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ANALYSIS OF MUTUAL COUPLING MODELS FOR PHASED ARRAY

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ANALYSIS OF MUTUAL COUPLING MODELS FOR PHASED ARRAY
CALIBRATION

A THESIS APPROVED FOR THE
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BY THE COMMITTEE CONSISTING OF

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Abstract

There is a demand for more effective phased array calibration both in initial and in situ setups, including but not limited to airborne and spaceborne radars. Mutual coupling is a method of calibration which involves gathering amplitude and phase components. However, obtaining mutual coupling information from a phased array is complicated due to array geometry, patch modeling, nulls in coupling, edge effects, and changes in time and temperature. As such, simulating these phased arrays becomes difficult with larger array sizes in electromagnetic solvers as the demand for computational memory increases.

This thesis introduces an array model meant to quickly provide mutual coupling data which can in turn be used to help in the implementation of future mutual coupling calibration algorithms. This accuracy of this model is verified using full wave simulations. Additionally, the parameters of this model are adjusted to the parameters of a real life patch array and observed for similar mutual coupling behavior.

Chapter 1

Introduction and Background

1.1 Motivation

Highly digital phased array radars are growing in demand due to their increased capabilities over typical mechanically steered radars. Such benefits include electronic beam steering and element level flexibility. One such radar being developed by the Advanced Radar Research Center (ARRC) is the Polarimetric Atmospheric Imaging Radar (PAIR), expected to be implemented in 2022 [1]. However, arrays such as these operate at different temperatures, operate across a somewhat wide band of frequencies, and can be subject to circuitry and mechanical errors. These in turn can affect the phases and amplitudes of each array element, which ultimately impacts the accuracy of the data obtained. Because of this, a phased array needs to be calibrated prior to operation, and repeatedly calibrated over a period of time to ensure that these errors are minimal.

A phased array is calibrated when the relative phases between the elements are both controlled and well known. A typical calibration method begins with measuring the amplitudes and phases for each array element and then measure in transmit and receive modes. This process is repeated for each frequency and temperature that the array will be in use for. Lastly, these measurements must be repeated periodically,
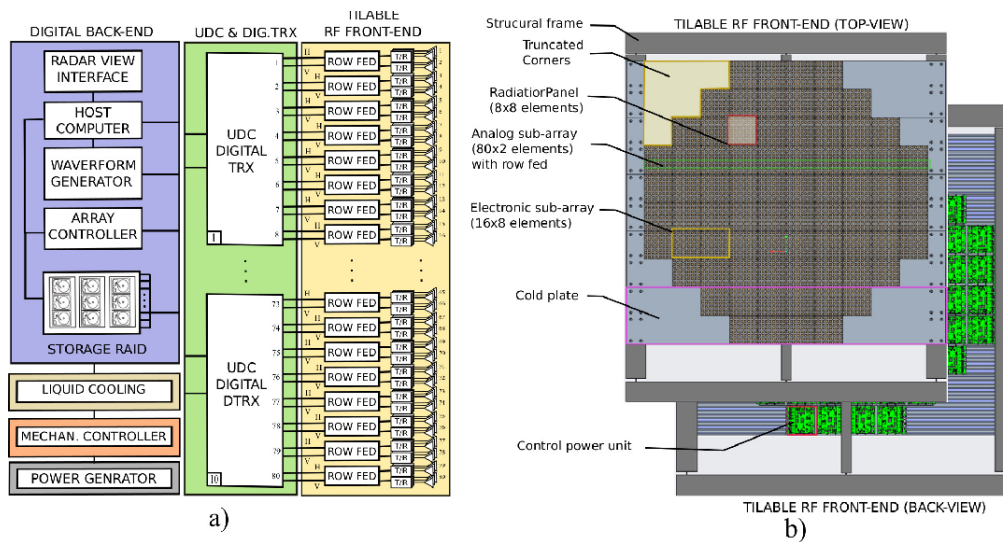
Figure 1.1: Simplified array architecture of Polarimetric Atmospheric Imaging Radar (PAIR) [1]

as the element phase amplitudes vary due to differences in temperature, circuitry and mechanical errors [2].

1.2 Calibration Methods

This section will briefly discuss the calibration methods used for phased array radars. The first, most common calibration method involves scanning in a near field chamber with a probe antenna [3]. This is considered the most reliable method, but is known to be complex and time consuming and not feasible for in situ calibration due to the need for a near field chamber [4]. Another method involves probes affixed to the peripherals of the phased array [5], [6]. While this method is beneficial for in situ calibration, an initial calibration is required for this method to work.

The calibration lines method uses transmission lines connected to each antenna array element [7]. Again, an initial calibration is required for this method to work. This method also increases the array aperture.
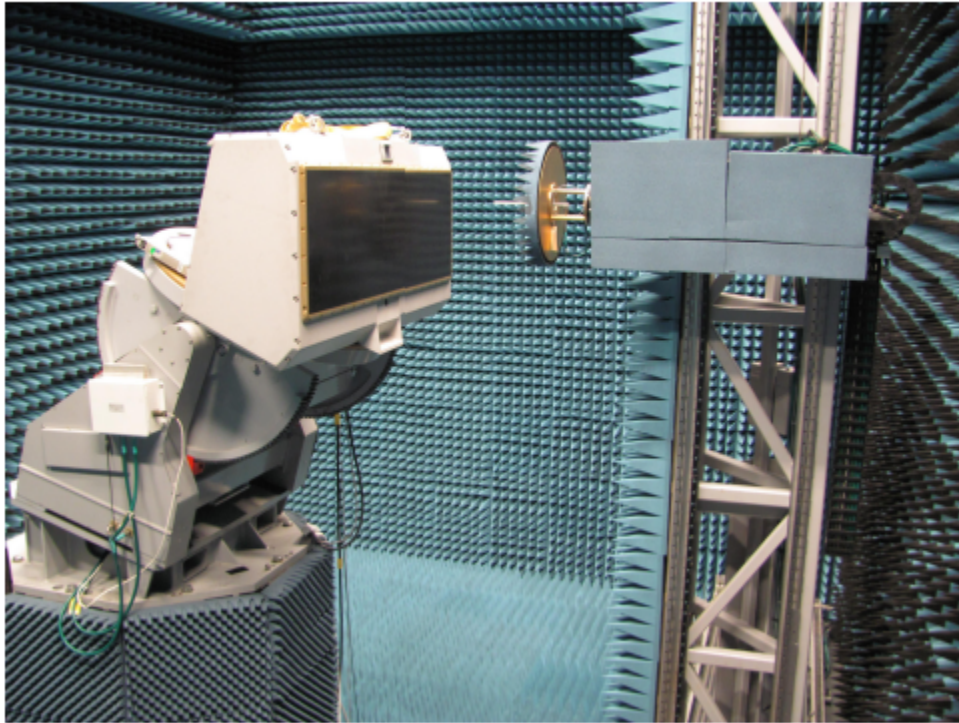
Figure 1.2: Antenna array calibration using a near field chamber [4]
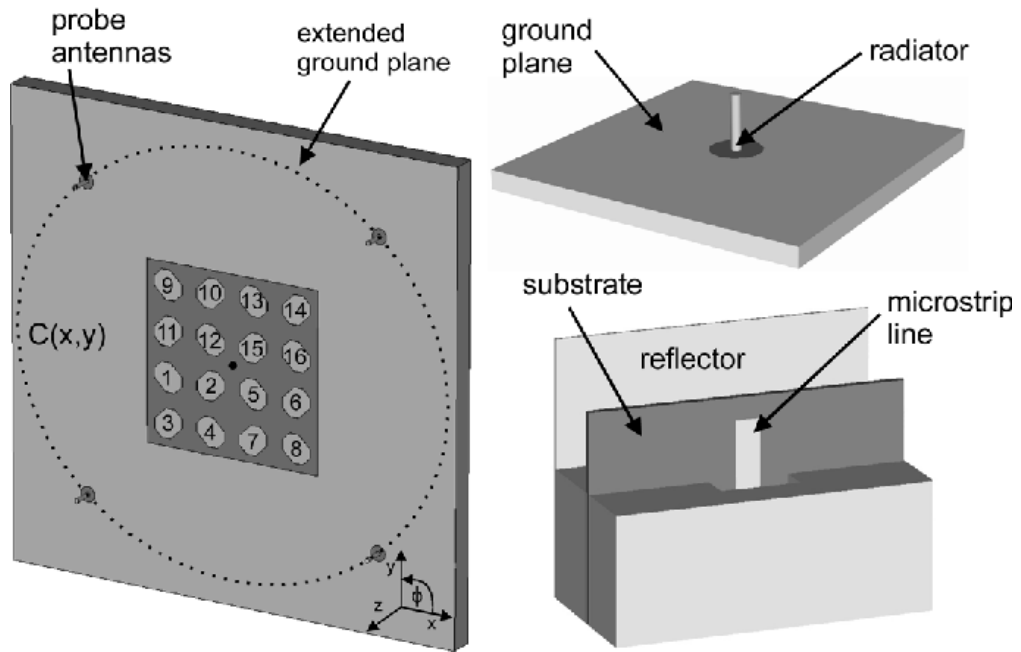
Figure 1.3: Calibration via peripheral probes [5]
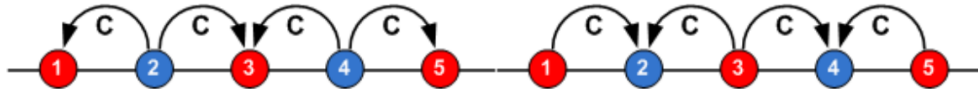
Figure 1.4: Mutual coupling calibration of a linear array for the receive (left side) with even elements (blue) being used and transmit (right) with odd elements (red) being used [4].
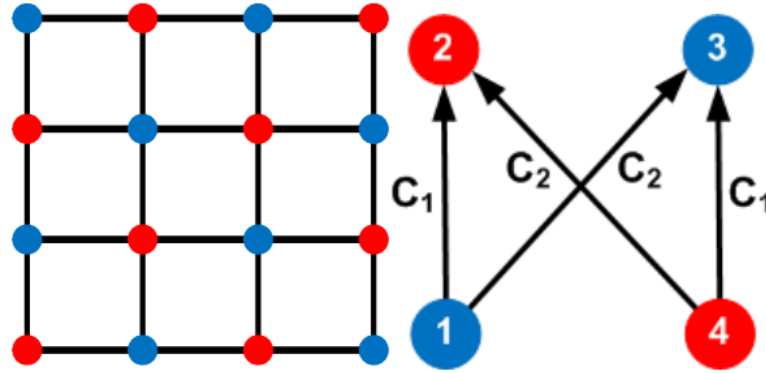
Figure 1.5: Mutual coupling calibration of a square array with elements 1 and 4 transmitting and elements 2 and 3 receiving, which calibrates the elements relative to each other [4].

The primary calibration method that will be discussed in this thesis is calibration via mutual coupling. All previously discussed calibration methods require some sort of initial chamber set up. This requirement makes these methods not feasible for airborne, spaceborne and mobile applications.

Calibration by mutual coupling is accomplished by using the mutual coupling of an array element to measure the phases and amplitudes of the other array elements [8], [4], [9], [10]. While this method does not require the use of a near field chamber, or any additional hardware, it requires that the mutual coupling between antenna elements to be suitable. If an unsuitable mutual coupling pair is chosen, the calibration can be extremely sensitive to the slightest changes of the array setting, such as temperature or cable movement. These errors then are difficult to eliminate.
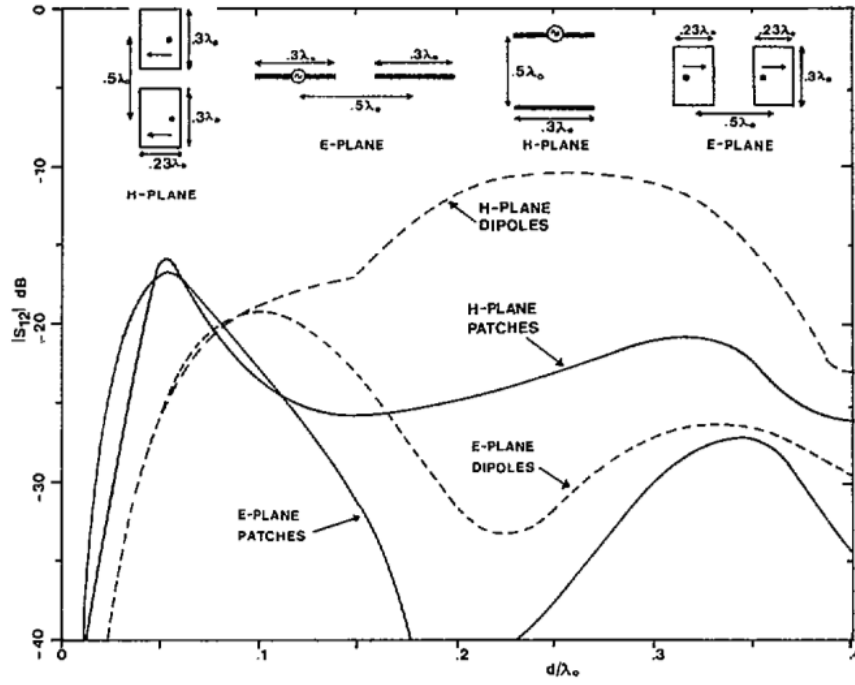
Figure 1.6: Patch antennas interacting with each other causing mutual coupling Drops [11]

1.3   Patch Antenna Arrays and Mutual Coupling

Patch antennas are low profile and planar, which means that they can be implemented in a large phased array antenna with ease. Unfortunately, patch antennas themselves have issues that can be amplified when placed in close proximity with each other in the form of arrays.

In an array, mutual coupling between element pairs should be equal to each other if the elements are equally spaced apart, and determining which mutual coupling pairs to use for calibration should theoretically be trivial. However, the effects of patch antennas can randomly cause the mutual coupling between certain elements to drop drastically. These elements are those unsuitable for array calibration.

Patch antenna arrays have effects which impact the mutual coupling between the

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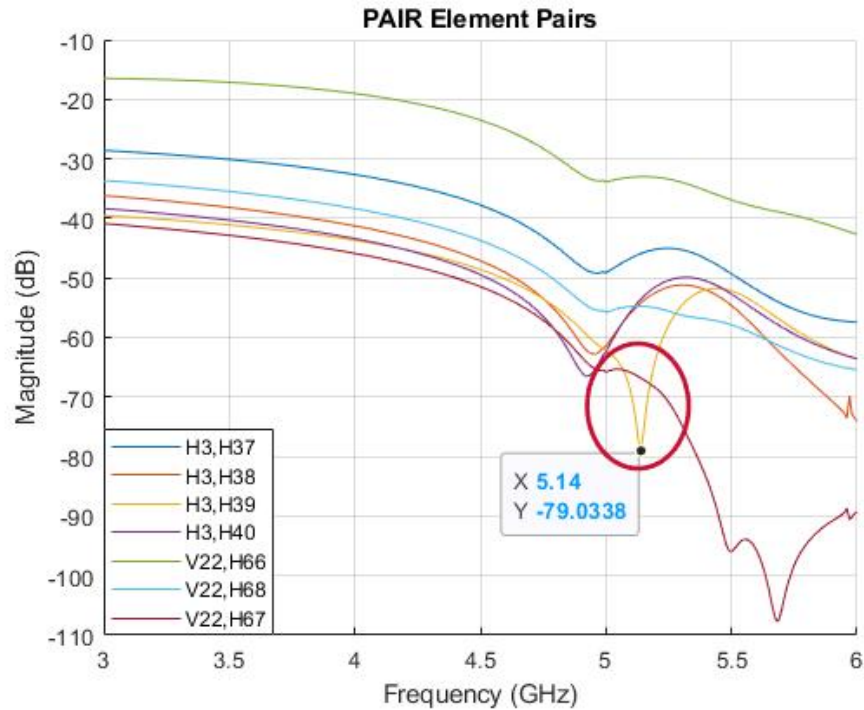
Figure 1.7: PAIR mutual coupling plot

array elements. A single patch antenna will generate surface waves due to the substrate and free space waves. The mutual couplings between the elements of a patch antenna array will suffer due to the interactions between the waves that are generated by each antenna. The result can create complications in the mutual coupling between element pairs.

The Polarimetric Atmospheric Imaging Radar [1] demonstrates these types of trends in mutual coupling, as evidenced by the given plot of mutual coupling. Sudden drops in mutual coupling are visible at multiple points on the plot. In particular, the coupling drop between elements H3 and H39 at frequencies 5.1 to 5.2 GHz is circled. These minima represent mutual coupling pairs that are unstable, and should not be used for array calibration. A 2-D mutual coupling plot of H3 and all other array elements is shown in Figure 1.8, which further shows the sharp change in mutual coupling behavior at H39.

