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ACTIVE REFLECTION COEFFICIENT ANALYSIS AND PREDICTION, MEASUREMENT AND MITIGATION METHODOLOGIES FOR CO-LOCATED MIMO RADARS IN TRANSMIT MODE

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**Multiband Multifunction Radio Frequency Sensing
Multispectral Sensing & Detection Division**

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Methodologies for Co-located MIMO Radars in Transmit Mode

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ABSTRACT

Modern radio frequency (RF) sensors are digital systems characterized by wide band frequency range, and capable to perform multi-function tasks such as: radar, electronic warfare (EW), and communications simultaneously on different sub-arrays. This demands careful understanding of the behavior of each sub-system and how each sub-array interacts with the others. A way to estimate and measure the active reflection coefficient (ARC) to calculate the active voltage standing wave ratio (VSWR) of multiple input multiple output (MIMO) radar when elements (or sub-arrays) are driven with different waveforms has been developed. This technique will help to understand and incorporate bounds in the design of MIMO systems and its waveforms to avoid damages by large power reflections and to improve system performance. The methodology developed consists of evaluating the active VSWR at each individual antenna element or sub-array from (1) estimates of the ARC by using computational electromagnetics (CEM) tools or (2) by directly measuring the ARC at each antenna element or sub-array. The former methodology is important especially at the design phase where trade offs between element shapes and geometrical configurations are taking place. The former methodology is expanded by directly measuring ARC using an experimental radar testbed Baseband-digital at Every Element MIMO Experimental Radar (BEEMER) system to assess the active VSWR, side-lobe levels and antenna pattern effects when different waveforms are transmitted. An optimization technique is implemented to mitigate the effects of the ARC in co-located MIMO radars by waveform design.

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Chapter 1

INTRODUCTION

There have been many advances in the area of multifunction MIMO radar systems, but several topics remain to be studied. Specifically, one needs to understand performance variations reflected on the expected total transmitted fields and the coupled power in electrically closed networked elements due to (1) the inter-element spacing; (2) geometric configuration; (3) polarization; and (4) the type of simultaneously transmitted waveforms (binary phased codes (BP), time division multiple access (TDMA), etc.). Addressing these issues is the goal of this work.

The contributions of this research are as follows. We will: (1) generalize a methodology to predict the total transmitted fields in the far field for arbitrary radiating elements and geometrical configuration; (2) generalize the methodology to record simultaneous reverse and forward waves of a co-located MIMO radar when simultaneously excited with different waveforms; (3) assess the performance impact of the total radiated fields for different cases; (i) with arbitrary waveforms (linear frequency modulated (LFM), TDMA, BP, and Doppler division multiple access (DDMA)); (ii) for linear and planar array of patch antennas; and (iii) for horizontal and vertical polarizations; (4) assess the performance impact of the ARC for LFM case, and (5) upgrade the Air Force Research Laboratory (AFRL) co-located MIMO radar testbed, to obtain real data of the total radiated fields and ARC and the validation of the an-

alytical methodology for the cases described above.

1.1 Motivation

The current trend is to develop multiple-input multiple-output (MIMO) radar systems capable of performing simultaneous radar and communication functions [1]. The reason for doing so is apparent; one realizes significant gains in both the footprint of the device as well as functionality. In fact, the advances of MIMO radar systems are motivated by the development of unmanned, attritable, low cost vehicles, which have limitations in cost, size, weight and power (C-SWaP). These low-cost agile vehicles require sensors capable of performing multiple functionalities (i.e. communications, ground moving target identification (GMTI), synthetic aperture radar (SAR), etc.). Combining several sensors into one multifunctional sensor capable of performing simultaneous functionalities has been proven effective to relax C-SWaP constraints [2]. But practical realization of such systems faces a significant bottleneck.

The key to effectively embed a multifunctional MIMO sensor on a small, low-cost, attritable vehicle is to understand the coupled power performance of different subsystems and the impact of this coupling on the function of the module. And this is the main problem this research addresses.

Understanding the impact on performance due to the coupled power between functions is imperative for hardware design and function management of such MIMO systems and its waveforms. A co-located MIMO radar system is typically formed by electrically close-networked subarrays performing low power applications such as radar and communications or high power applications such as electronic warfare. In the latter scenario, it stands to reason that there is a potential to damage the radio frequency (RF) system's transmitter due to unexpected coupled power between the networked subarrays [3]. As a result, the analysis and development of methodologies

to assess the coupled power impact on co-located MIMO radar performance is of great importance.

However, this problem, while easily stated, is not trivial. To properly capture the impact of coupled power, one needs to include sufficient physical phenomenology for assessing coupling in multi-functional systems and its impact on performance. The characterization of coupled power demands (a) higher fidelity modeling of antenna element type, geometrical configuration, and polarization; (b) measurement of the reverse and forward waves to calculate the active reflection coefficient, the total antenna pattern in the far field when the system is executing simultaneous functions; and (c) analysis technique to estimate the active voltage standing wave ratio (VSWR) and the performance degradation of the simultaneous functions due to coupled power. As is evident, this holistic understanding of fully coupled MIMO radar systems is challenging. As a result, most of the analysis are piecemeal. Some considered multi-functionally ignoring coupled power, others assessed mutual coupling but for single functionality like angle of arrival. Very few consider multi-functionality and coupled power. Because mutual coupling should not be ignored, the pattern multiplication concept cannot be applied. An approximation to the total radiated fields of a MIMO transmission, when narrow band waveforms are applied, considering mutual coupling and different excitations can be represented as [4]

$$E(u, v) \approx f^i(u, v) \sum_n (1 - \Gamma_n^a) a_n e^{jk(x_n u + y_n v)} \quad (1.1)$$

where (u, v) is a transformation from the (θ, ϕ) -space with $u = \sin\theta \cos\phi$ and $v = \sin\theta \sin\phi$, $f^i(u, v)$ is the isolated element pattern, (x_n, y_n) are the coordinates of each element in the xy -plane (accounts for element positions, geometrical configuration, and inter-element spacing between elements), the coupling effects are captured with Γ_n^a , the ARC. The ARC is a function of the S-matrix, S_{nm} , and a_n the excitation for

element n [4, 5, 6]. Γ_n^a is the ARC observed in antenna n due to all the other antenna, m , elements

$$\Gamma_n^a = \frac{b_n}{a_n} = \frac{\sum S_{nm} a_m}{a_n} \quad (1.2)$$

where a_n represents the amplitude and phase of the forward coupled wave on element n , defined as the excitation of antenna n , and b_n represents the amplitude and phase of the reverse wave in antenna n . S_{nm} is the conventional S-parameter defined as the passive ratio of the signal coupled to port n from a signal incident on port m , when all other ports are terminated [7].

A special case of Equation (1.1) is when mutual coupling is ignored ($\Gamma_n^a = 0$). This special case is known as the pattern multiplication concept and presents the approximation to the radiated fields used by early researchers, which assumes that the element current distribution does not vary from element to element.

In the spirit of demonstrating why applying the pattern multiplication concept to coherent co-located MIMO radars is not the correct approach, let's estimate the radiated fields of 6 isotropic elements, $f^i(u, v) = 1$, placed on the x -axis, the radiators are separated by 0.5λ , ignoring coupling effects, $\Gamma_n^a = 0$, where all elements have a unitary excitation, $a_n = 1 \forall n$. The fields generated with this approach can be observed on Figure 1.1.

Figure 1.2 is obtained with (1.1) for a ULA with unitary excitations ($a_n = 1 \forall n$). But this time using the V-pol estimated ARC, Γ_n^a , at each element and the isolated element pattern, $f^i(u, v)$, modeled with SENTRi as described in Chapter 4. The differences between Figure 1.1 and Figure 1.2 reveal that the total radiated fields are affected when the coupling between elements and the antenna element type are considered. It appears that the null locations were not changed ($u = \pm 0.4, u = \pm 0.6$),

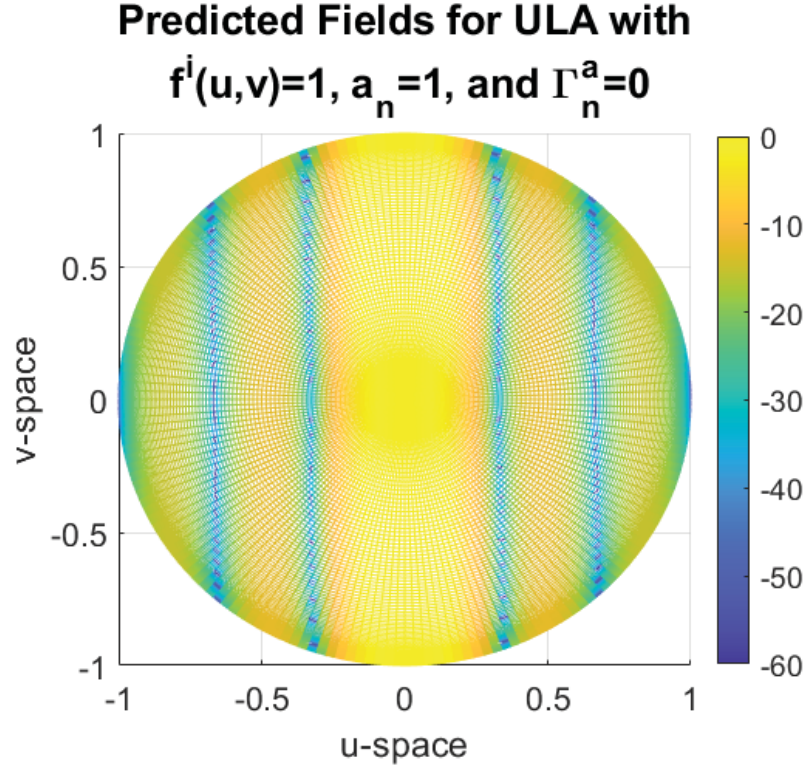


Figure 1.1: Radiated fields of an array of 6 isotropic elements using Equation (1.1)

but the energy on the main lobe of Figure 1.2 is more centered in $u = 0$, and the first sidelobe level decreased to -12 dB.

Figure 1.3 is the normalized radiated fields (at a specific time) for the ULA configuration with vertical polarizations obtained with Equation (1.1). We used the isolated element pattern, $f^i(u, v)$, as described in Chapter 4. Figure 1.3 was generated using the excitations, $a_n = [e^{j\pi} \ e^{j\pi} \ e^{j0} \ e^{j0} \ e^{j\pi} \ e^{j\pi}]$. The selected excitations are considered at one instant of time or one code "chip". The normalized radiated fields depict nulls at $u = \pm 0.2$ with an amplitude below -20 dB and energy centered at $u = 0$. Since the excitation values considered a_n are symmetric, it appears the nulls are also symmetric with respect to $u = 0$.

