, the idea of my supervisor was to decrease the distance between both antennas in order to study the behavior of these antenna at different frequencies range and how the coupling is increasing as long as the distance is decreased and how mutual coupling affect the correlation and radiation efficiency and thus will affect the capacity of the system. In this section the distance is minimized to 5 mm between the two antennas where two discrete ports have been used instead of microwave guide ports see figures 4.22 and 4.23 for front and back views which belong to our design. The system will be simulated via CST microwave studio and MPA. Now follow same steps mentioned previously in chapter 3 sections 3. Take into account to decrease the distance between antennas and adding components to the system is a technique to increase the radiation efficiency.

Two pictures belong to front and back view model for our system using CST microwave studio shown respectively below figures 4.22 and 4.23

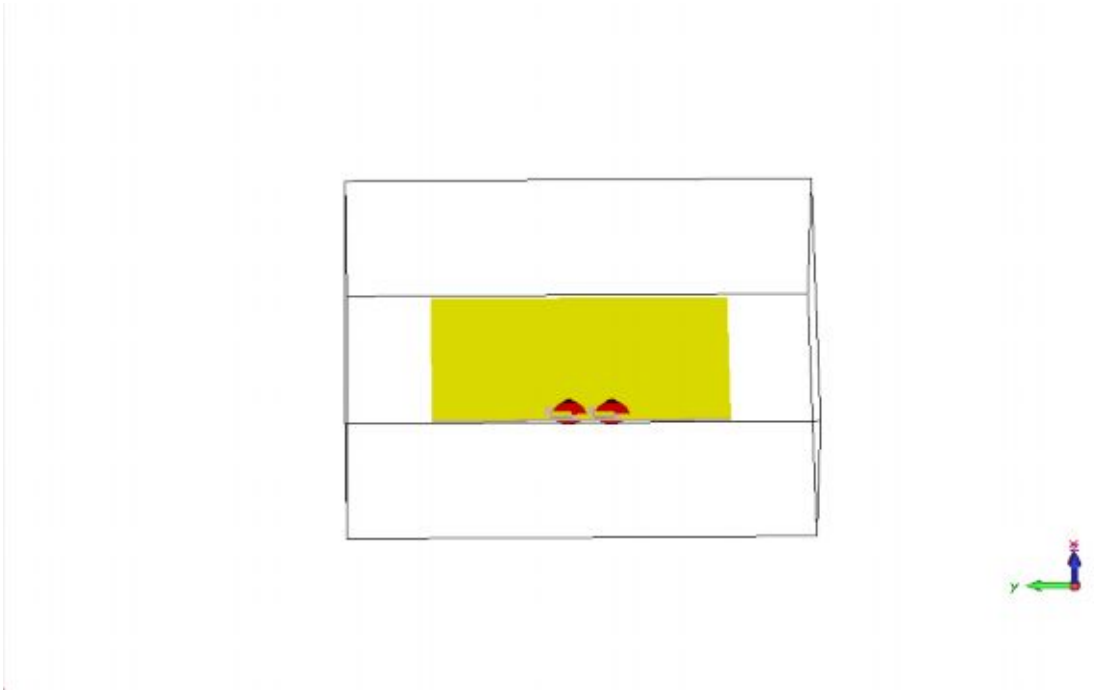

Figure 4.22 *Front view of WiMAX at 2.46 GHz.*

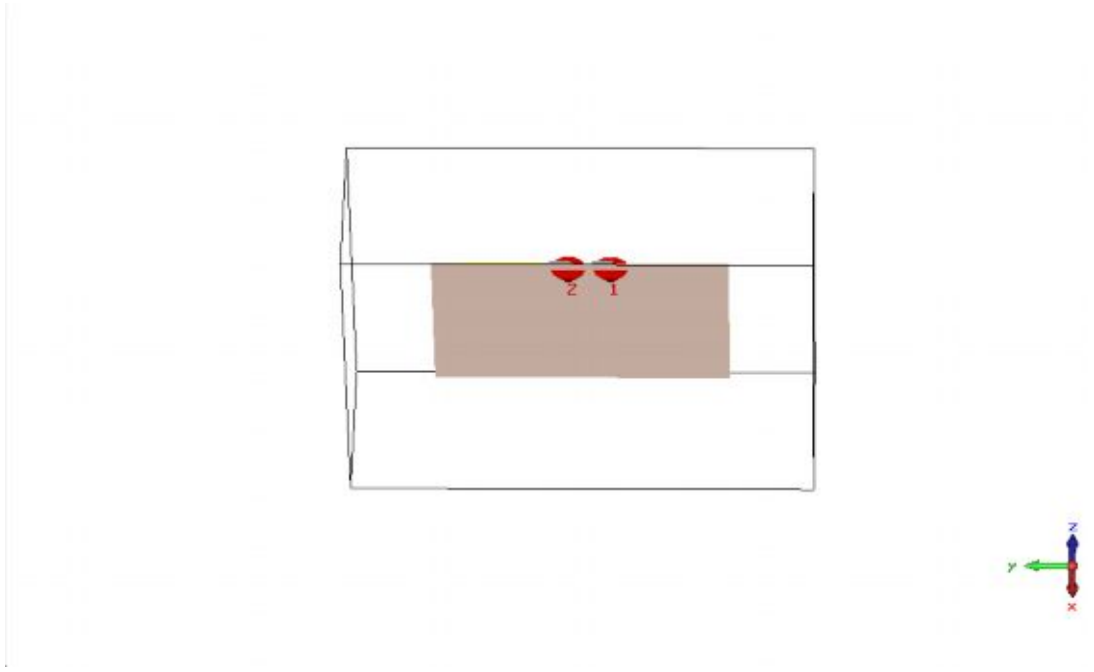

Figure 4.23 *Back view of WiMAX at 2.46 GHz.*

Simulations are done under distance of 5 mm using CST, where embedded far-field patterns have been exported and imported to MPA. The total radiation efficiency, correlation and apparent diversity gain at different frequency range simulations are represented in table 4.16 and 4.17 respectively

	Total rad. Eff. A1		***Total rad. Eff. A2***	
Frequency [GHz]	***CST***	***MPA***	***CST***	***MPA***
2.42	*0.2987*	*0.2959*	*0.2389*	*0.2363*
2.43	*0.3164*	*0.3135*	*0.2563*	*0.2536*
2.44	*0.3340*	*0.3309*	*0.2735*	*0.2706*
2.45	*0.3514*	*0.3481*	*0.2903*	*0.2872*
2.46	***0.3687***	***0.3652***	***0.3064***	***0.3033***
2.47	*0.3860*	*0.3824*	*0.3219*	*0.3186*
2.48	*0.4035*	*0.3998*	*0.3368*	*0.3334*
2.49	*0.4210*	*0.4171*	*0.3511*	*0.3475*

Table 4.16 *Total radiation efficiency computed in CST and MPA for 50Ω system.*

	Correlation	
Freq. [GHz]	**CST**	**MPA**
2.42	*0.7408*	*0.7468*
2.43	*0.7517*	*0.7515*
2.44	*0.7627*	*0.7624*
2.45	*0.7788*	*0.7786*
2.46	***0.7987***	***0.7985***
2.47	*0.8206*	*0.8204*
2.48	*0.8426*	*0.8425*
2.49	*0.8633*	*0.8631*

Table 4.17 *Correlation between antennas port using CST & MPA for 50Ω system.*

It is noticeable that our resonant frequency is shifted from 2.6 GHz to 2.46 GHz, which is 140 MHz that is due to small distance between antennas besides it will be clear in the second section when we change the source impedances and adding lumped components to the system how the frequency will be shifted. Furthermore it is capable of being seen how the total radiation efficiency is decreased by reducing the distance between antennas and how the correlation is increased too; that is caused by mutual coupling between antennas rising up as a result of small distance between them.

Representation graphs for total radiation efficiency and correlation depending on frequency are in the following

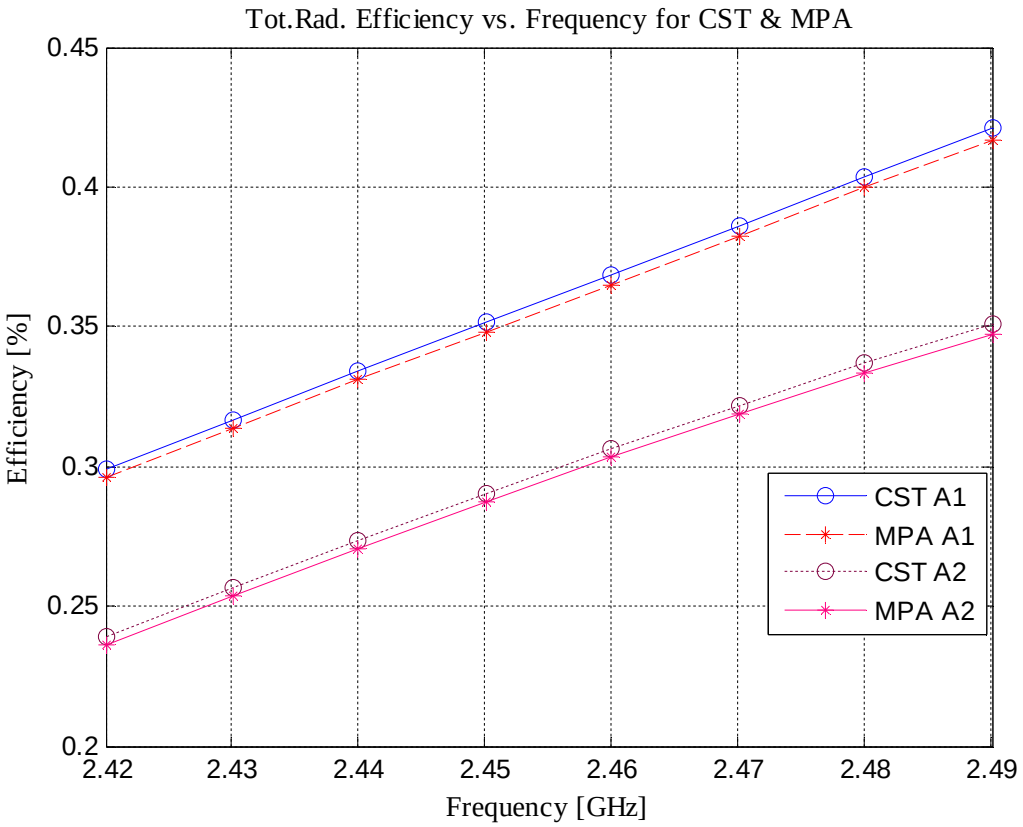

Figure 4.24 *Total rad. Eff. Computed by CST & MPA for 50Ω system.*

As we see (CST A1, MPA A1) belong to simulation results done by CST and MPA for port one of the antenna number one which corresponds to -4.43 dB, while (CST A2, MPA A2) belong to port two of antenna number two which corresponds to -5.22 dB at the resonant frequency 2.46 GHz.

Correlation graph representation in the following

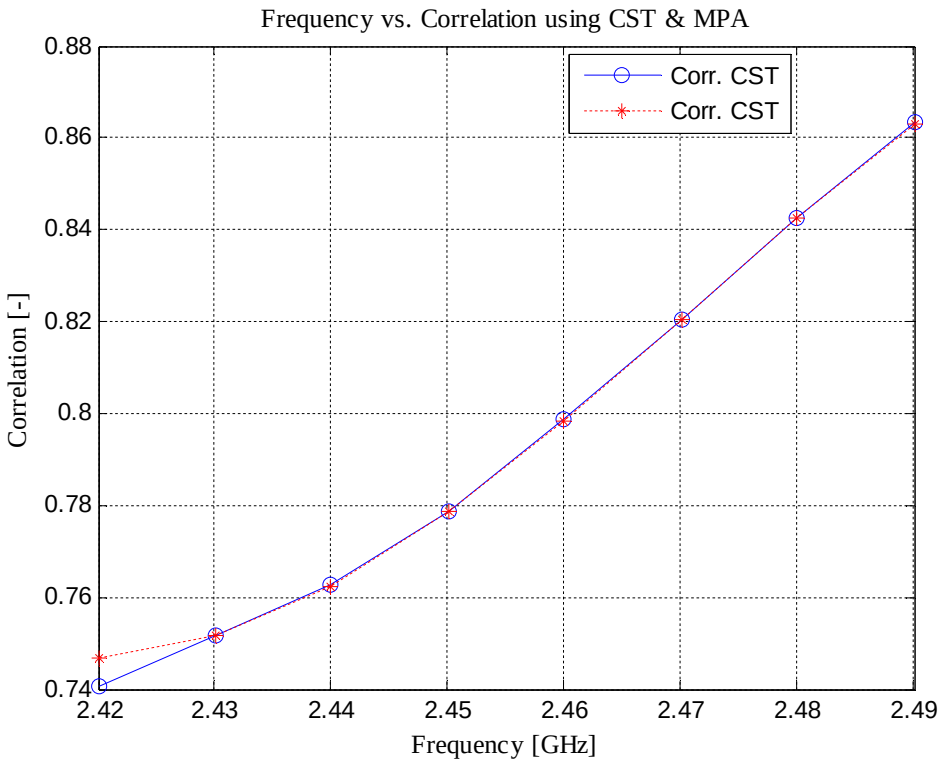

Figure 4.25 *Frequency vs. Correlation computed by CST & MPA for 50Ω system.*

The diversity gain simulation results is shown in table 4.18 and figure 4.26 below

	Diversity Gain [dB]	
Freq. [GHz]	**CST**	**MPA**
2.42	*6.6473*	*8.2556*
2.43	*6.5939*	*8.2214*
2.44	*6.4675*	*8.1393*
2.45	*6.2719*	*8.0092*
2.46	***6.016***	***7.8332***
2.47	*5.7143*	*7.616*
2.48	*5.3843*	*7.366*
2.49	*5.0462*	*7.0945*

Table 4.18 *Diversity gain between antennas port using CST & MPA for 50Ω system.*

Diversity gain graph is represented in the following

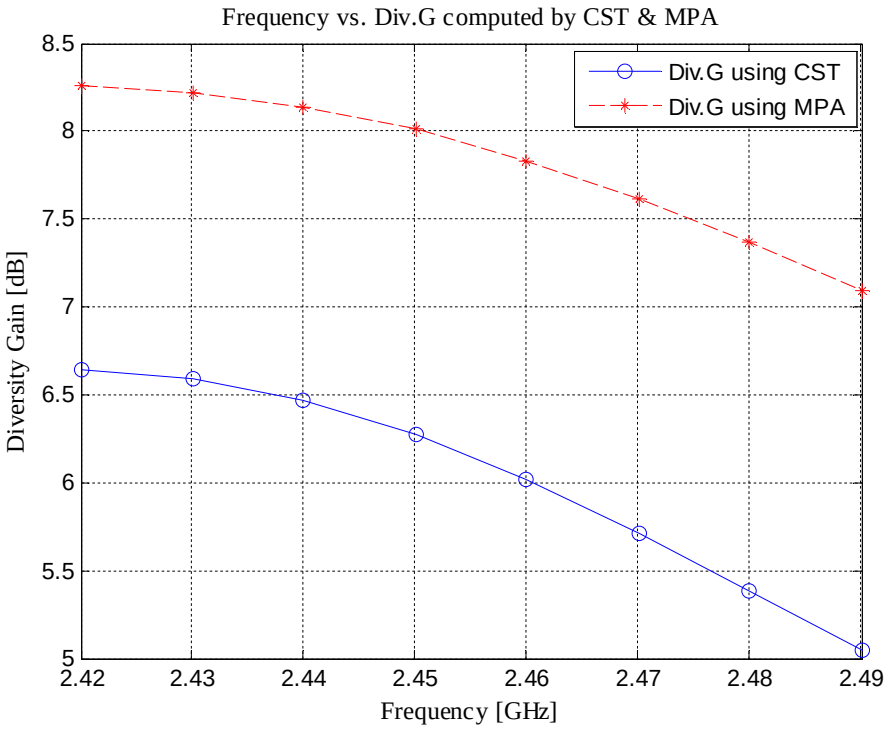

Figure 4.26 *Diversity gain vs. Frequency computed by CST & MPA for 50Ω system.*

4.2.2.5 Changing source impedance at 5 mm

We have studied in the previous simulations for our system at 11 mm apart the effective of source impedances on antenna performance. Imitate the example in section 4.2.2.3 the concept of changing source impedances to$R \pm jX$. Several optimization has been done using CST and MPA and the best results belong to the value corresponds to $Z_s = 30 - j30$. Keep in mind the effective diversity gain will be calculated at 1% probability level using equations (2.3) and (2.4) since both antennas are the same and designed of same material and having similar total radiation efficiencies.

Table 4.19 and figure 4.27 shows us the total radiation efficiencies computed by CST and MPA at the resonant frequency 2.46 GHz

	Total rad. Eff. A1		***Total rad. Eff. A2***	
Freq [GHz]	CST P1	MPA P1	CST P2	MPA P2
2.42	*0.4425*	*0.4498*	*0.4034*	*0.3578*
2.43	*0.4580*	*0.4607*	*0.4455*	*0.3698*
2.44	*0.4728*	*0.4774*	*0.4892*	*0.3809*
2.45	*0.4867*	*0.4896*	*0.3920*	*0.3910*
2.46	***0.4994***	***0.5005***	***0.4307***	***0.3999***
2.47	*0.5106*	*0.5098*	*0.4717*	*0.4075*
2.48	*0.5202*	*0.5174*	*0.5148*	*0.4136*
2.49	*0.5279*	*0.5231*	*0.5598*	*0.4181*

Table 4.19 *Total radiation efficiency computed in CST & MPA for a 30-j30 source impedances.*

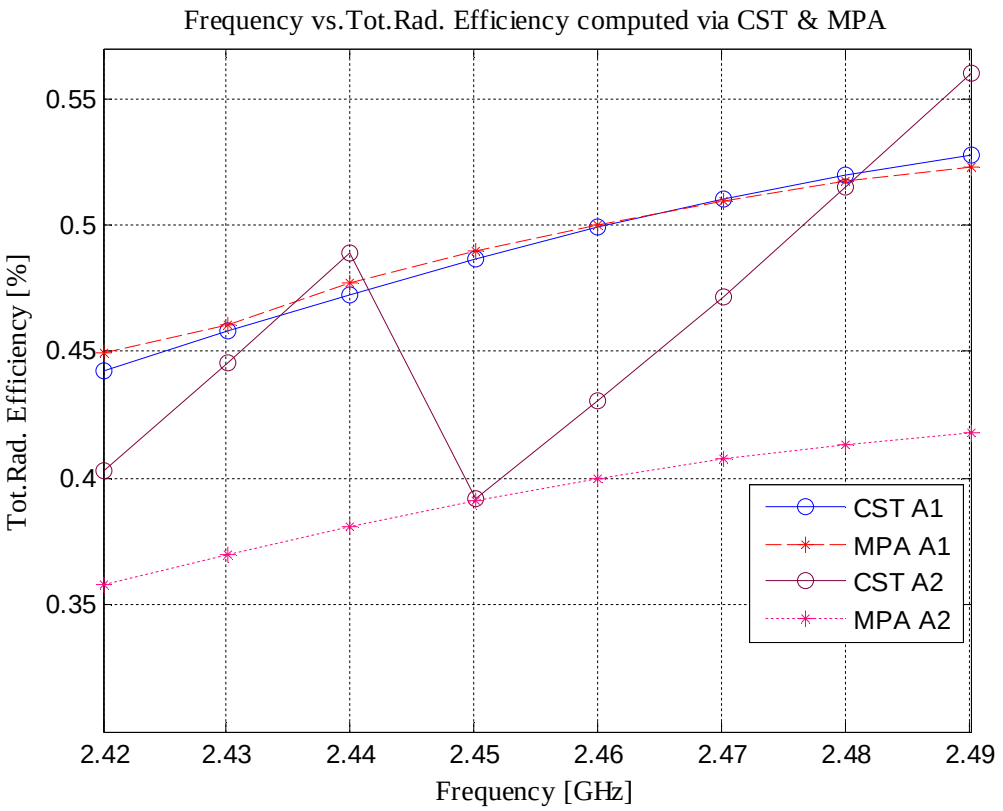

Figure 4.27 *Total radiation efficiency computed in CST & MPA for a 30-j30 source impedances.*

Closer view of the network which has been added between the ports of antennas in order to increase the total radiation efficiencies can be seen in figure 4.28

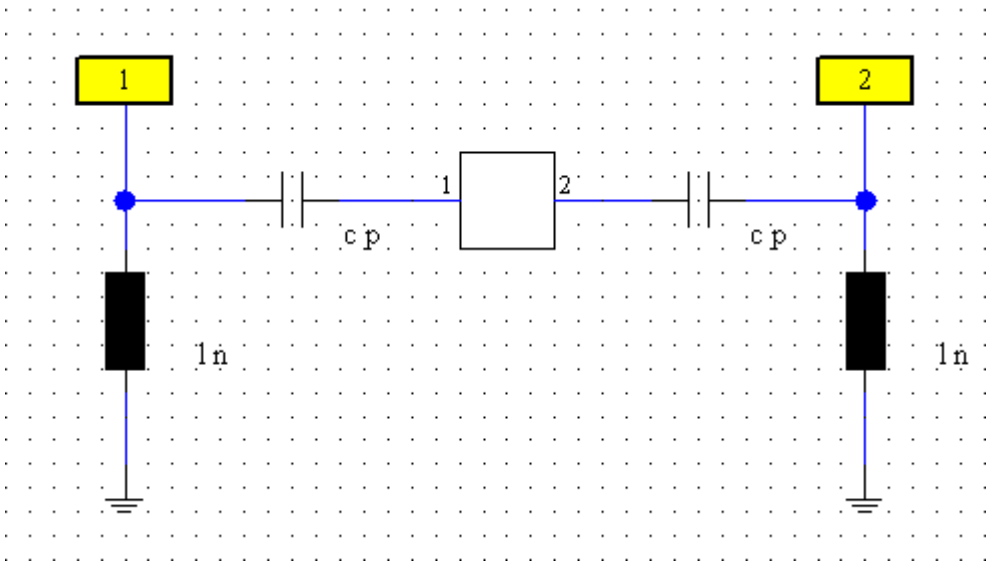

Figure 4.28 *Circuit schematic for adding components between antenna ports.*

Source impedances of values $Z_s = 30 - j30$ have been converted to series capacitors and shunt inductance to be added between antenna ports. Where series capacitors have been added in series of values *1.2 pF*, and two shunt inductance of values *5 nH*.