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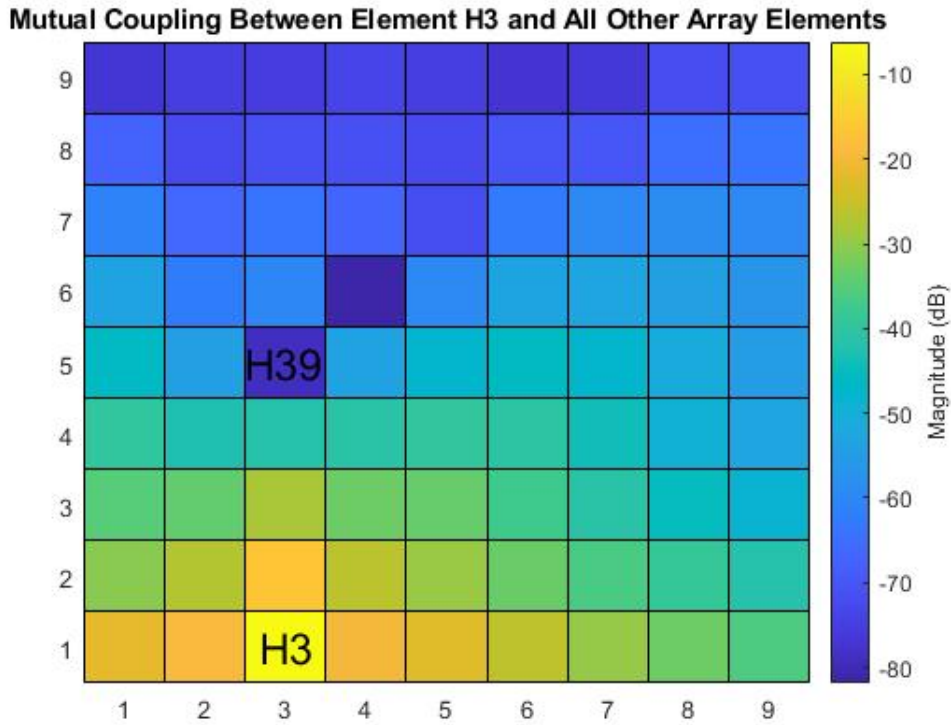
Figure 1.8: 2D mutual coupling view between H3 and all other pairs at 5.14 GHz for PAIR

These minima in mutual coupling are not predictable for each array. The surface waves and free space waves interact at random. This will make the mutual coupling pairs for each phased array different. The optimal solution would be to have the S-Parameters for the array already obtained, and modify the calibration algorithm to account for these mutual coupling anomalies. A mutual coupling algorithm can be programmed to detect and avoid unstable mutual coupling pairs [12], [13].

1.4 Simulation and Modeling of Array Mutual Coupling

As previously discussed, an indicator of an unsuitable mutual coupling pair is present in the form of sharp minima in a mutual coupling magnitude plot. However, obtaining
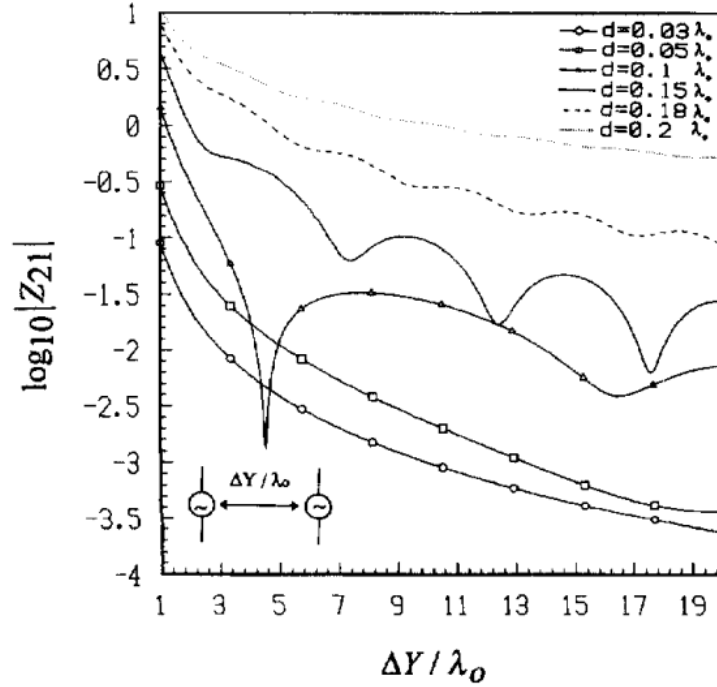
Figure 1.9: Mutual coupling example [14]

the S-Parameters of large, complex antenna arrays is often difficult and time consuming due to a number of factors.

Highly digital antenna arrays in practice are sizeable and complicated in structure, especially those with dual polarization capabilities. Typically, S-Parameters of these arrays are obtained through physical measurements or full wave simulations. If a physical rendition of such an array exists, its S-Parameters can be measured and used. Otherwise, such an array can be constructed and simulated in an electromagnetic solver such as ANSYS HFSS, Altair FEKO, or CST Microwave Studio. While differing in solving methods, these solvers provide accurate S-Parameter data over a frequency sweep input by the user.

HFSS uses a finite element method to solve structures. This method creates a tetrahedral mesh of the structure and then employs this finite element method to solve for the fields based on the partial differential forms of Maxwell's equations. An HFSS sim-

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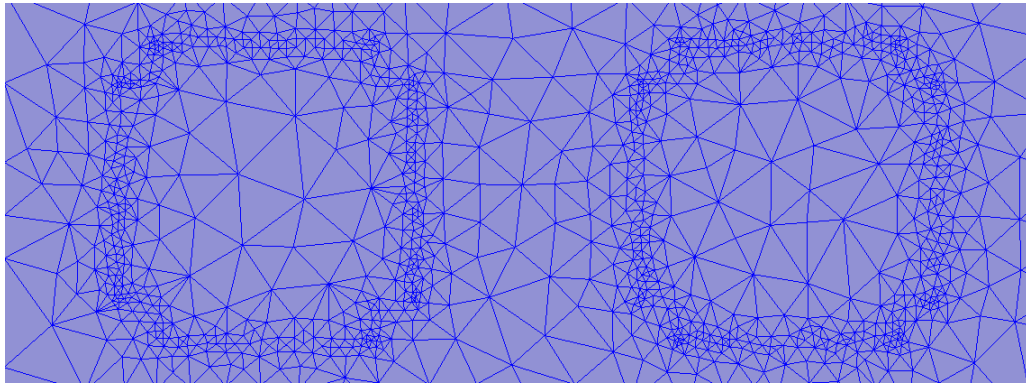
Figure 1.10: View of a converged HFSS mesh on two PAIR antenna elements

ulation is complete when it is converged. The HFSS convergence criteria is set by the user. For this case, it is determined by the max delta S. Delta S is defined as the maximum change in S-Parameter magnitude between two successive passes. If the Delta S is not achieved on an adaptive pass, the solver will increase number of mesh elements by subdividing the mesh in areas with the solution error and repeat the simulation. This procedure will repeat until converged, or if the maximum number of passes, also input by the user, is reached [15]. This can result in structures with a great number of mesh elements to solve, as depicted in Figure 1.10.

While FEKO primarily uses Method of Moments. This means that only the structure will be meshed, as opposed to HFSS which will mesh both the structure and the space surrounding it. Method of Moments will take a surface current model mesh used for a structure and solve for fields using the integral forms of Maxwell's equations. This type of solver can use less memory due to its use of basis functions.

While these electromagnetic solvers provide accurate data, they have limitations. Large, complex structures being simulated will require a great amount of computational power and memory. An insufficient amount of either of these will impair simulation progress.

In some work environments, another solution is to run these simulations on a cluster.
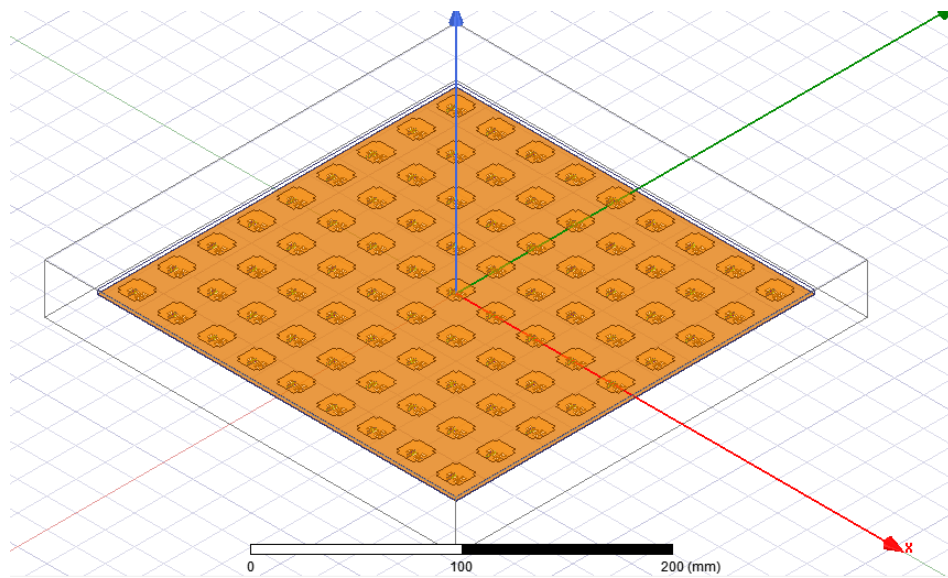
Figure 1.11: PAIR, a 9x9 patch antenna array, as modeled in HFSS

A simulation cluster is set of servers/computers which work together as a single entity. This means that the amount of RAM available is greatly increased. While this is useful, there are limitations to a cluster. A work environment will have one cluster shared by many employees. As such, in an environment where there is a demand for multiple simulations cluster access could be limited by the demand for it, meaning that if many people require the use of a cluster, one's experiment may be limited by wait times. Additionally, even with access to much RAM, this does not always solve the issue of simulation time. To demonstrate this, a cluster was used to simulate the Polarimetric Atmospheric Imaging Radar (PAIR) in HFSS. This simulation was completed with a frequency sweep of 81 points and a max delta S of 0.02. This also used the most basic parameters of the cluster; more nodes can be used, but does not guarantee that the simulation will converge quicker. Additionally, the cluster is utilized by other people which can limit the number of nodes that one person can use.

The simulation data, meaning the information for the amount of time for the simulation to complete for this array, was obtained and pictured in 1.12.

Figure 1.12: Total elapsed time for PAIR simulation to complete in HFSS

Figure 1.13: HFSS mesh data for PAIR

From the data in Figures 1.13 and 1.12 it can be concluded that even with a simulation cluster, a high mesh simulation can be time consuming. Additionally, work clusters are typically have more than one user. As such, the speed of the simulation could also depend on who requires use of this cluster. Ultimately, these methods employed are costly and laborious. There is a need for faster array modeling that can generate the mutual coupling behavior observed in patch arrays. These in turn can be used to test and refine mutual coupling calibration algorithms. Such an array model must avoid the complications that come with the electromagnetic solvers. This can be achieved by using simple calculations of crossed dipole antenna arrays combined in parallel.

1.5 Parallelization by Y-Parameters

For the crossed dipoles to usefully mimic the effects of patch antenna array mutual coupling for developing calibration algorithms, multiple dipole arrays can be parallelized to simulate the effects of surface waves and other complex coupling mechanisms. In this work, this is done by combining a crossed dipole array radiating in free space with a crossed dipole array radiating in a dielectric whose constant is selected to tune to the effects of patch antenna arrays.

The crossed dipoles will be combined in parallel following simulation of the MATLAB model for a crossed dipole array of free space, and a crossed dipole array set in dielectric. The model exports the S-Parameters of crossed dipole arrays in files. To parallelize the arrays, the S-Parameters for each array must be converted to Y-Parameters. Conversion to these parameters will simplify the math required for the arrays.

Conversion to Y-Parameters will mean that the combination of arrays is achieved by summing the Y-Parameter files together. If the S-Parameters are converted to Z-Parameters, the combination in parallel is achieved through equation 1.1, where n is the
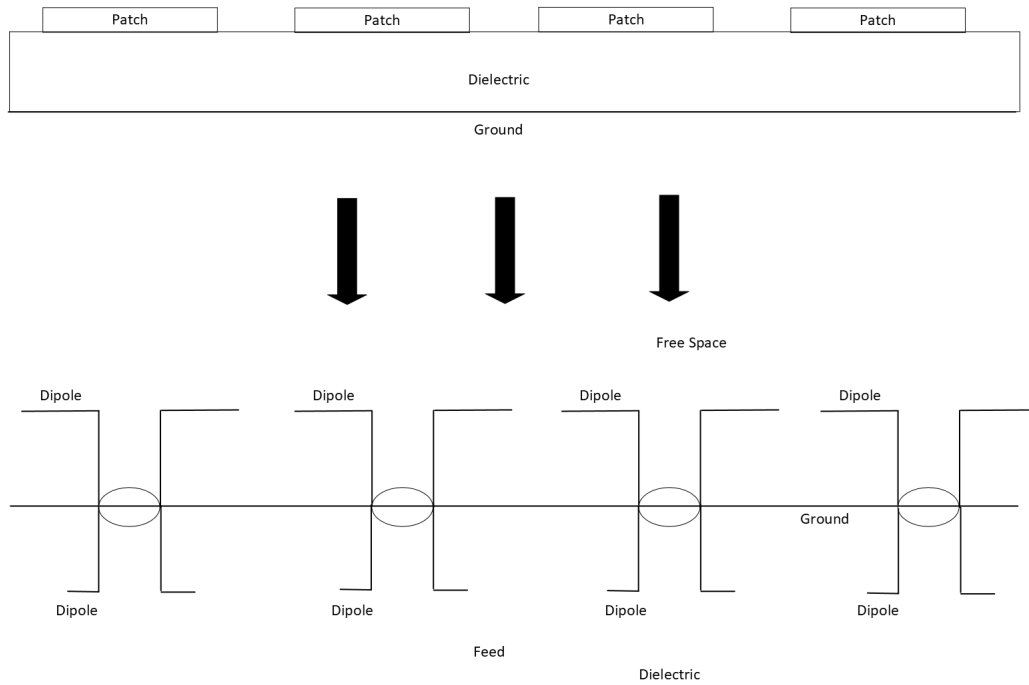
Figure 1.14: The dipole array being equivalent to a patch antenna array

total number of Z-Parameter files. This is slightly different in that there is no conversion to Y-Parameters, but is also a valid method of combination.

$$\frac{1}{Z_{total}} = \frac{1}{Z_1} + \frac{1}{Z_2}... + \frac{1}{Z_n} \tag{1.1}$$

The waves radiated by the dipoles in dielectric will interact with the radiated waves of the dipoles free space, either constructively or destructively. These interactions can cause drops in mutual coupling between antenna array elements which can mimic the mutual coupling effects observed in patch antenna arrays.

1.6 Research Objective

MATLAB can be used to simplify large, complicated antenna arrays. The purpose of this thesis is to analyze the models of antenna arrays created in MATLAB to generate

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S-parameter files that can ultimately mimic the mutual coupling effects of an actual patch antenna array.

1.7   Research Significance

These files, generated from this MATLAB model, can then be used to build and refine mutual coupling calibration algorithms. With this method in hand, those building mutual coupling calibration algorithms can utilize more time working on those algorithms, rather than obtaining S-Parameter files.

1.8   Thesis Outline

The first section of this thesis discusses the different methods of patch modeling, and then describes MATLAB array model. The second section is of simulation outputs from the MATLAB model. First, a 5x5 array is simulated to test basic functionality. Then, an 8x8 array is tested to best match the size of a real life patch array. Both of these MATLAB array results are compared to those from full wave solvers. Once this is achieved, MATLAB simulations will then be adjusted to those of a real life patch antenna array to ensure that this model is still functional even with patch array parameters. Finally, the goals of this research will be reiterated and future work will be discussed.

Chapter 2

Mutual Coupling Model

2.1 Modeling Patch Antenna Arrays

2.1.1 Patch Antenna Overview

Patch antennas are low profile, versatile antennas used for a variety of applications. Inexpensive and simple to manufacture, a patch antenna consists of a very thin conductive strip set over a substrate of a certain thickness and over a ground plane. There are also a number of methods to feed patch antennas. The fact that patch antennas are simple and cost effective makes them ideal for creating phased arrays. However, there are issues that impact overall performance which must be examined prior to their implementation.