Predicted Fields for ULA with $f^i(u,v) \neq 1$, $a_n = 1$, and $\Gamma_n^a \neq 0$ for V-pol

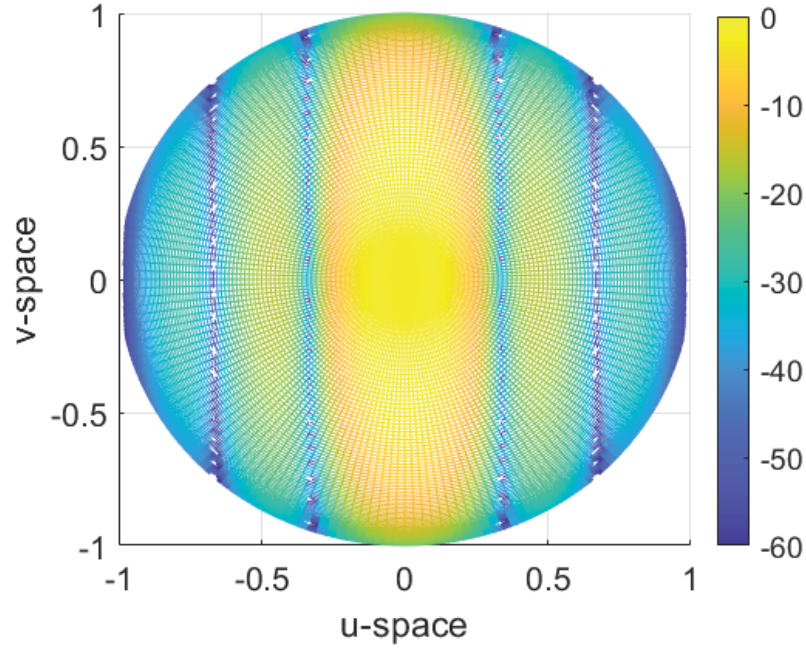
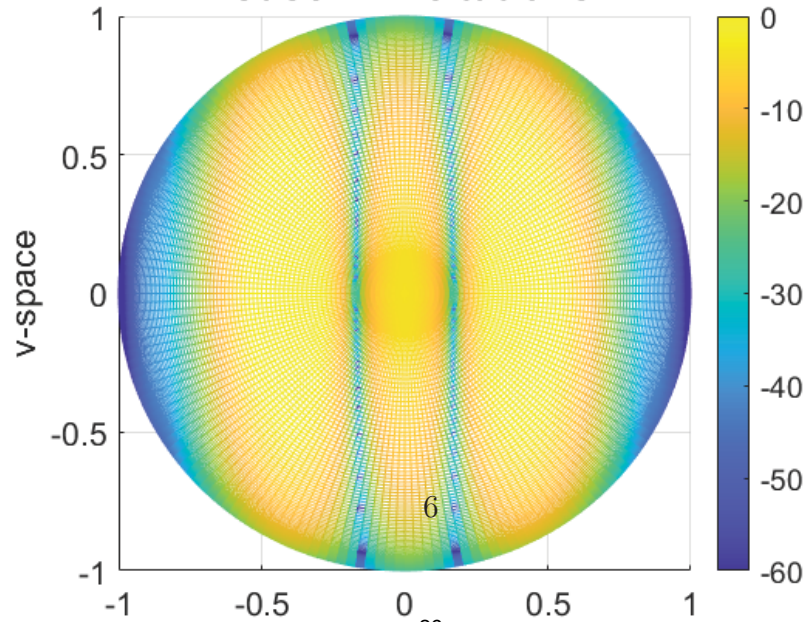


Figure 1.2: Approximated normalized radiated fields of a MIMO radar considering mutual coupling, the isolated radiation pattern for vertical polarization, applying uniform excitations, (1.1). Colorbar units in dB.

Radiated Fields for ULA with Case 1 Excitations



The comparison between Figures 1.1-1.3 demonstrates that the mutual coupling and the excitation selected play an important role on the radiated fields, which is observed by the changes in the null location and amplitudes. In addition, a comparison of Figure 1.1 with Figure 1.3 clearly highlights the importance and shows the impact of this research. What should be taken away from these figures is that (i) antenna mutual coupling and the excitations of the elements play an important role in the performance of the radiation pattern of a MIMO radar system and that (ii) these parameters must be considered in the design of the system and its waveforms.

To contextualize our research, we provide an overview of work that has been done in the past.

1.2 Background

The word "radar" evolved from the acronym to "radio detection and ranging". A radar transmits a signal into a specific direction and receives the reflected signal from objects within that direction. In other words, it receives an echo of the transmitted signal, from which information such as the size, speed, angular location and range of a target can be extracted [8]. With mechanically steered arrays, such as the one shown in Figure 1.4, the radar beam must be re-positioned mechanically to cover a new direction of interest. This type of radar uses the same excitation or waveform across all elements and uses only one power source to drive the entire array.

In any antenna array, elements that are electrically close interact with one another altering the currents or impedances. Whether the antennas are transmitting and/or receiving, some of the energy is interchanged between the antennas [9, 10] compromising their performance. Mutual coupling can cause increased side-lobes, as well as changes in gain, beam-width, null locations, and bandwidth, among others effects [9, 10, 11, 12, 13, 14, 15, 16]. For instance, there has been work dedicated to



Figure 1.4: Mechanically steered arrays. (Figure taken from militaryaerospace.com)

understand mutual coupling on systems performing single functions in passive mode. The assessment of mutual coupling effects on the performance of adaptive arrays has been done in Refs. [17, 18, 11], while that on phased arrays for direction finding can be found in [19, 12, 15].

Mutual coupling can also be observed on adaptive antenna arrays. Hui in [20] considers the scattering effect of other antennas within the array to re-define mutual impedances and to accurately position the nulls of the radiation pattern in angle of arrival (AOA) applications. Hui [12] uses a modified concept of mutual impedance to characterize the mutual coupling effects in receiving array antennas for direction finding of incoming signals. The work described in [19] estimates AOA of radiation sources with an antenna array and considering mutual coupling between its elements. Yuan [21] uses computational electromagnetic (CEM) techniques, specifically the method of moments (MOM) and considers mutual coupling effects on antenna elements placed on an infinite ground plane. Pasala [15] shows that mutual coupling between ele-

ments of a phased array system degrades the performance direction of arrival (DOA) estimation algorithms. Pasala used CEM to compensate for the mutual coupling on adaptive algorithms by correcting for the voltage at the antenna terminals using an impedance matrix estimated from MOM. The work presented in [13] describes the design of a mutual coupling compensation network for a monopole receiving array, and [16] presents an analysis of a linear array antenna that includes the effects of mutual coupling. Dandekar [22] investigates the benefit of mutual coupling compensation via using a MOM approach that computes the array response to be applied towards the direction of arrival of a uniform circular array antenna. Mutual coupling is observed in adaptive antenna arrays affecting the performance of such arrays. Gupta in [17] and [18] demonstrated that the performance of an adaptive array on the signal-to-interference-plus-noise-ratio or SINR depends on the electromagnetic properties of the antenna array. His work [17, 18] ignores coupling effects and such effects are an important electromagnetic property of real arrays. In [11] Gupta describes that adaptive arrays experience significant degradation on SINR when the inter-element spacing is large and drastic degradation if the separation between elements is smaller than half a wavelength. The metric Gupta uses to analyze coupling effects on adaptive antenna arrays is the SINR.

When dealing with single functions in active mode, Pozar [7] used the active reflection coefficient (ARC) as a metric for assessing phased array performance, whereas [23] applied the active input impedance of the elements as a function of scanning angle. The ARC is a function of the excitation and scattering matrix, and since a phased array transmits the same waveform across all elements, but may change the phase to steer the beam, then for phased arrays the ARC is only a function of the phase and of the scattering matrix.

Modern RF sensors are also evolving towards a capability to execute multiple func-



Figure 1.5: Active electronic scanning array. (Taken from airforce-technology.com)

tions such as communication, electronic warfare, and radar tasks such as search, tracking, and imaging simultaneously. As commercial communication and defense systems consume more spectrum, multi-functional operation demands techniques to alleviate spectral congestion and to improve the efficiency by sharing the spectrum between different functions. MIMO is a technique that enables diverse multi-functionality and allows transmission of simultaneous independent waveforms from different radiators or sub-arrays. Even though the multi-functionality of MIMO techniques could be the key approach to accommodate these features, the concept demands careful understanding of each function, its behavior and how each subsystem, defined by function and sub-array, interacts with one another. Early digital signal processing research on these type of sensors [24] ignored electromagnetic effects, such as coupling or interactions between elements.

MIMO arrays will be highly digital, capable of self-calibrating, perform simultaneous tasks by applying multi-functional waveforms, and characterized by a wide band frequency range. Each element or sub-array transmits a different waveform providing

multi-functionality to the system [25]. A notional representation of such a modern system is shown in Figure 1.6.



Figure 1.6: Multi-functional RF sensor.

MIMO was initially used in the area of telecommunications to improve the capacity of a radio link. The MIMO system employed multiple antennas transmitting different streams of information from several de-correlated transmitters at both ends of the link to overcome fading problems caused by multi-path propagation [26, 27, 28, 29].

Recently, MIMO techniques have been used by the radar community [30, 31, 32] to provide improvements on target detection capabilities, spatial resolution, parameter identification, and interference rejection [30, 32, 33, 34, 35]. A MIMO radar is a system that can offer waveform diversity because the system can transmit different orthogonal waveforms that are separated at the receiver's end [36, 30, 32, 33, 34, 35, 37, 38, 39, 40, 41, 42, 43, 44, 45]. In addition to waveform diversity, MIMO radars can also achieve spatial diversity when transmit and receive elements are separated

[30, 32, 34, 46, 47, 48].

MIMO radar antennas can be configured to be widely separated [8, 30, 32, 34, 46, 47, 49] or co-located [30, 32, 34, 39, 41, 49]. According to [34] there are two main configurations of MIMO radars: statistical and coherent MIMO radars. Statistical or distributed MIMO radars have all antenna elements widely separated providing a diversified view of the target and each transmit-receive pair has a difference reference frame. Because of the wide separation of the elements, non-coherent processing is widely used (phase information is not considered). In the case of moving target indication, having widely separated antennas reduces the possibility of the target being buried in stationary ground clutter [50, 51]. The coherent or co-located MIMO radars have all elements spaced electrically close in a sub-array cohering a beam towards certain direction in space. Each transmit-receive pair has the same reference frame. Because of the electrically small separation of the elements, coherent processing can be done using the same phase reference (phase information is considered). As a result, this configuration improves angular resolution and allows direction finding [30, 32, 34]. Angular resolution can be further improved by using sparse arrays [49]. Coherent MIMO radars have the same structure as a phased array [39]. Phased arrays transmit the same waveform at each transmit element and are able to cohere and steer the transmitted energy to form a focused beam [9, 10, 51]. A key aspect of MIMO radar systems is the ability to transmit multiple orthogonal waveforms or uncorrelated waveforms at each transmit element, each illuminating the scene uniformly [8, 30, 32, 34, 39, 46, 47, 49]. While this means that no beam scanning is necessary, the transmit gain of a focused beam is lost.

The diversity in the waveform transmission and the localization resolution are limited by the MIMO system's bandwidth [38, 52]. Therefore to provide waveform flexibility and localization resolution, the system requires a wide-band antenna. Another

desired characteristic of MIMO radar systems is the ability to track multiple targets at the same time [42]. This is possible when the array antenna is divided into sub-arrays to form beams and unique waveforms towards each target [39, 40, 41, 44, 53, 54]. When mutual coupling is present, the transmitted waveforms will be somewhat different from what the signal is believed to be when mutual coupling is not present [36, 55]. For these cases, the isolation between elements is extremely important to reduce the mutual coupling [56].