ITEM	*CST* 50 Ω *System*		*CST* $R \pm jX$ *System*	
Antenna	A_1	A_2	A_1	A_2
Efficiency [%]	***0.3687***	***0.3064***	***0.4994***	***0.4307***

Table 4.20 *Comparison results between 50Ω system and varying source impedances.*

Table 4.20 shows the great effect of varying the source impedances on the system and how it influences the efficiency, correlation and coupling of the antennas. Keep in mind that our simulation has done at resonant frequency 2.46 GHz while the real measurements in section 5.3.3 have been done at 2.6 GHz.

4.3 WiMAX at 3.5 GHz

A new target for designing is established having same antenna elements in section 4.2 but only frequency range is different as shown in table 4.21

ITEM	NEEDED
Frequency range (GHz)	3.3-3.8
Return Loss (dB)	≥-10
Efficiency (%)	50%
Height (mm)	1
Length (mm)	5
Width	3
Material	Ceramic

Table 4.21 *Antenna Parameters.*

The distance between new antennas is 7mm where our resonance frequency is 3.5 GHz and mounted on PCB of dimension *72 mm x 40 mm*. following same steps and procedures done for WiMAX at 2.6 GHz using CST microwave studio and MPA simulations. The model is designed using CST microwave studio, to study the behavior of antennas with respect to radiation efficiency between the ranges of 2.5-3.5 GHz where different frequencies have been monitored to calculate the far field patterns. Moreover to study also the performance with respect to RL and coupling between antennas ports at different frequencies.

Two pictures belong to front and back view using CST microwave studio respectively shown below.

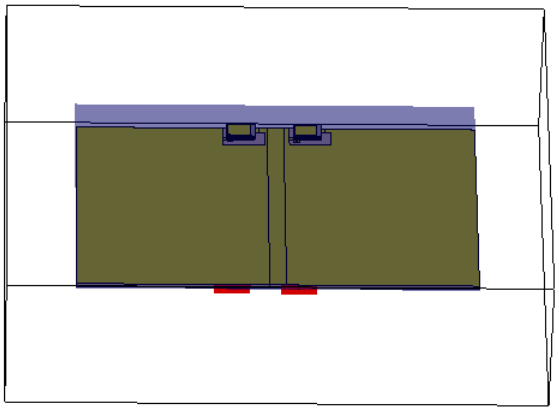

Figure 4.29 *Front view of WiMAX at 3.5 GHz.*

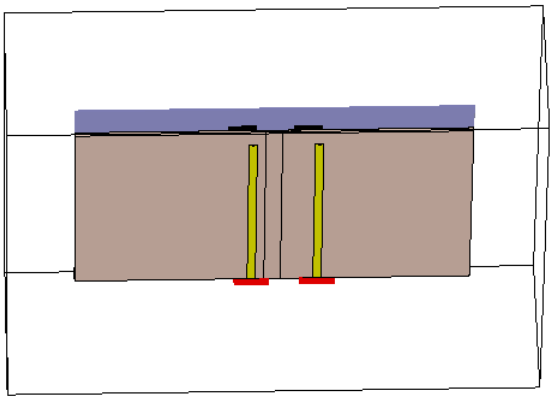

Figure 4.30 *Back view of WiMAX at 3.5 GHz.*

Compare results between CST microwave studio and MPA for 50 Ω systems with respect to total radiation efficiency following table 4.22 and figure 4.31

	Total rad. Eff. A1		***Total rad. Eff. A2***	
Frequency [GHz]	***CST***	***MPA***	***CST***	***MPA***
2.5	*0.0382*	*0.0366*	*0.0268*	*0.0259*
2.7	*0.0616*	*0.0599*	*0.0455*	*0.0440*
2.9	*0.1037*	*0.1023*	*0.0835*	*0.0808*
3.1	*0.1752*	*0.1747*	*0.1664*	*0.1603*
3.3	*0.3217*	*0.3225*	*0.3655*	*0.3504*
3.5	***0.5625***	***0.5611***	***0.5868***	***0.5625***
3.7	*0.6051*	*0.5984*	*0.5125*	*0.4937*
3.9	*0.4962*	*0.4891*	*0.4259*	*0.4106*
4.1	*0.3077*	*0.3026*	*0.2868*	*0.2763*
4.3	*0.1843*	*0.1807*	*0.1842*	*0.1777*
4.5	*0.1213*	*0.1181*	*0.1254*	*0.1210*

Table 4.22 *Total radiation efficiency computed in CST and MPA for 50Ω system.*

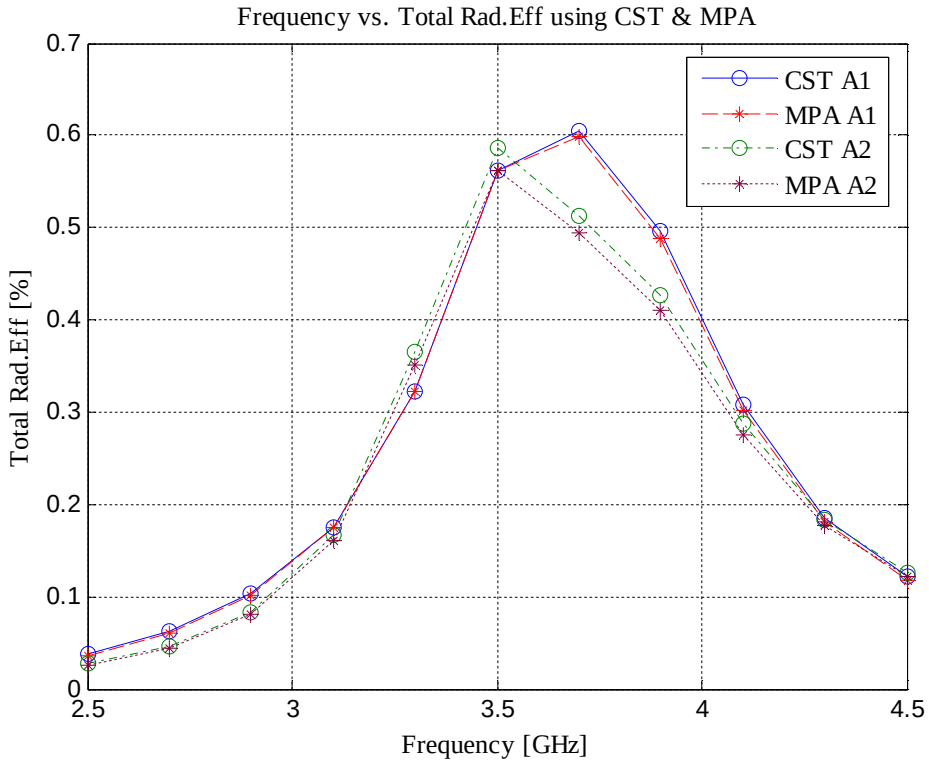

Figure 4.31 *Total rad. Eff. Computed by CST & MPA for 50Ω system.*

While correlation and diversity gain obtained by CST and MPA are in the following table 4.23 and figure 4.32

	Correlation	
Freq. [GHz]	**CST**	**MPA**
2.5	*0.8980*	*0.8973*
2.7	*0.8365*	*0.8355*
2.9	*0.7217*	*0.7203*
3.1	*0.4878*	*0.4855*
3.3	*0.1173*	*0.1145*
3.5	***0.0822***	***0.0842***
3.7	*0.3528*	*0.3497*
3.9	*0.6032*	*0.6005*
4.1	*0.6161*	*0.6131*
4.3	*0.5420*	*0.5382*
4.5	*0.4821*	*0.4777*

Table 4.23 *Correlation between antennas port using CST & MPA for 50Ω system.*

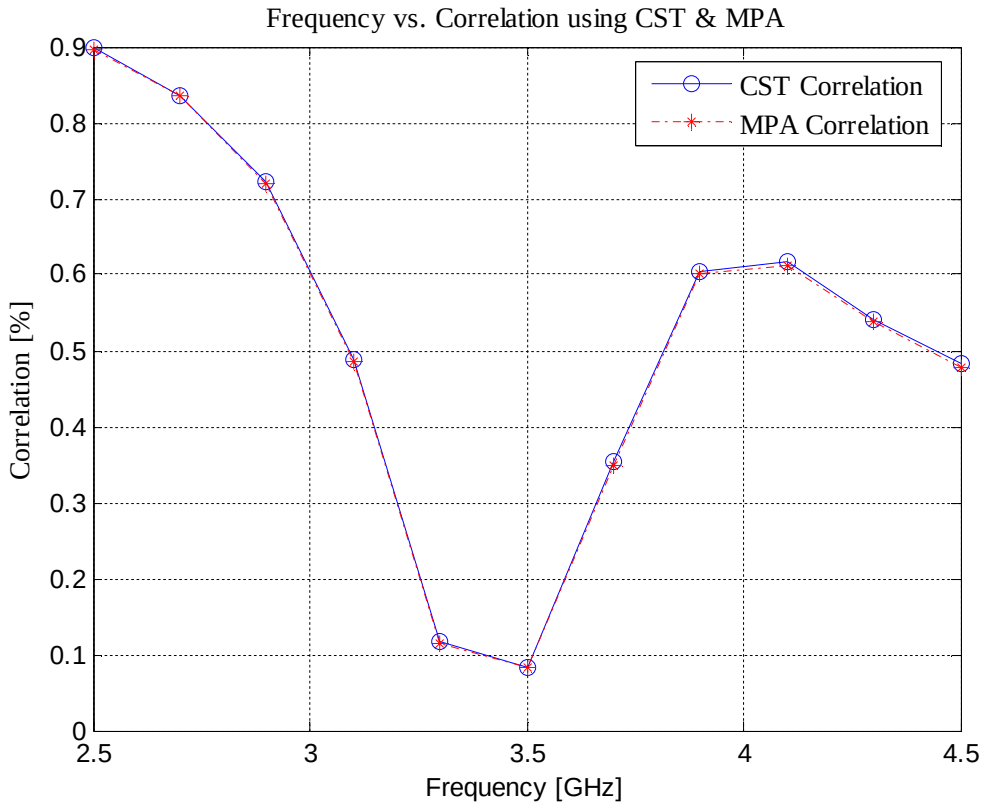

Figure 4.32 *Frequency vs. Correlation computed by CST & MPA for 50Ω system.*

The diversity gain is represented in table 4.24 and figure 4.33

	Diversity Gain [dB]	
Freq. [GHz]	**CST**	**MPA**
2.5	*4.3988*	*6.5351*
2.7	*5.4787*	*7.4482*
2.9	*6.9216*	*8.4346*
3.1	*8.7293*	*9.4227*
3.3	*9.9308*	*9.9716*
3.5	***9.9661***	***9.9847***
3.7	*9.3566*	*9.7191*
3.9	*7.9755*	*9.041*
4.1	*7.8766*	*8.9893*
4.3	*8.4036*	*9.2661*
4.5	*8.7609*	*9.4439*

Table 4.24 *Diversity gain between antennas port using CST & MPA for 50Ω system.*

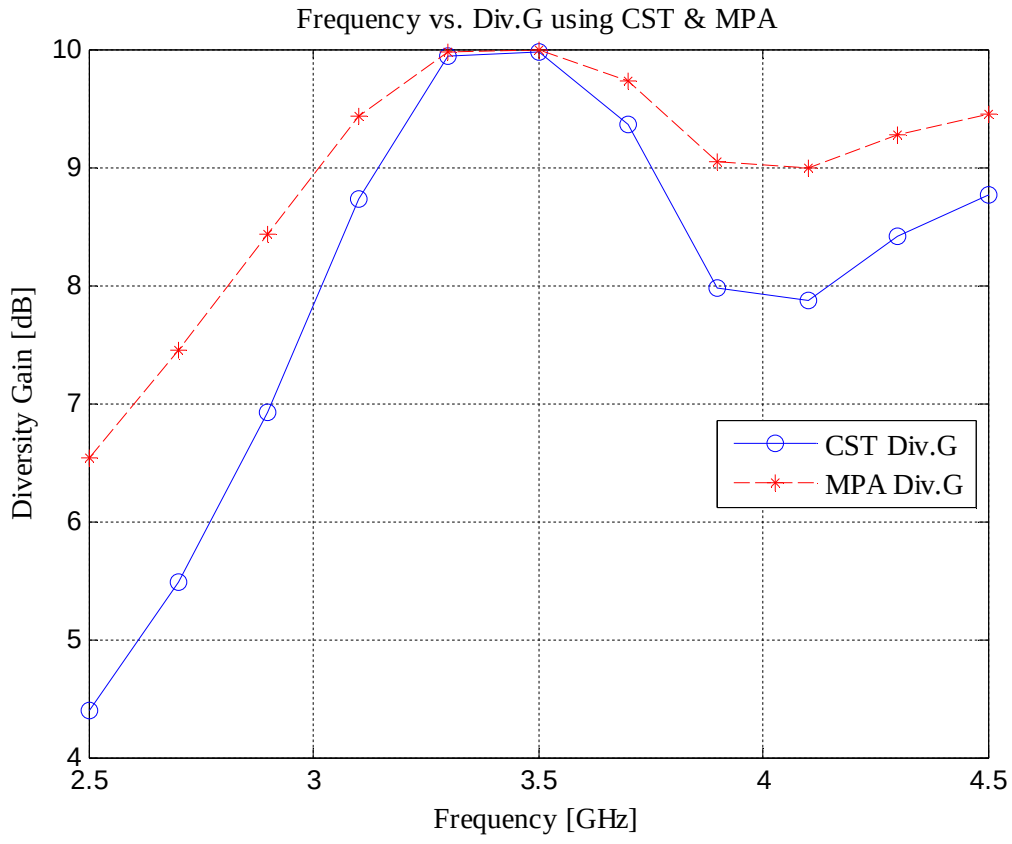

Figure 4.33 *Frequency vs. Diversity gain computed by CST & MPA for 50Ω system.*

According to table 4.21, the total radiation efficiency of first antenna corresponds to -2.44 dB, and the total radiation efficiency of the second antenna corresponds to -2.315 dB.

A lot of simulations have been done to increase efficiency of both antennas, but as a result of fact we could not increase efficiency neither by adding components between antenna ports, nor by varying source impedances and that's due to our high resonance frequency which is 3.5GHz. Simulation results will be available in Appendix [1].

5. Measurements

5.1 Reverberation chamber

The measurements of the system will be done under the control of reverberation chamber [17] as shown in figure 5.1

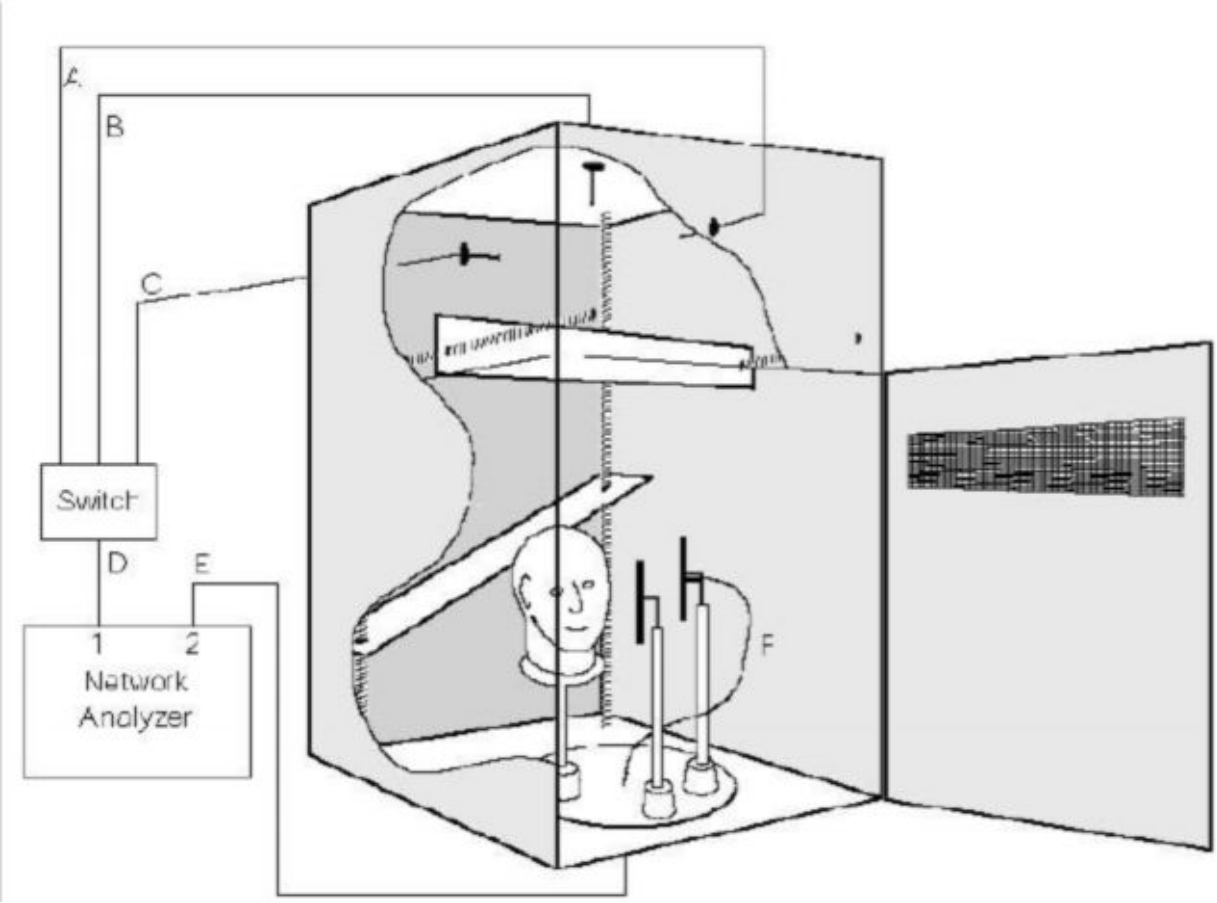

Figure 5.1 *Schematic drawing of reverberation chamber (© Bluetest).*

The reverberation chamber has been used for a couple of decades for some types of electromagnetic compatibility measurements. It's a metal cavity that is sufficiently large to support many resonant modes, which are perturbed with movable stirrers creating fading environment [18]. The reverberation chamber is used to measure diversity gain, radiated power, radiation efficiency, total radiation power and MIMO system capacity accurately. The measurements in the reverberation chamber will be at 1% cumulative probability. Efficiency measurements have been done three times using reference antenna which is planted in three

different positions (vertically, horizontally and $\measuredangle 45^{\circ}$), three positions are done for more accuracy and to know the amount of losses through the system. Vector network analyzer is used to calibrate the inner cables of the reverberation chamber and to calculate S_{21} between the reference antenna and antennas which are mounted in the wall. By taking the ratio between test antenna and reference antenna, the calculation of efficiency can be obtained.

Designed antennas are replaced instead the reference one in order to measure their efficiency which are obtained from the known efficiency of the reference antenna. The measurements are done by connecting the first antenna to a source while the other is terminated to 50 Ω inside the reverberation chamber. Similarly measurements are done for second antenna while the first one is terminated by repeating the same environment.