Firstly, patch antennas are lossy and low bandwidth. These effects are more pronounced at higher frequencies, as demonstrated by the effect of the loss tangent of the substrate. One way to combat this is to increase the substrate thickness [16] but these can lead to the increase in surface waves. As discussed in Chapter 1, surface waves interacting with each other can cause sudden drops in mutual coupling which in turn can affect calibration algorithms using mutual coupling pairs. As such, it is important to consider the MATLAB model to best predict these mutual coupling drops while
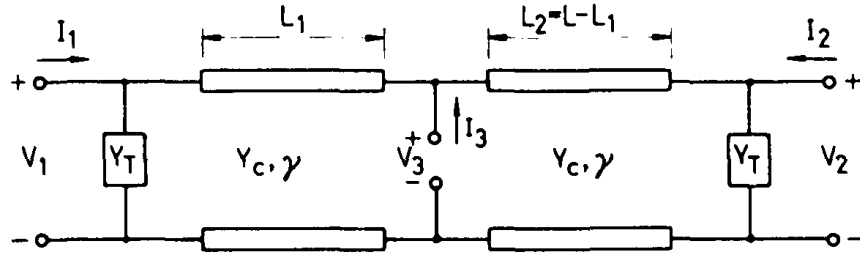
Figure 2.1: Patch antenna modeled as a 3 port transmission line from [17]

attempting to improve radiation efficiency.

Although easy to fabricate, patch antennas are difficult to model mathematically. There are multiple different modeling methods, each with their own benefits and drawbacks. This makes simulation in an environment like MATLAB complicated.

The two patch modeling methods first introduced in this chapter will be the transmission line model and the cavity model. Each of these will be discussed explain why they are not ideal for simulating mutual coupling between patch antenna elements in a simple manner.

2.1.2 The Transmission Line Model

The first model being discussed is the transmission line model. Primarily highlighted in [17], the transmission line model decomposes the patch antenna into a simple three port model shown in the figure. This model is used to generate an admittance matrix. The input admittance can be determined as long as there is a single feed point for a patch antenna.

$$Y_{in} =$$
$$2Y_c[\frac{Y_c^2 + Y_s^2 - Y_m^2 + 2Y_sY_ccoth(\gamma L) - 2Y_mY_ccsch(\gamma L)}{(Y_c^2 + Y_s^2 - Y_m^2)coth(\gamma L) + (Y_c^2 - Y_s^2 + Y_m^2)cosh(2\gamma \Delta)csch(\gamma L) + 2Y_sY_c}]$$

$$(2.1)$$
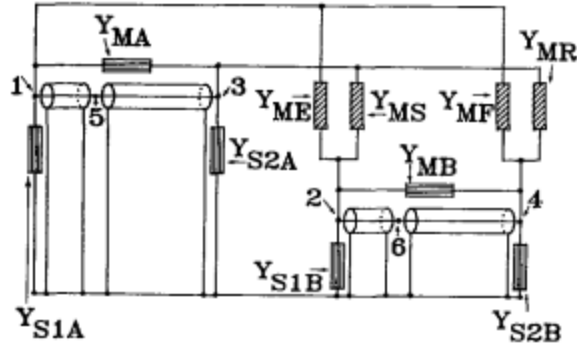
Figure 2.2: Mutual coupling as modeled with a transmission line model [18]

Y_c is the characteristic admittance of the microstrip line of the patch, Y_m is the mutual admittance, Y_s is the self admittance, $\gamma = \alpha + j\beta$, and L, L_1, and L_2 are as defined in 2.1.

The transmission line model has its benefits for a single patch antenna. However, the patch antenna modeled using the transmission line assumes a microstrip feedline, which may not be the case for all patch antenna simulations. Additionally, this model struggles with accurately depicting mutual coupling [18].

2.1.3   The Cavity Model

The cavity model is another well known method of modeling patch antennas. This considers the perimeter of the patch antenna as magnetic walls of a cavity, with the fields inside the antenna as different modes.

The cavity model also struggles with modeling mutual coupling between patch antennas. While it has been achieved in some cases [20], the restrictions that the cavity model does not make it an efficient method for modeling mutual coupling effects from patch antenna arrays.
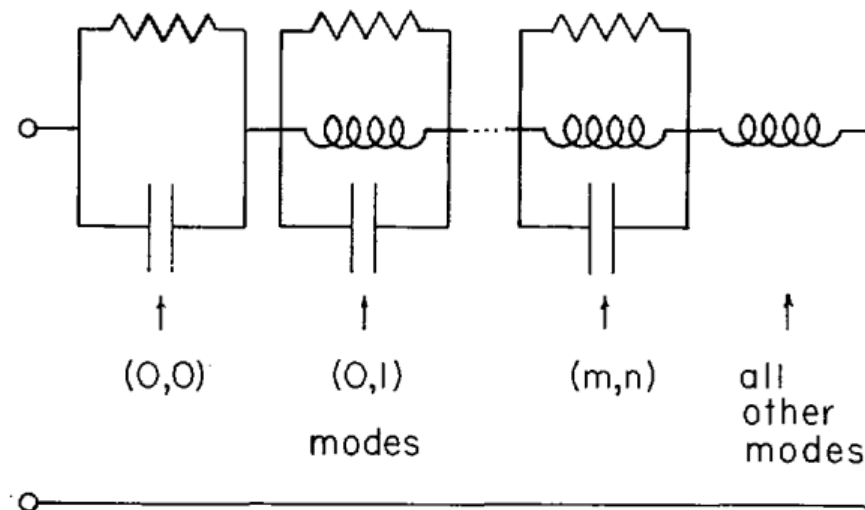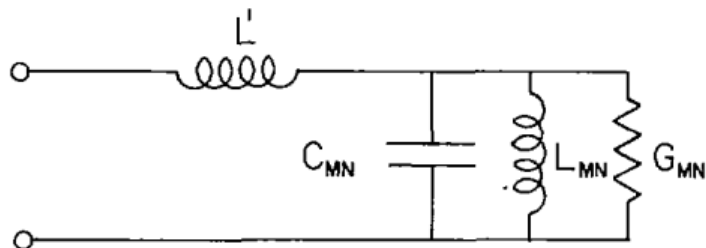
Figure 2.3: Patch antenna modeled as a cavity from [19]
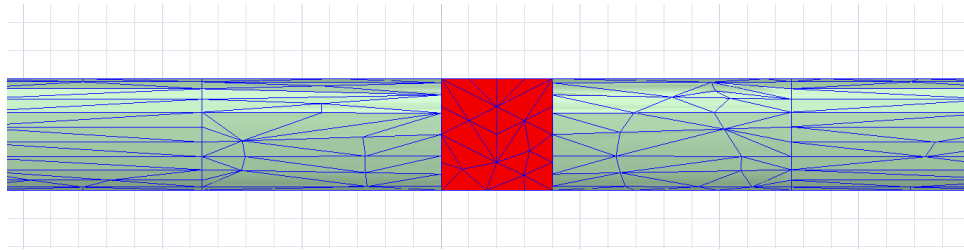
Figure 2.4: FEM mesh created on a dipole, viewed at feed point

2.2 Full Wave Electromagnetic Solvers and Numerical Methods

Full wave electromagnetic solvers yield the most accurate patch antenna data when compared to the transmission line and cavity models [16] Two of the methods employed by full wave electromagnetic solvers are the Finite Element Method (FEM), used by HFSS and Method of Moments (MoM), used by FEKO.

FEM creates a mesh of the model to be solve and divides it into smaller elements. Using these smaller elements, the differential forms of Maxwell's equations can be used to solve for the fields. From this, other parameters can be calculated.

MoM employs the integral forms of Maxwell's equations in the frequency domain to solve for current and charge density of a structure [16]. This method does not discretize the area around the structure in addition to the structure, like FEM does. As such, this, along with the usage of basis functions, allows for FEKO to simulate faster than HFSS with at the cost of accuracy. Additionally, FEKO models multilayered dielectric media through planar Green's functions on an infinite plane with finite thickness, which is used in chapter 3 when FEKO simulations are needed.

The full wave solvers can accurately depict patch antennas over a time consuming process. To expedite the process to obtain mutual coupling data, mathematical models can be employed. However, the math to model patch antennas accurately ultimately involves the use of Green's function. While there have been many successes in

$$T_m = k_2 \cos(k_1 h) + j k_1 \sin(k_1 h)$$

$$T_e = k_1 \cos(k_1 h) + j k_2 \sin(k_1 h)$$

$$\tilde{G}_{xx} = \frac{-j}{\omega \varepsilon_0} \left[\frac{k_x^2 k_1 k_2 \sin(k_1 h)}{\beta^2 T_m} + \frac{k_y^2 k_0^2 \sin(k_1 h)}{\beta^2 T_e} \right]$$

$$\tilde{G}_{xy} = \frac{-j}{\omega \varepsilon_0} \left[\frac{k_x k_y k_1 k_2 \sin(k_1 h)}{\beta^2 T_m} - \frac{k_x k_y k_0^2 \sin(k_1 h)}{\beta^2 T_e} \right]$$

$$\tilde{G}_{yy} = \frac{-j}{\omega \varepsilon_0} \left[\frac{k_y^2 k_1 k_2 \sin(k_1 h)}{\beta^2 T_m} + \frac{k_x^2 k_0^2 \sin(k_1 h)}{\beta^2 T_e} \right]$$

$$\tilde{G}_{yx} = \tilde{G}_{xy}$$

Figure 2.5: Example of Green's functions used to solve for the fields for a rectangular patch antenna [21]

numerically modeling patch antennas [21] and subsequent patch arrays [22], [23] the complexity of the math does not provide a quick solution for those in need of mutual coupling data for calibration algorithms.

Figure 2.5 gives an example of the Green's functions required to solve for a single rectangular patch antenna, where h is the the substrate height, ω is the radial frequency, $\beta = \frac{2\pi}{f}$, ε_0 the permitivity constant, and k_1, k_2 are propagation constants. This demonstrates that numerically modeling multiple patches will be complex and challenging.

2.3 A Simplified Dipole Array Model

While modeling patch antennas themselves through algorithms is complex and time consuming, there exists a simple numerical method which can model patch antenna like mutual coupling data. This can be found in the form of crossed dipole arrays combined in parallel. By modeling crossed dipoles instead of patches, the induced EMF method
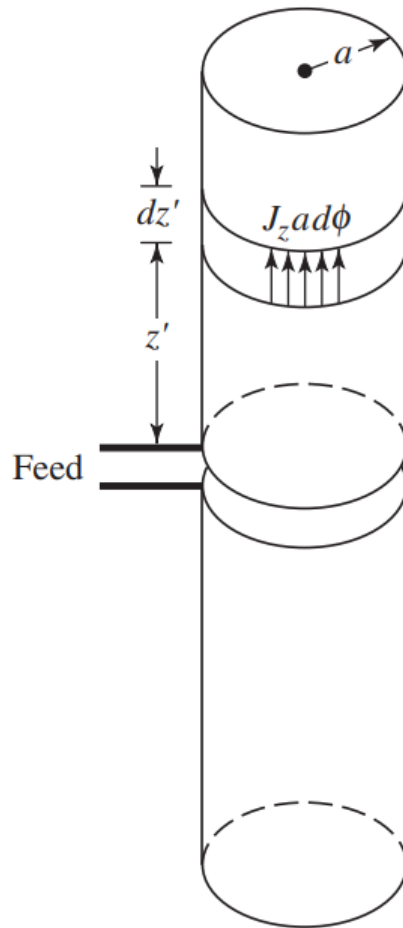
Figure 2.6: Visualization of Induced EMF Method from [16]

can be employed for S-Parameters, which dramatically reduces the complexity of the math.

The induced EMF method is a strategy used to calculate the self and mutual impedances of a dipole antenna. This method provides closed form solutions for single dipoles [16] and as such is used for this instance for simple dipole models. For its use in any application, the near field of the dipole must first be calculated.

The Induced EMF Method assumes an infinitesmal dipole. This assumption comes from the determination of the near fields when obtaining the E field of an infinitesmal

dipole [16].

While a very small radius wire dipole is difficult to achieve in practice, a wire radius can be made to be reasonably small in the MATLAB model. Once the near field of these dipoles are calculated, the self and mutual impedances can be calculated. To obtain these, near field is used to calculate the input impedance, assuming a uniform current distribution along the wire. The products are calculated when the current density is at a maximum, yielding equations 2.2 and 2.3 [24], [25].

$$R_{ant} = \frac{\eta}{2\pi sin^2(\frac{kL}{2})}[\gamma_e + ln(kL) - C_i(kL) + \frac{1}{2}sin(kL)[+Si(2kL-$$
$$2S_i(kL)] + \frac{1}{2}cos(kL)[+C_i(2kL) - 2C_i(kL) + \gamma_e + ln(kL)]] \quad (2.2)$$

$$X_{ant} = \frac{\eta}{2\pi sin^2(\frac{kL}{2})}[+S_i(kL) + \frac{1}{2}cos(kL)[-S_i(2kL) + 2S_i(kl)]+$$
$$\frac{1}{2}sin(kL)[C_i(2kL) - 2C_i(kL) + C_i(2k\frac{a^2}{L})]] \quad (2.3)$$

L is the dipole length, a is the dipole antenna radius, η is the impedance of the array medium, either free space or through a dielectric, γ_e is 0.57721566 , $k = \frac{2\pi}{\lambda}$, and C_i and S_i represent cosine and sine integrals respectively. These are written as

$$C_i = \int_0^x \frac{cost}{t}dt \quad (2.4)$$

and

$$S_i = \int_0^x \frac{sint}{t}dt \quad (2.5)$$

The results of 2.2 and 2.3 are used to populate the Z matrix. Once this Z matrix is complete, it can be used to calculate S-Parameters and as such, mutual coupling.

2.4 Mutual Coupling MATLAB Model

The MATLAB model used in this case has a variety of parameters used to tune the crossed dipoles to best fit the antenna array of patches. It is important to note that the crossed dipoles are used to account for the dual polarization of the patches. Were these patches single polarization, then the array would simply be an array of dipoles. The most important parameters of the MATLAB model are discussed below.

- Dipole length - the length of the dipoles are set to the desired resonant frequency. For example, for a patch antenna array operating at 3 GHz, the dipole lengths would be tuned to be resonant at 3 GHz. This is following the equation, where c is the speed of light, f is the desired frequency, and ε_r is the dielectric constant in which the dipoles are set.

$$l = 0.48 \frac{c}{f\sqrt{\varepsilon_r}} \tag{2.6}$$

  These dipoles will also change in size depending on the dielectric constant.

- Dielectric constant - this is the medium in which the crossed dipole array is set. This is not the same as the patch antenna substrate. The value in that case must be between one and two to effectively match the crossed dipole array. For initial simulations, however, actual dielectrics are used: RO4350B and RO5880.

- Ground plane distance - the distance from the ground plane to the dipoles must be kept at least a quarter wavelength through the dielectric. Any shorter distance will cause the dipoles to not adequately radiate due to the interactions between the antennas and the ground plane.

- Spacing - the spacing between the antennas must be set equal to that of the distance between the microstrip patches. For example, if the distance between

patches of an actual antenna array is 25 mm, then the spacing between the crossed

dipole arrays must be set to 25 mm.

- Dipole radius - the induced EMF method operates on the assumption that the dipole wires are very thin. While creating an infinitely small radius dipole in software is difficult, setting the radius to a very small value is feasible. This value is set to 0.0002 meters for all simulations, and it is not changed.

- Other model parameters - There are other parameters in this array model that should be considered when simulating, but will not necessarily keep the arrays from mimicking a patch antenna array. Parameters such as number of segments for these dipoles, which can refine the results but also impede the simulation time due to giving the software more to solve.

2.5 Calculation of Crossed Dipole Array Coupling in MATLAB

The user inputs the desired parameters outlined above. The user can also choose the number of segments in each dipole. This allows for more accuracy but also slows the simulation time, so it is important to consider the number of segments when running the simulation. The start and stop frequencies are input by the user in addition to the number of frequency points. This information will be used to carry out a frequency sweep. Again, while more frequency points makes plots smoother and allows for more data to work with, it will also slow the simulation. The user will then input the desired dielectric constant for the first simulation. Once these parameters are set, the simulation can be run.