Mutual coupling on MIMO radars requires careful attention for high power applications where the reverse energy can be large enough to damage the transmitter. Transmitter-induced distortions from high power radars induce alterations to the intended waveforms [57, 58]. Active arrays are implemented with power amplifiers, and these amplifiers cause substantial unwanted interference and out-of-band transmissions that could appear in neighboring channels through mutual coupling [59, 60, 61].

Typical MIMO signal processing algorithms assume that the waveforms emitted from each antenna element are orthogonal [30]. The waveform orthogonality assumption can be enforced using time, frequency, time-frequency, or coding degrees of freedom [62, 63]. For a code division MIMO system, the waveform emitted from each element is inherently non-coherent and non-stationary in time.

Pioneers in the field of multi-functionality have enhanced the state-of-the-art by combining simultaneous radar and communication functions utilizing multi-beam radar and communications waveform design [64], incorporating tandem-hopped techniques for embedding communication signals on radar functions [65, 66], and applying waveform optimization techniques to increase joint radar and communications performance [67, 68, 69, 70].

Others have demonstrated the feasibility of a joint radar-communications receiver used for communications and synthetic aperture radar functions [71], and the im-

plementation with software defined radios [72], deriving bounds and concepts for multi-functionality [73, 74], introducing metrics [75] and system performance [76, 77] for the spectrum sharing problem analysis between radar and communications [78]. The work of [79, 80, 81] provide a comprehensive overview and a starting point to researchers working on these areas.

The realization that one needs a more complete full coupled solution, or a solution wherein the operation is correlated to both power and spatial coupling is more recent. Few researchers have addressed the coupling effects for co-located multi-function MIMO radar systems. For instance, Babur [36] stressed the importance of understanding the impact of mutual coupling on MIMO in active mode and its effect with space time codes radiated signals and validated results with using a linear array of patch radiators. Babur assumes independence between transmit and receive modes. She studies the impact of coupling effects on beam-forming during transmission when ideal orthogonal and typical space-time codes are simultaneously radiated. The coupling analysis on the beam-forming during transmit is achieved by applying different values to the coupling coefficients, which are then used to form the beams. The existence of antenna coupling was validated with a collection of experimental data. Babur improved the degradation caused by the coupling with a calibration technique.

Next, Arnold [82] developed a mathematical model that quantifies the effects of mutual coupling from a uniform linear array (ULA) of dipoles on target detection performance of a MIMO radar using orthogonal excitations. The model developed by Arnold establishes a connection between the virtual array wide-band signals and physical coupling. With this analysis, the author is able to separate contributions from coupled paths obtained with different case scenarios. To improve the performance in target detection, Arnold explored impedance transformers or impedance matching

networks under different conditions. Arnold was able to demonstrate that the presence of antenna coupling created a 12° of target location error and increased side-lobe levels to 8 dB. Arnold analyzes changes in target detection performance through the SNR and the side-lobe level.

Schmid et al. [83] incorporated calibration techniques on MIMO radar systems using frequency modulated continuous wave (FMCW) to compensate for mutual coupling effects on side-lobe levels.

Mutual coupling effects have been studied for receive mode, and Savy [4] used the concepts developed in [7] to produce the first analysis of ARC and active VSWR for a code division MIMO radar using a uniform linear array of dipoles as the transmit aperture.

According to Savy [4] the random phase transmission from a coherent co-located MIMO radar is important for the transmit antenna as random like or opposite phases between neighboring elements can add constructively or destructively. Because the system transmits different waveforms or excitations across all elements, the ARC is a function of phase, amplitude, and scattering matrix. Savy estimated the ARC by estimating the scattering or S-parameters with the closed form solution of the uniform linear dipole antenna array. The scattering parameters, and the element excitations were then used to calculate the ARC, the active VSWR, and the element patterns [7].

Colon-Diaz et al. [5] extended Savy's approach applying computational electromagnetics (CEM) to compute the ARC from any type of antenna element. This work is discussed in Chapter 2. Also, the methodology developed in [5] is validated in [6]. Using dual directional couplers (DDC) to obtain direct measurements of the forward and reverse waves, proportional to the coupled power, on each radiator of a dipole array. Additionally, [84] controlled the degradation caused by the coupling effects with

a waveform designed to limit the coupling between the elements to a given value. The first direct measurement of the ARC on a co-located MIMO radar and analysis of the effects of the antenna mutual coupling and the excitations on the performance of the antenna patterns by comparing the expected and measured antenna patterns are presented in [85].

1.3 Summary of the Chapters that Follow

The remaining of this document is organized as follows:

Chapter 2: Novel Active Reflection Coefficient Analysis for Co-located MIMO Radar Applications Using CEM Modeling - A methodology to assess co-located MIMO radars in transmit mode is discussed. This chapter explains a flexible methodology to obtain the ARC by using CEM tools, specifically MOM. The methodology allows ARC calculation of three different linear arrays acting as co-located MIMO radars in transmit mode, when each element is radiating random phase coded waveforms. Then the active VSWR was calculated to obtain an estimate of the system performance. In addition a Monte Carlo technique of 10,000 realizations is applied to obtain an estimate of how these parameters will affect system performance.

Chapter 3: Measurement of Active Reflection Coefficient for Co-located MIMO Radar Using Dual Directional Couplers - The methodology previously discussed is validated with experimental data. The collected data is obtained from direct measurements of reverse and forward coupled ports of dual directional couplers (DDC) to determine the ARC. Then the active VSWR is calculated to obtain an estimate of the system performance.

Chapter 4: Analysis of Impact of Co-located MIMO Radar Transmitting Arbitrary Waveforms on ARC and Antenna Pattern - Validation of the methodology previously developed by directly measuring the ARC and the beam-patterns on co-located MIMO

radars is presented. In addition, the effects that mutual coupling and the excitations have in the radiated fields on a MIMO radar transmission are analyzed.

Chapter 5: Performance Compensation of Mutual Coupling Effects via Waveform Design - An approach to control or mitigate ARC effects on multi-functional systems will be presented. A waveform design optimization technique to constrain the coupled power to a specific value is described.

Chapter 6: Conclusions - This chapter provides conclusions of the current work.

Chapter 7: Future Work - This chapter provides a description for future work.

NOVEL ACTIVE REFLECTION COEFFICIENT ANALYSIS USING COMPUTATIONAL ELECTROMAGNETIC TOOLS

In this chapter, mutual coupling is analyzed from calculations of the active VSWR and the reflected power of a coherent co-located MIMO radar when random phase coded waveforms are transmitted. The scattering matrices of a co-located MIMO radar antenna array were obtained from CEM modeling methods. A Monte Carlo simulation of 10,000 realizations was used to produce time-varying random phase codes and estimate distributions for the VSWR and reflected power.

2.1 Introduction

Co-located MIMO radar technology has been proposed as an alternative to traditional scanning arrays [30]. By transmitting orthogonal waveforms at each element, a MIMO radar illuminates the entire surveillance volume with each pulse, rather than sweeping a beam through the search area as a traditional phased array might. In addition, the increased degrees-of-freedom offered by the orthogonal waveforms provides superior angular resolution as compared to traditional arrays [30, 41, 86]. However, it should be noted that the increased flexibility offered by MIMO technology is not without tradeoffs, most particularly in the reduction in SNR and potential to transmit power in the imaginary space (i.e. in directions beyond the spatial endfire direction) [87, 88, 3, 80]. As with any new technology, it is important to revisit underlying assumptions and examine whether they require updating.

One key physical effect of using an array of antennas is mutual coupling. Mutual coupling arises when the time-varying current on an antenna element couples

to nearby elements, exciting currents on them [9]. Typical MIMO signal processing algorithms assume that the waveforms emitted from each antenna element are orthogonal [30]. The waveform orthogonality assumption can be enforced using time, frequency, time-frequency, or coding degrees of freedom [62, 63]. The latter case is the most interesting from a mutual coupling perspective. Specifically, for a phased array the same signal is sent through each element, offset only by a steering phase. For a code division MIMO system, the waveform emitted from each element is inherently non-coherent and non-stationary in time.

The first examination of the non-stationary nature of coded MIMO emissions and their impact on mutual coupling was done by Savy in [4]. Specifically, he used the concepts developed in [7] to produce the first analysis of active reflection coefficient and active VSWR for a code division MIMO radar using a uniform linear array of dipoles as the transmit aperture. This process provided the analytical active reflection coefficient of the array when excited by random binary phase codes. However, this procedure lacks flexibility when considering arbitrary geometric arrangements and antenna elements. Therefore, we examine the use of CEM tools, specifically Method of Moments (MoM), to investigate the effects of mutual coupling for co-located MIMO transmission using code division waveforms. In the spirit of [4], we focus on transmitter effects (e.g. VSWR, power reflection), rather than the far field beam-pattern effects (as was examined in [36]). In particular, we produce the distributions of the VSWR and power reflection caused by the time-varying, random phase codes, and consider several common types of antenna elements.

The benefits of improving our understanding are two-fold. First, knowledge of mutual coupling can improve calibration procedures and provide key information to system designers (especially with respect to transmitter losses). Second, recent research has examined the impact of amplifiers on waveform characteristics, and considered

methods of including hardware effects into waveform optimization routines[57, 58, 89]. A better understanding of mutual coupling along with more sophisticated modeling tools (through use of CEM) will provide a similar avenue of joint hardware-waveform optimization for MIMO transmit schemes.

2.2 Mutual Coupling Analysis Computational Electromagnetic Modeling

The scattering parameters or S-parameters are the key to estimating the active VSWR and the mutual coupling. In this chapter, computational electromagnetic modeling provides accurate field predictions for arbitrary antenna structures enabling the derivation of the S-parameters.

Procedure

The steps needed to calculate the active reflection coefficient and active VSWR are depicted in Figure 2.1. First, the waveform must be defined, which will provide the frequency and phase information needed for the analysis. The antenna is described by its CAD model and its electromagnetic constitutive parameters, conductivity (σ), permittivity (ϵ), and permeability (μ). This information is used to generate the discretized antenna geometry or mesh used by the CEM engine [90]. Finally, the S-parameters are computed with the CEM technique known as Method of Moments [90], which in conjunction with the amplitude and phase information obtained from the waveform generator will define the active reflective coefficient and VSWR [7]. There are several different CEM methodologies that can be employed. The objective of this research is not to go into details on CEM methodologies, but the work of [90] and [91] offer a more in depth description of all the different techniques and applications. A basic description on the methodology used will be expanded upon in the next section.