5.2 WiMax 2.6 GHz for 50 Ω system at 11 mm

5.2.1 RL

The return loss and coupling were carried out with HP 8753D 30KHz -6GHz VNA. Since it is necessary to connect two ports of VNA to the device, the two full ports calibration will result an accurate measurements to measure reflection because the signal from port 2 will come towards port 1 therefore it is disturbing the performed reflection measurements. The characteristics impedances for both antennas are measured with S_{11} and S_{22} parameters. As we can see in figure 5.2 RL indicates below -10dB according to our required specification.

5.2.2 Coupling

Coupling was measured between both antennas as seen in figure 5.3. The high coupling as a result of fact is due to small distance between antennas which is less than half a wavelength at our central frequency 2.6 GHz. It is obvious that coupling is less than -5dB which is quite acceptable according to our design specification.

Representation graphs for RL and coupling using VNA respectively are shown below

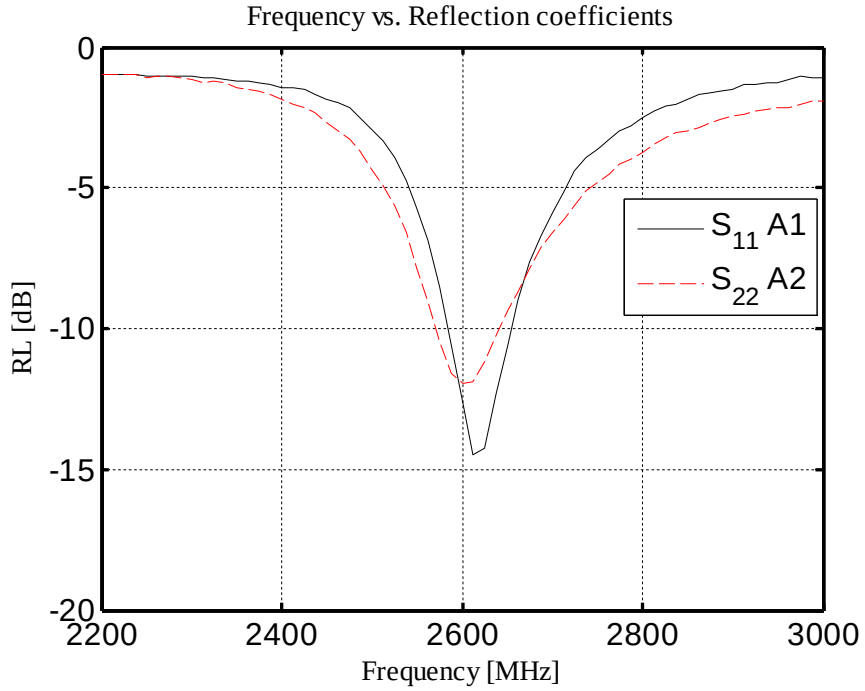

Figure 5.2 *VNA measurements result for RL vs. Frequency.*

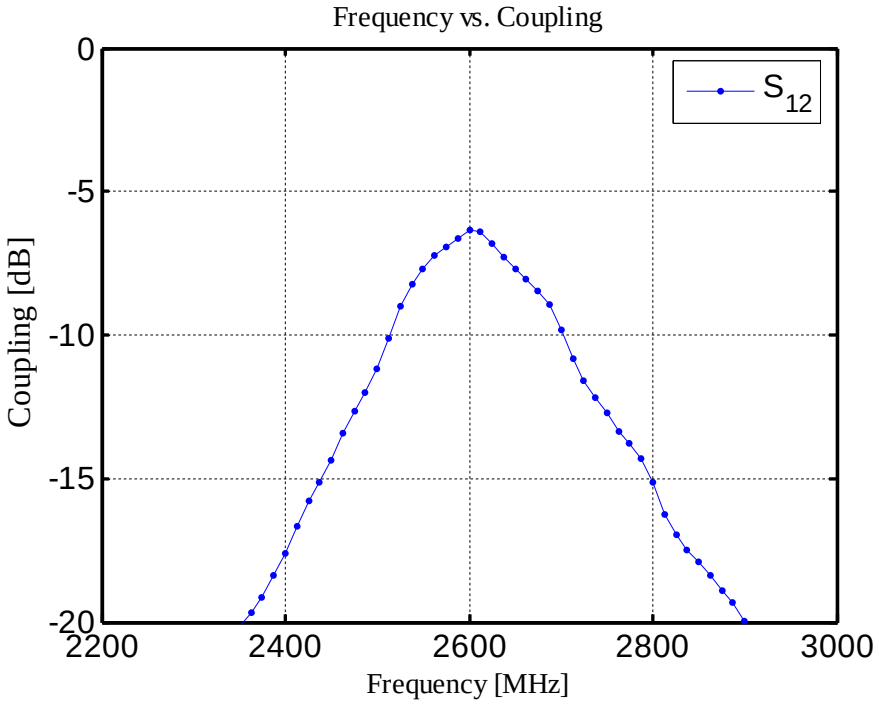

Figure 5.3 *VNA measurements result for Coupling vs. Frequency.*

5.2.3 Efficiency

Efficiency measurements have been done three times using reference antenna which is planted in three different positions (vertically, horizontally and ∡45°), three positions are done for more accuracy and to know the amount of losses through the system. Vector network analyzer is used to calibrate the inner cables of the reverberation chamber and to calculate S_{21} between the reference antenna and antennas which are mounted in the wall. Designed antennas are replaced instead the reference one in order to measure their efficiency which are obtained from the known efficiency of the reference antenna. The measurements are done by connecting the first antenna to a source while the other is terminated to 50 Ω inside the reverberation chamber. Similarly measurements are done for second antenna while the first one is terminated by repeating the same environment. The measurements are generated in MATLAB as shown in figures 5.4 below.

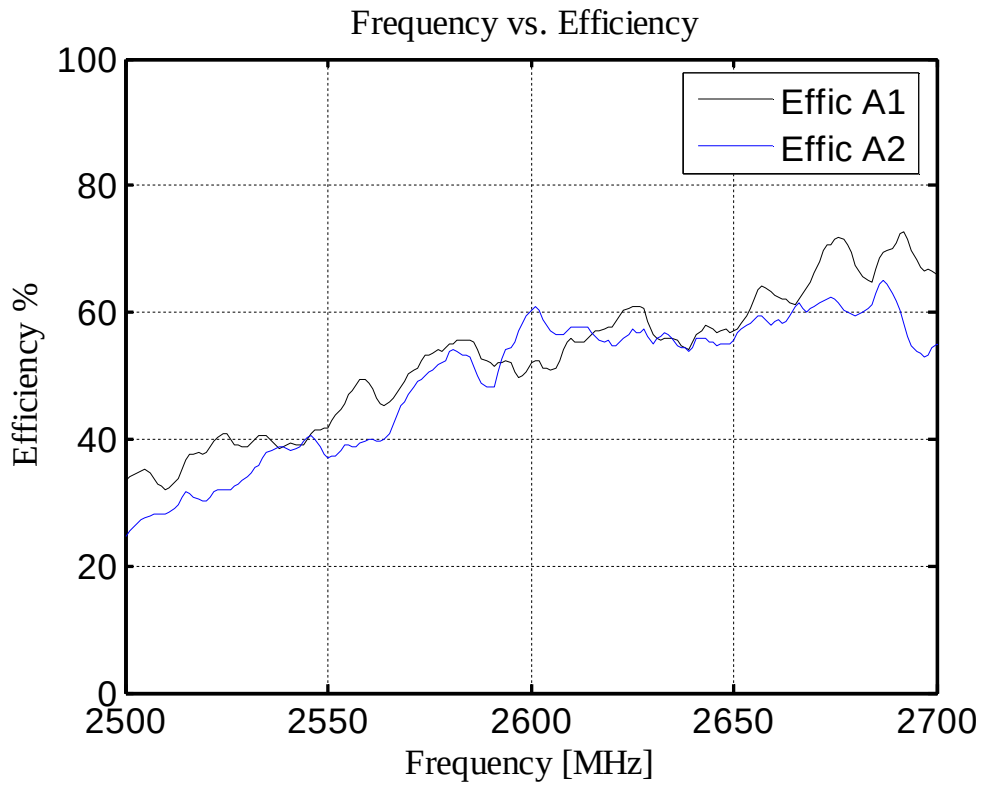

Figure 5.4 *Radiation efficiency vs. Frequency is measured by reverberation chamber.*

Antenna 2 has higher efficiency than antenna 1 because the ground field is less than antenna 1 and in opposite direction of the feed which means antenna 2 has better position.

5.2.4 Diversity gain

We can use MATLAB to plot cumulative density functions as shown in figure 5.5

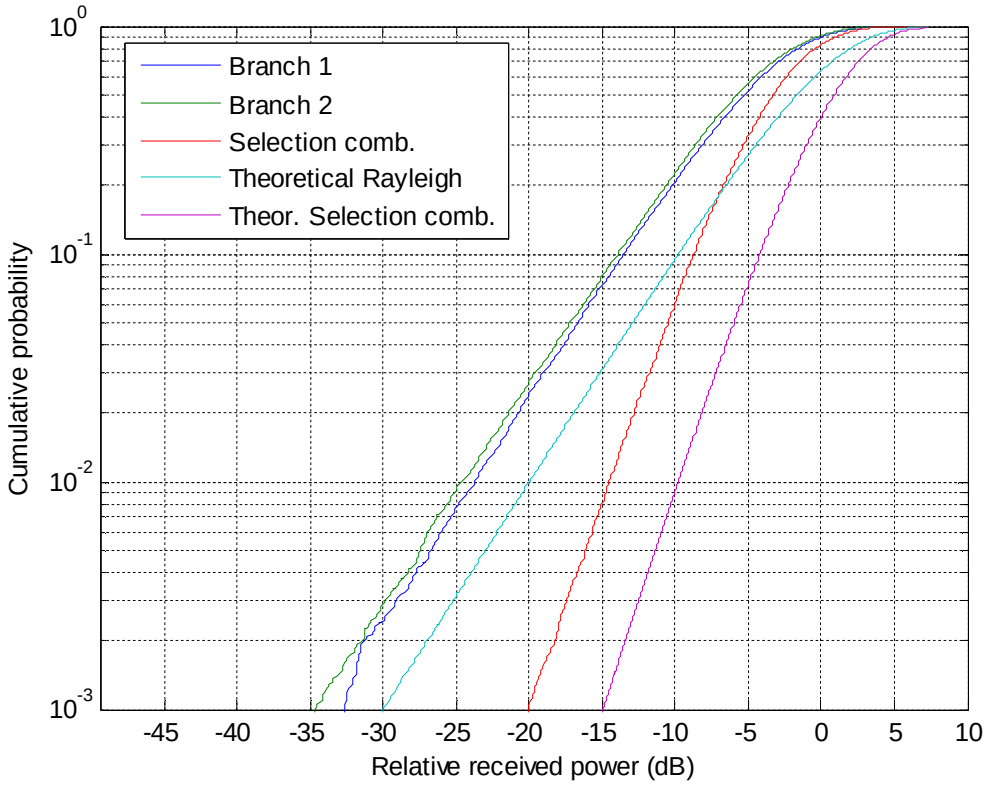

Figure 5.5 *Measurements result for diversity gain by reverberation chamber.*

The apparent diversity gain is 9.222 dB at 1% probability; effective diversity gain is 5.739 dB at 1% probability while the correlation between branch 1 and branch 2 is 0.309.

5.3 WiMAX 2.6 GHz for 50 Ω system using discrete ports

5.3.1 RL

The return loss was carried out by HP 8753D 30KHz-6GHz VNA. The characteristics impedances for both antennas are measured S_{11} and S_{22} parameters. For comparison purposes the result is plotted in graph. CST microwave studio simulations were also fulfilled. See figure 5.5.

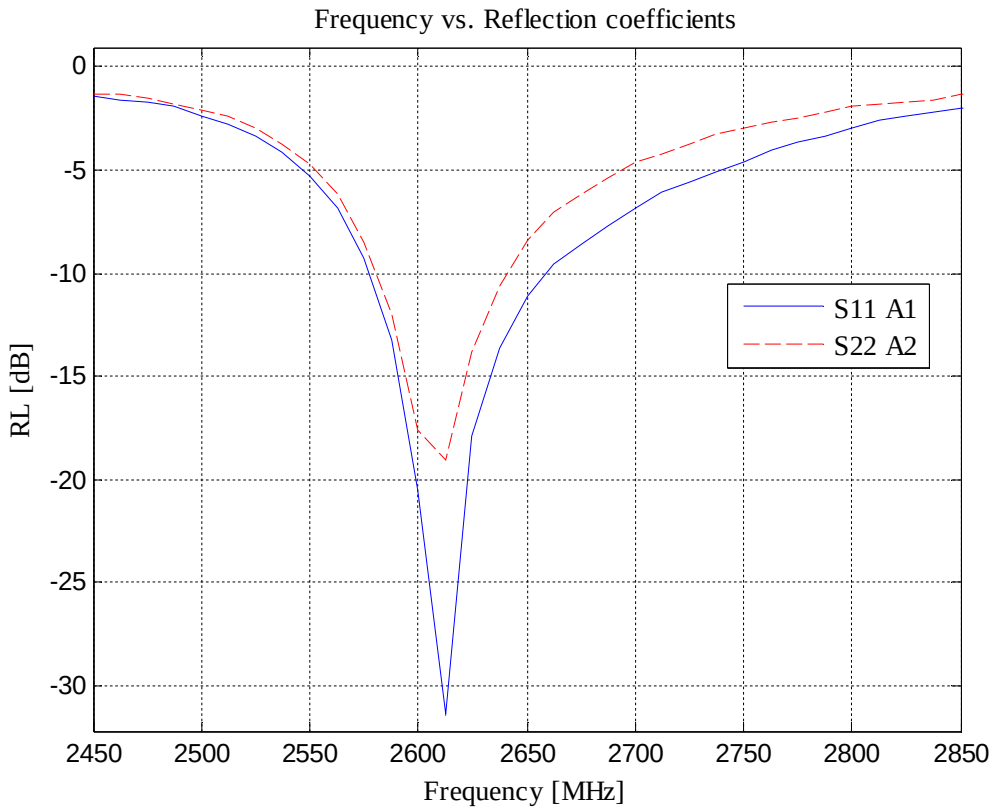

Figure 5.6 *VNA measurements result for RL vs. Frequency.*

5.3.2 Coupling

Coupling was simulated and measured between antenna ports using CST microwave studio and HP 8753 vector network analyzer respectively. As long as the distance between antennas decrease as long as the coupling between them increases. See figure 5.6 which shows the high coupling between antennas -3.64 dB.

Representation graph of coupling measured by VNA shown below

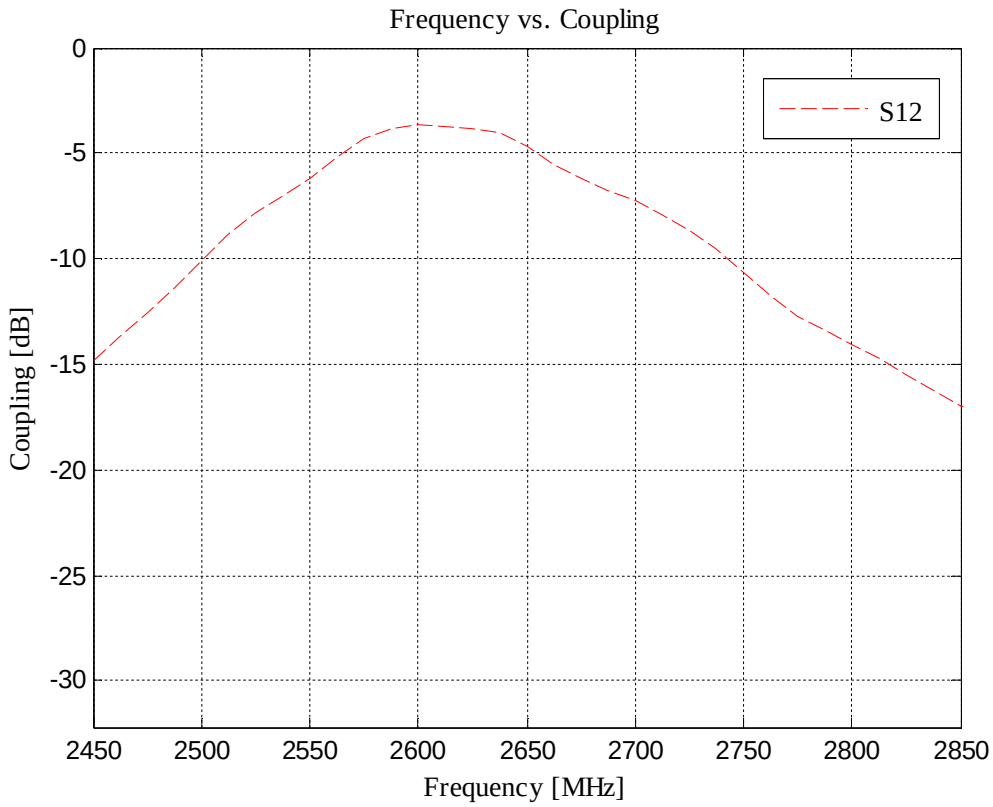

Figure 5.7 *VNA measurements result for Coupling vs. Frequency.*

5.3.3 Efficiency

Similarly in section 5.2.3 the efficiency is measured in the reverberation chamber and generated in MATLAB. Graph 5.7 shows efficiency of both antennas, graphically efficiency of A1 corresponds to -4.2 dB which is 38%, and of A2 corresponds to -5.2 dB which is 30% at the resonance frequency 2.6 GHz.

Representation graph for radiation efficiency

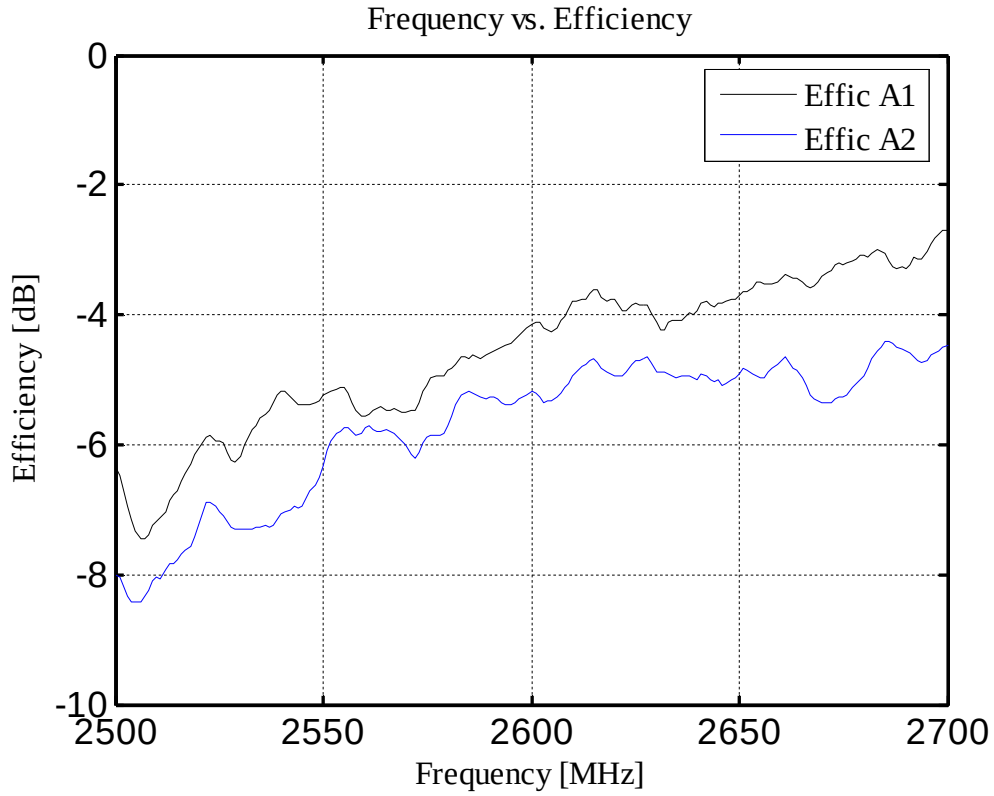

Figure 5.8 *Radiation efficiency vs. Frequency is measured by reverberation chamber.*

5.3.4 Varying source impedances

Previously in chapter 4, we proved the effect of changing source impedances on the system and how CST microwave studio simulations demonstrate increase of efficiency of both antennas. Furthermore these source impedances were changed to lumped elements and mounted on the PCB and then measured by reverberation chamber, figure 5.8 indicates how the efficiency is increased for both antenna using MIMO systems.