The simulation will begin by displaying the array of crossed dipoles of the set size, so the parameters can be checked. The simulation will then create self impedance
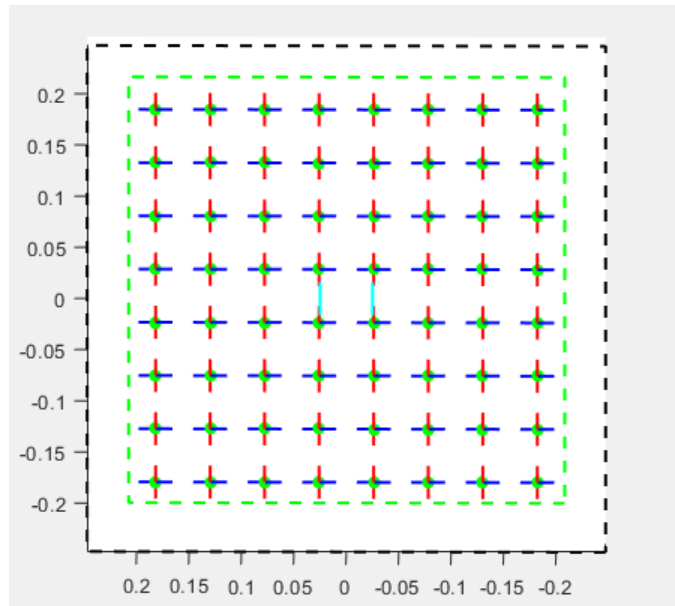
Figure 2.7: The array of crossed dipoles as displayed by the MATLAB simulation

according to the induced EMF method, using the dipole lengths and the wave number
to calculate. Using the self impedance, the Z-Matrix of the array is populated with
values. This is done for horizontal and vertical coupling values, providing the dual
polarization. An additional line is used to convert the Z-Matrix into S-Parameters,
and both the S-Parameters of the array and the Z-Matrix are output into separate files.
The MATLAB model lastly outputs the total time elapsed since the beginning of the
simulation.

This simulation must be repeated at least twice to obtain the desired files: first for
free space, second for the dielectric.

Once the parameters are converted to Y-Parameters, these parameters are summed,
and then converted back to S-Parameters. This new S-Parameter combination will be
exported to a file which can be used for plotting.
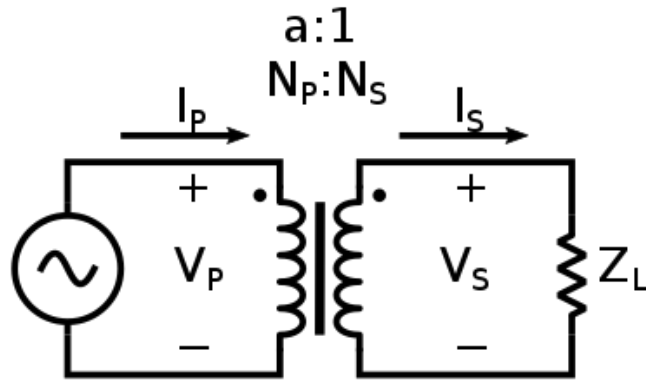
Figure 2.8: An ideal transformer, from [26]

2.6 Parallelization by Ideal Transformers

In some cases parallelization by Y-parameters is not sufficient to demonstrate that the array can match to the appropriate frequency. To rectify this, ideal transformers must be implemented. This method considers a set of ideal transformers plugged into each element of each crossed dipole array. This will exist so to tune the antenna to the desired impedance of 50 Ohms and have more consistent matching to the input impedance of a patch antenna array.

The schematic in figure 2.9 demonstrates how the ideal transformers are supposed to interact with each antenna element. An ideal transformer is lossless with 100 percent efficiency. This is not a transformer that is implemented in any real life situation, and is as such optimal for these simulations. The ideal transformer can be used to transform a circuit from one impedance to another using equation 2.7.

$$Z'_L = a^2 Z_L \tag{2.7}$$

where Z'_L is the load impedance of the first circuit, Z_L the load impedance of the sec-
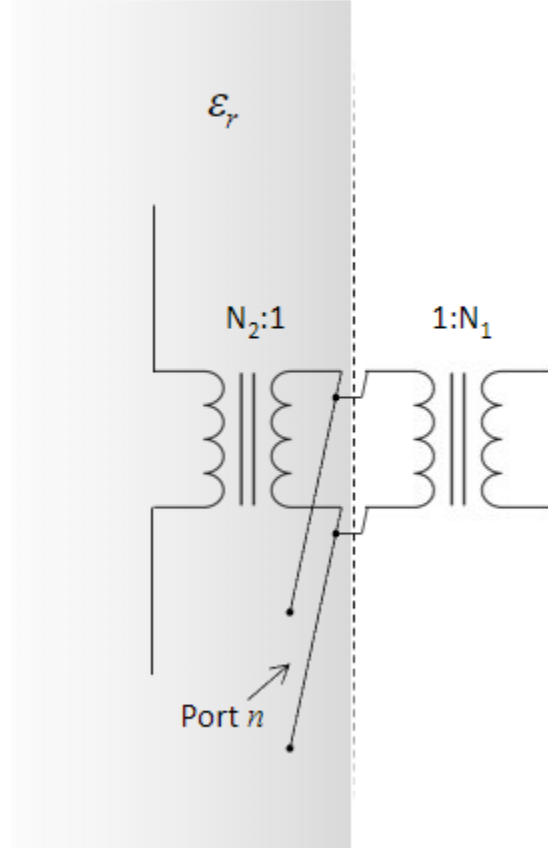
Figure 2.9: Example Schematic of Ideal Transformers with the Crossed Dipole Arrays

ond circuit, and *a* is the transformer ratio [26], which are different for both free space and dielectric constants. These transformers are mathematically implemented using equation 2.8.

$$Y_{total} = Ratio_{FreeSpace} * Y_{FreeSpace} + Ratio_{Dielectric} * Y_{Dielectric} \qquad (2.8)$$

The transformer ratios are tuned to best fit and match to the return loss parameters.

2.7 Summary

This section detailed the MATLAB model as modeled by crossed dipoles to best mimic a patch antenna array. Firstly, an overview of the typical patch antenna model equations were given to explain the difficulties with mathematical modeling. Secondly, the primary method to generate the S-Parameters of the array was discussed. The important model parameters were then outlined and discussed, and an overview of the model simulation was given. Finally, the method by which the crossed dipole arrays are parallelized was discussed using a conversion to Y-Parameters. However, sometimes simple conversion to Y parameters is not sufficient for combining these arrays in parallel. To rectify this, power combiners were discussed as an alternative, in addition to the concept of ideal transformers. These simple methods will reduce the time needed to obtain S-parameters of patch antenna arrays, because they will eliminate the immediate need for measured S-parameters or the need for EM solver simulations. Ultimately, the ideal transformers were considered as the simplest alternative to combining the crossed dipole arrays in parallel.

Chapter 3

Simulation Outputs

3.1   Simulating a 5x5 Array

The first set of simulations have been carried out to ensure that the MATLAB model is functional and can be comparable to the results from an electromagnetic solver.

Table 3.1 gives a list of parameters which were adjusted for this simulation. For this and future tables in this chapter, λ is wavelength, k_0 is propagation constant, c is the speed of light, and ε_r is dielectric constant.

Table 3.1: MATLAB Model Parameters for Array Simulation

Parameter	Value
Center Frequency	3 GHz
Dipole Length	$0.48 * c/(f\sqrt{\varepsilon_r})$
ε_r	3.66 (RO4350B), 2.2 (RO5880), 1 (free space)
k_0	$2\pi/\lambda$
Array Spacing	52 mm
Distance from Ground Plane	$\lambda/(4\sqrt{\varepsilon_r})$

The figure displays the layout of the array, for referencing of elements. First, a simulation was carried out for a crossed dipole array in free space. Next, a simulation was carried out for a crossed dipole array set in a dielectric. Both of these simulations used a frequency sweep of 1.5 to 4.5 GHz, with a resonant frequency of 3 GHz. The dielectric in this case was chosen to be RO4350B, as that is a typical dielectric used

5-H 30-V	10-H 35-V	15-H 40-V	20-H 45-V	25-H 50-V
4-H 29-V	9-H 34-V	14-H 39-V	19-H 44-V	24-H 49-V
3-H 28-V	8-H 33-V	13-H 38-V	18-H 43-V	23-H 48-V
2-H 27-V	7-H 32-V	12-H 37-V	17-H 42-V	22-H 47-V
1-H 26-V	6-H 31-V	11-H 36-V	16-H 41-V	21-H 46-V

Figure 3.1: 5x5 array layout with elements 21 and 15 indicated

for a microstrip patch antenna. Once both simulations were complete, the arrays were parallelized using the method stated in 2. The first element pair considered for the 5x5 array was the element pair 21 and 15.

The first figure demonstrates the mutual coupling from each individual antenna array, one in dielectric and the other in free space and then the two combined in parallel.

From this simulation it can be determined that there is a sharp drop in mutual coupling at 3.06 GHz. This demonstrates that the mutual coupling between these elements would not be ideal for array calibration. There is an additional drop in mutual coupling at 1.95 GHz.

To further observe this, 2D models of the array were created to observe the mutual coupling of one element between all other array elements. These were generated at the frequencies at which the mutual coupling drops were observed.

The mutual coupling between another array element pair was examined. This was simply to ensure that this model can be used for multiple element pairs, and that its
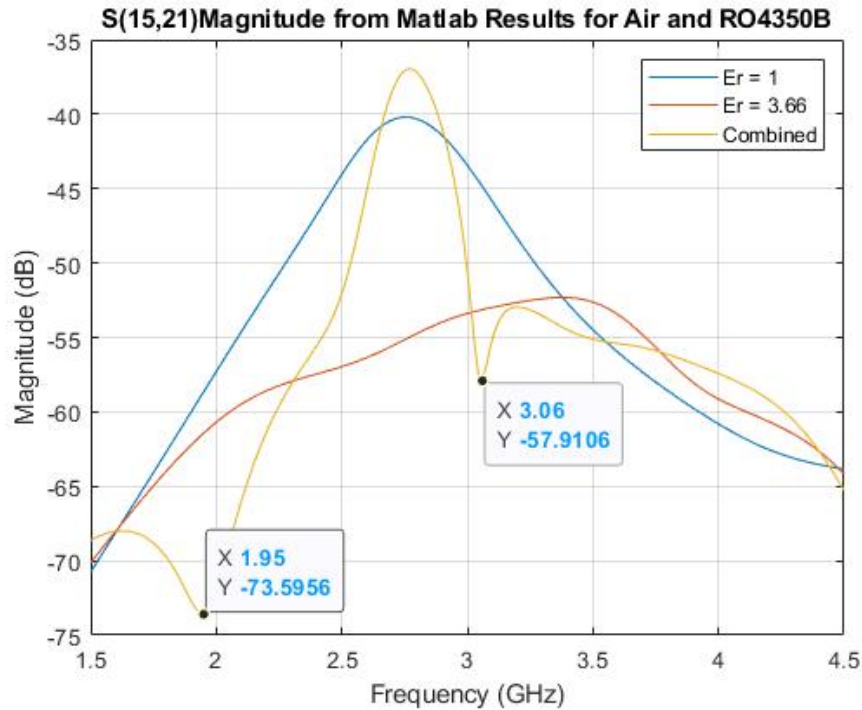
Figure 3.2: Elements 21 and 15 mutual coupling for RO4350B and air

success is not dependent necessarily on a single element pair. The next element pair was chosen to be elements 7 and 18. This is to demonstrate that the simulation maintains accuracy for element pairs at a different distance from each other.

The crossed dipole array in free space was also combined in parallel with the crossed dipole array set in a different dielectric– RO5880. This dielectric has a different constant to RO4350B, and it was important to ensure that this model is functional even with different dielectric constants. For this dielectric, the mutual coupling between elements 7 and 18 was considered.

According to the mutual coupling plot for elements 7 and 18, there are drops in mutual coupling at 2.91 GHz and 3.105 GHz. These are the spots where this element pair should not be used for mutual coupling calibration.

The simulation using RO5880 demonstrates a drop in mutual coupling primarily in
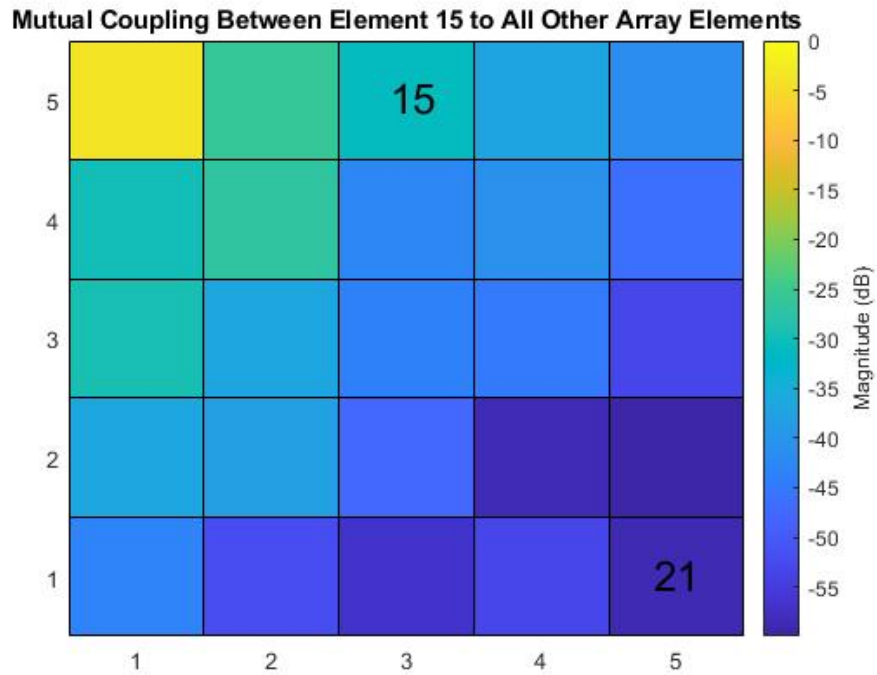
Figure 3.3: 2D mutual coupling between element 15 and all other array elements at 3.06 GHz for RO4350B and air

5-H 30-V	10-H 35-V	15-H 40-V	20-H 45-V	25-H 50-V
4-H 29-V	9-H 34-V	14-H 39-V	19-H 44-V	24-H 49-V
3-H 28-V	8-H 33-V	13-H 38-V	18-H 43-V	23-H 48-V
2-H 27-V	7-H 32-V	12-H 37-V	17-H 42-V	22-H 47-V
1-H 26-V	6-H 31-V	11-H 36-V	16-H 41-V	21-H 46-V

Figure 3.4: Array layout with elements 7 and 18 indicated

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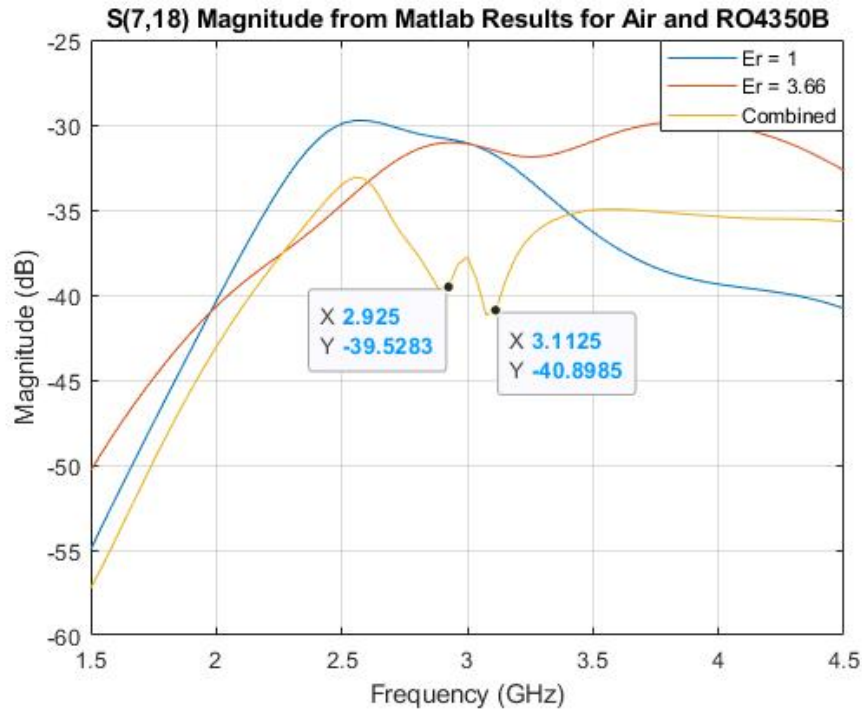
Figure 3.5: Mutual coupling between elements 7 and 18 For RO4350B and air

two locations. The first drop was at 2.28 GHz, and the second was at 2.73 GHz. In this case, it would not be ideal to use this mutual coupling pair at either of those frequencies.

2D models of the mutual coupling at the frequency drops were also generated for the air and RO5880 array combination.