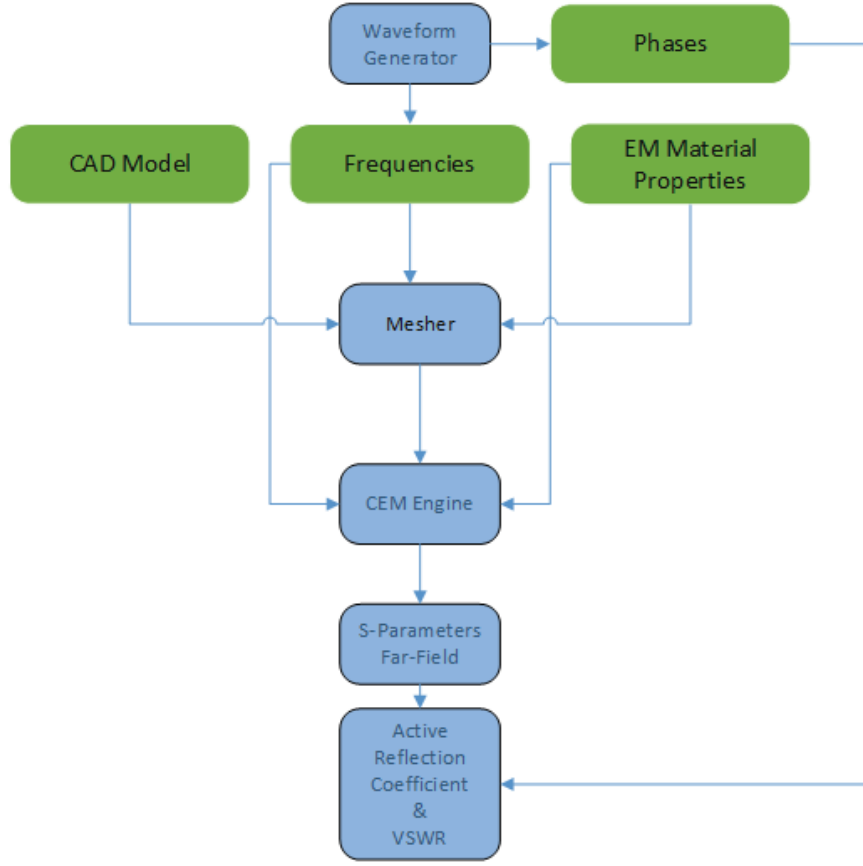


Figure 2.1: Flowchart to obtain active reflection coefficient and VSWR.

Computational Electromagnetic Methods

CEM methods are used to estimate electromagnetic interactions between field excitations on a target by solving Maxwell's equations in the frequency domain or in the time domain [91]. These numerical methods represent an approximation of the electromagnetic fields or surface currents as a linear combination of basis functions of N terms, written as

$$\begin{aligned}
g(z') &\simeq a_1 g_1(z') + a_2 g_2(z') + \dots + a_N g_N(z') \\
&= \sum_{n=1}^N a_n g_n(z')
\end{aligned} \tag{2.1}$$

where a_n are unknown constants to be determined by the numerical methodology and g_n are known functions. Maxwell's equations and its related vector wave equation can be represented in operational form L as

$$L(g) = h \tag{2.2}$$

where h denotes the excitation function, in this case the antenna excitation. An approximated solution for equation (2.2) can be found in the average sense by discretizing the continuous infinite space using a suitable set of vector testing functions t_m and in conjunction with (2.1) the discretized system is written as

$$\sum_{n=1}^N a_n \langle L(g_n), t_m \rangle = \langle h, t_m \rangle, m = 1, 2, \dots, N \tag{2.3}$$

where $\langle, \rangle$ represent the innerproduct operation [90]. Equation (2.3) can be expanded into a set of N equations with N unknowns, which can be organized into matrix form $ZI = V$ as

$$[Z_{mn}][I_n] = [V_m] \tag{2.4}$$

where $Z_{mn} = \langle L(g_n), t_m \rangle$, $I_n = a_n$ and $V_m = \langle h, t_m \rangle$. The unknown a_n can be found by solving (2.4) using matrix inversion techniques [90]. The S-parameters are extracted from the relation between the discretized source and the coefficients a_n of the elements enclosed by the excitation. The calculation of the ARC and active VSWR will be expanded in the next section.

2.3 Early Simulations Focusing on the Analysis of Coupling Effects Under Different Inter-Element Spacing and Polarization

It is a challenge to implement co-located MIMO radars on small platforms without understanding mutual coupling effects between the elements in transmit mode. This coupling will cause a single element to transmit its own signal, but also the signals of nearby elements.

Varying the separation between elements of an antenna array will influence the mutual coupling effects experienced by the elements within the array. As part of the research goal: “to develop validated methodology to understand, analyze and predict mutual coupling effects on co-located MIMO radars”, this section shows simulations of linear arrays with different element spacing when transmitting random binary codes. Using the methodology developed in [5], the active reflection coefficient effects are estimated from the mutual coupling parameters. If the elements are electrically closer, there will be larger coupling between two nearby antenna elements due to near field interactions; therefore the individual elements will experience more reflections (which can be seen on the behavior of the ARC and active voltage standing wave ratio, VSWR). In addition, different element polarizations were simulated and investigated. Different element polarizations clearly excite different creeping waves impacting the active reflection coefficient. These results provide a better understanding and proof that MIMO transmission must be considered for the antenna element design, its inter-element spacing, and its polarization. Otherwise, unexpected levels of reflected energy could compromise the backend electronics.

As a first step, a baseline of three different antenna elements is considered. The elements are a dipole, a patch, and a horn (as shown on Figures 2.2, 2.3, and 2.4, (respectively) and they are analyzed by estimating their reflection coefficient and the

corresponding VSWR. A common criteria of acceptable return loss for a transmitting antenna is that its VSWR is less than 2 [92] [93] [94]. To maintain this criteria ($VSWR \leq 2$) the reflection coefficient cannot be greater than 0.3333. The VSWR is calculated from Equation (2.5)

$$VSWR_n = \frac{1 + |\Gamma_n|}{1 - |\Gamma_n|} \quad (2.5)$$

where Γ_n represents the ARC of antenna n .

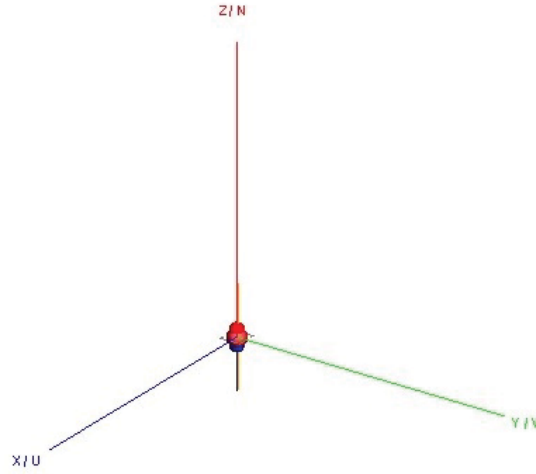


Figure 2.2: Single dipole. The reflection coefficient or S_{11} for single dipole is 0.2902 ($VSWR = 1.818$).

All three elements should be considered good antennas since their VSWR is less than 2. From these results it is clear to see that the reflection coefficient and VSWR observed from the horn antenna are the lowest (0.08645 and 1.189). The second step is to complete an analysis of the coupling effects due to variations of both inter-element spacing and polarization on the linear array configuration. The purpose of this analysis is to better understand the influence these parameters have on the active reflection coefficient and VSWR. Analysis of the vertical polarization is the

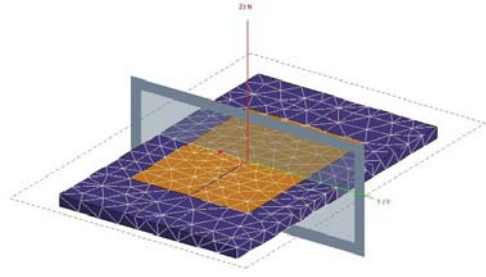


Figure 2.3: Single patch. The reflection coefficient or S_{11} for patch antenna is equal to 0.3192 (VSWR = 1.9838).

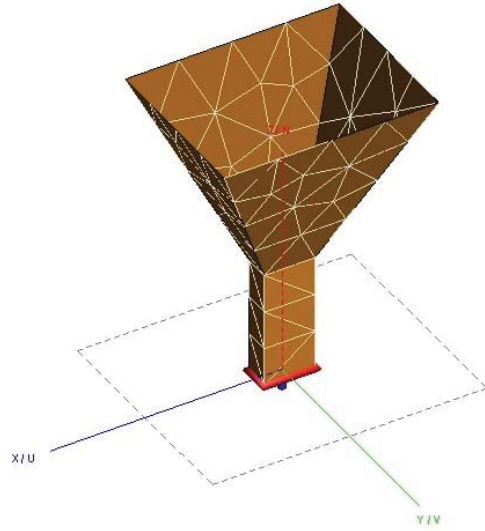


Figure 2.4: Single horn. The reflection coefficient or S_{11} for horn antenna is equal to 0.08645 (VSWR = 1.189).

initial case, followed by the analysis of the arrays with horizontal polarization. Both polarization cases are expanded by varying element spacing.

2.3.1 Vertical Polarization

For the first case the distance of each element of a linear array (center to center) is 3.117λ . The dipoles, patches, and horns are oriented in such a way that the electric

field is vertically polarized. Figure 2.5, depicts the element configuration of a pair of horns, patches, and dipole antennas, presenting the separation from feed to feed, R , the element orientation, and the dimensions of each element. The dimensions of the elements includes width, W , length, L , and electric field direction for horns and patches. D represents the length of the dipole antennas.

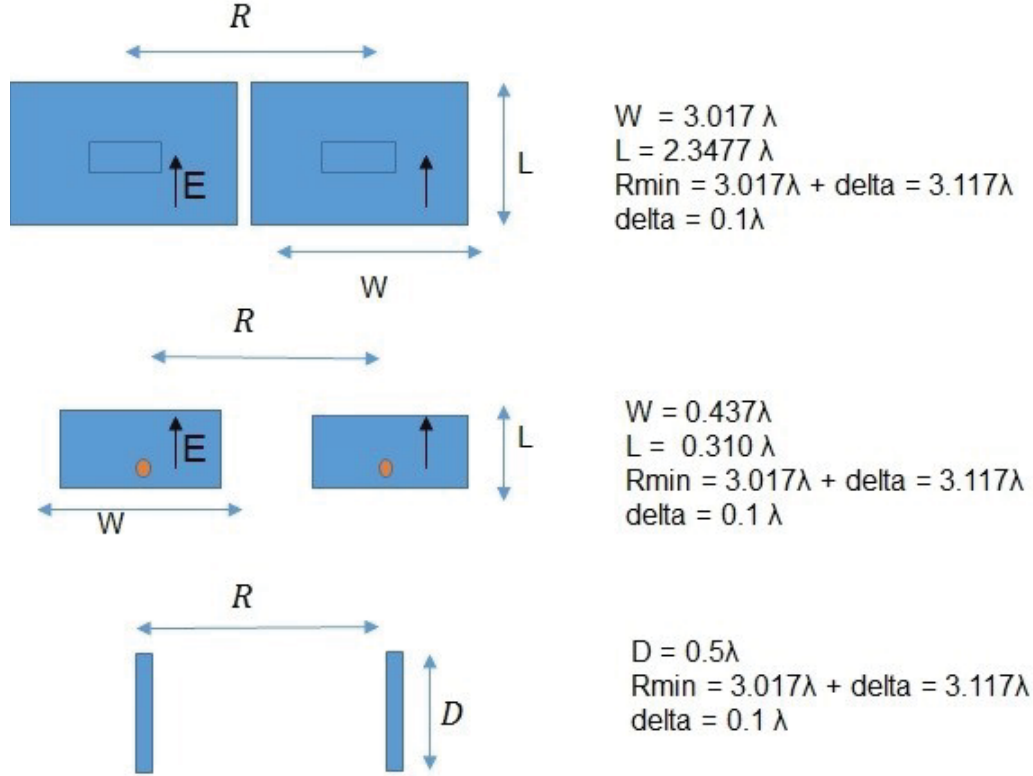


Figure 2.5: Pairs of horns, patches, and dipoles depicting their orientation, dimensions, and separation.