Representation graph for adding lumped components between the ports of antennas can be seen

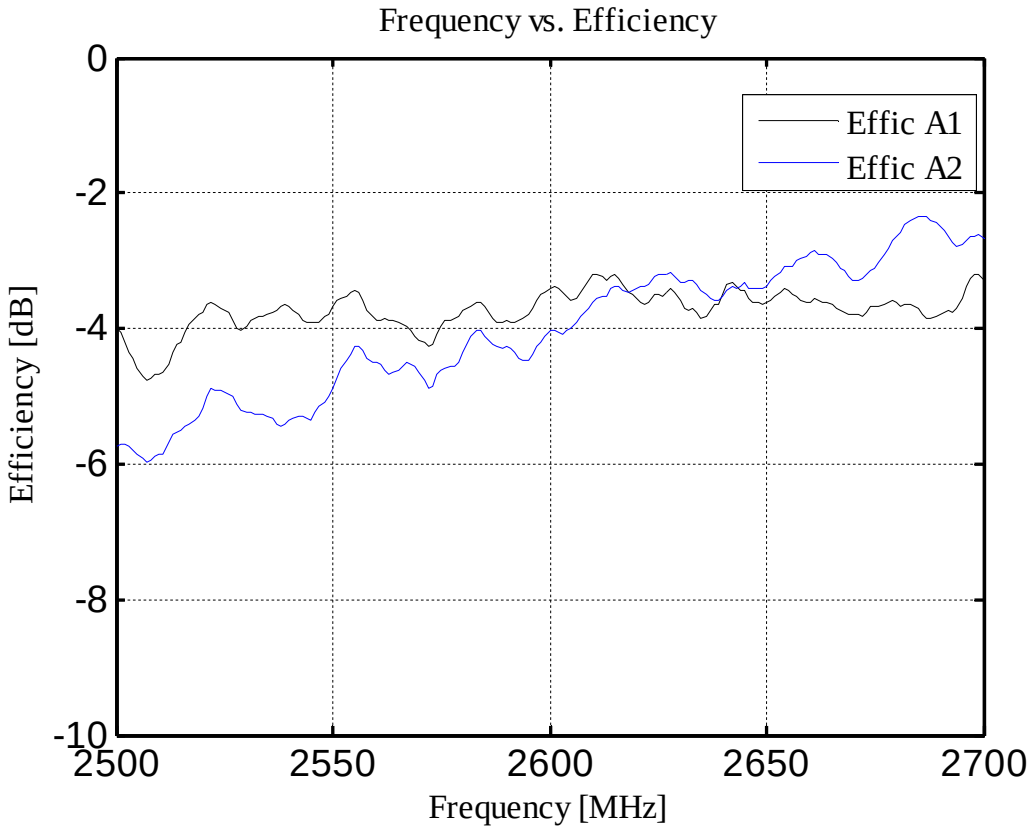

Figure 5.9 *Radiation efficiency vs. Frequency by adding lumped elements is measured by reverberation chamber.*

As we can see the efficiency of A1 is increased to -3.4 dB which belong to 45.7% and of A2 is increased to -4 dB which belongs to 39.8%.

6. Conclusion and discussion

This project has aimed on improving antennas on MIMO system for e.g. WiMAX from an antenna point of view. The parameters to improve are total radiation efficiency and correlation between the embedded far-field patterns. Standard ceramic antenna from Ethertronics and standard lumped components have been used and simulated plus built for extracting simulated results and measurements. We have used MPA since it is one of the most essential parts in this project to optimize both efficiency and correlation. Two parallel dipoles were designed and simulated for comparison purposes in order to achieve the validation of MPA.

What is observed is that we have used different techniques to increase total radiation efficiencies and decrease the correlation between the ports of antennas, one of these techniques was to put the antennas pretty close to each other in order to be able to have some effect of changing the port impedance which can be considered as another technique. For WiMax at 2.6 GHz, we need to put the antennas with a 5 mm separation to increase the total radiation efficiency. This is off course an extreme case e.g. on USB-sticks, where the conditions for high efficiency is already bad due to coupling between the antennas but yet, we can increase it by altering the port impedance. It is also important to comprehend that the correlation also increases as we increase the efficiency, which will decrease the diversity gain. A trader off is needed or better, an optimization of the effective diversity gain (which include the total radiation efficiency and the correlation). This can be done fast with the MPA since the main expected behavior of MPA during optimization process is to increase total radiation efficiency and decrease correlation in short time.

In this project 3 different cases have been constructed as followed in chapter 4 to study the performance of antennas by increasing the total radiation efficiency and decrease correlation. First case was to implement matching network between the ports of antennas which has an effect with respect to antenna behaviors as it seen in [19] using PIFA, while in our case for WiMAX at 2.6 GHz and 14 mm apart this technique did not show any changes or influence to increase total radiation efficiency either by MPA or CST microwave studio. On the other hand the second and third cases were to decrease the distance between antennas ports and varying the source

impedance, it was clear how total radiation efficiency is increased at 11 mm where A1 of -1.24 dB and A2 of -0.91 dB, and 5 mm where A1 of -3 dB and A2 of -3.6 dB, simulations using CST microwave studio show significant increase in total radiation efficiency. See appendix [1] for both cases.

To discuss about MPA, has the aptitude to calculate total radiation efficiency, correlation and diversity gain in a short time, has the capability to optimize matching network and source impedances between the ports of antenna for different frequencies at the same time. In contrast, disparity between simulations and real measurements was so clear, which needs more study why such quarrel between the final results.

7. Future work

An optimization of effective diversity gain with WiMAX at 2.6 GHz antenna, 5 mm separated is feasible. Using CST and MPA to find the components values that will maximize the effective diversity gain in a uniform propagation environment. A weighted propagation environment is being programmed in MPA and it is of great interest to optimize effective diversity gain in an e.g. office environment. This is suggested as a future master thesis.

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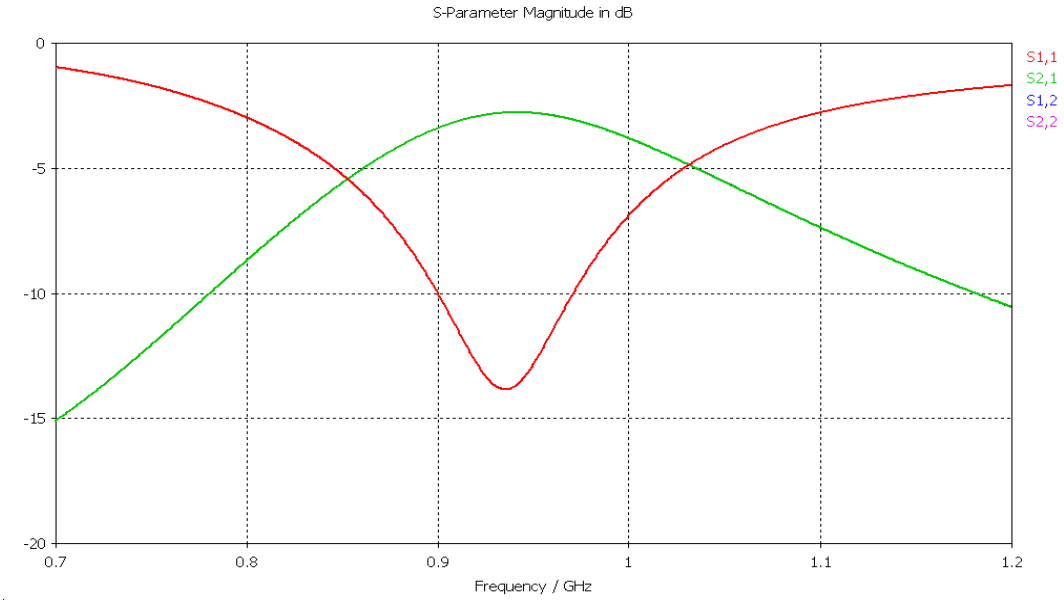
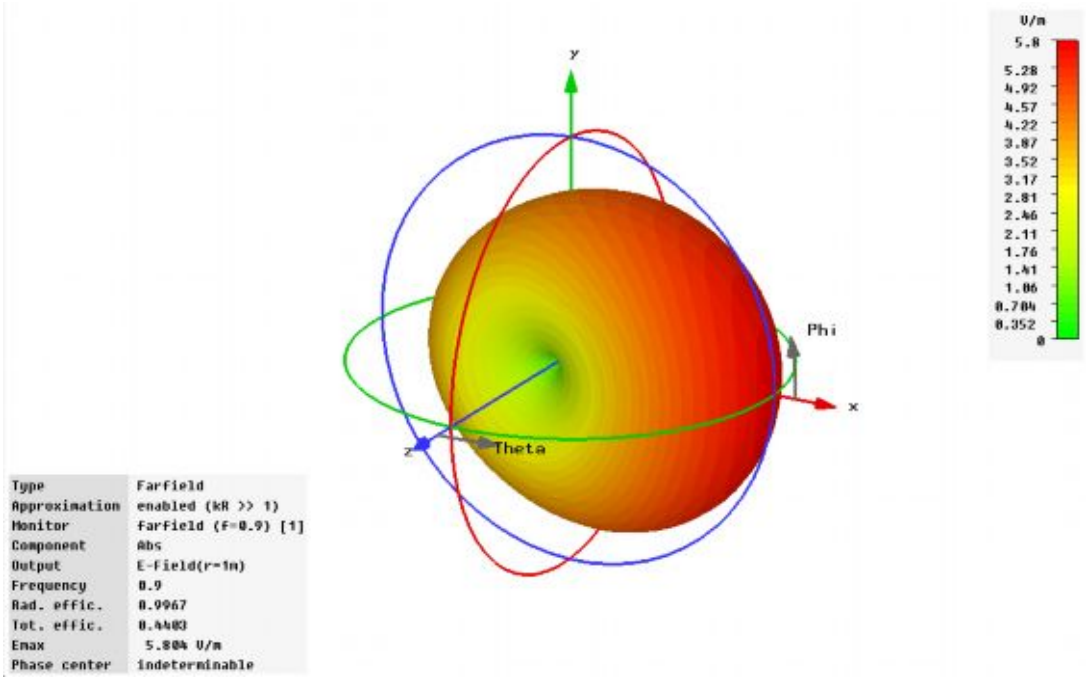
Appendix 1: CST microwave studio simulation results

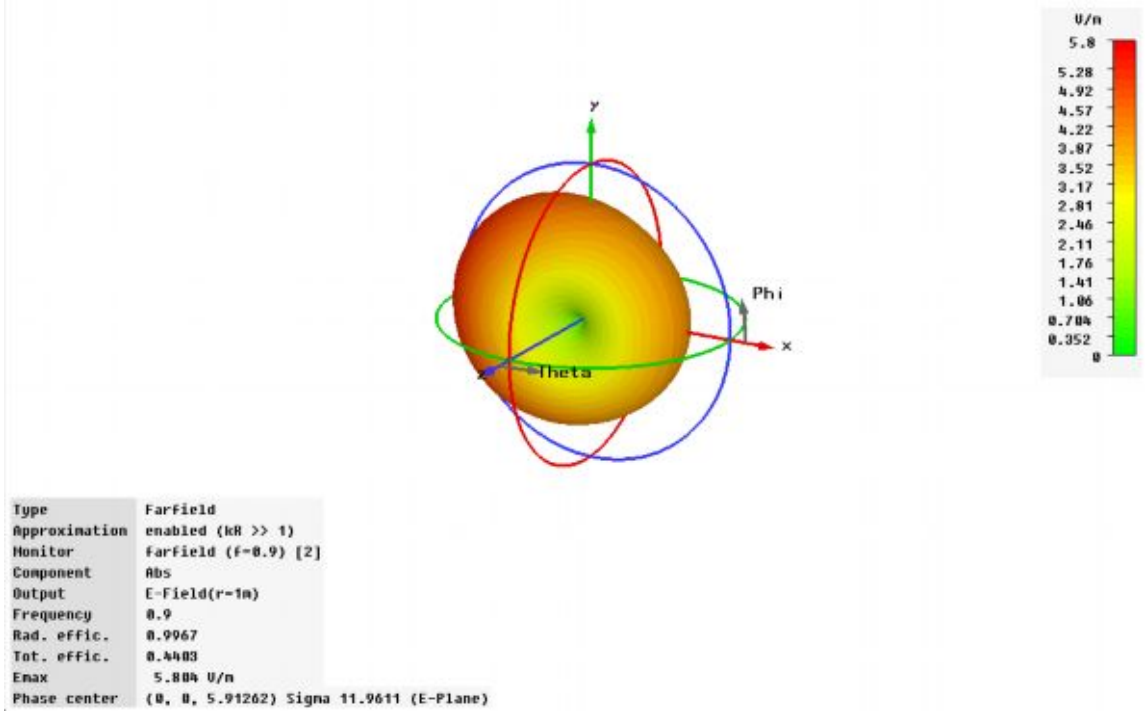
1. **Dipoles 19 mm apart (no components)**



Appendix 1.1 S-parameters response for 2 parallel dipoles.



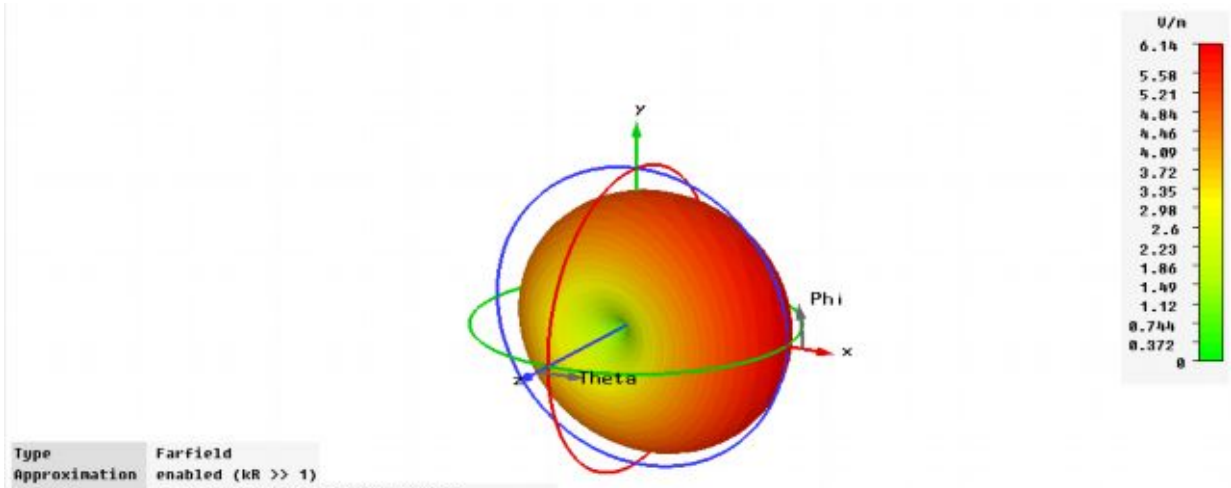
Appendix 1.2 3D plot of Far field pattern for antenna 1 at 900 MHz.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=0.9) [2]
Component	Abs
Output	E-Field(r=1m)
Frequency	0.9
Rad. effic.	0.9967
Tot. effic.	0.4403
Emax	5.804 V/m
Phase center	(0, 0, 5.91262) Signa 11.9611 (E-Plane)

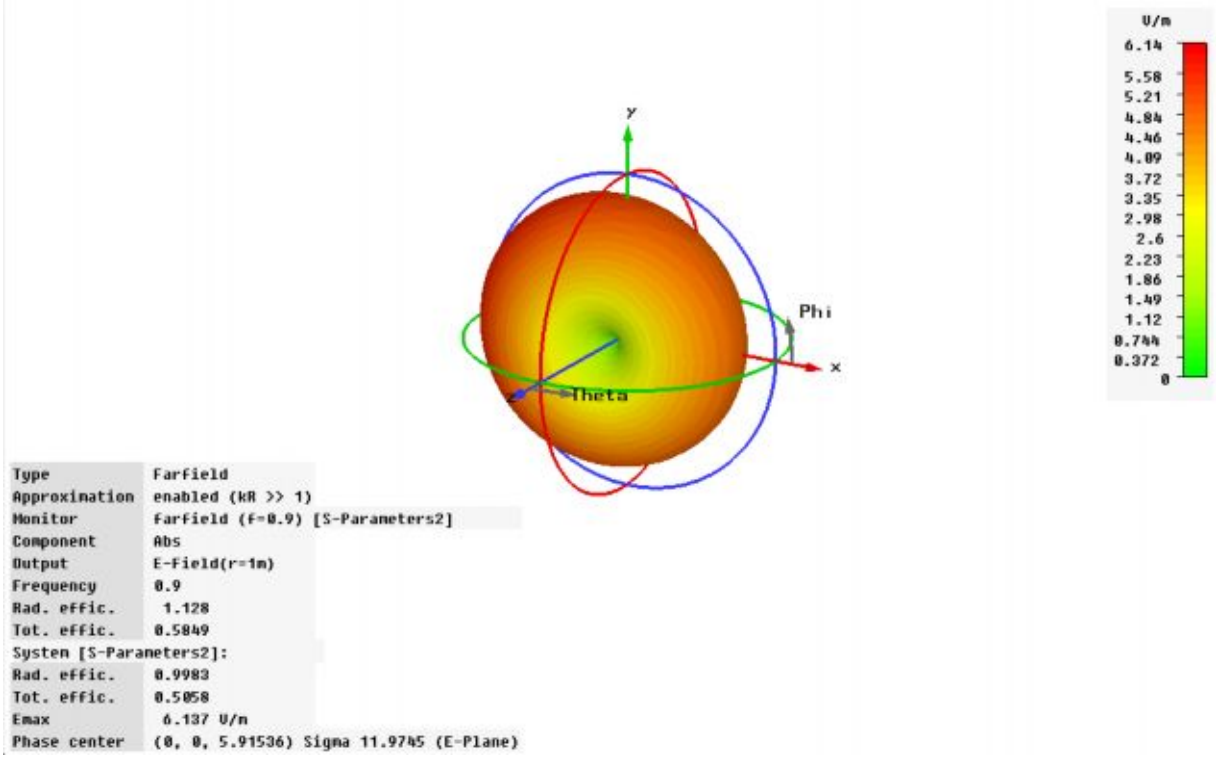
Appendix 1.3 3D plot of Far field pattern for antenna 2 at 900 MHz.

1.1 Dipoles 19 mm apart (with components)



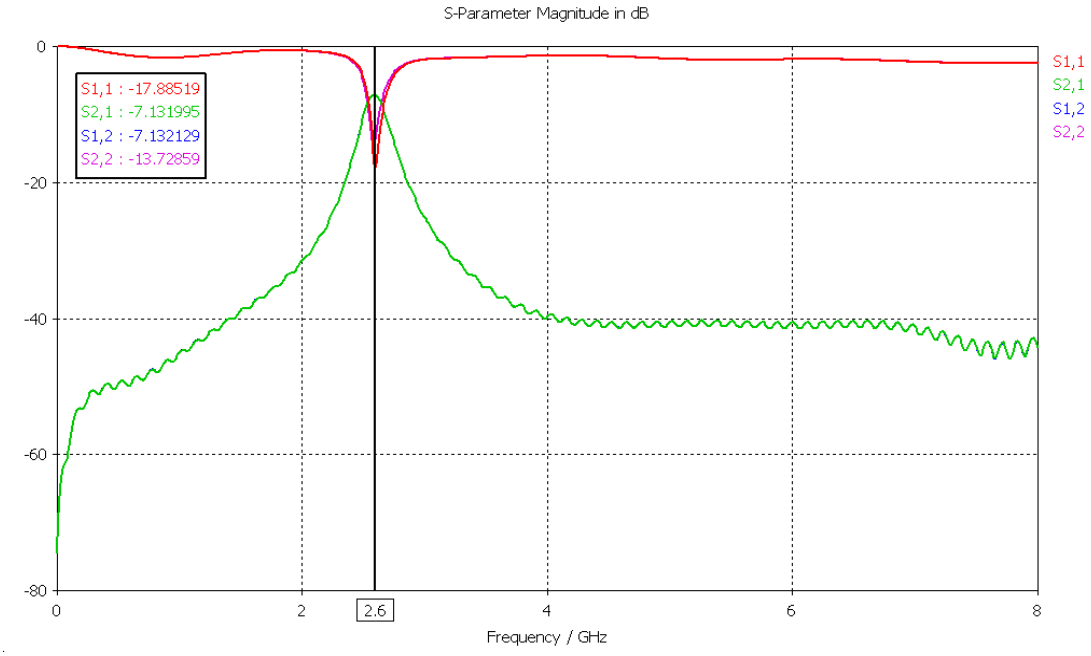
Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=0.9) [S-Parameters1]
Component	Abs
Output	E-Field(r=1m)
Frequency	0.9
Rad. effic.	1.128
Tot. effic.	0.5849
System [S-Parameters1]:	
Rad. effic.	0.9983
Tot. effic.	0.5058
Emax	6.137 V/m
Phase center	(-643.855, 647.759, 9041.17) Signa 75761.9

Appendix 1.4 3D plot of Far field pattern for antenna 1 at 900 MHz.