A 5x5 array is one such large enough to demonstrate that this MATLAB simulation is sufficient for large antenna arrays, but can still be modeled in an electromagnetic solver without too many issues. To ensure that the MATLAB model is accurately predicting the mutual coupling for the crossed dipole array combinations, the MATLAB results must be compared to those from an electromagnetic solver.

FEKO is the first full wave electromagnetic solver employed. FEKO models a multilayer dielectric as 2D infinite planes with finite thickness, using planar Green's functions for calculations [27]. As the MATLAB model assumes an infinite dielectric,

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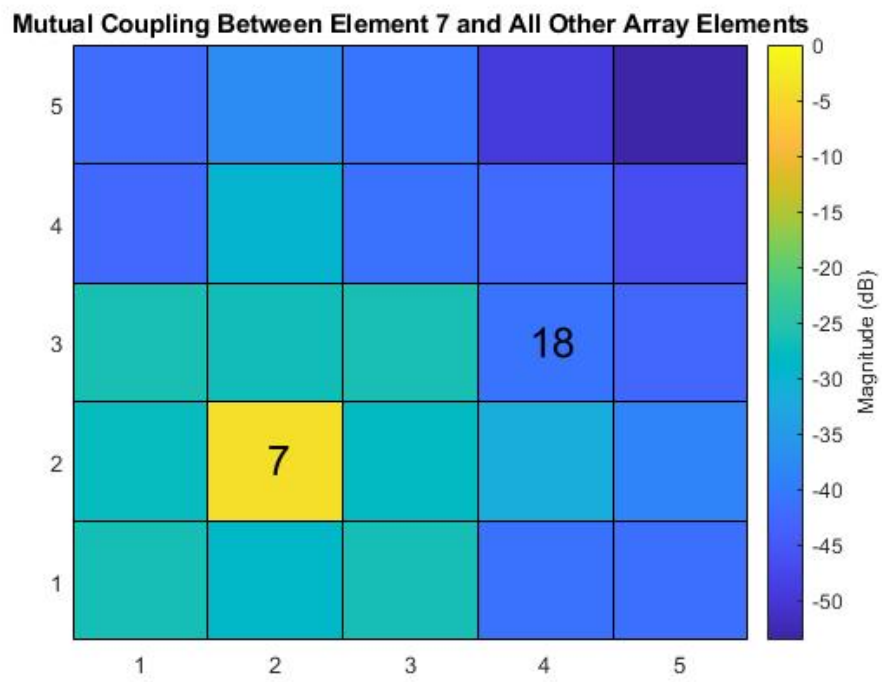
Figure 3.6: 2D mutual coupling between element 7 and all other array elements at 2.99 GHz for air and RO4350B
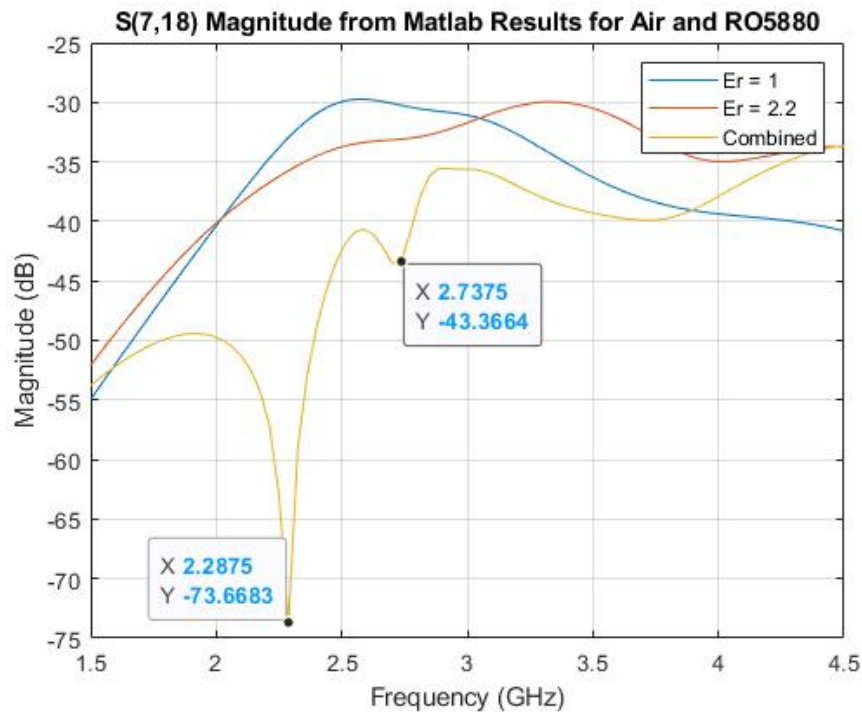
Figure 3.7: RO5880 comparison figure

FEKO results will be the closest to the MATLAB model.

However, HFSS must also be used to verify functionality. Because of how FEKO models dielectric layers, the dielectric itself will not be discretized and solved like it would in HFSS. This could cause issues regarding the accuracy of the dielectric itself. As such, simulations are also carried out using HFSS. The dielectric is modeled as a box of finite size surrounding the dipoles. The box cannot be of infinite size because HFSS meshes both the structure and the dielectric, which as established becomes increasingly demanding on computational memory with size.

First, the comparison between the mutual coupling between elements 21 and 15 was tested. FEKO demonstrates that the drops in mutual coupling for this element pair are at 1.935 GHz and 3.03 GHz. This result shows that the model in MATLAB is accurate with respect to this element pair. The HFSS model demonstrates a similar

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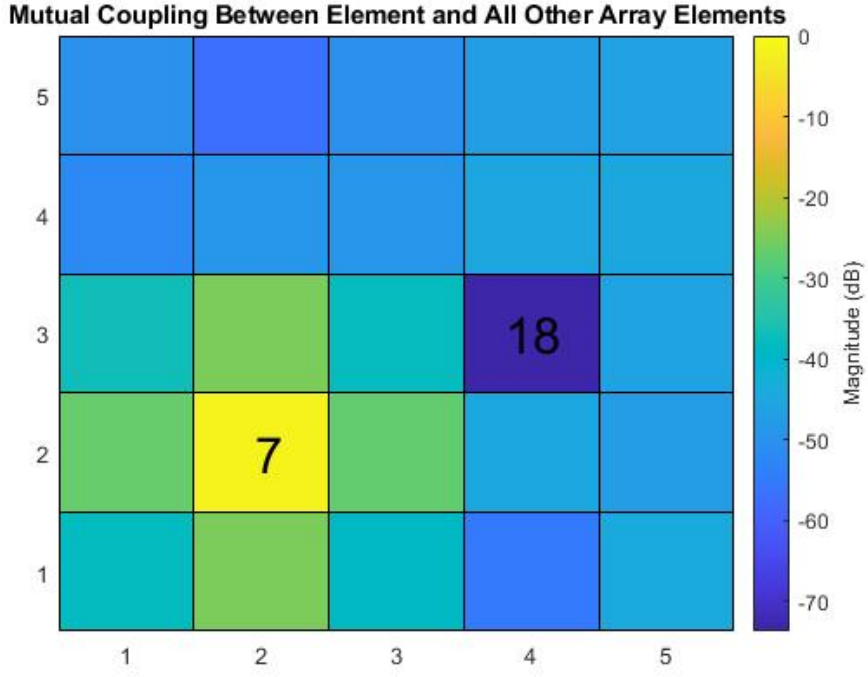
Figure 3.8: 2D mutual coupling between element 15 and all other array elements at 2.28 GHz for air and RO5880
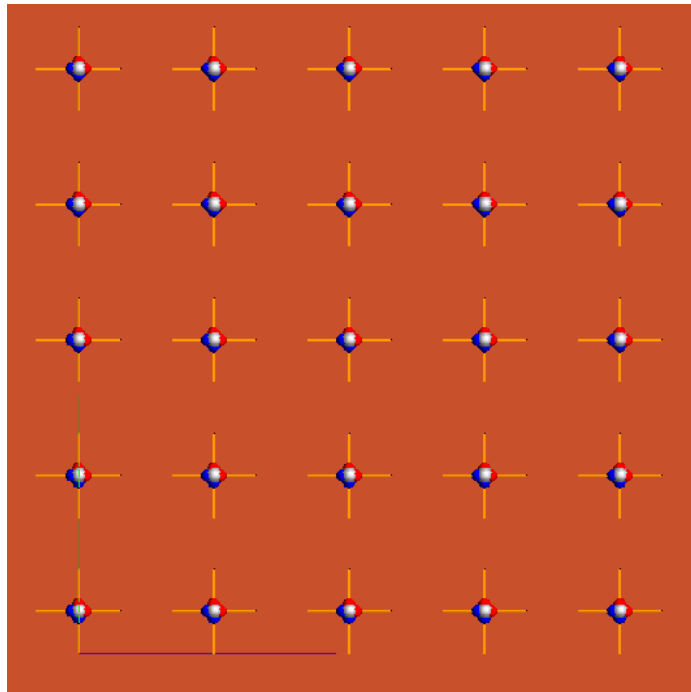
Figure 3.9: The crossed dipole array as modeled in FEKO
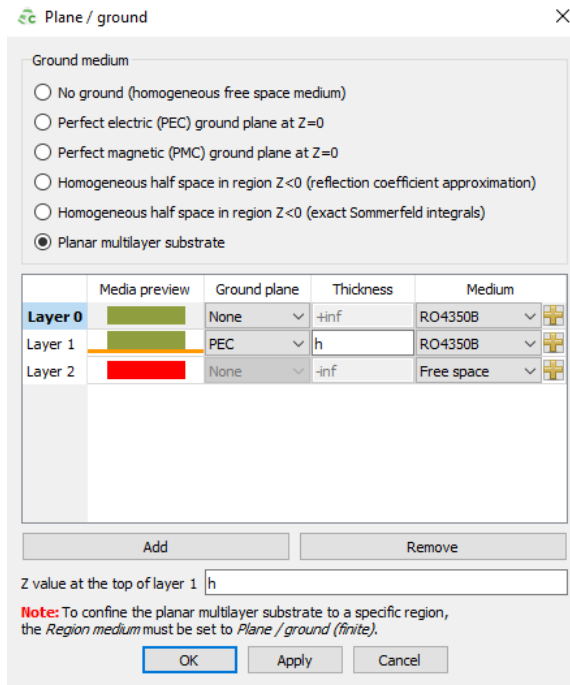
Figure 3.10: FEKO modeling an infinite substrate
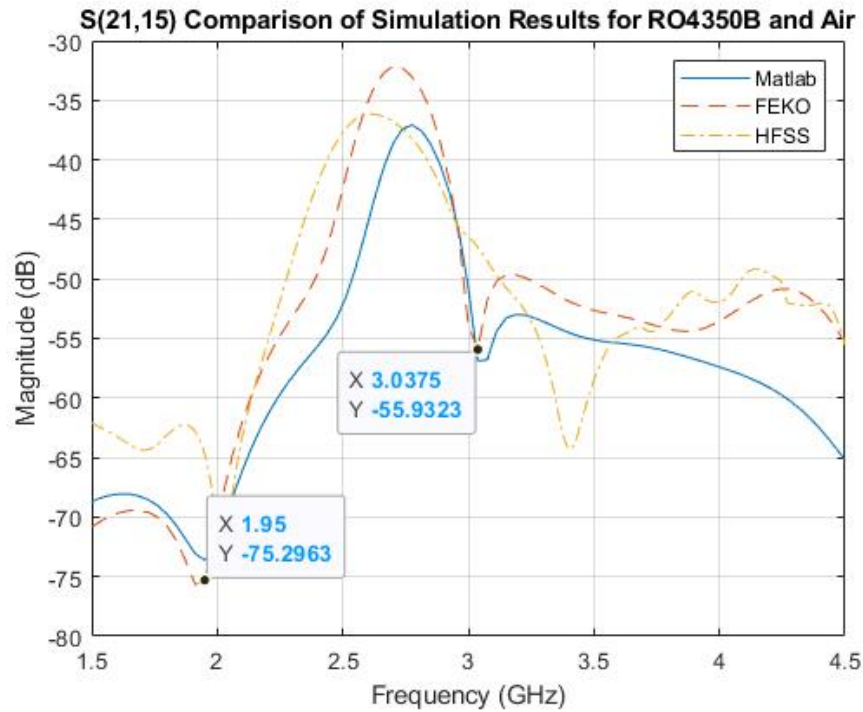
Figure 3.11: Comparison between MATLAB, HFSS and FEKO for elements 15 and 21
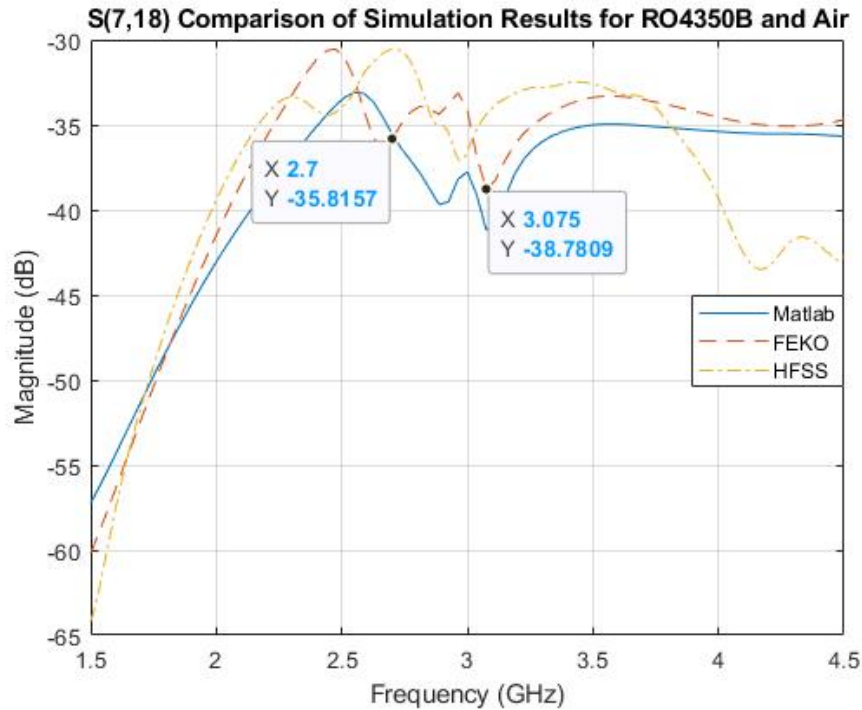
Figure 3.12: Coupling for elements 7 and 18 with RO4350B

trend in mutual coupling between this pair. The differences in the HFSS model can be attributed to the finite size of the dielectric box.

The next element pair considered was that of 7 and 18.

Both figures demonstrate the accuracy of MATLAB with respect to FEKO, and to a lesser extent, HFSS. While there are some discrepancies, such as the magnitude and minima exact location, it can be concluded that this model is accurate for crossed dipole array combinations. Further discrepancies in HFSS come from the finite size of its dielectric.

3.2   Simulating an 8x8 Array

While the functionality of the 5x5 crossed dipole array has been confirmed, it is ideal to consider a larger array due to considerations of actual patch antenna arrays.
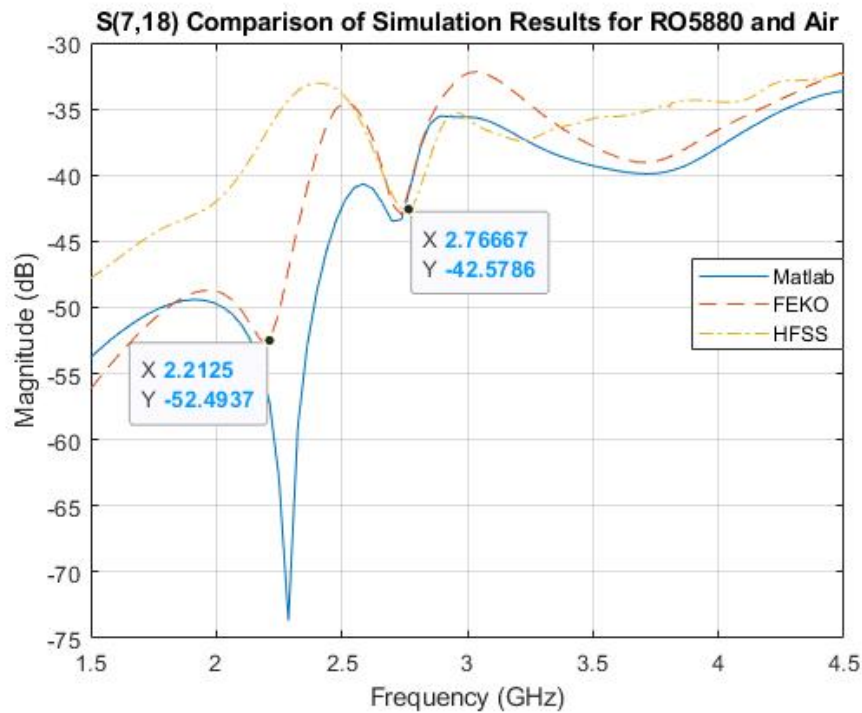
Figure 3.13: Coupling for elements 7 and 18 with RO5880

Typical patch antenna arrays in practice can be anywhere from 8x8 elements to 9x9 elements or more. For example, PAIR is a 9x9 element array and HORUS, a patch antenna array currently in development, is an 8x8 element array [28]. This section is simply to ensure that the MATLAB model is functional for larger arrays prior to implementation for actual patch antenna arrays.