Figures 2.6 to 2.11 depict the active reflection coefficient of the three 12-element linear arrays (horns, patches, and dipoles) with a uniform separation of 3.117λ . Figures 2.6, 2.8, and 2.10 represent single tone transmissions (meaning the same waveform was transmitted from each antenna, simultaneously and independently) while Figures 2.7, 2.9, and 2.11 present MIMO transmissions with random binary phase

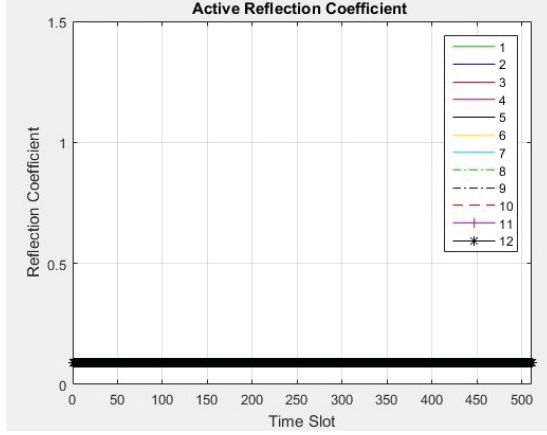


Figure 2.6: 12-element horn array single tone transmission. Vertical polarization.

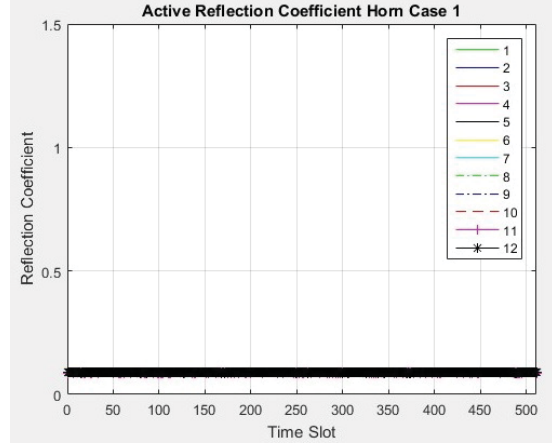


Figure 2.7: 12-element horn array MIMO transmission. Vertical polarization.

codes (independently transmitted from each antenna).

It can be seen that for both transmissions (single tone and MIMO transmission), the patch array (Figure 2.8-2.9) experiences greater reflected power than the dipole (Figures 2.10-2.11) and horn arrays (Figures 2.6-2.7). Considering the variation of the reflection coefficient for all cases of a MIMO transmission, the variations are minimum for the horn array (Figures 2.6-2.7) and are larger for the dipole array (Figures 2.10-2.11). Since the horn is a directive antenna element its coupling is the weakest of the three cases. The inter-element spacing of the patch and dipole arrays is considered to be in the far field. The far field region is expressed as $R \geq 2D^2\lambda$, where R is the distance between elements and D is the largest dimension of the element [9]. The largest dimension of a patch antenna is 0.437λ and for the dipole is 0.5λ . For this scenario, that R is equal to 3.117λ , which indicates the inter-element spacing of the patch and dipole arrays are in the far field.

The horn array (Figure 2.6-2.7) has an active reflection coefficient much less than 0.333, therefore the VSWR of this array will be less than 2. Recall that a VSWR

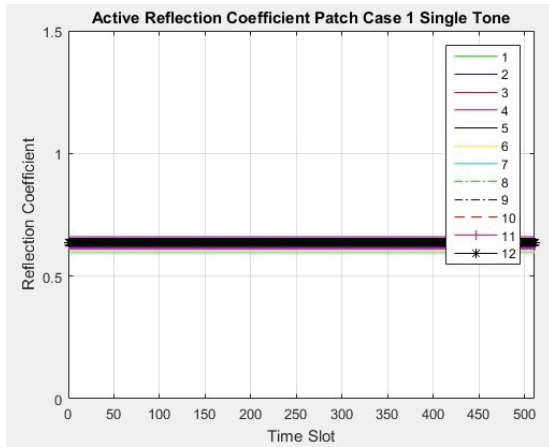


Figure 2.8: 12-element patch array single tone transmission. Vertical polarization.

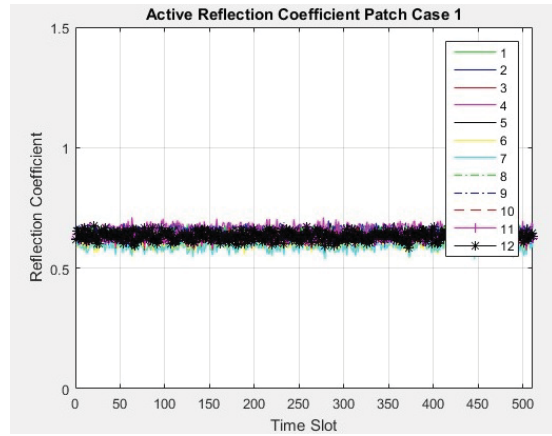


Figure 2.9: 12-element patch array MIMO transmission. Vertical polarization.

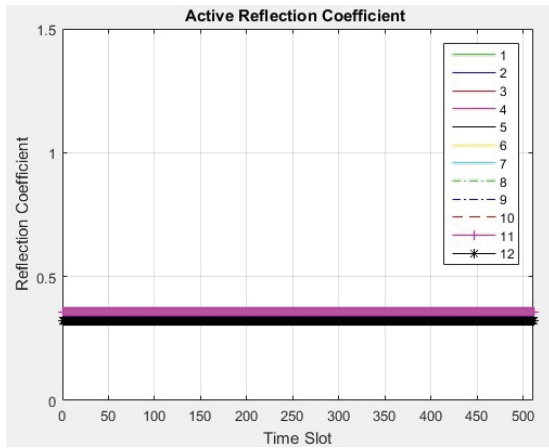


Figure 2.10: 12-element dipole array single tone transmission. Vertical polarization.

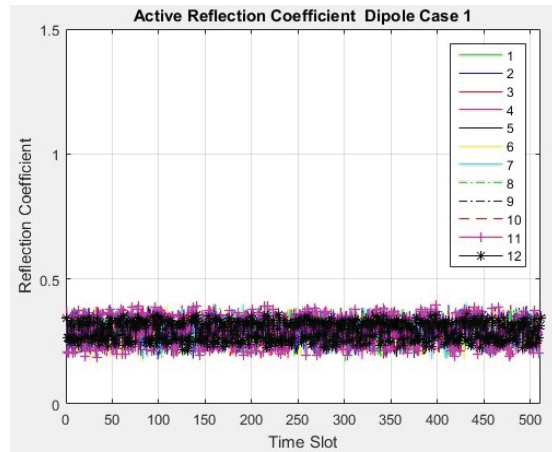


Figure 2.11: 12-element dipole array MIMO transmission. Vertical polarization.

less than 2 is generally acceptable for a transmit antenna. The patch (Figure 2.8-2.9) and dipole (Figure 2.10-2.11) arrays display active reflection coefficients greater than 0.3333, meaning that these antennas show a VSWR greater than 2.

The second scenario analyzed for vertical polarization is when the patches and the dipoles were moved to a closer position (0.537λ) as in Figure 2.12.

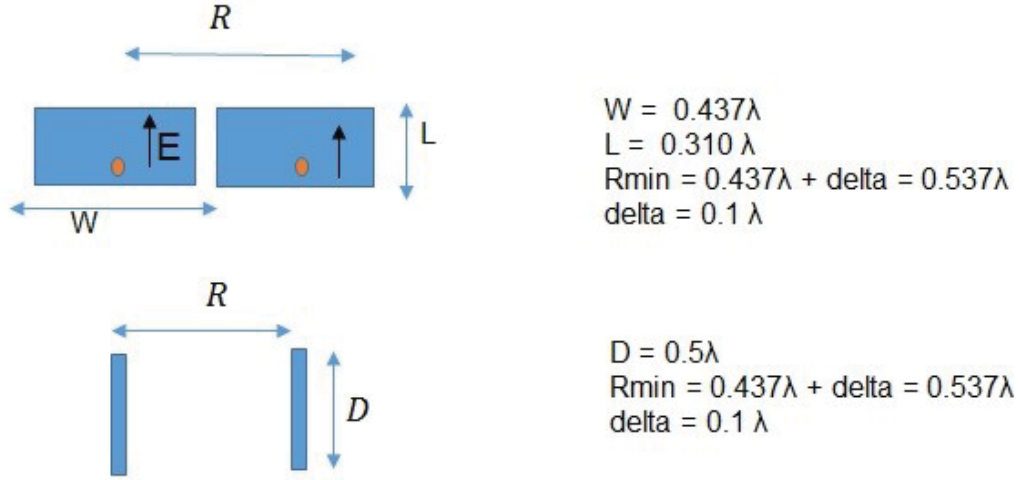


Figure 2.12: Pair of patches and dipoles depicting their orientation, dimensions, and separation.

Figures 2.13 and 2.15 depict single tone transmissions for patch and dipole arrays with vertical polarizations. MIMO transmissions for patch and dipole arrays with vertical polarization are shown in Figures 2.14 and 2.16.

Comparing the case of smaller but still uniform spacing between patch and dipoles, both with vertical polarization, it can be seen that the values of the reflection coefficient are larger for the patch array. However, the variations of the reflection coefficient are larger for the dipole array. The inter-element spacing of this scenario can still be considered to be in the far field, and the expression $R \leq 2D^2/\lambda$ is valid [9].

Comparing Figures 2.8-2.9, with Figures 2.13-2.14 the farther the patch elements are placed from each other the weaker the coupling becomes. Figures 2.15-2.16 show

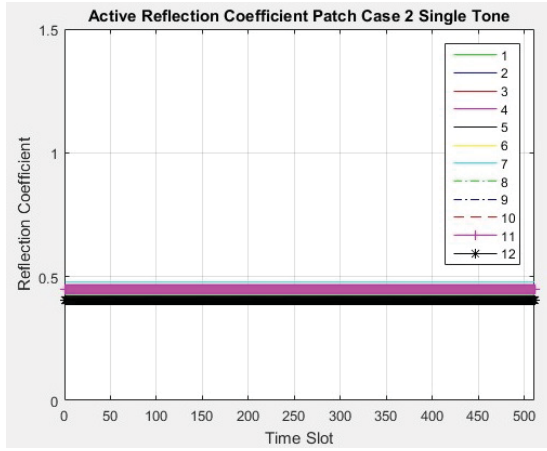


Figure 2.13: 12-element patch array single tone. Vertical polarization.

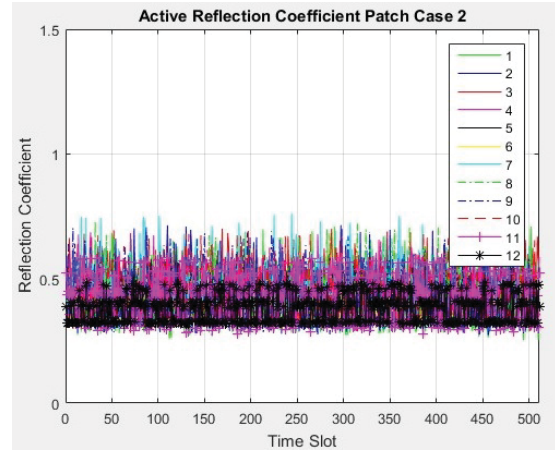


Figure 2.14: 12-element patch array MIMO. Vertical polarization.