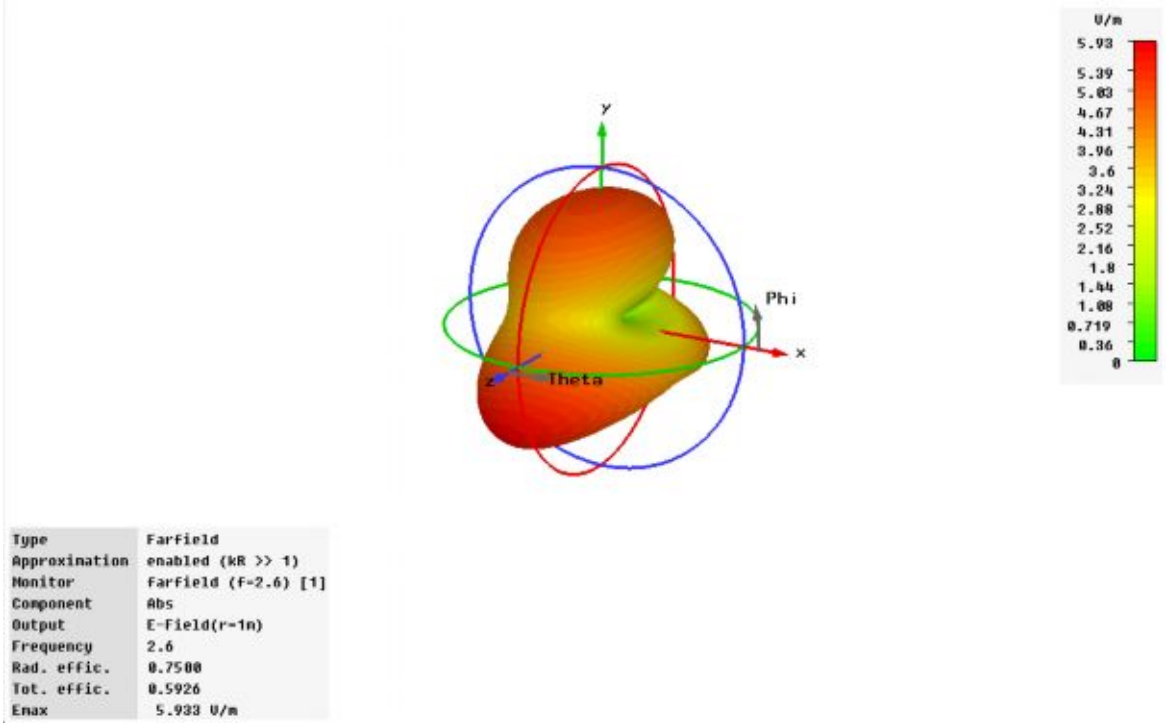


Appendix 1.5 3D plot of Far field pattern for antenna 2 at 900 MHz.

1.2 WiMAX 14 mm apart at 2.6 GHz

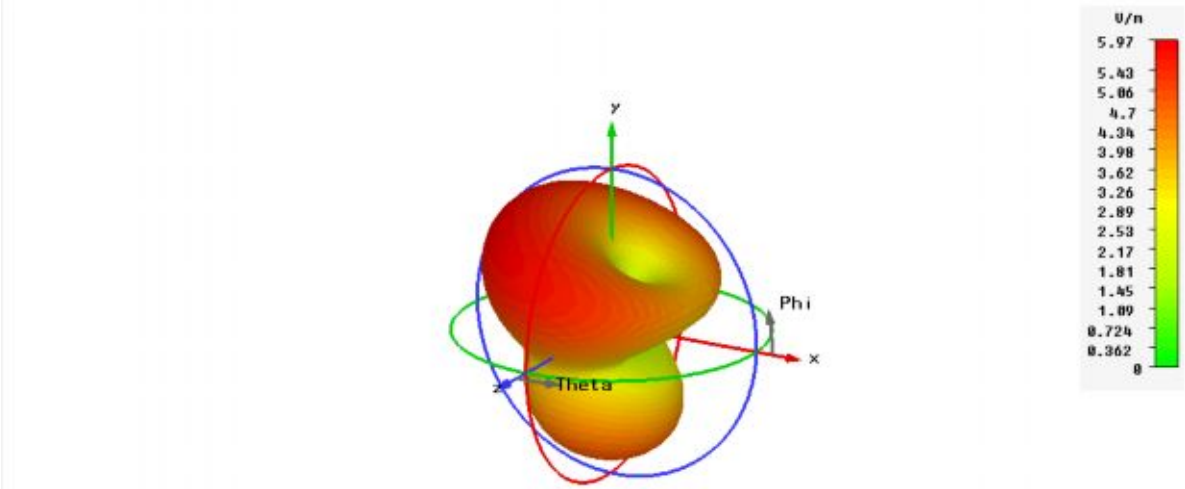


Appendix 1.6 S-parameters response.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.6) [1]
Component	Abs
Output	E-Field(r=1m)
Frequency	2.6
Rad. effic.	0.7508
Tot. effic.	0.5926
Emax	5.933 V/m

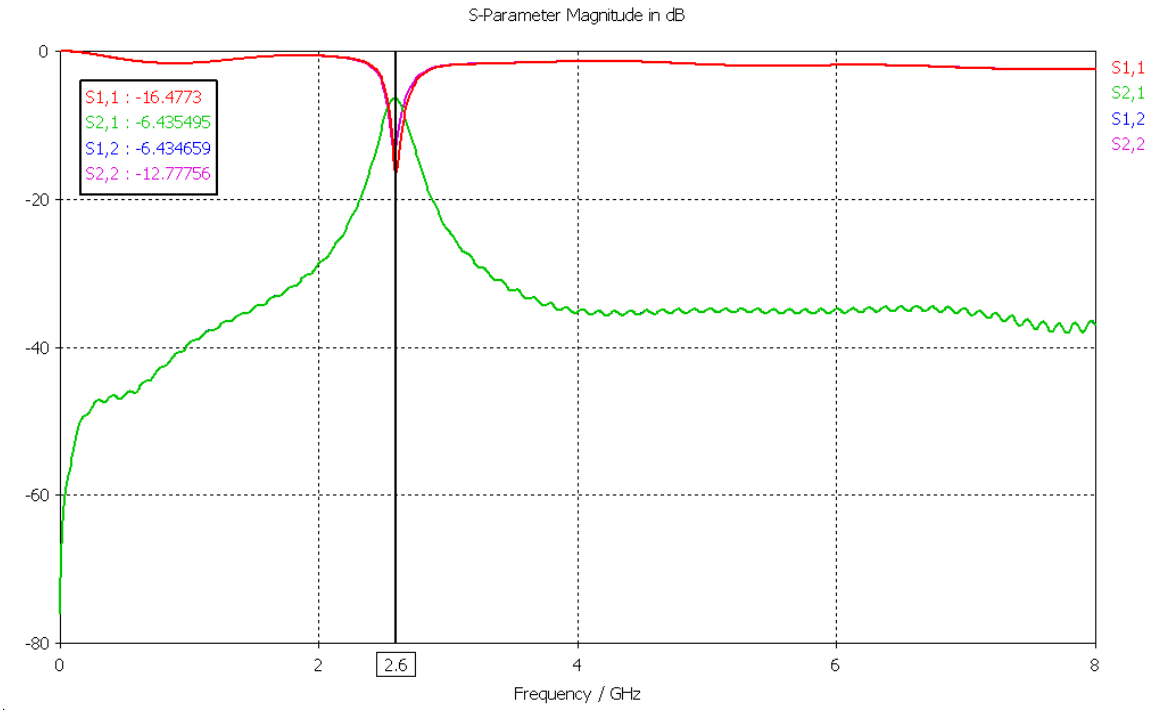
Appendix 1.7 3D plot of Far field pattern for antenna 1 at 2.6GHz.



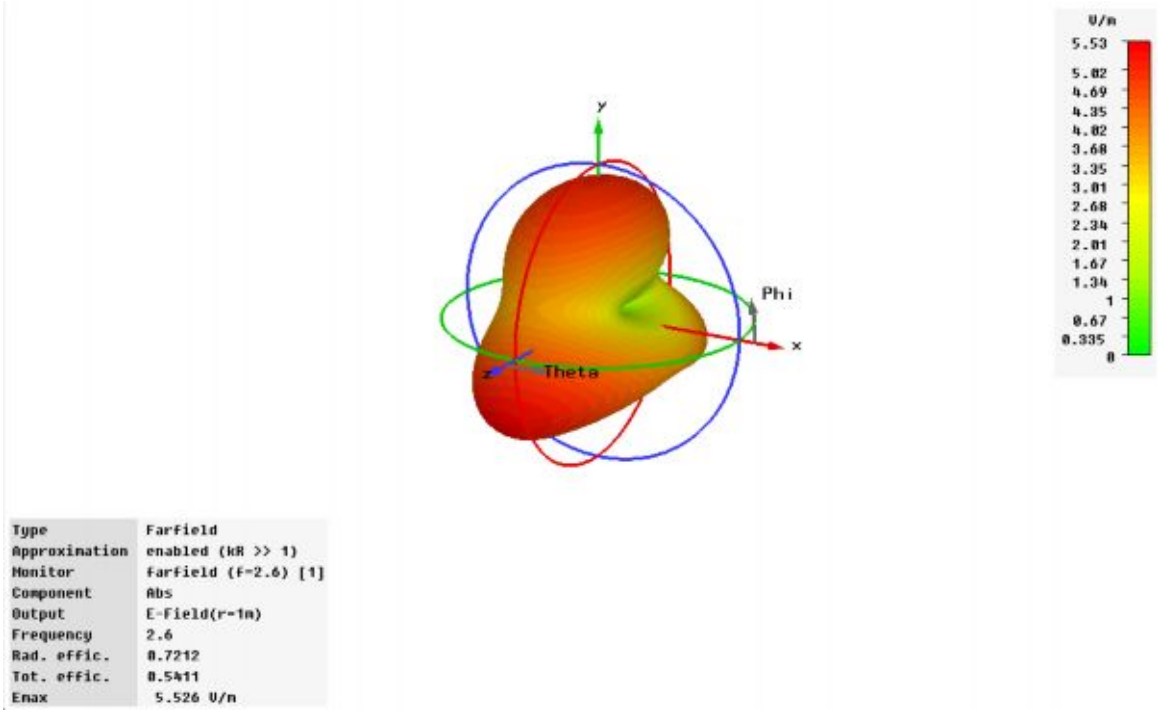
Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.6) [2]
Component	Abs
Output	E-Field(r=1m)
Frequency	2.6
Rad. effic.	0.7528
Tot. effic.	0.5752
Emax	5.969 V/m

Appendix 1.8 3D plot of Far field pattern for antenna 2 at 2.6GHz.

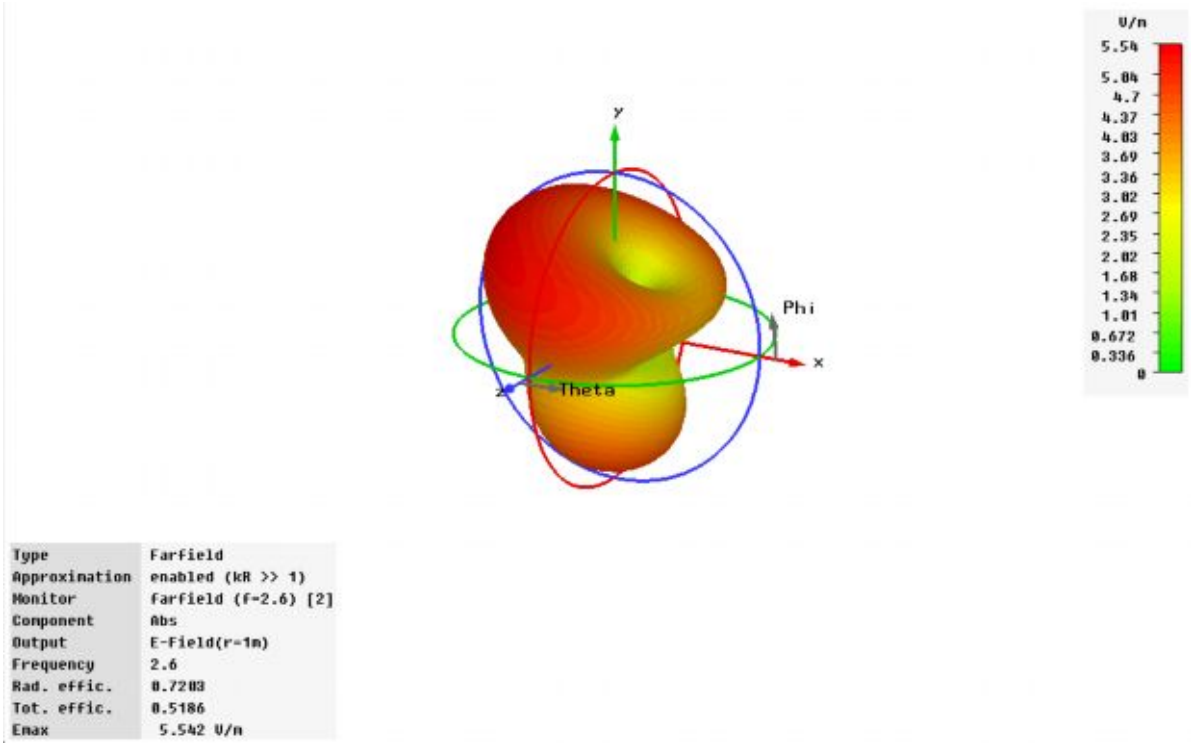
1.3 WiMAX 11 mm apart at 2.6 GHz (no components)



Appendix 1.9 S-parameters response.

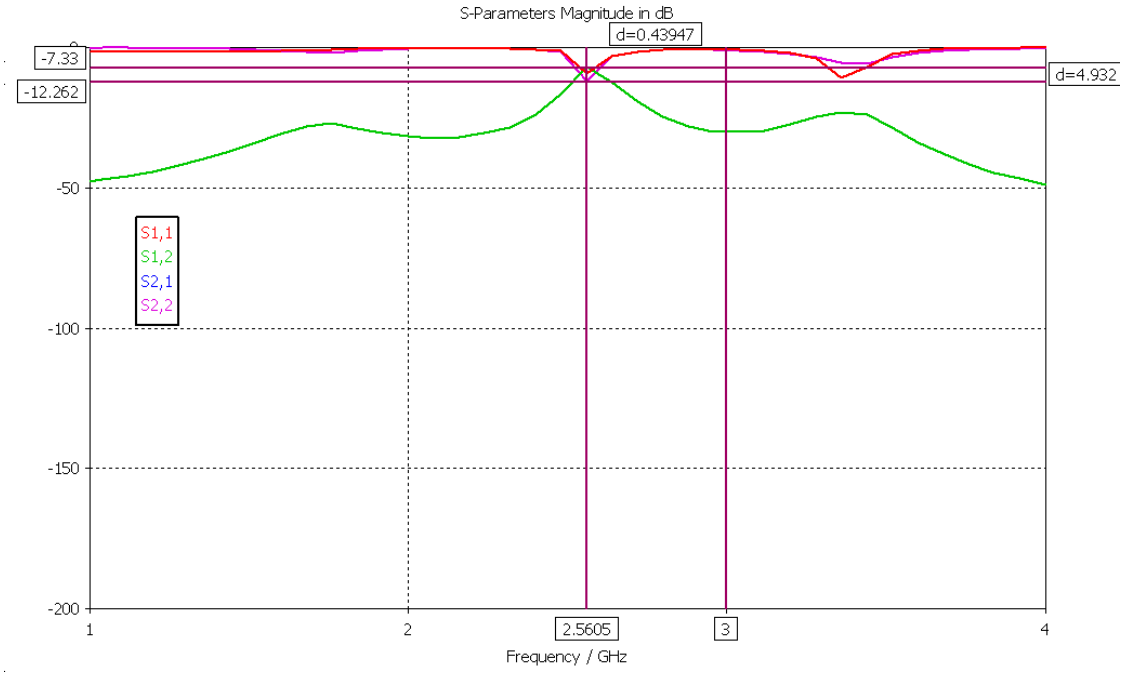


Appendix 1.10 3D plot of Far field pattern for antenna 1 at 2.6GHz

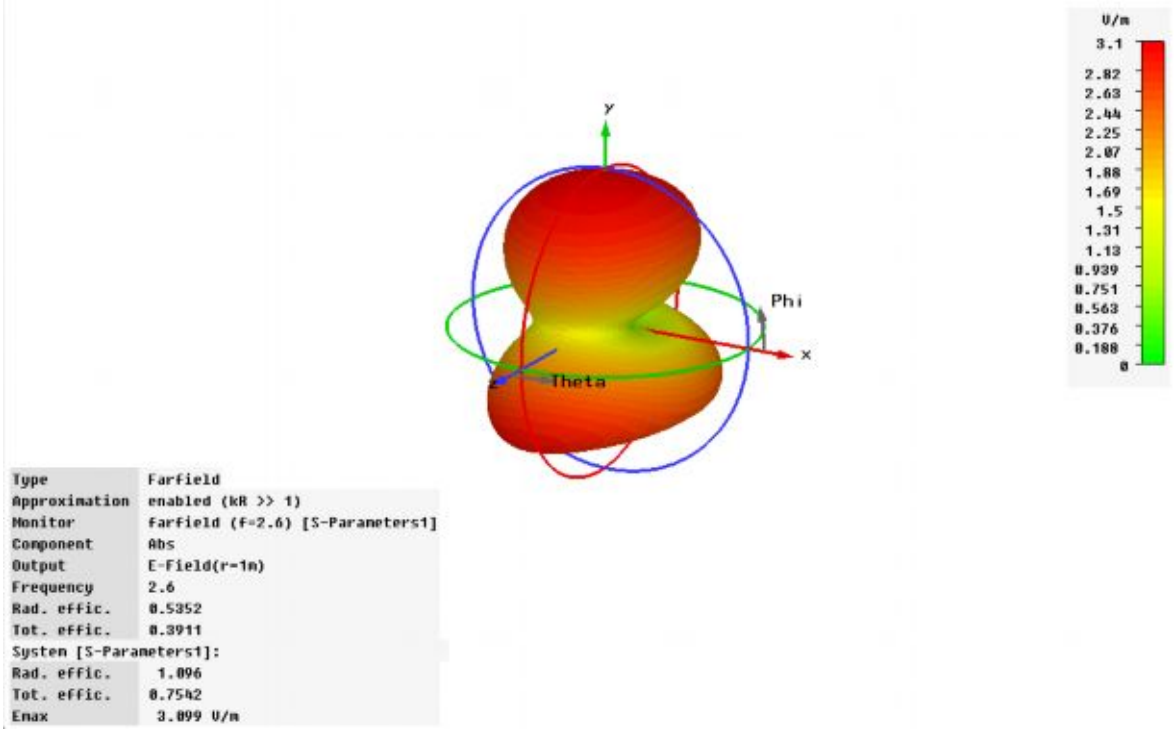


Appendix 1.11 3D plot of Far field pattern for antenna 2 at 2.6GHz

1.4 WiMAX 11 mm apart at 2.6 GHz (with components)

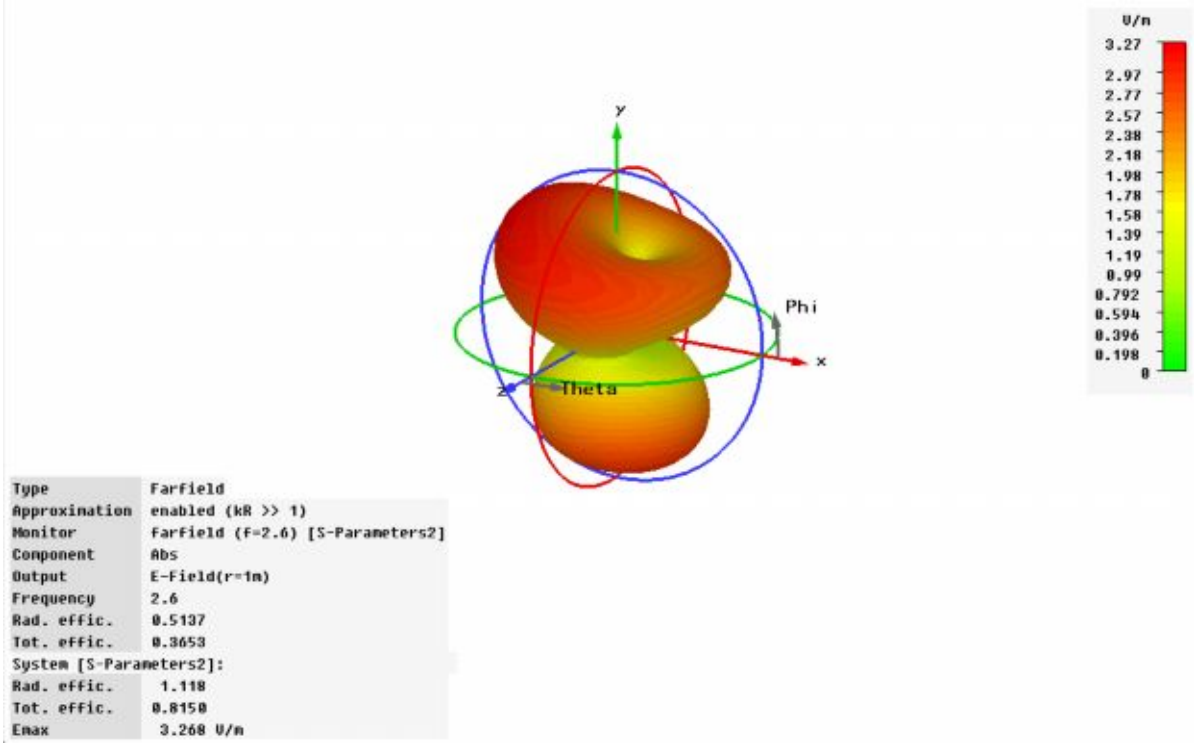


Appendix 1.12 S-parameters response.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.6) [S-Parameters1]
Component	Abs
Output	E-Field(r=1m)
Frequency	2.6
Rad. effic.	0.5352
Tot. effic.	0.3911
System [S-Parameters1]:	
Rad. effic.	1.096
Tot. effic.	0.7542
Emax	3.099 V/m