The values in Table 3.1 were used to simulate the 8x8 arrays.

The element numbers used for reference are different than those using the 5x5 array. The 8x8 array layout is given in the figure. For this case, the mutual coupling between array elements 19 and 38 are considered. These are considered for both 4350B as a dielectric and for RO5880 as a dielectric.

These simulations were also compared to those carried out in FEKO to ensure that the model in MATLAB is maintaining accuracy even with larger sized arrays.

8-H 72-V	16-H 80-V	24-H 88-V	32-H 96-V	40-H 104-V	48-H 112-V	56-H 120-V	64-H 128-V
7-H 71-V	15-H 79-V	23-H 87-V	31-H 95-V	39-H 103-V	47-H 111-V	55-H 119-V	63-H 127-V
6-H 70-V	14-H 78-V	22-H 86-V	30-H 94-V	38-H 102-V	46-H 110-V	54-H 118-V	62-H 126-V
5-H 69-V	13-H 77-V	21-H 85-V	29-H 93-V	37-H 101-V	45-H 109-V	53-H 117-V	61-H 125-V
4-H 68-V	12-H 76-V	20-H 84-V	28-H 92-V	36-H 100-V	44-H 108-V	52-H 116-V	60-H 124-V
3-H 67-V	11-H 75-V	19-H 83-V	27-H 91-V	35-H 99-V	43-H 107-V	51-H 115-V	59-H 123-V
2-H 66-V	10-H 74-V	18-H 82-V	26-H 90-V	34-H 98-V	42-H 106-V	50-H 114-V	58-H 122-V
1-H 65-V	9-H 73-V	17-H 81-V	25-H 89-V	33-H 97-V	41-H 105-V	49-H 113-V	57-H 121-V

Figure 3.14: Crossed dipole array layout for 8x8 size with elements 19 and 38 Indicated

For RO4350B and free space combination, there are drops in mutual coupling at 2.325 GHz and 2.88 GHz. When compared to FEKO, this mutual coupling drops remain relatively the same. For this scenario, the accuracy of the model has been verified.

For the crossed dipole array combination of RO5880 and free space, there is a drop in mutual coupling at 3.225 GHz. This minima was also demonstrated in the FEKO simulation array combination. This model has been satisfactorily verified to function for a larger sized array. Therefore, the next step is to verify that this MATLAB model can adequately model a patch antenna array.

3.3 Comparison of Simulation Times

The purpose of the MATLAB simulation is to provide a robust method of obtaining S-Parameters for a patch antenna array without the time consuming process of measuring the actual patch S-parameters or simulating the patch antenna in an electromagnetic solver. As such, one final consideration must be in reference to the simulation times. It has been established in 1 that HFSS simulations take a great amount of time. However,
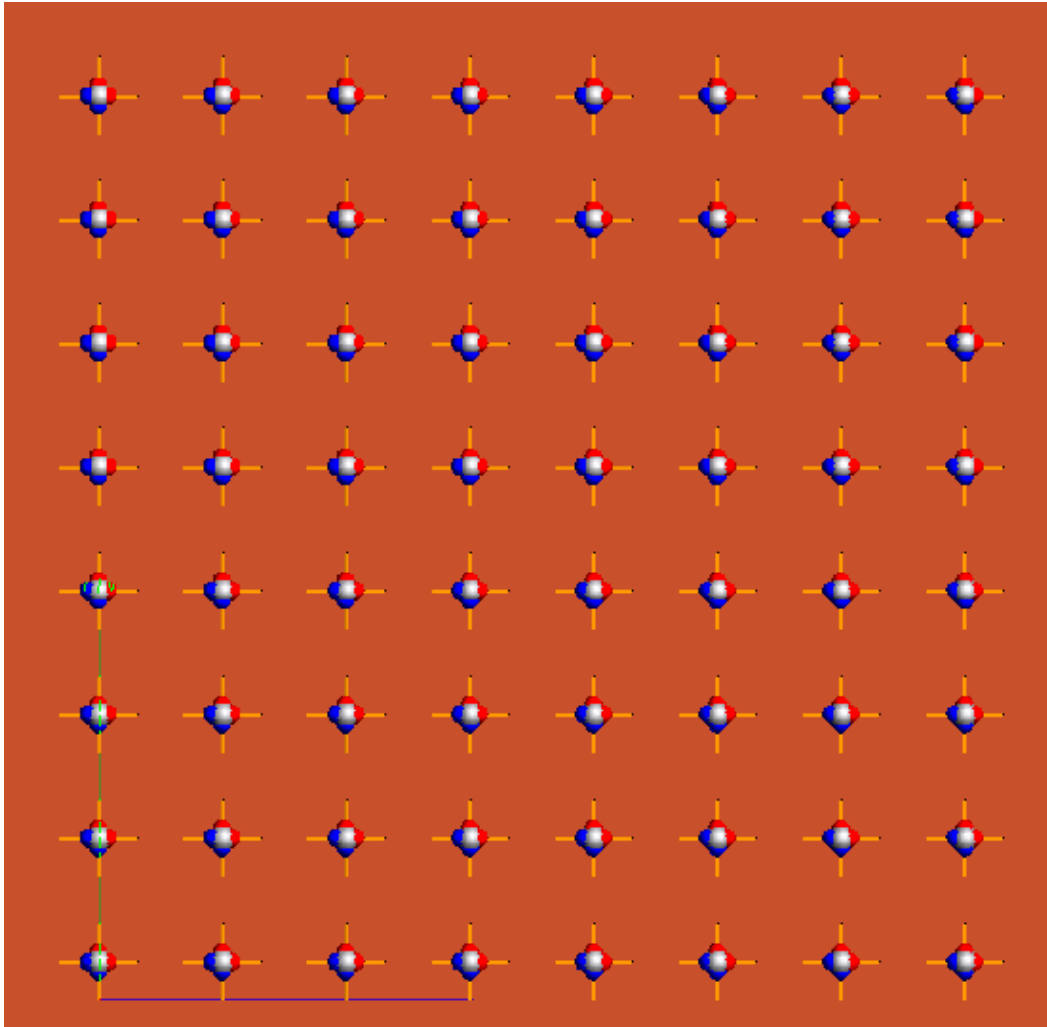
Figure 3.15: 8x8 crossed dipole array as modeled in FEKO
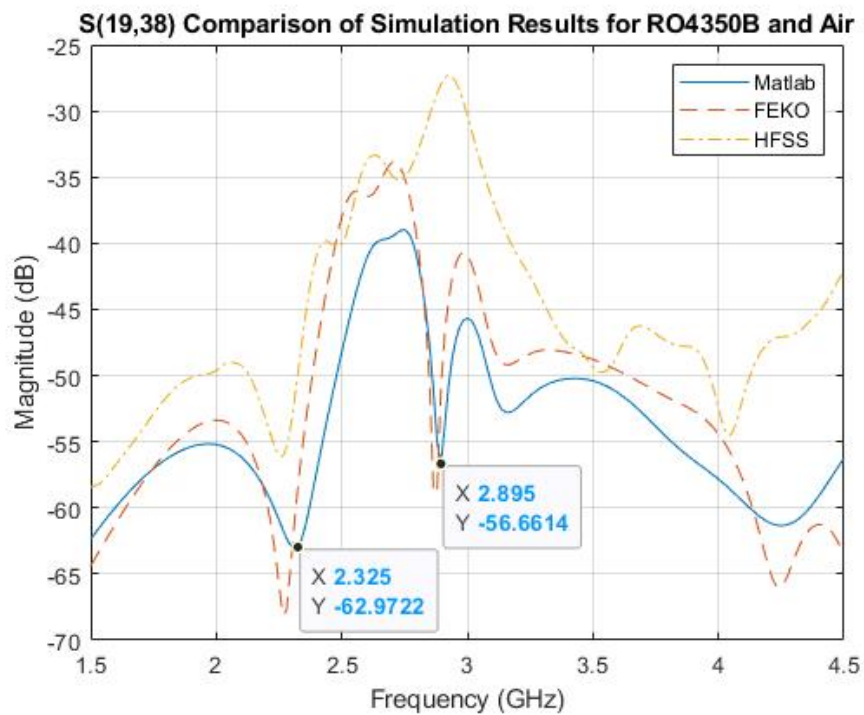
Figure 3.16: Plot comparison between Matlab, HFSS and FEKO for elements 19 and 38
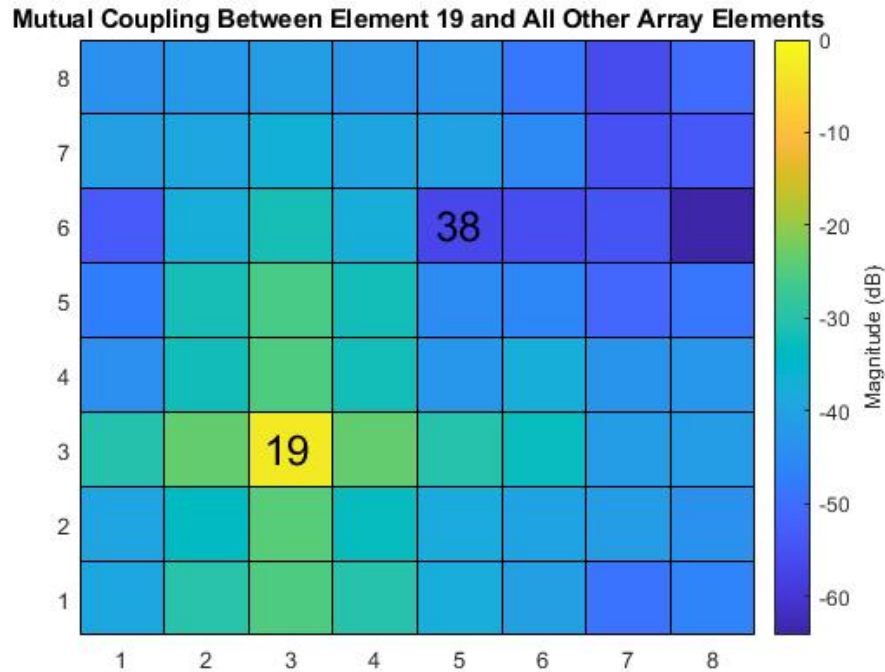
Figure 3.17: 2-D mutual coupling plot at 2.895 GHz for RO4350B and air

FEKO simulates quicker than HFSS, so there is a need to determine how the MATLAB model compares to FEKO time wise. In this case, the simulation times for the 8x8 MATLAB model are taken and compared to the simulation times from FEKO. These are all carried out with a frequency sweep between 1.5 to 4.5 GHz, with the number of frequency points being 81 points, 201 points and 451 points. The simulation sweep type used for FEKO was with linearly spaced discrete points. This is slower than a continuous (interpolated) range sweep setting but also more accurate for data.

Table 3.2: Comparison Between Simulation Times for Matlab and FEKO.

	81 Points	201 Points	451 Points
Matlab	298.48 seconds	800.03 seconds	2727.43 seconds
FEKO	624.98 seconds	1556.13 seconds	3522.18 seconds

The first table will have the time to complete the simulation of a crossed dipole array. It is important to note that two of these simulations must be carried out to simulate

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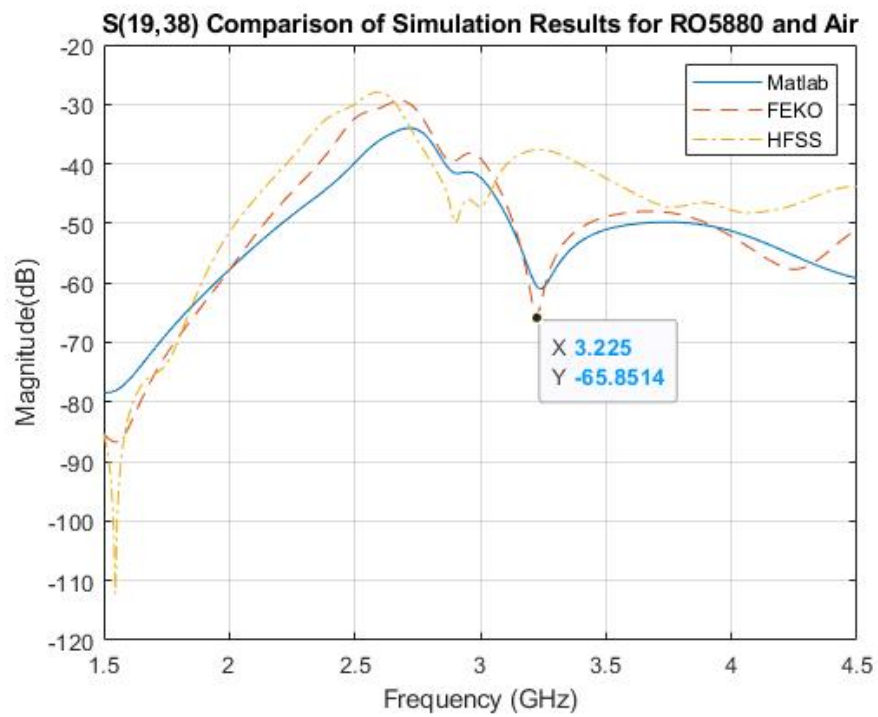
Figure 3.18: Plot comparison between Matlab and FEKO for elements 19 and 38 for RO5880 and air
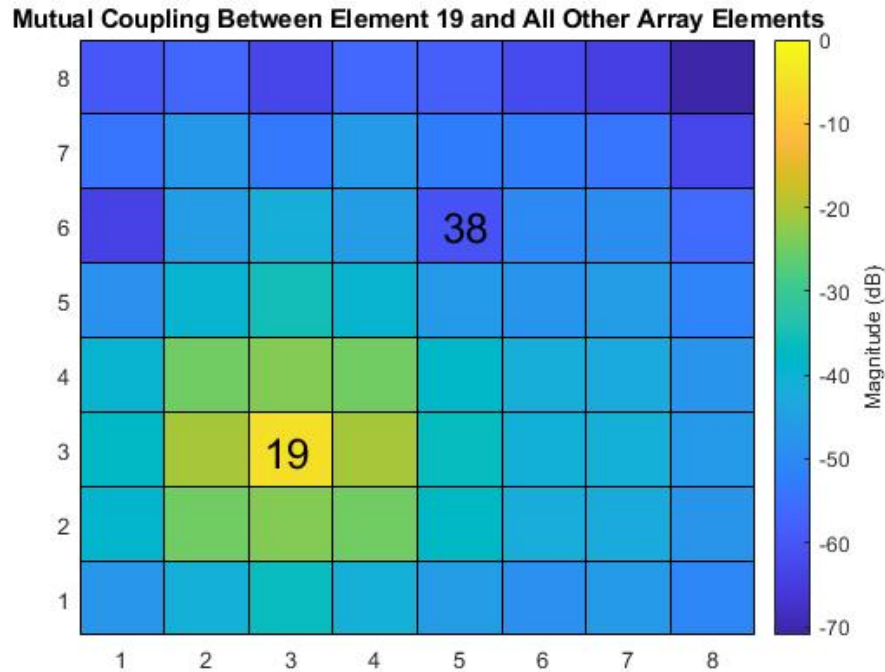
Figure 3.19: 2-D mutual coupling plot at 3.225 GHz for RO5880 and air

an equivalent patch antenna array. The times for the simulations to complete do vary somewhat with the change in dielectric constants by a few seconds.

The results of the simulation times are discussed in the table. For both softwares, the simulation time increases with the number of points input by the user, as to be expected. For the frequency sweeps consisting of 81 points and 201 points, it can be observed that the simulation time for the Matlab model is approximately half the time of the FEKO model. It must be noted that two simulations need to be conducted to model one patch antenna array, so the total simulation time is actually double what is presented in the table.

From these results, it can be observed that the MATLAB model has reasonable accuracy to the FEKO model while also having a faster simulation time. Again, there are some discrepancies in terms of magnitudes and exact minima for mutual coupling

plots. For the subject of this research, such discrepancies can be overlooked for the time being. The purpose of the MATLAB model is to roughly estimate the mutual coupling magnitudes between element pairs and mimic the effects of patch antennas interacting to mutual coupling drops.