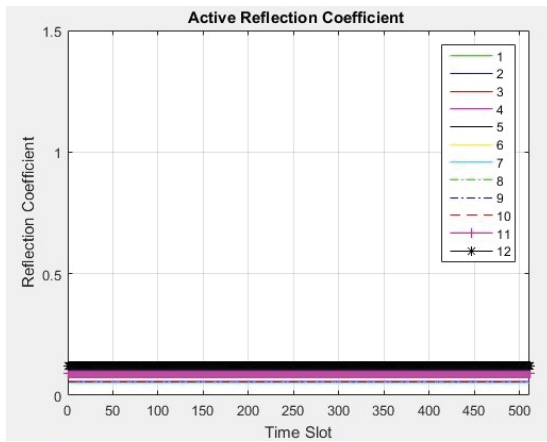


Figure 2.15: 12-element dipole array single tone.

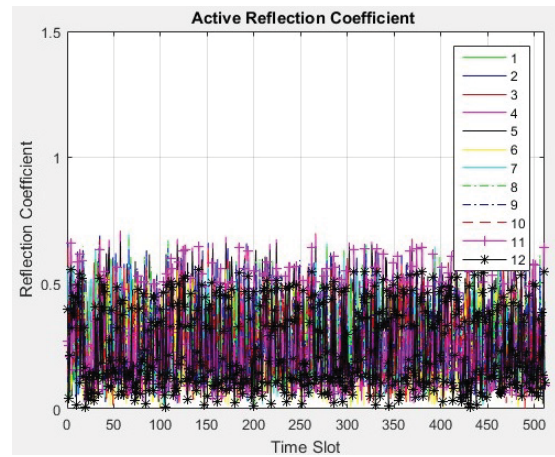


Figure 2.16: 12-element dipole array MIMO.

stronger coupling than is seen in Figures 2.10-2.11, where the inter-element spacing is smaller.

The patch (Figure 2.13-2.14) and dipole (Figure 2.16) arrays display active reflection coefficients greater than 0.3333 ($VSWR \geq 2$).

2.3.2 Horizontal Polarization

In this scenario the dipoles, patch, and horn antennas were placed so that the electric field is horizontally polarized. The separation between antennas is uniform at a distance of 2.4477λ . Figure 2.17, shows pairs of horns, patches, and dipole antennas, with the dimensions and separations used in the simulation.

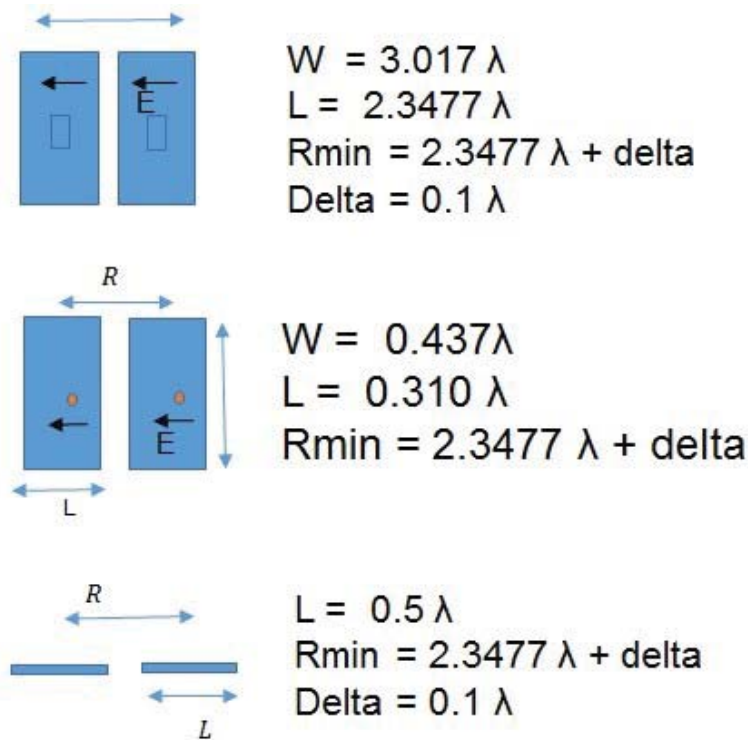


Figure 2.17: Pairs of horns, patches, and dipoles depicting their orientation, dimensions, and separation.



Figure 2.18: 12-element horn array single tone. Horizontal polarization.

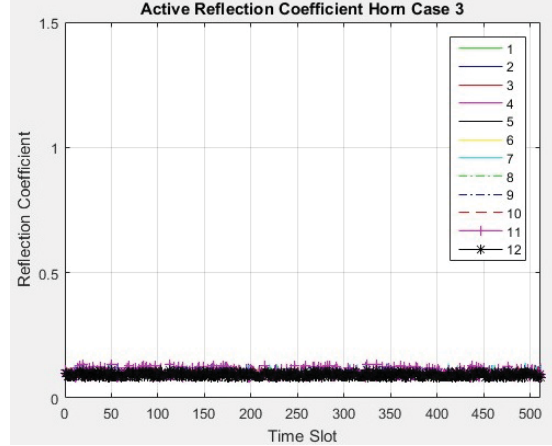


Figure 2.19: 12-element horn array MIMO. Horizontal polarization.

Figures 2.18-2.23 depict the active reflection coefficient of the three linear arrays (horns, patches, and dipoles) at a separation of 2.4477λ . Figures 2.18, 2.20, and 2.22 represent single tone transmissions (meaning the same waveform was transmitted) while the Figures 2.19, 2.21, and 2.23 present MIMO transmissions with random binary phase codes.

The scenario where horn, patch, and dipole antennas have horizontal polarization with uniform distance between feeds shows that the patch array (Figure 2.20-2.21) has a larger reflection coefficient than the dipole (Figure 2.22-2.23) or horn arrays (Figure 2.18-2.19). The variation of the reflection coefficient is minimum for the horn array and is comparable to the dipole array. The patch array presented the largest variation of the active reflection coefficient of the three arrays. Comparing Figures 2.11 and 2.23, dipole array with vertical and horizontal polarizations, respectively, it is clear that the dipole array oriented on a horizontal polarization (collinear arrangement) presents a weaker coupling (Figure 2.23) than the coupling seen from the dipole array oriented with a vertical polarization (Figure 2.11).

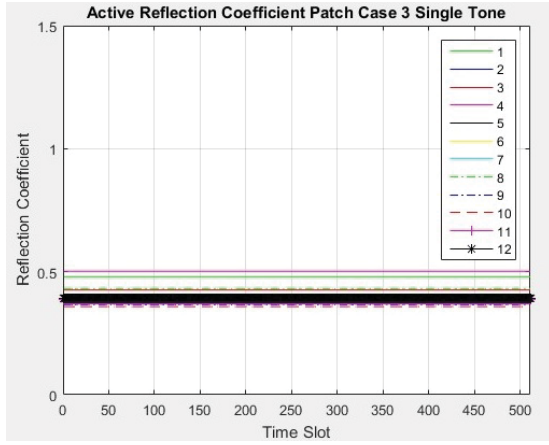


Figure 2.20: 12-element patch array single tone. Horizontal polarization.

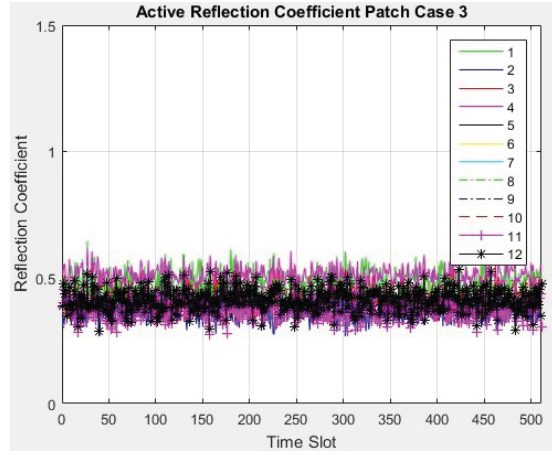


Figure 2.21: 12-element patch array MIMO. Horizontal polarization.

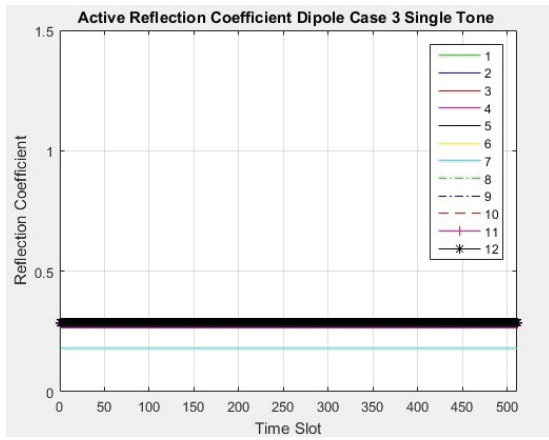


Figure 2.22: 12-element dipole array single tone.

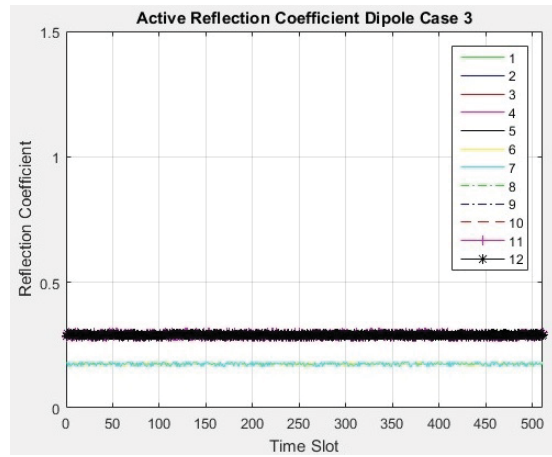


Figure 2.23: 12-element dipole array MIMO.

The patch (Figure 2.20-2.21) and dipole (Figure 2.22 to 2.23) arrays display active reflection coefficients greater than 0.3333 ($\text{VSWR} \geq 2$). The horn array (Figure 2.18-2.19) presents active reflection coefficients less than 0.3333 ($\text{VSWR} \leq 2$).

Another case useful to understand how the inter-element spacing and polarization influence coupling between elements is presented in Figure 2.24, where the centers of the patches and dipoles were moved to a closer distance of 0.60λ . For this case, the inter-element spacing is considered to be in the far field since the expression $R \leq 2D^2/\lambda$ is still met [9].

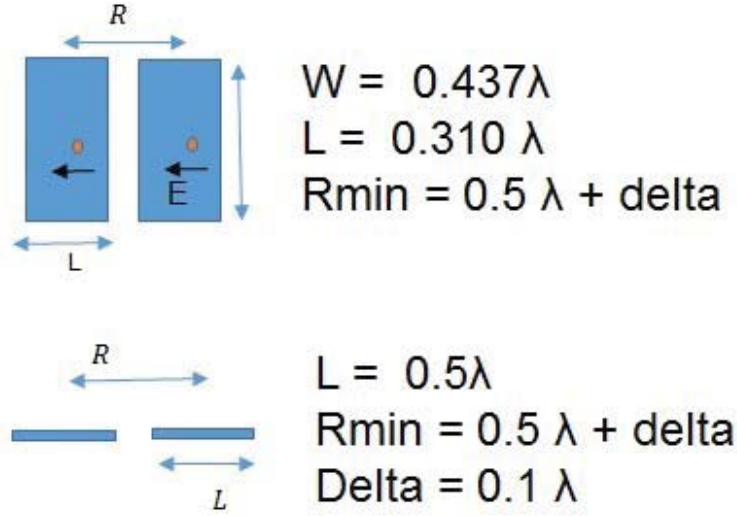


Figure 2.24: Cartoon of pair of patches and dipoles depicting their orientation, dimensions, and separation.