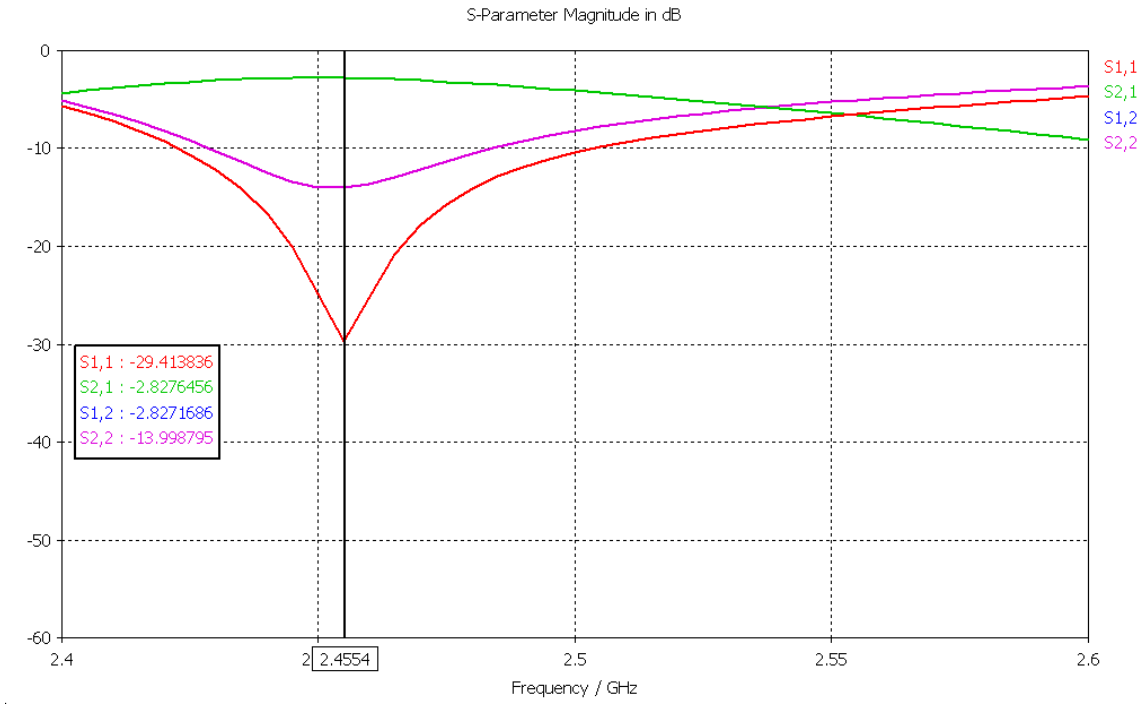
Appendix 1.13 3D plot of Far field pattern for antenna 1 at 2.6GHz.



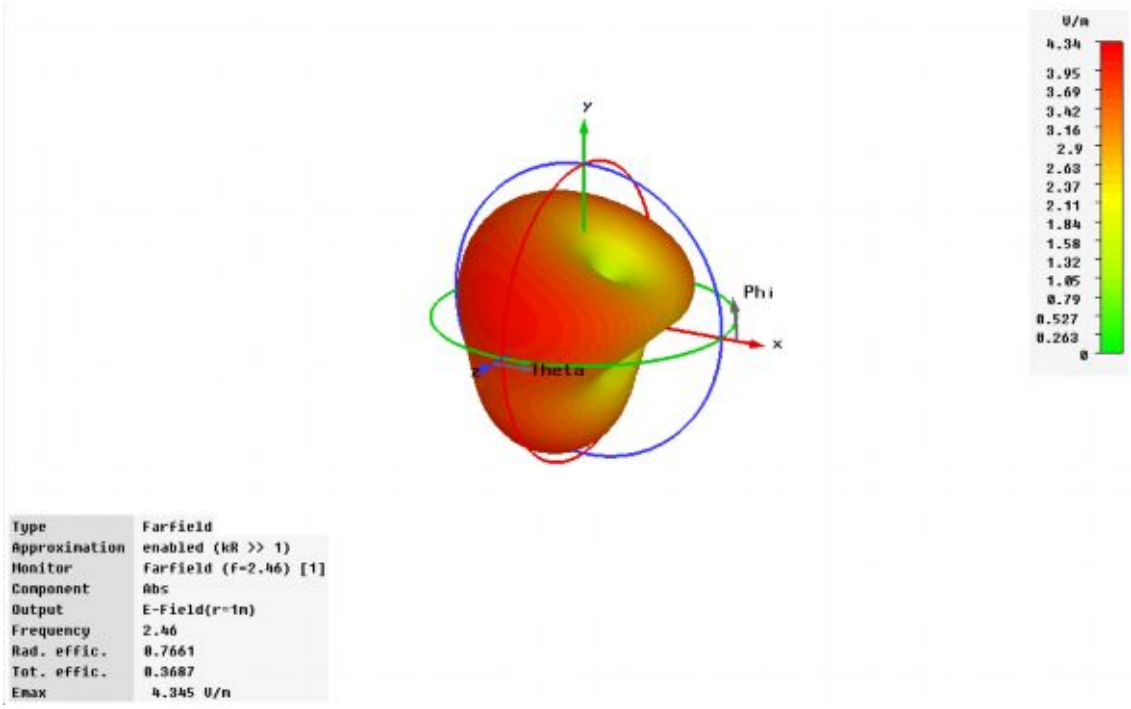
Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.6) [S-Parameters2]
Component	Abs
Output	E-Field(r=1m)
Frequency	2.6
Rad. effic.	0.5137
Tot. effic.	0.3653
System [S-Parameters2]:	
Rad. effic.	1.118
Tot. effic.	0.8150
Emax	3.268 V/m

Appendix 1.14 3D plot of Far field pattern for antenna 2 at 2.6GHz.

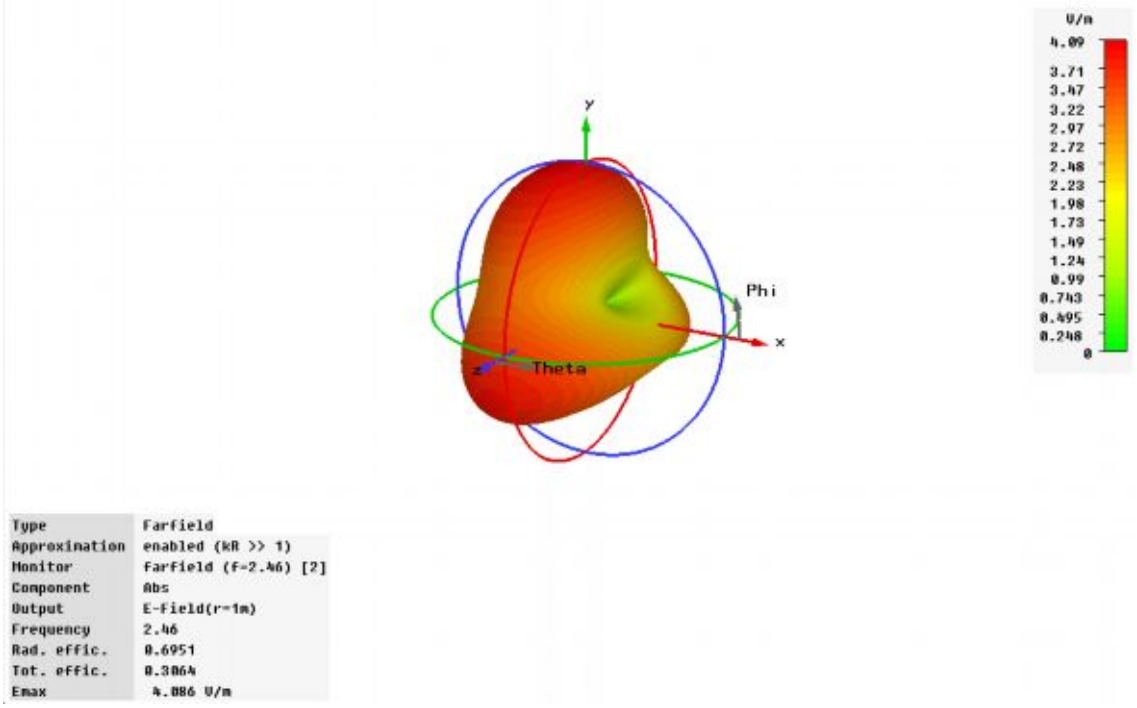
1.5 WiMAX 5 mm apart at 2.46 GHz (no components)



Appendix 1.15 S-parameters response.

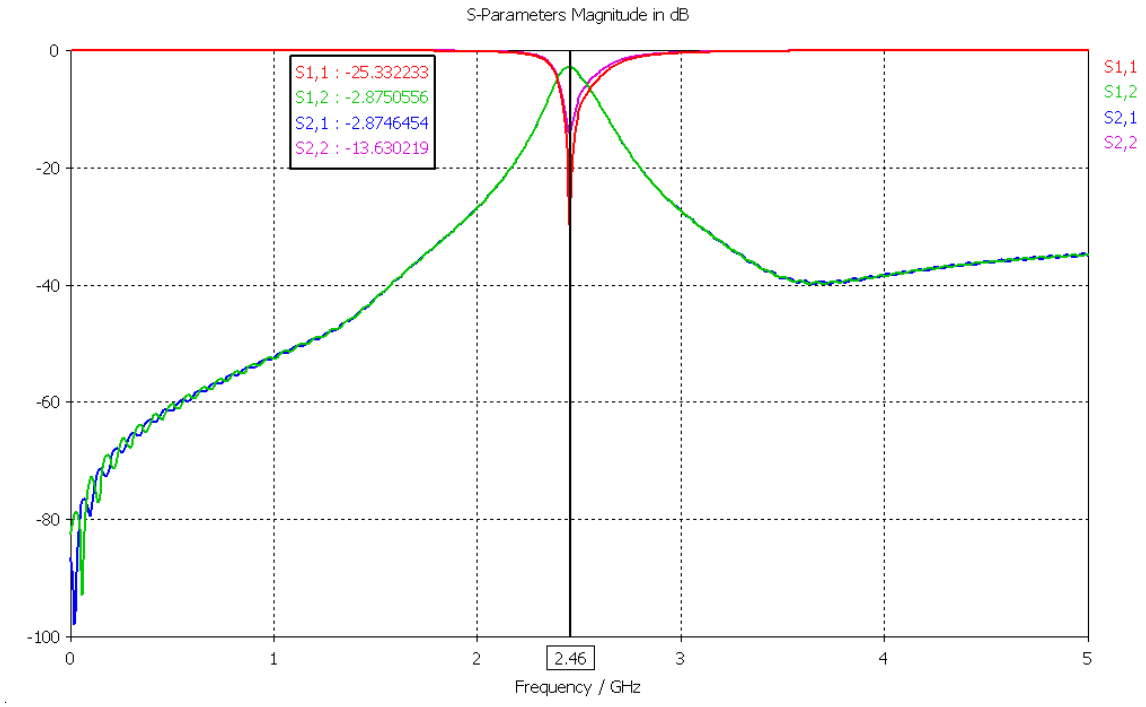


Appendix 1.16 3D plot of Far field pattern for antenna 1 at 2.46GHz.

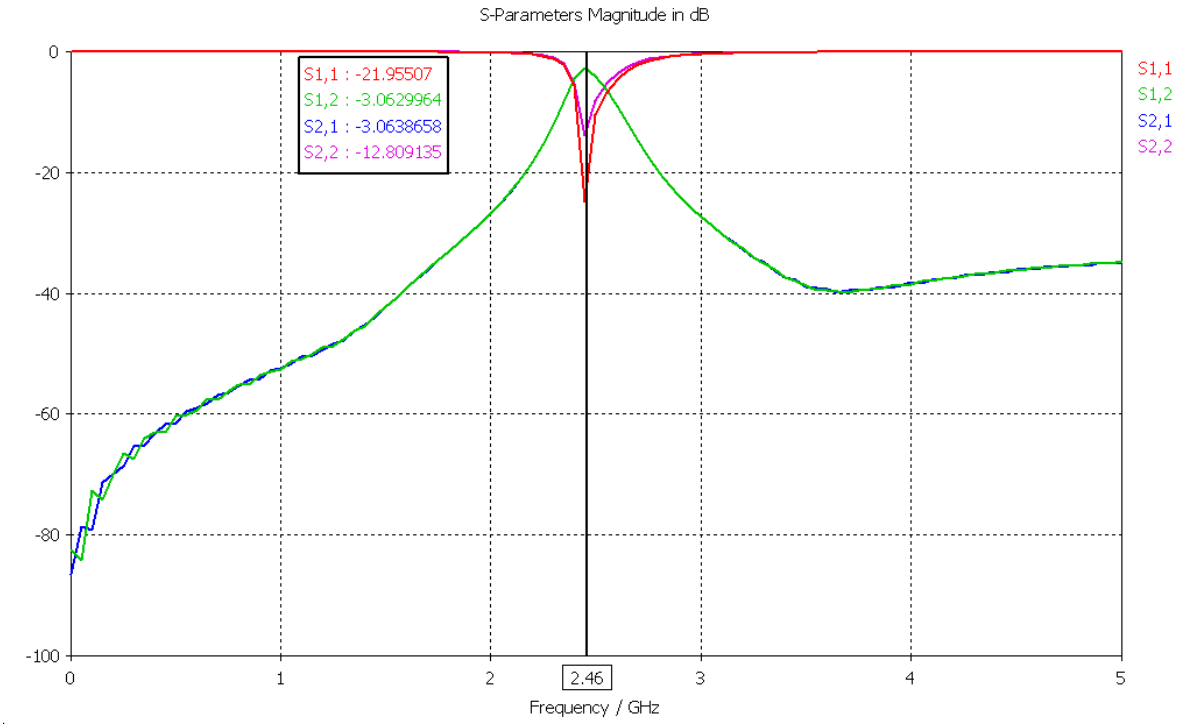


Appendix 1.17 3D plot of Far field pattern for antenna 2 at 2.46GHz.

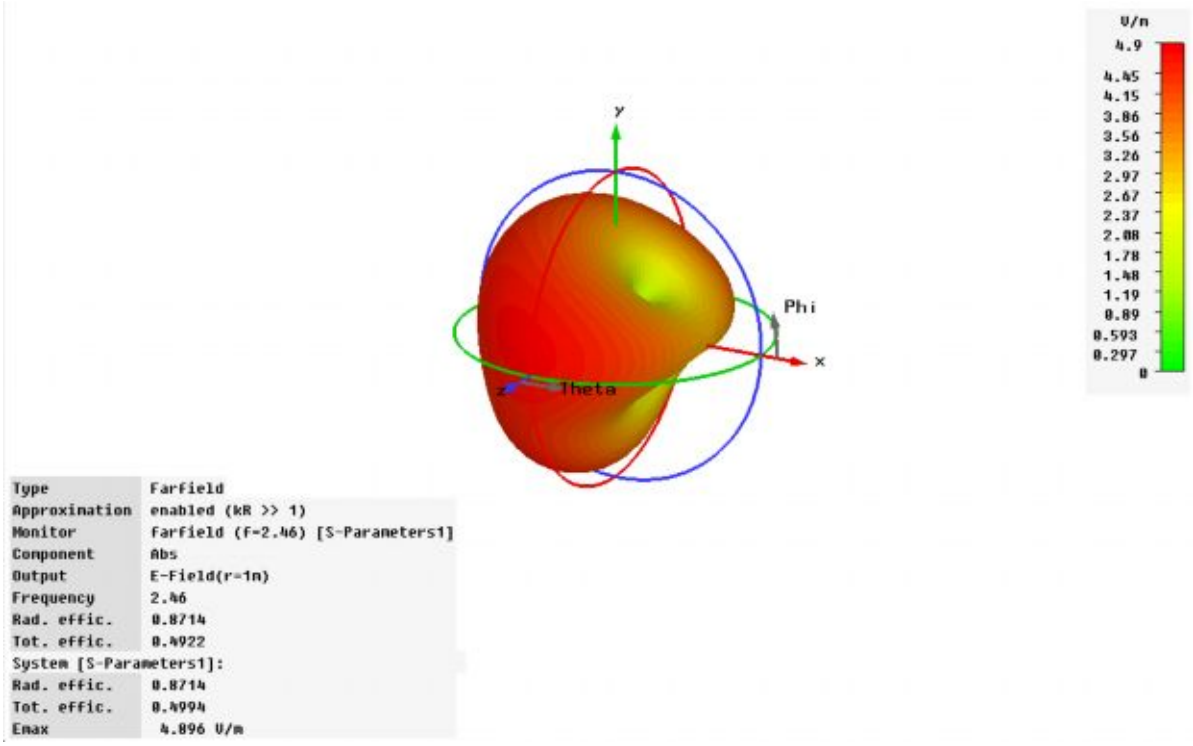
1.6 WiMAX 5 mm apart at 2.46 GH (with components)



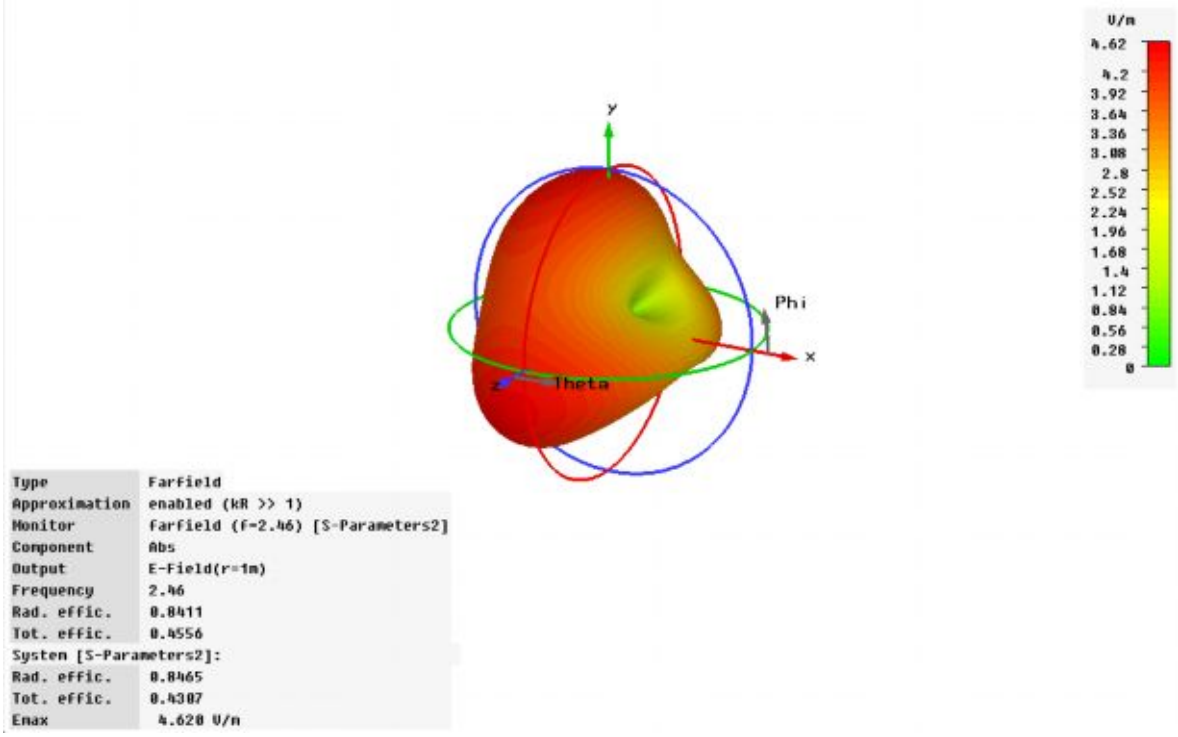
Appendix 1.18 S-parameters response for port 1.