3.4   Simulating an Array Similar to PAIR

3.4.1   Initial Simulations

The parameters of the MATLAB model were tuned to best fit those of PAIR, including to match at the frequency of 5.4 GHz. It is important to note that due to the assumption of infinite dielectric, the results of the MATLAB simulation in this case will not directly correlate to those of the PAIR simulation. The purpose of this section is to ensure that the MATLAB model can still produce this patch array mutual coupling behavior even when the parameters of the model are changed to those similar to a real life patch antenna array. The initial simulations were carried out using the paramneters listed in Table 3.3.

Table 3.3: Matlab Model Parameters for PAIR.

Parameter	Value
Center Frequency	5.4 GHz
Dipole Length	$0.48 * c/(f\sqrt{\varepsilon_r})$
ε_r	1 (for free space), 2 (for dielectric)
k_0	$2\pi/\lambda$
Array Spacing	27.5 mm
Distance from Ground Plane	$\lambda/(4\sqrt{\varepsilon_r})$

Initially, the simulations were carried out by using the MATLAB model to generate two sets of S-parameters. The first set is the crossed dipole array in free space, modified to best match the parameters from PAIR. The second set is the crossed dipole array in
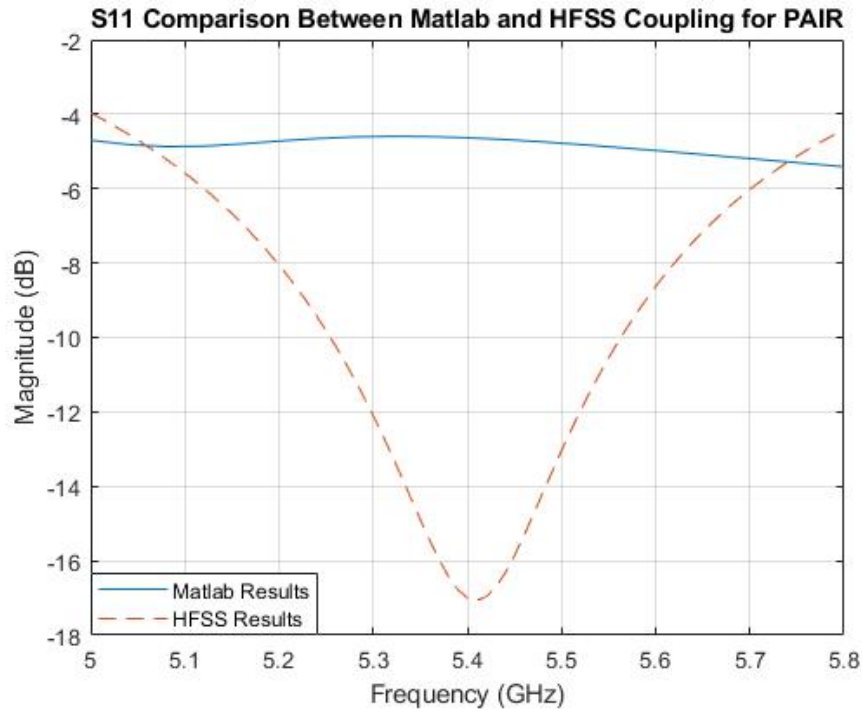
Figure 3.20: PAIR S11 compared to MATLAB

dielectric. While this dielectric constant will be used to best mimic the effects of the patch substrate, so this number will be between 1 and 2.

The return loss of a patch antenna element was checked to determine if the MATLAB simulated array is behaving the same as the results of PAIR from HFSS.

The initial figure demonstrating the comparison between the return loss of the simulated PAIR and the return loss of the MATLAB model for PAIR indicated that simple Y parallelization is insufficient. There is poor matching between the MATLAB model and the simulated model for PAIR.

A further examination of the return loss for the individual crossed dipole arrays was also undertaken to determine the source of the inconsistency. The result indicated that in particular, the crossed dipole array simulated in the arbitrary dielectric demonstrated poor matching, even with tuning the dipole lengths.
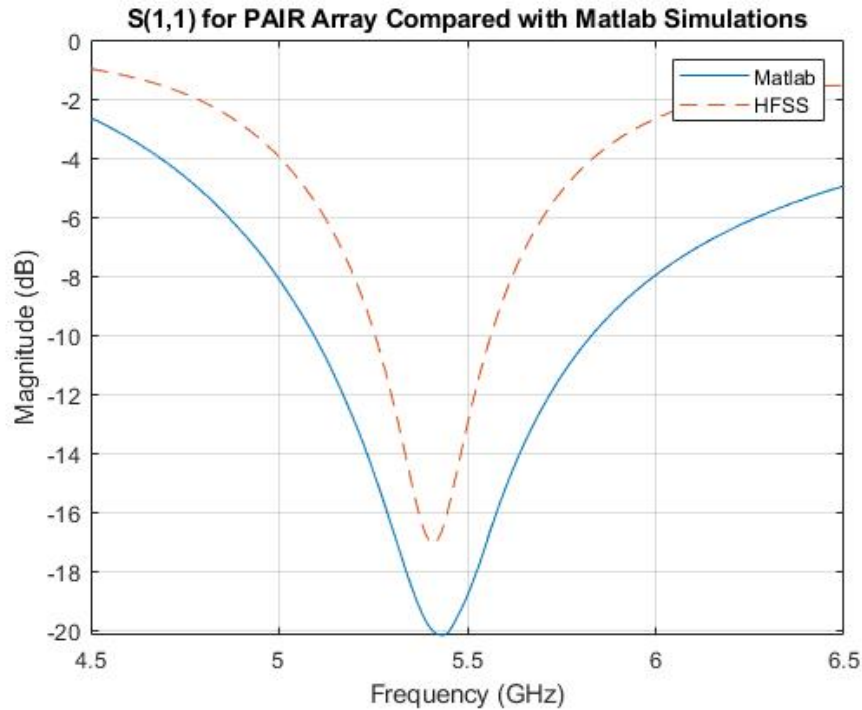
Figure 3.21: New return loss plot for PAIR, MATLAB vs. HFSS for dielectric constant of 1.25

To rectify this, the next method of parallelization must be implemented. This involves ideal transformers input into each crossed dipole array element. This is for both the free space crossed dipole array and the dielectric dipole array. Then, the arrays are once again converted to Y-parameters, summed, and converted back to S-parameters. The results following this method are more akin to what should be seen in a patch antenna array.

This new array had to be adjusted to best fit at 5.4 GHz. This means that the dipole lengths needed to be adjusted as well as the dielectric constant. The dielectric constant of the crossed dipole array set in the dielectric was also adjusted. From both Figures 3.21 and 3.22 the effects of the changing dielectric on the return loss can be observed.

Both dielectric constants demonstrate better matching at 5.4 GHz following the implementation of the ideal transformers. The dielectric can also somewhat help tune to

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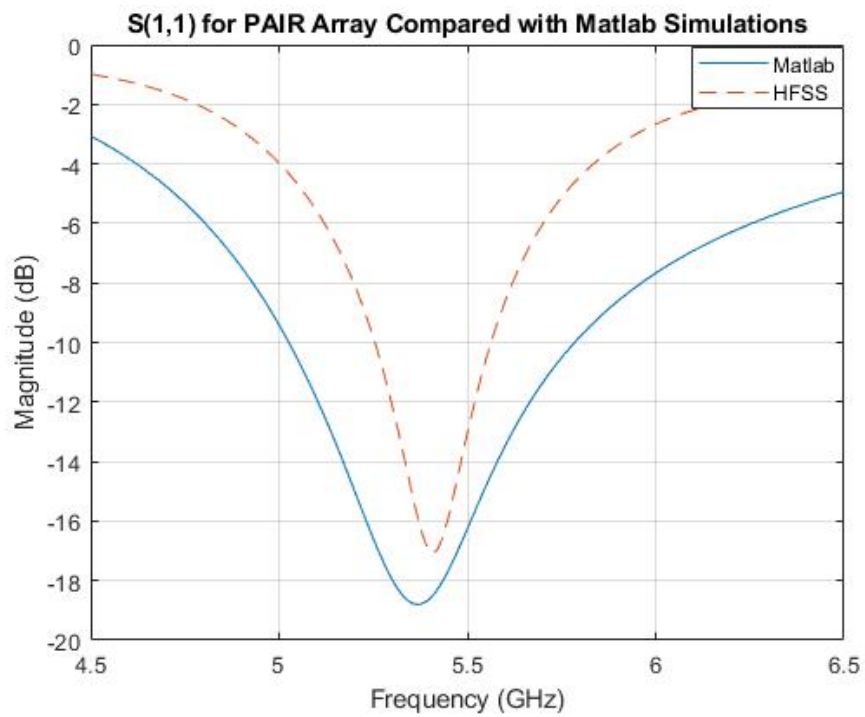
Figure 3.22: Return loss plot for PAIR, MATLAB vs. HFSS for dielectric constant of 1.75

frequency and can also improve the bandwidth. The bandwidth may not be a necessary component of this research however, as the most important part of this section is to ensure that the mutual coupling behavior is still present with this crossed dipole array combination. Table 3.4 includes the revised values used in the MATLAB model after tuning. This table also includes the ratios of the ideal transformers described in 2.8.

Table 3.4: MATLAB model parameters for PAIR after tuning with transformer ratios.

Parameter	Value
Center Frequency	5.4 GHz
Dipole Length	$0.45 * c/(f\sqrt{\varepsilon_r})$
ε_r	1 (free space) 1.75 (dielectric)
k_0	$2\pi/\lambda$
Array Spacing	27.5 mm
Distance from Ground Plane	$\lambda/(4\sqrt{\varepsilon_r})$
$Ratio_{FreeSpace}$	0.235
$Ratio_{Dielectric}$	0.357

Next, the mutual coupling pairs of this patch antenna array generated by the MAT-LAB model are observed to determine if there are any observable minima. This will indicate where such pairs are non ideal to be used for mutual coupling array calibration.

The transformer ratios also impact bandwidth. Figure 3.23 demonstrates that the transformer ratios defined in Table 3.4 yield better bandwidth.

Some randomly selected mutual coupling pairs from this MATLAB model are displayed in the Figures 3.24 and 3.25. While the mutual coupling pairs from 3.25 will be analyzed further, that and 3.24 demonstrate how the transformer ratios can be adjusted to change the mutual coupling pairs. Furthermore, the transformer ratios which yield the better bandwidth have sharper mutual coupling minima.

There are multiple areas in the plot of 3.25 where the MATLAB model has demonstrated significant minima in mutual coupling. Such minima are highlighted within this plot. Even though these mutual coupling pairs have not necessarily been properly

50

Figure 3.23: Return losses from MATLAB model using different ideal transformer ratios compared to HFSS simulation of PAIR

Figure 3.24: Mutual coupling pairs from the MATLAB model with transformer ratios 0.1369 and 0.2500.

Figure 3.25: Mutual coupling pairs from the MATLAB model with transformer ratios 0.235 and 0.357.

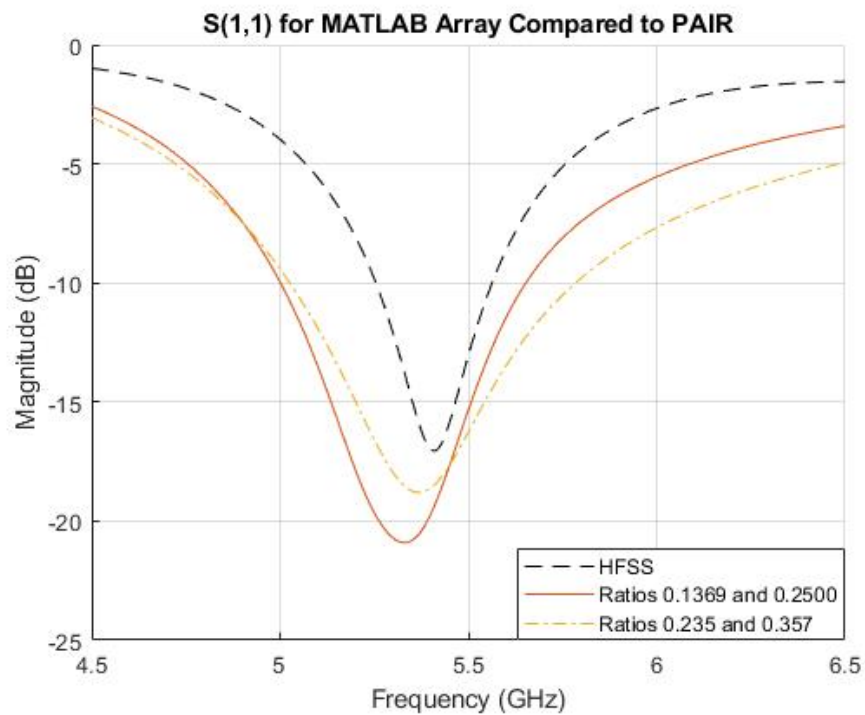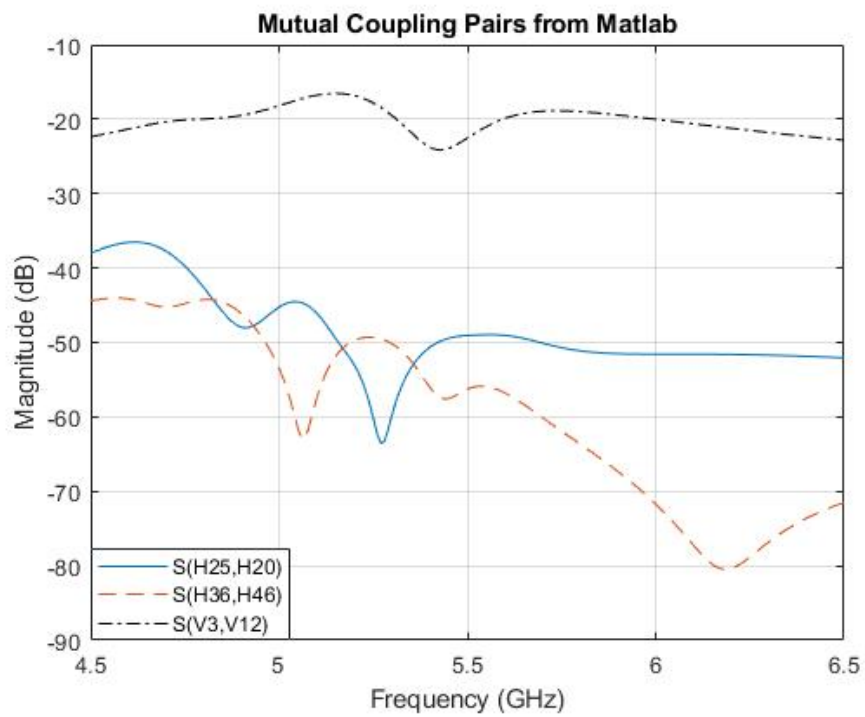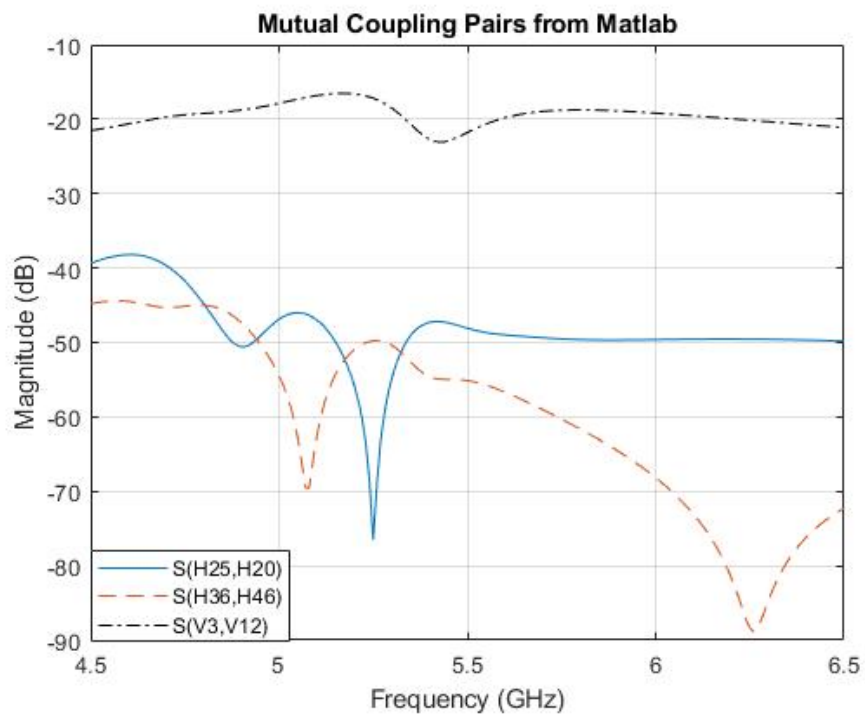|								
9-H 90-V	18-H 99-V	27-H 108-V	36-H 117-V	45-H 126-V	54-H 135-V	63-H 144-V	72-H 153-V	81-H 162-V
8-H 89-V	17-H 98-V	26-H 107-V	35-H 116-V	44-H 125-V	53-H 134-V	62-H 143-V	71-H 152-V	80-H 161-V
7-H 88-V	16-H 97-V	25-H 106-V	34-H 115-V	43-H 124-V	52-H 133-V	61-H 142-V	70-H 151-V	79-H 160-V
6-H 87-V	15-H 96-V	24-H 105-V	33-H 114-V	42-H 123-V	51-H 132-V	60-H 141-V	69-H 150-V	78-H 159-V
5-H 86-V	14-H 95-V	23-H 104-V	32-H 113-V	41-H 122-V	50-H 131-V	59-H 140-V	68-H 149-V	77-H 158-V
4-H 85-V	13-H 94-V	22-H 103-V	31-H 112-V	40-H 121-V	49-H 130-V	58-H 139-V	67-H 148-V	76-H 157-V
3-H 84-V	12-H 93-V	21-H 102-V	30-H 111-V	39-H 120-V	48-H 129-V	57-H 138-V	66-H 147-V	75-H 156-V
2-H 83-V	11-H 92-V	20-H 101-V	29-H 110-V	38-H 119-V	47-H 128-V	56-H 137-V	65-H 146-V	74-H 155-V
1-H 82-V	10-H 91-V	19-H 100-V	28-H 109-V	37-H 118-V	46-H 127-V	55-H 136-V	64-H 145-V	73-H 154-V

Figure 3.26: Array layout with elements H20 and H25 highlighted

matched to the simulations of PAIR, this plot is evidence enough that such a set of data can be used to work with a mutual coupling calibration algorithm, because the patterns demonstrated in this plot can be accounted for in these calibration algorithms.