Figures 2.25 and 2.27 present the active reflection coefficient for single tone transmissions while MIMO transmissions with random binary phase codes are shown on Figures 2.26 and 2.28.

This is the scenario where the dipole elements are the closest. The results show that the patch array (Figure 2.25-2.26) has a greater reflection coefficient than the dipole array (Figure 2.27-2.28) and that the variation of the reflection coefficient is

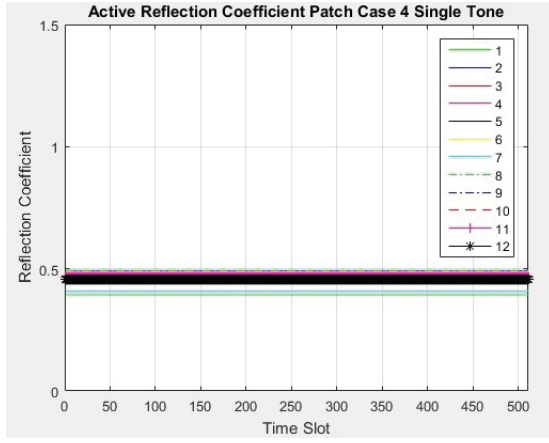


Figure 2.25: 12-element patch array single tone. Horizontal polarization.

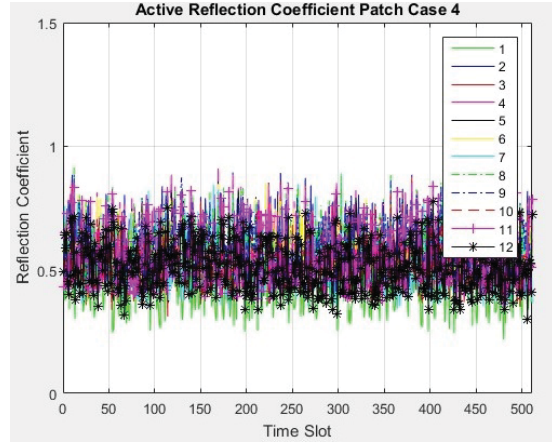


Figure 2.26: 12-element patch array MIMO. Horizontal polarization.

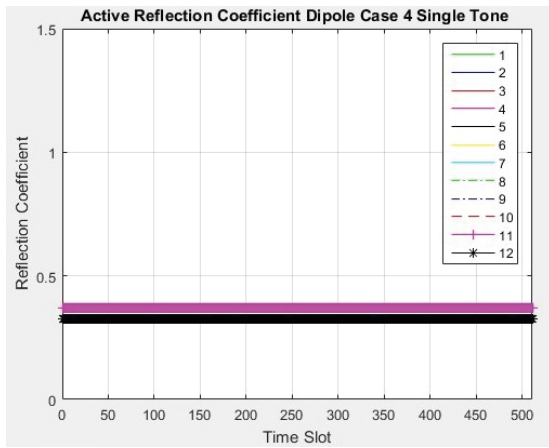


Figure 2.27: 12-element dipole array single tone. Horizontal polarization.

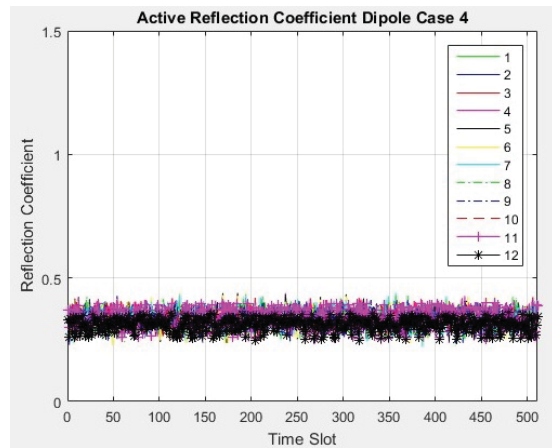


Figure 2.28: 12-element dipole array MIMO. Horizontal polarization.

greater for the patch array (Figure 2.25-2.26) than for the dipole array (Figure 2.27-2.28). The active reflection coefficients for the patch and dipole arrays are greater than 0.333 ($\text{VSWR} \geq 2$).

Figure 2.29 shows a patch array with an inter-element spacing of 0.41λ with a horizontal polarization.

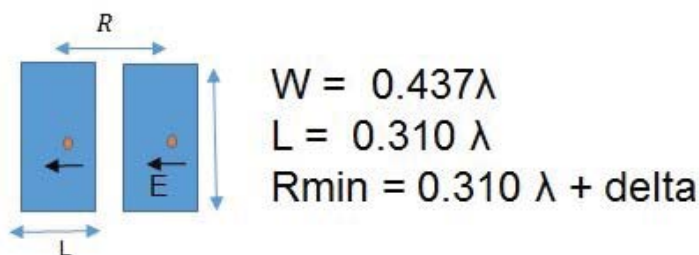


Figure 2.29: Pairs of patch antennas depicting orientation and spacing.

This case, where the inter-element spacing of the patch antennas is minimum or 0.41λ and still in the far field (the larger dimension for the patch array is 0.437λ) clearly shows that the closer the patch elements are and with a horizontal polarization the stronger the coupling between elements, when comparing Figures 2.30 and 2.31 with Figure 2.25 to 2.26. The active reflection coefficient is much greater than 0.333 (Figure 2.30 to 2.31) indicating a VSWR greater than 2.

2.3.3 Additional Case

To prove the existence of greater problems in MIMO radar transmissions, the dipole array with a vertical configuration at a spacing of 0.41λ was analyzed, see Figure 2.32.

It can be seen that some of the values of the active reflection coefficient of a MIMO transmission on the dipole array are greater than 1, Figure 2.34. The cause to this phenomena is that the dipoles are placed too close to each other and are located



Figure 2.30: 12-element patch array single tone. Horizontal polarization.

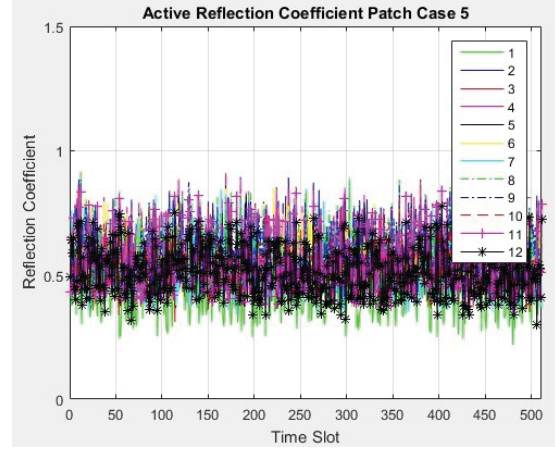
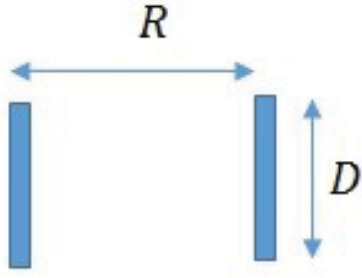


Figure 2.31: 12-element patch array MIMO. Horizontal polarization.



$$D = 0.5\lambda$$

$$R_{\min} = 0.31\lambda + \delta = 0.41\lambda$$

$$\delta = 0.1\lambda$$

Figure 2.32: Pair of dipoles with vertical polarization with inter-element spacing equal to 0.41λ .

in the radiating near field region. The radiating near field region is represented by $0.62\sqrt{\frac{D^3}{\lambda}} \leq R \leq 2\frac{D^2}{\lambda}$ [9] (page 32) where D is (for the dipole case) equal to 0.5λ . This also means that there is a lot of energy fed to the antenna that was not able to be radiated to space, but instead ‘radiates’ into the invisible domain because the element drive impedance became largely reactive [95]. In this specific scenario the reactance is negative (i.e. capacitive). This corresponds to reactive power stored near the antennas, which can lead to big power reflections that could damage the

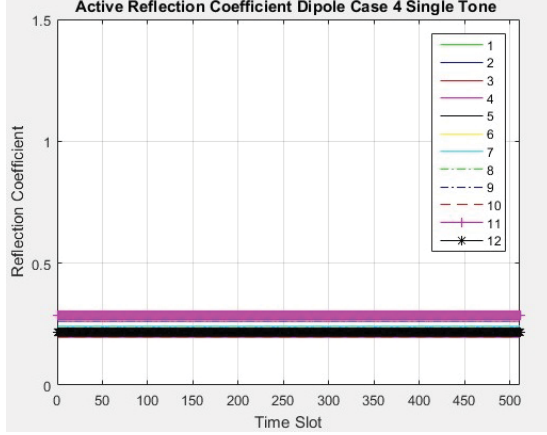


Figure 2.33: 12-element dipole array single tone. Vertical polarization.

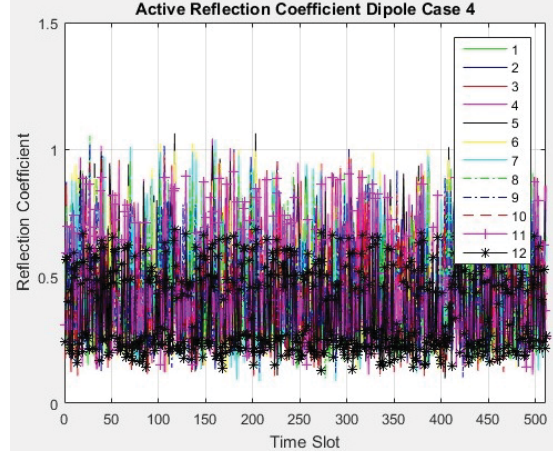


Figure 2.34: 12-element dipole array MIMO. Vertical polarization.

transmitter [3].

When the active reflection coefficient is greater than 1 (Figure 2.34), the calculated VSWR will have a negative value. The strong coupling due to the orientation of the elements and the small spacing between leads to high levels of reverse power in certain elements at certain instances of time.

2.3.4 Overall Analysis

The analysis of the horn array demonstrates that the elements are largely uncoupled, especially when oriented with a vertical polarization. This weak coupling is caused by the direction radiation pattern of this type of element. It is possible to observe some coupling, see Figure 2.19, when the elements of this array are oriented with a horizontal polarization, and used for MIMO transmissions. The configuration for this scenario can be seen in Figure 2.17. According to [23] there are three major events that cause mutual coupling in a patch array. The first reason is caused by near field coupling because of the small separation between elements. This near field coupling

effect of the patch array can be observed on Figure 2.31, which depicts the scenario where the patches had the smallest inter-element separation, oriented in a horizontal polarization, and the array was used for MIMO transmissions. The configuration of this scenario is depicted in Figure 2.29. Second, coupling is caused by radiation along the ground plane and finally, surface waves appear when the surface mode is excited in the dielectric. All elements on the patch array share the same ground plane and substrate, which cause surface waves to propagate. To reduce coupling on a patch array, surface waves guided by substrate and ground plane must be mitigated and additionally the radiation in the horizontal direction must be suppressed.