Appendix 1.19 S-parameters response for port 2.

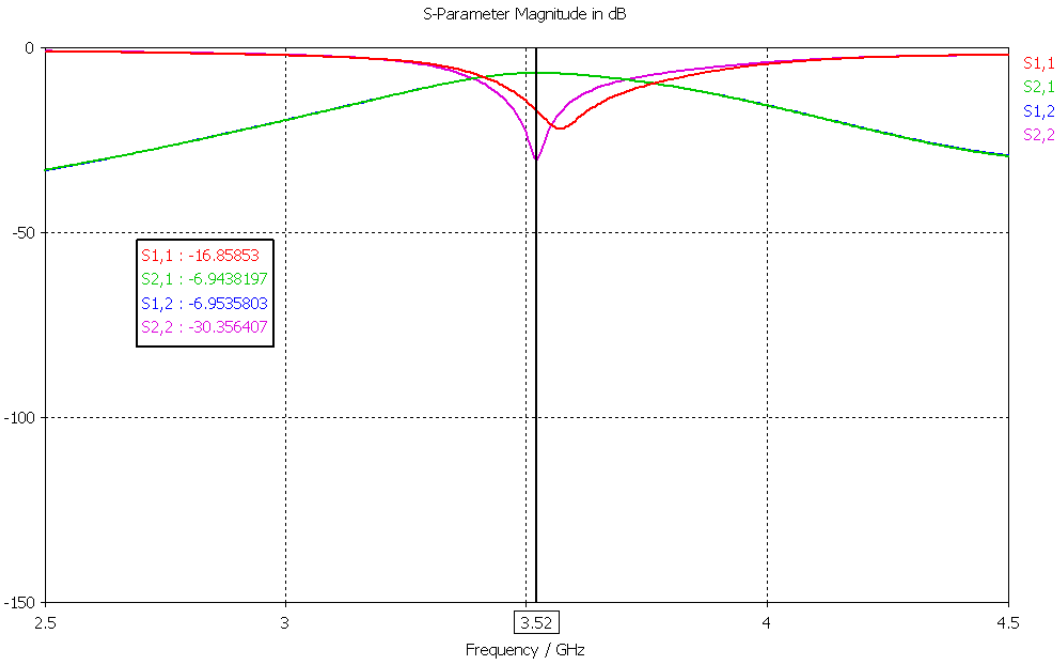


Appendix 1.20 3D plot of Far field pattern for antenna 1 at 2.46GHz.

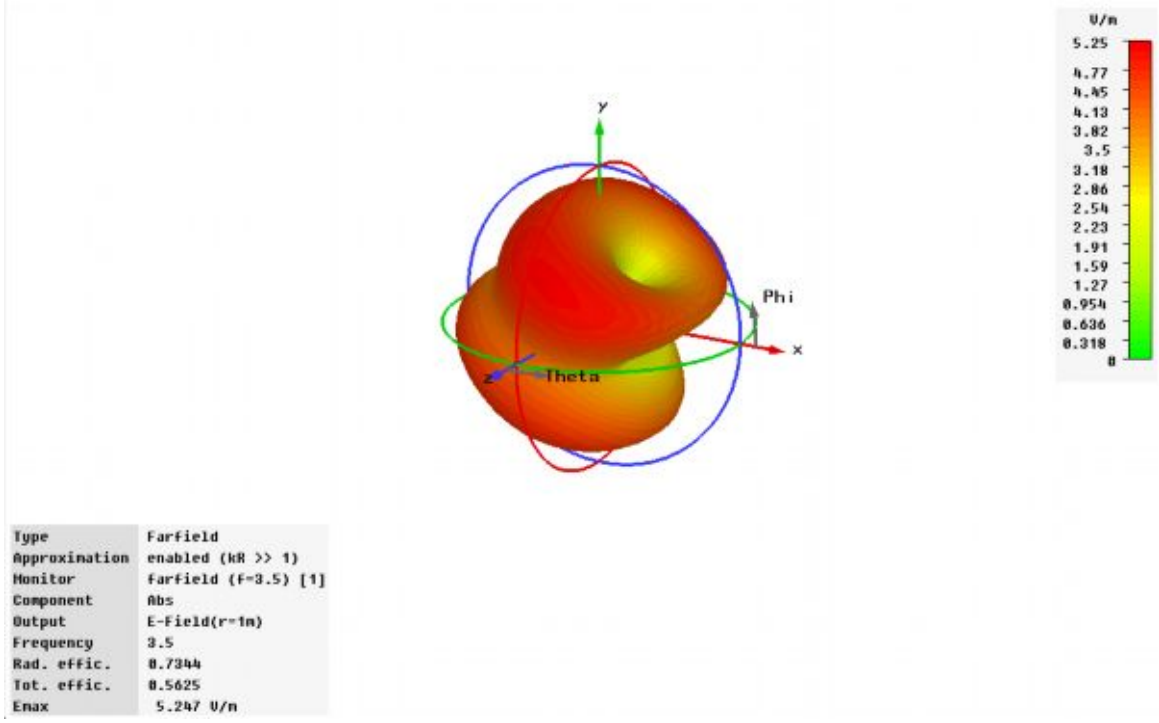


Appendix 1.21 3D plot of Far field pattern for antenna 2 at 2.46GHz.

1.7 WiMAX 7 mm apart at 3.5 GHz.

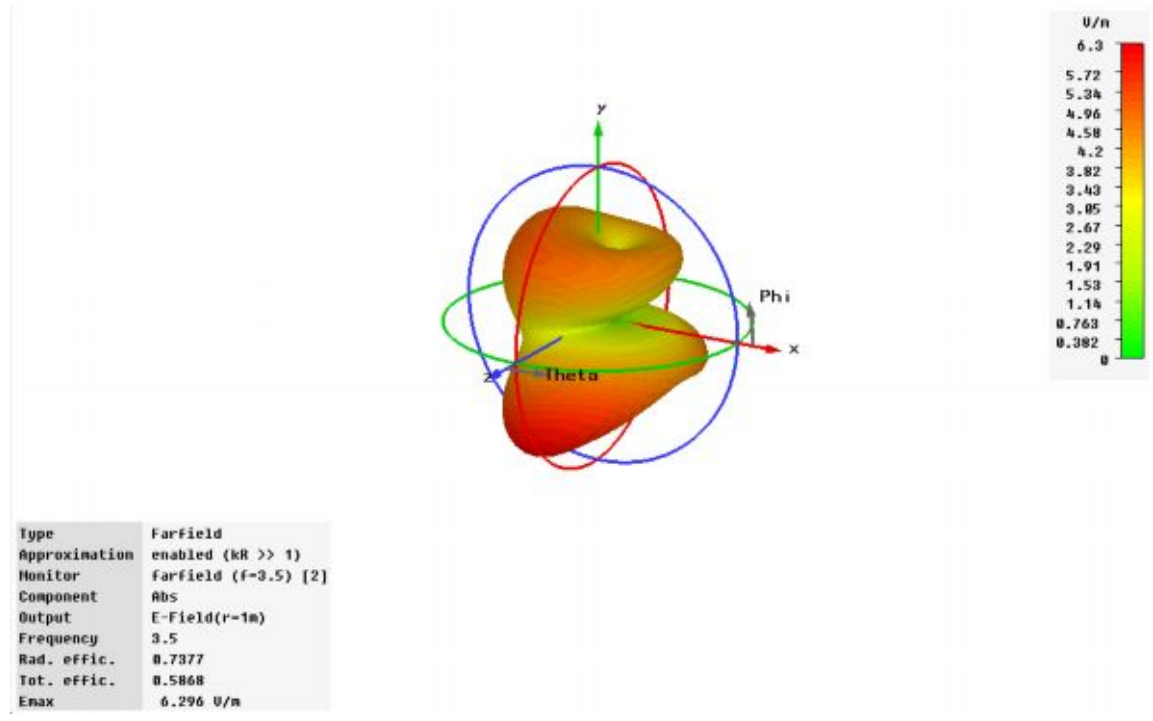


Appendix 1.22 S-parameters response.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=3.5) [1]
Component	Abs
Output	E-Field(r=1m)
Frequency	3.5
Rad. effic.	0.7344
Tot. effic.	0.5625
Emax	5.247 V/m

Appendix 1.23 3D plot of Far field pattern for antenna 1 at 3.5 GHz.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=3.5) [2]
Component	Abs
Output	E-Field(r=1m)
Frequency	3.5
Rad. effic.	0.7377
Tot. effic.	0.5868
Emax	6.296 V/m

Appendix 1.24 3D plot of Far field pattern for antenna 2 at 3.5 GHz.

Appendix 2: MPA simulation results and optimization values

2.1 Parallel dipoles 19 mm apart

```
------------  Result file Efficiency ---------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
8e+08; 1; 0.35301; 2; 0.35548;
8.1e+08; 1; 0.36909; 2; 0.37189;
8.2e+08; 1; 0.38344; 2; 0.38657;
8.3e+08; 1; 0.39586; 2; 0.39933;
8.4e+08; 1; 0.40631; 2; 0.41009;
8.5e+08; 1; 0.4148; 2; 0.41885;
8.6e+08; 1; 0.42142; 2; 0.42572;
8.7e+08; 1; 0.42633; 2; 0.43079;
8.8e+08; 1; 0.42967; 2; 0.43421;
8.9e+08; 1; 0.4316; 2; 0.43613;
9e+08; 1; 0.43223; 2; 0.43663;
9.1e+08; 1; 0.43161; 2; 0.43574;
9.2e+08; 1; 0.42976; 2; 0.43352;
9.3e+08; 1; 0.42668; 2; 0.42996;
9.4e+08; 1; 0.42235; 2; 0.42506;
9.5e+08; 1; 0.41681; 2; 0.4189;
9.6e+08; 1; 0.41013; 2; 0.41158;
9.7e+08; 1; 0.40245; 2; 0.40326;
9.8e+08; 1; 0.39395; 2; 0.39415;
9.9e+08; 1; 0.38485; 2; 0.3845;
1e+09; 1; 0.37534; 2; 0.37449;
```

Appendix 2.1 MPA results of radiation efficiency with no components.

```
------------  Result file Efficiency ---------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
8e+08; 1; 0.40876; 2; 0.41008;
8.1e+08; 1; 0.42403; 2; 0.42551;
8.2e+08; 1; 0.43819; 2; 0.43983;
8.3e+08; 1; 0.4511; 2; 0.45291;
8.4e+08; 1; 0.4627; 2; 0.46468;
8.5e+08; 1; 0.47292; 2; 0.47507;
8.6e+08; 1; 0.48177; 2; 0.48408;
8.7e+08; 1; 0.48923; 2; 0.4917;
8.8e+08; 1; 0.49535; 2; 0.49797;
8.9e+08; 1; 0.5002; 2; 0.50295;
9e+08; 1; 0.50385; 2; 0.50672;
9.1e+08; 1; 0.50638; 2; 0.50935;
9.2e+08; 1; 0.50789; 2; 0.51095;
9.3e+08; 1; 0.5085; 2; 0.51163;
9.4e+08; 1; 0.50829; 2; 0.51146;
9.5e+08; 1; 0.50737; 2; 0.51057;
9.6e+08; 1; 0.50583; 2; 0.50903;
9.7e+08; 1; 0.50377; 2; 0.50694;
9.8e+08; 1; 0.50125; 2; 0.50438;
9.9e+08; 1; 0.49836; 2; 0.50142;
1e+09; 1; 0.49514; 2; 0.4981;
```

Appendix 2.2 MPA optimization results of radiation efficiency with components.

2.2 WiMAX 14 mm apart at 2.6 GHz

```
------------  Result file Efficiency -------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.5e+09; 1; 0.30778; 2; 0.36236;
2.52e+09; 1; 0.37011; 2; 0.42621;
2.54e+09; 1; 0.43667; 2; 0.48613;
2.56e+09; 1; 0.50089; 2; 0.53441;
2.58e+09; 1; 0.55563; 2; 0.5658;
2.6e+09; 1; 0.59513; 2; 0.57911;
2.62e+09; 1; 0.61637; 2; 0.57686;
2.64e+09; 1; 0.61931; 2; 0.56336;
2.66e+09; 1; 0.60621; 2; 0.5425;
2.68e+09; 1; 0.5804; 2; 0.51645;
2.7e+09; 1; 0.54535; 2; 0.4859;
```

Appendix 2.3 MPA results of radiation efficiency.

2.3 WiMAX 11 mm apart at 2.6 GHz

```
------------  Result file Efficiency ---------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.5e+09; 1; 0.26409; 2; 0.32115;
2.52e+09; 1; 0.31627; 2; 0.37623;
2.54e+09; 1; 0.37392; 2; 0.42885;
2.56e+09; 1; 0.43209; 2; 0.47254;
2.58e+09; 1; 0.48458; 2; 0.50263;
2.6e+09; 1; 0.52563; 2; 0.51784;
2.62e+09; 1; 0.55131; 2; 0.51991;
2.64e+09; 1; 0.56027; 2; 0.51219;
2.66e+09; 1; 0.55369; 2; 0.49764;
2.68e+09; 1; 0.53423; 2; 0.47789;
2.7e+09; 1; 0.50517; 2; 0.45332;
```

Appendix 2.4 MPA results of radiation efficiency with no components.

```
------------  Result file Efficiency -------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.5e+09; 1; 0.47584; 2; 0.58489;
2.52e+09; 1; 0.56985; 2; 0.68521;
2.54e+09; 1; 0.67373; 2; 0.78104;
2.56e+09; 1; 0.77855; 2; 0.86061;
2.58e+09; 1; 0.87312; 2; 0.91541;
2.6e+09; 1; 0.94709; 2; 0.94311;
2.62e+09; 1; 0.99335; 2; 0.94689;
2.64e+09; 1; 1.0095; 2; 0.93283;
2.66e+09; 1; 0.99764; 2; 0.90632;
2.68e+09; 1; 0.96257; 2; 0.87035;
2.7e+09; 1; 0.91021; 2; 0.82561;
```

Appendix 2.5 MPA optimization results of radiation efficiency with components for case no. 10.

2.4 WiMAX 5 mm apart at 2.46 GHz

```
------------  Result file Efficiency ----------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.42e+09; 1; 0.29591; 2; 0.23637;
2.43e+09; 1; 0.31352; 2; 0.25361;
2.44e+09; 1; 0.33091; 2; 0.27067;
2.45e+09; 1; 0.34812; 2; 0.28729;
2.46e+09; 1; 0.36527; 2; 0.3033;
2.47e+09; 1; 0.38249; 2; 0.31867;
2.48e+09; 1; 0.39981; 2; 0.33341;
2.49e+09; 1; 0.41717; 2; 0.34753;
```

Appendix 2.6 MPA results of radiation efficiency with no components.

```
------------  Result file Efficiency ----------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.42e+09; 1; 0.4498; 2; 0.35784;
2.43e+09; 1; 0.46407; 2; 0.36982;
2.44e+09; 1; 0.47742; 2; 0.38095;
2.45e+09; 1; 0.48965; 2; 0.39105;
2.46e+09; 1; 0.50052; 2; 0.39995;
2.47e+09; 1; 0.50985; 2; 0.40751;
2.48e+09; 1; 0.51745; 2; 0.4136;
2.49e+09; 1; 0.52318; 2; 0.41813;
```

Appendix 2.7 MPA optimization results of radiation efficiency with components.

2.5 WiMAX 7 mm apart at 3.5 GHz

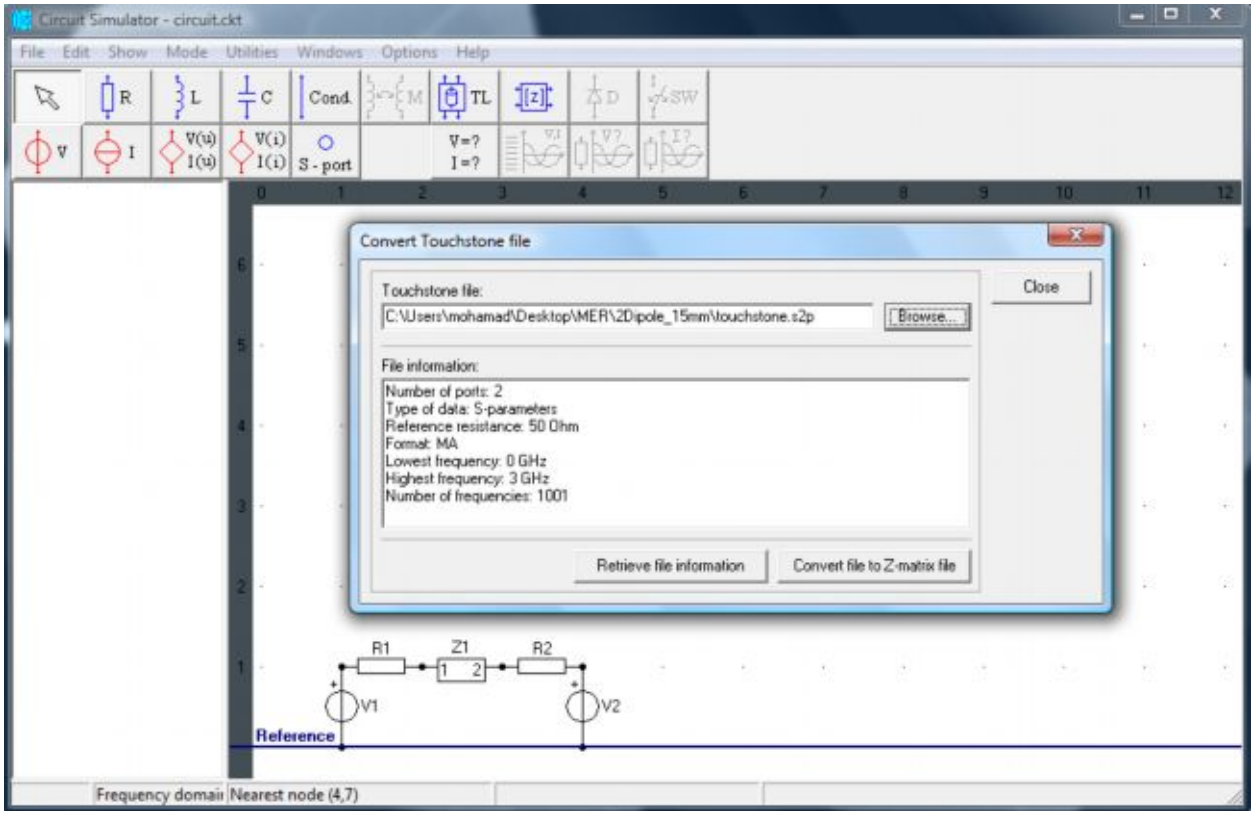
```
------------  Result file Efficiency ----------
Freq;  Port no; Radiation efficiency;
[MHz]; [-];     [-]; ...
2.5e+09; 1; 0.036648; 2; 0.025916;
2.7e+09; 1; 0.0599; 2; 0.04405;
2.9e+09; 1; 0.10235; 2; 0.080821;
3.1e+09; 1; 0.17473; 2; 0.16031;
3.3e+09; 1; 0.32253; 2; 0.35045;
3.5e+09; 1; 0.56112; 2; 0.56255;
3.7e+09; 1; 0.59847; 2; 0.49373;
3.9e+09; 1; 0.48917; 2; 0.41067;
4.1e+09; 1; 0.30268; 2; 0.27638;
4.3e+09; 1; 0.18075; 2; 0.17778;
4.5e+09; 1; 0.11813; 2; 0.12106;
```

Appendix 2.8 MPA results of radiation efficiency.