For the sake of clarity, one such mutual coupling pair was further examined. The initial figure displays the mutual coupling plots for several element pairs.

This next figure displays that between elements H20 and H25. This figure shows two significant drops in mutual coupling. One is at 4.9 GHz, then the other is at 5.25 GHz. Such drops would indicate that this mutual coupling pair should be avoided when it comes to choosing pairs for calibration algorithms. However, pairs with patterns such as these can be useful for the detection and avoidance of such elements for better array calibration.

A 2-D plot of mutual coupling at 5.25 GHz further demonstrates that this model can exhibit the same mutual coupling behaviors as that of those found in actual antenna arrays.
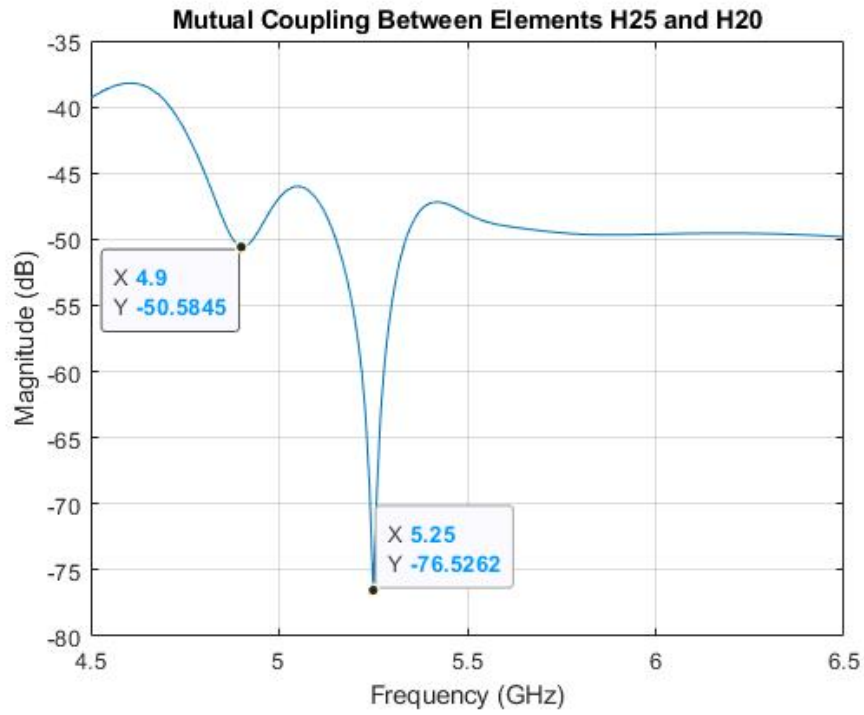
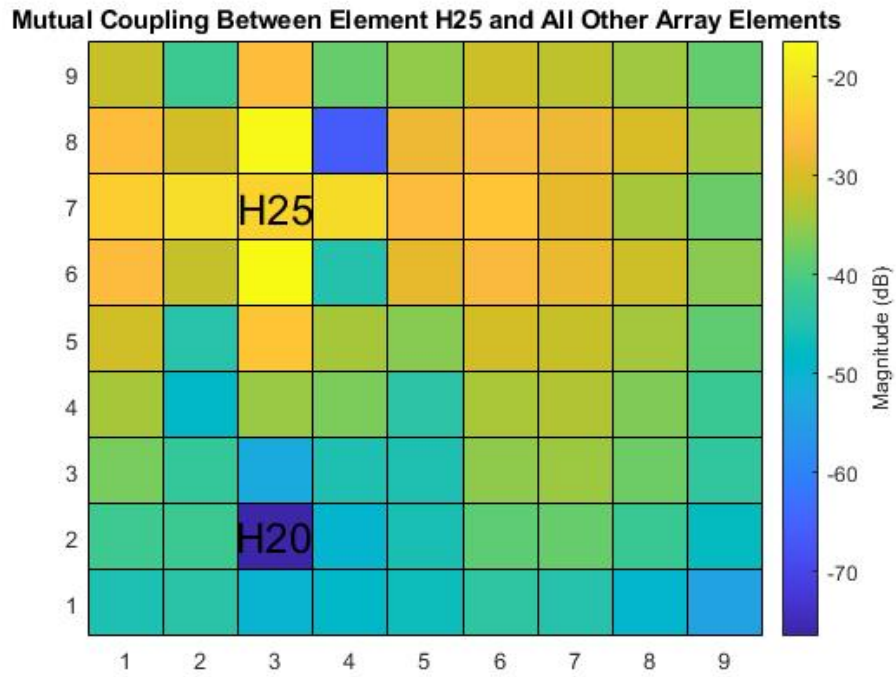Figure 3.27: Mutual coupling between elements H20 and H25

Figure 3.28: 2-D mutual coupling plot at 5.25 GHz for H25

9-H 90-V	18-H 99-V	27-H 108-V	36-H 117-V	45-H 126-V	54-H 135-V	63-H 144-V	72-H 153-V	81-H 162-V
8-H 89-V	17-H 98-V	26-H 107-V	35-H 116-V	44-H 125-V	53-H 134-V	62-H 143-V	71-H 152-V	80-H 161-V
7-H 88-V	16-H 97-V	25-H 106-V	34-H 115-V	43-H 124-V	52-H 133-V	61-H 142-V	70-H 151-V	79-H 160-V
6-H 87-V	15-H 96-V	24-H 105-V	33-H 114-V	42-H 123-V	51-H 132-V	60-H 141-V	69-H 150-V	78-H 159-V
5-H 86-V	14-H 95-V	23-H 104-V	32-H 113-V	41-H 122-V	50-H 131-V	59-H 140-V	68-H 149-V	77-H 158-V
4-H 85-V	13-H 94-V	22-H 103-V	31-H 112-V	40-H 121-V	49-H 130-V	58-H 139-V	67-H 148-V	76-H 157-V
3-H 84-V	12-H 93-V	21-H 102-V	30-H 111-V	39-H 120-V	48-H 129-V	57-H 138-V	66-H 147-V	75-H 156-V
2-H 83-V	11-H 92-V	20-H 101-V	29-H 110-V	38-H 119-V	47-H 128-V	56-H 137-V	65-H 146-V	74-H 155-V
1-H 82-V	10-H 91-V	19-H 100-V	28-H 109-V	37-H 118-V	46-H 127-V	55-H 136-V	64-H 145-V	73-H 154-V

Figure 3.29: Array layout with elements H36 and H46 highlighted

The other mutual coupling pair observed was that between elements H36 and H46, again to demonstrate that these behaviors are still present in elements at different spacings from each other.

The 2-D mutual coupling plot for element H36 was also observed at 5.07 GHz and this again demonstrates the same behavior.

As such, the S-Parameter block generated by this MATLAB code is sufficient for building and testing such algorithms. Additionally, it is achievable to model these coupling pairs for large patch antenna arrays.

Even with the somewhat same parameters as those in the HFSS simulation of PAIR, the MATLAB model generates the patch antenna array characteristics that are needed for calibration algorithms within reason. From this, the MATLAB model can be used to reasonably generate a set of S-parameters that can adequately mimic the effects of a patch antenna array.
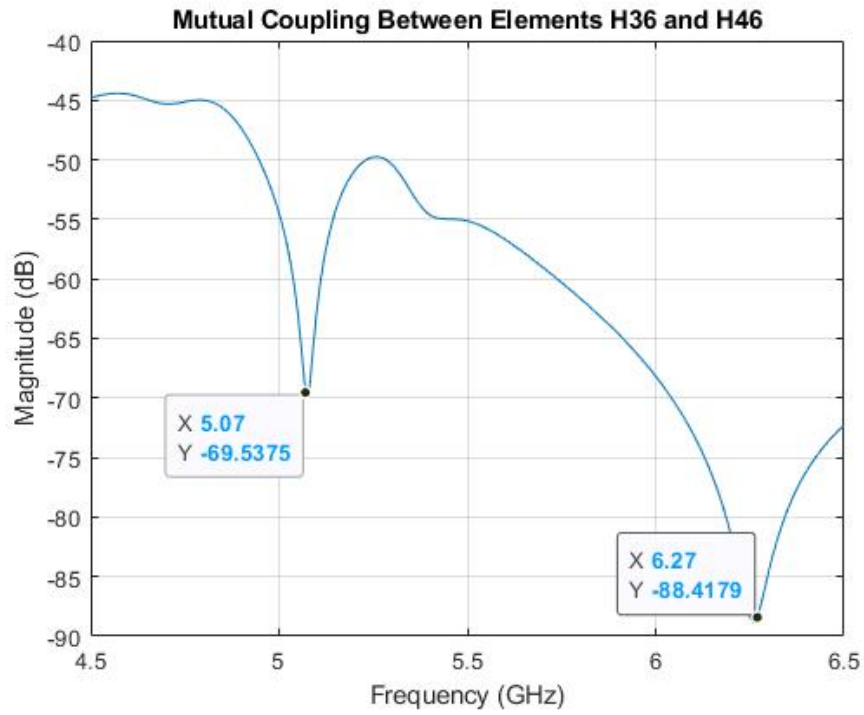
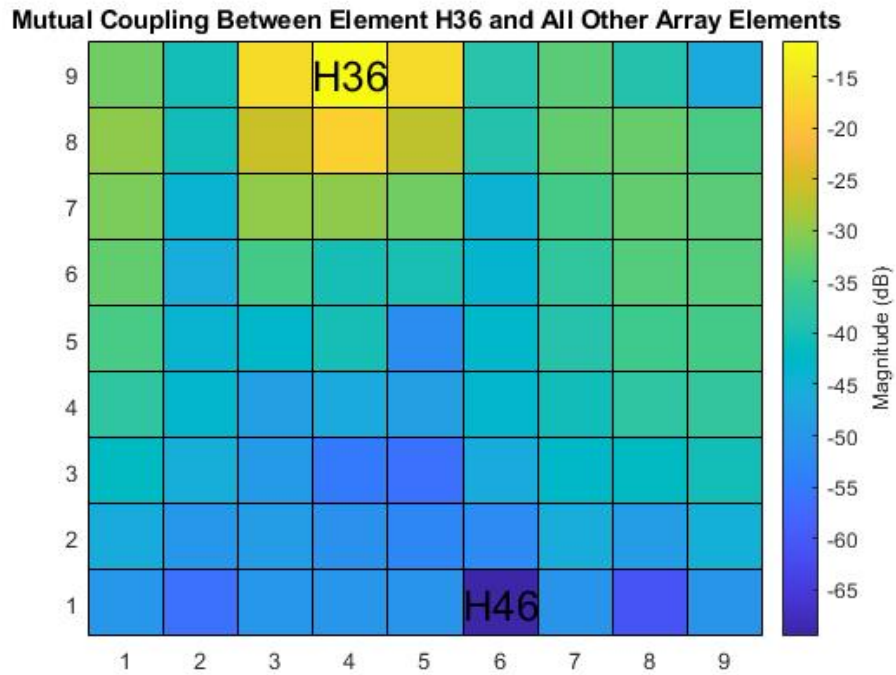Figure 3.30: Mutual coupling between elements H36 and H46

Figure 3.31: 2-D mutual coupling plot at 5.07 GHz for H36

3.5 Simulation Time for PAIR

One last subject to consider is the time it takes for the simulation to complete for the MATLAB model. As discussed in the introduction, the HFSS model simulation takes a significant amount of time to complete. It is important to consider the time it takes for the full MATLAB model simulation to execute to ensure that this method can be an ideal replacement for full wave EM simulations or physical measurements. For this table, the simulation time represented is that for one such crossed dipole array.

Table 3.5: Simulation time for an Array similar PAIR as carried out in MATLAB.

	81 Points	201 Points	451 Points
MATLAB	1345.70 seconds	3507.10 seconds	8504.02 seconds

The simulation time was slower when attempting to mimic the effects of PAIR. PAIR is a 9x9 array of patches, so this is to be expected. However, even with the slower times, the MATLAB model outpaced the HFSS model quite significantly while maintaining accuracy to the actual array. This presents a model that is sufficient to generate S-parameters within reason. These can then be used to input into mutual coupling calibration algorithms.

3.6 Summary

The results from the simulations demonstrate that a MATLAB model of crossed dipoles combined is sufficient to model mutual coupling behaviors of patch antenna arrays. The initial simulations used simple crossed dipole arrays, combined those and then subsequently comparing those results to those demonstrated in FEKO and HFSS. When the functionality of a 5x5 crossed dipole array combination was verified, the functionality of an 8x8 crossed dipole array combination was simulated in MATLAB

and then compared to FEKO and HFSS. The results from these simulations demonstrated that this MATLAB model is sufficient for larger antenna arrays.

There was some issue when initially comparing the MATLAB model to simulate a patch antenna array such as PAIR. To rectify this, a different combination method was used. Instead of converting the S-parameters to Y-parameters and then summing, as was the previous method, a set of virtual ideal transformers had to be employed. This was achieved using simple equations modeled in MATLAB. Once these ideal transformers were implemented, the crossed dipole arrays were combined in parallel by conversion to Y parameters. The resulting mutual coupling magnitudes for some element pairs of the MATLAB model were then observed.

Chapter 4

Conclusion

4.1 Conclusion

The mutual coupling effects of patch antenna arrays can be mimicked using a parallel combination of crossed dipole arrays. The crosssed dipole arrays are simulated by incorporating the induced EMF method with a MATLAB model. Two sets of S-Parameters are needed: one with an array set in free space, the other with the array set in dielectric. The two crossed dipole array S-parameter sets can be combined in parallel to demonstrate the effects of patch antenna array mutual coupling.

The initial simulations demonstrated that a crossed dipole array combined in parallel with another can be effectively modeled within reasonable accuracy with FEKO and HFSS. Once this was verified, the MATLAB model's parameters were adjusted to fit the parameters of a real life array, PAIR. When the traditional method of array parallelization yielded poor matching, implementing ideal transformers allowed for mutual coupling effects to be modeled.

4.2   Future Work

This MATLAB model can be further tuned to model different types of patch antenna arrays. While this thesis utilized the parameters of PAIR, HORUS is another such array which can be simulated. Additionally, the model could be modified to mimic the effects of non rectangular arrays, such as the Cylindrical Polarimetric Phased Array Radar.

Ultimately, the purpose of this MATLAB model is to provide a robust and effective method of obtaining S-Parameters which can model patch antenna mutual coupling behavior. This MATLAB model will reduce the need for electromagnetic solvers and manual antenna array measurements as it can help generate S-Parameter files with patch antenna array mutual coupling behavior in a more timely manner.

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