Appendix 3: Software's instruction

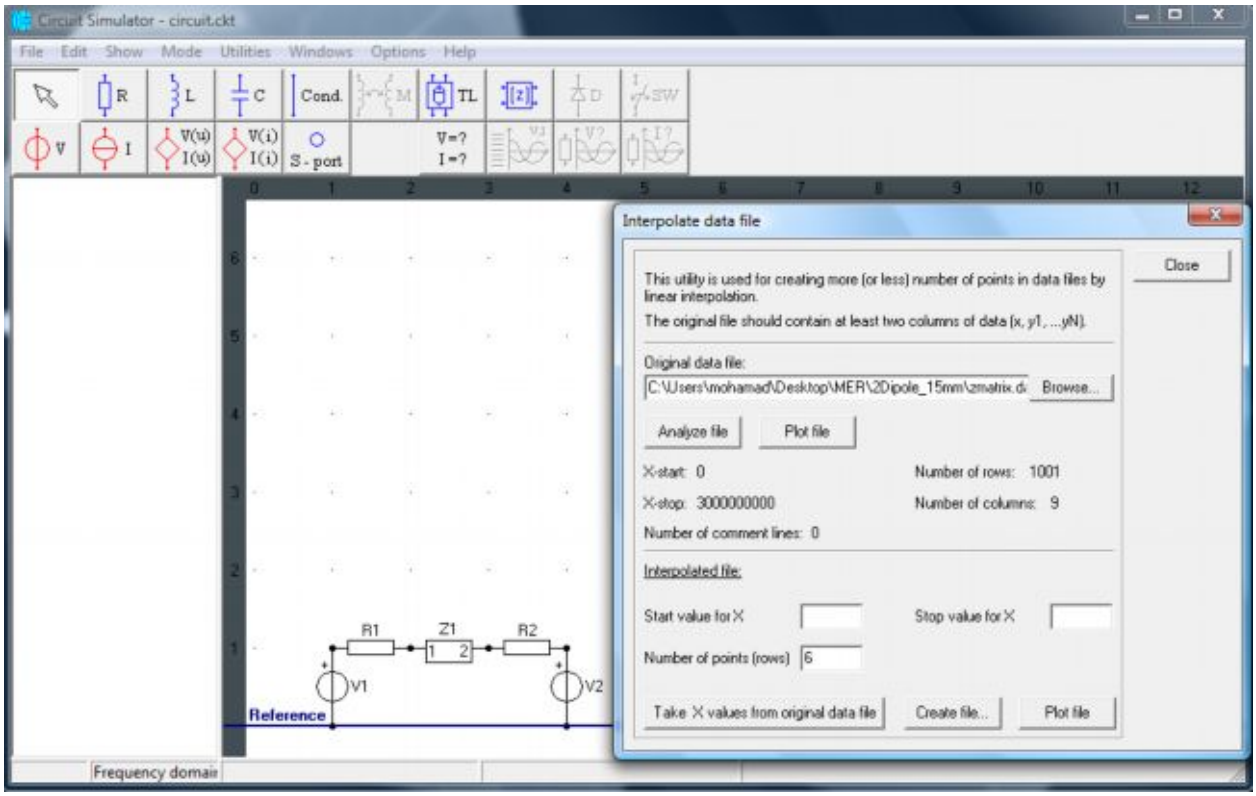
3.1 CircSim

First of all we have to export s-parameters resulted from CST microwave studio and save it as touchstone file with extension .s2p. The touchstone file will be imported to CircSim in order to convert to Z-matrix file.

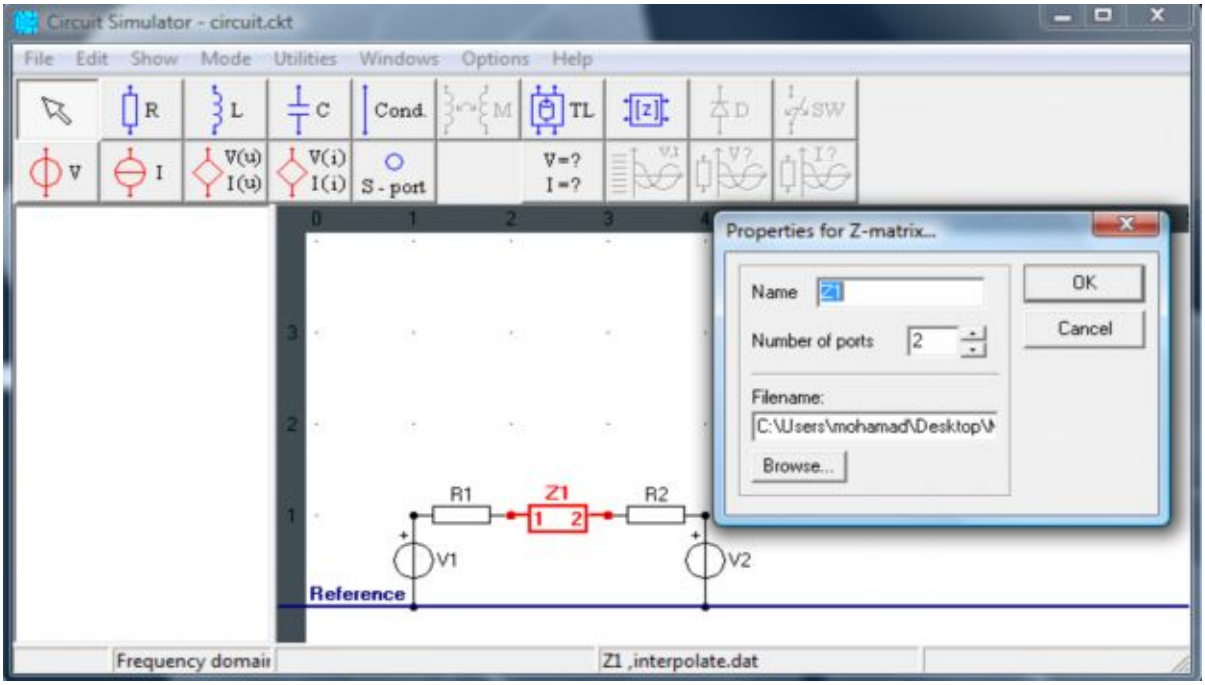


Appendix 3.1Convert touchstone files to Z-matrix.

Next step is to interpolate data files which is converted from far-fields pattern in CST microwave studio and saved as (ASCII) plot data. This interpolate data file will be used as input circuit which is Z_1. The interpolated data file has starting frequency and stopping one, depends about the range of frequencies will be used. Define the interpolate data file with respect to Z_1 and save it as shown in appendix 3.3. Now CircSim is ready to interact with MPA.



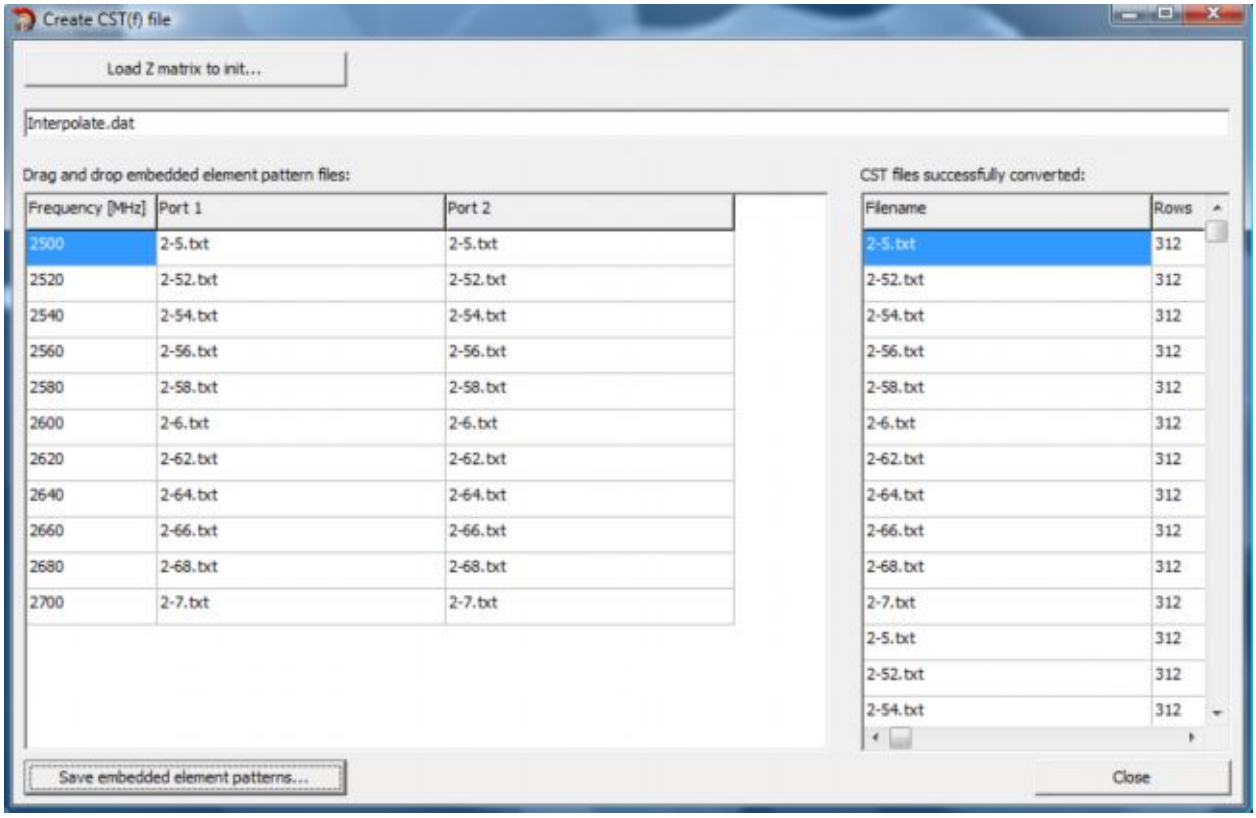
Appendix 3.2 Interpolate data file from Z-matrix



Appendix 3.3 Saving interpolate data file.

3.2 Multi Port Antenna Evaluator MPA

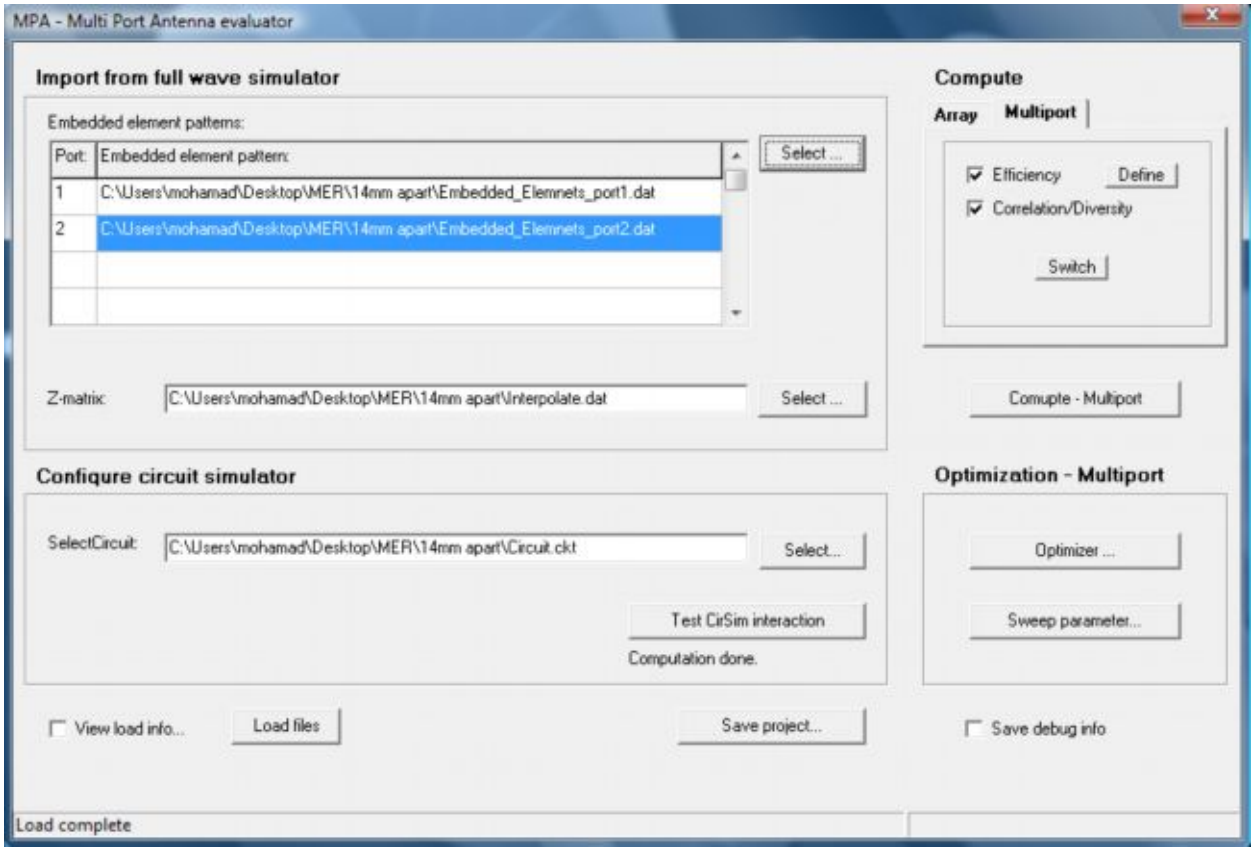
Run MPA software, in the full wave simulators choose create CST (f) files. Load interpolate data file in the load Z matrix box. Furthermore drag all far-field patterns which have been converted from CST microwave studio to txt file for antenna 1 (port 1) and antenna 2 (port 2) to create embedded elements.



Appendix 3.4 Creating embedded elements for MPA.

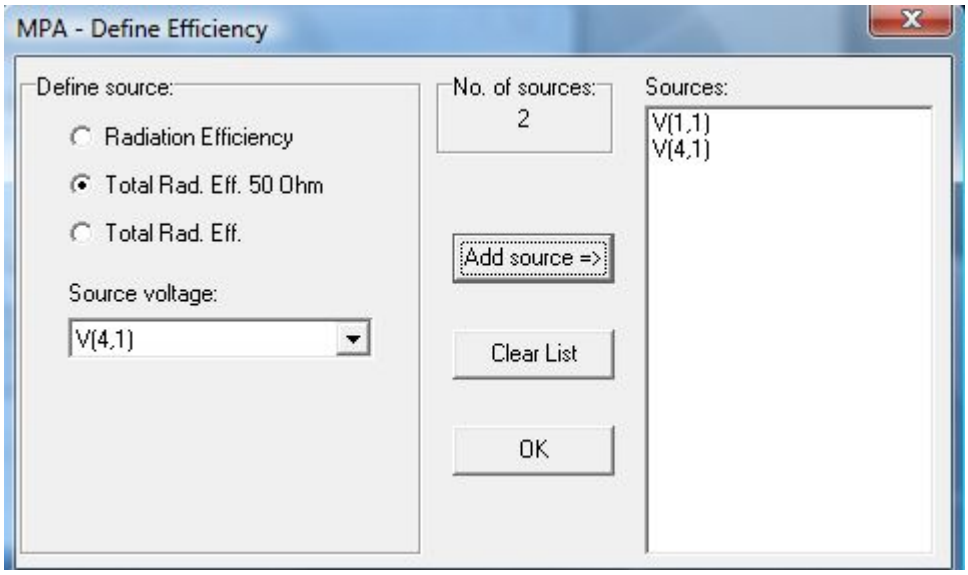
We have to take in consideration that the far-fields in CST microwave studio should have plot mode and scaling belong to E-field and linear scaling of reference distance of 1 m and to use the far-field approximation to get good results in MPA simulations.

Import all data to MPA; click the test button to interact between MPA and CircSim; the files should be loaded to calculate total radiation efficiency, correlation and diversity gain for the multiport systems.

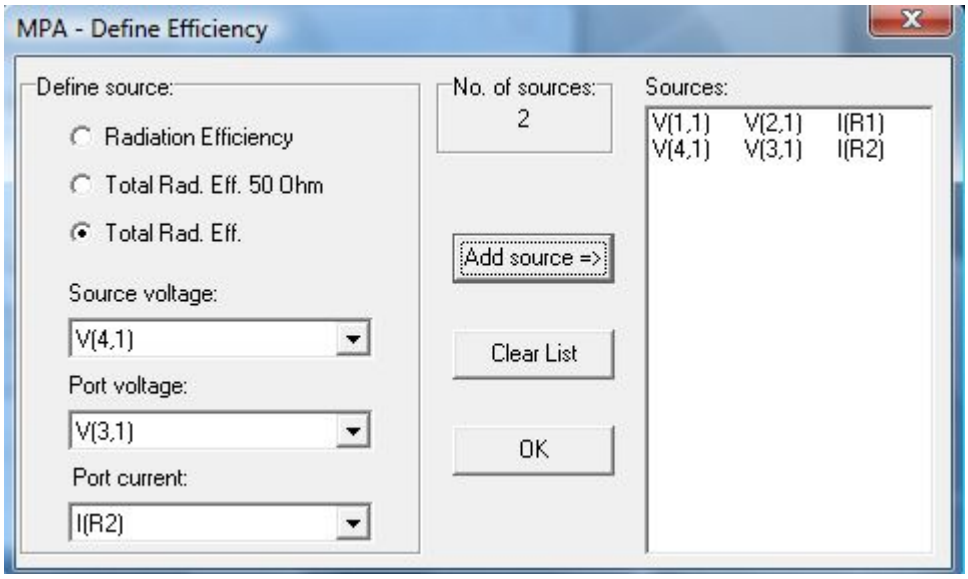


Appendix 3.5 Multiport computations using MPA.

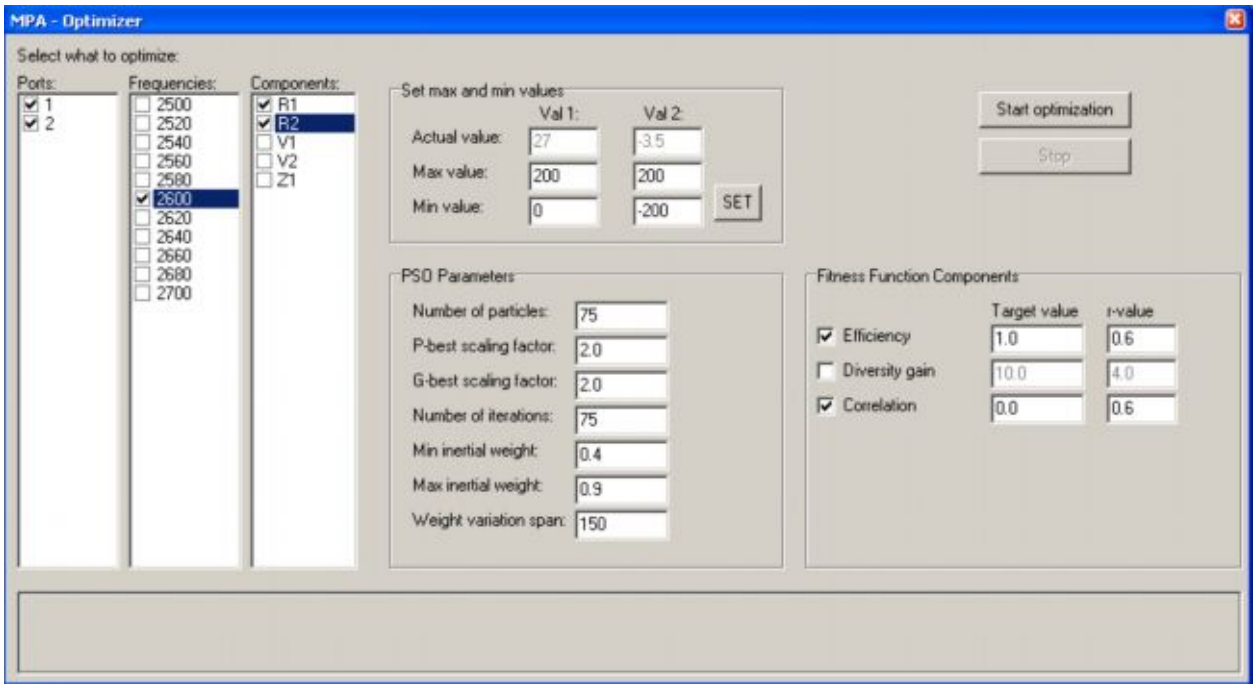
We can compute three types of efficiencies in MPA but we will use two of them; one belongs to 50 Ω where all ports need a definition of its sources, which are defined in same order as in the full wave solver in this case one antenna will be under test while the other is terminated to 50 Ω when it is calculating the total radiation efficiency. For each port the source voltage is defined, and one belong when we varying the source impedances, for each port the source voltage, port voltage and port current is defined [13].



Appendix 3.6 Multiport computation for 50 Ω system.



Appendix 3.7 Multiport computation for changing source impedances.



Appendix 3.8 Optimization process using MPA.

For more information's and details how to use MPA can be found in MPA manual [13].