It was found that the coupling between elements is stronger when the patch and horn elements are oriented with a horizontal polarization. On the other hand, the dipole array presents a stronger coupling when the elements are configured on a vertical polarization (Figure 2.11, Figure 2.16, and Figure 2.34). It is important to mention that this entire analysis was achieved for a single frequency.

2.3.5 Summary of Early Simulations Focusing on the Analysis of Coupling Effects Under Different Inter-Element Spacing and Polarization

There are publications on co-located MIMO radars [31] [96] [97] [41] [98] [40] [49] [99] [100] [101] [102] [103] [104] [105] [106] [107] expanding on the use of antenna arrays with inter-element spacing of 0.5λ that ignore reflections and mutual coupling effects. In the analysis discussed it was proven that, even with an inter-element spacing greater than 0.5λ some arrays exhibit undesirable reflections, displaying a VSWR is larger than 2. This can be seen on the arrays with vertical polarization (Figures 2.8-2.11, and Figures 2.13-2.14, and 2.16) and on the arrays with horizontal polarization (Figures 2.20-2.23, and Figures 2.25-2.28). In addition to this discovery, it is important to remember that the antenna element coupling can potentially change

the orthogonality of MIMO waveforms [108], making their separation at the receiver challenging. After discussing the results and analyzing the cases, it is fair to conclude that it is very important to consider and carefully select, in addition to the antenna element [5], the element spacing and polarization when designing an antenna for transmissions for co-located MIMO radar. The health and performance of the co-located MIMO radar will depend on these considerations. The health of the system will be degraded by unsafe reflections or by energy not transmitted to space. The performance of the radar would be in jeopardy since not all the desired energy was radiated.

2.4 Novel Mutual Coupling Analysis and Cases

In this section, three cases of linear array antennas are analyzed. Results will be presented for each case when different antenna elements are used: dipoles, patches, and horns. A phase coded waveform was generated and transmitted from each array. The waveform is modeled as a pulse train divided into N_c sub-pulses or chips, where each chip contains a different phase. The phase sequence of length N_c is randomly selected. The model is based on [4] and [109].

$$y_m(t) = \sum_{p=0}^{N_c-1} W_{mp} e^{j2\pi F t} u((t - p\Delta_t)/\Delta_t) \quad (2.6)$$

where W_{mp} and F represent the phase and frequency of the transmitted waveform by antenna m at time p , Δ_t is the duration of a single chip and the unit step function $u(t)$ is defined by

$$u(t) = \begin{cases} 1 & : |t| \leq 1/2 \\ 0 & : |t| > 1/2 \end{cases}$$

The ARC and active VSWR are obtained using the procedure described by Pozar

[7]. The active reflection coefficient and the VSWR are calculated for each pulse train transmitted simultaneously from each antenna using the computed numerical S-parameters, S_{mn} , for the dipole array [90]. The active reflection coefficient for antenna n , Γ_n^a

$$\Gamma_n^a = \frac{b_n}{a_n} = \frac{\sum S_{nm}a_m}{a_n} \quad (2.7)$$

where a_n represents the amplitude and phase of the forward coupled wave on element n , defined as the excitation of antenna n , and b_n represents the amplitude and phase of the reverse wave in antenna n . S_{nm} is the conventional S-parameter defined as the passive ratio of the signal coupled to port n from a signal incident on port m , when all other ports are terminated [7]. The active VSWR describes the power reflected into antenna n and is defined in terms of the active reflection coefficient as

$$VSWR_n = \frac{1 + |\Gamma_n|}{1 - |\Gamma_n|} \quad (2.8)$$

A Monte Carlo simulation was used to produce time-varying randomly-selected values of phase codes to demonstrate the VSWR and reflected power ratio, $|\Gamma_n|^2$, over time for the three cases. The algorithm ran for 10,000 realizations, which provided a converged representation of the statistical behavior of a co-located MIMO radar in transmit mode.

First, a linear antenna array of dipoles is analyzed. Each dipole is of length equal to $\lambda/2$ and radius equal to $\lambda/500$. The inter-element spacing between dipoles is equal to $\lambda/2$ and the port impedance is 50 Ohms. The geometry is presented in Figure 2.35.

Figure 2.36 displays the active reflection coefficient for each antenna dipole during one pulse train. The active reflection coefficient was obtained using (2.7), with

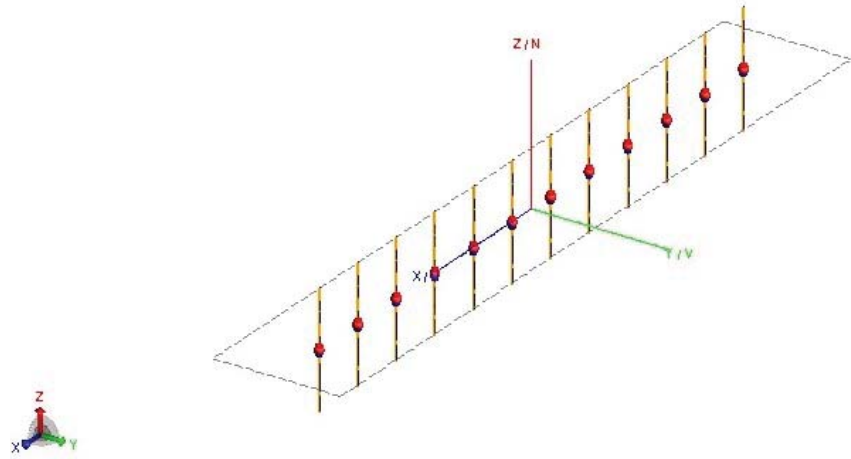


Figure 2.35: 3D view of a dipole linear array model with $\lambda/2$ inter-element spacing.

th phase code excitations from the Monte Carlo simulation, and the coupling parameters obtained from the Method of Moments solution. It can be seen that the active reflection coefficient varies from element to element, which means that the dipoles experience coupling effects. The results of using time-varying randomly selected values of phase codes of center and edge elements are presented in Figure 2.37-2.39. Figure 2.37 presents the probability density function of the VSWR for the center, first and last antenna elements of the array and also depicts virtually identical traces for the first and last elements because they experience the same amount of reflections. The plot from Figure 2.38 describes the cumulative density function (CDF) or the cumulative probability of the VSWR for values less than or equal to a specific VSWR value. It is noticed that the probability of obtaining a VSWR less than 2, which is considered a good performance by [110], for the center element, is approximately 61 percent, while for the first and last elements, is 55 percent. This performance metric was introduced by [4] into the MIMO radar community for a uniform linear array of dipoles and has been expanded in this work to analyze different antenna array elements. It

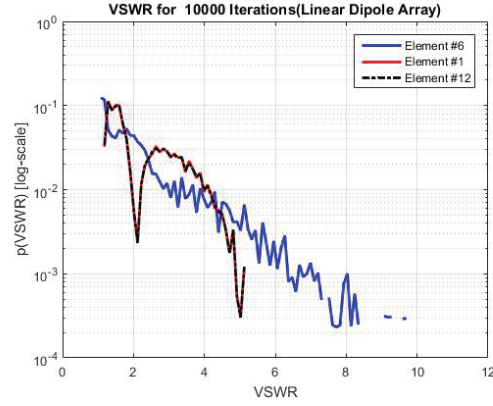
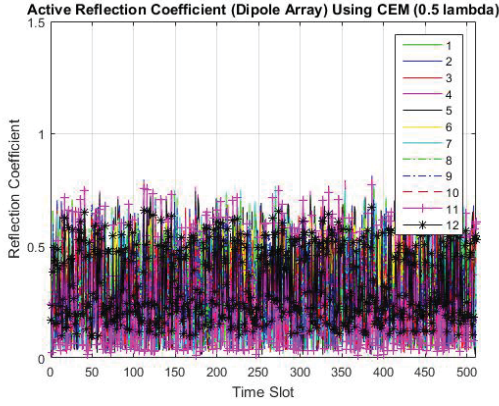


Figure 2.36: Active reflection coefficient of linear dipole array for one pulse train. Figure 2.37: Probability of dipole linear array model.

is important to mention that if the VSWR is greater than 2, significant undesired energy is transmitted into the element in question. Figure 2.38 shows that the center element has a greater probability of obtaining a VSWR larger than 4, representing more energy coupled than those elements in the corners, degrading the transmitting MIMO radar performance. Figure 2.39 shows the probability of reflected power for the center element and depicts that the first and last elements experience the same reflected power. Over time, on average, the center element reflects 13 percent of the power back to the transmitter, while for first and last elements a 14 percent of the power is reflected back to the transmitter.

Secondly, a linear array of patch antennas independently fed with a voltage source of magnitude equal to 1 Volt, phase equal to 0 degrees, and a port impedance of 50 Ohms, is depicted in Figure 2.40. Each patch is of size 0.31λ by 0.45λ with an off-center feed distance of 0.08λ . There is a distance of 0.47λ between the center points of two patches, 0.157λ between patches and a distance of 0.078λ from the edges (only for the first and last elements). All patches are laying on a substrate of size 5.6λ by 0.75λ , with $\epsilon_r = 2.2$ F/m, and substrate height equal to 0.0287λ . Figure 2.41

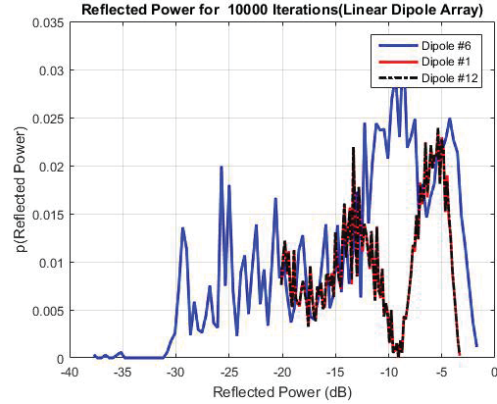
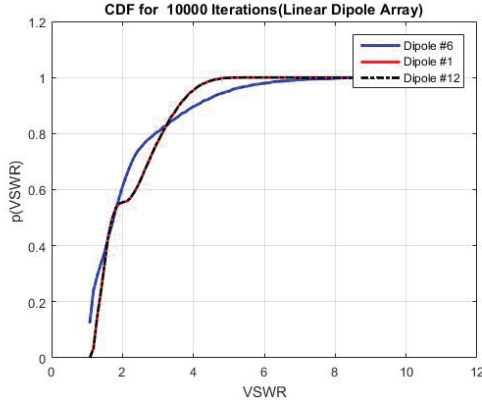


Figure 2.38: CDF of dipole linear array model. Figure 2.39: Reflected power of dipole linear array model.

depicts the active reflection coefficient of each patch for a single pulse train. Note that the active reflection coefficient has the bulk of its values between 0.6 and 0.8. This means that the patches experience a larger lever of reflection than was seen in the previous case (dipole array) during an individual pulse train. Figure 2.42 presents the VSWR probability for the center, first and last antenna elements of the patch antenna array. It can be seen the probability density for each element decreases as the VSWR increases. Figure 2.43 shows the probability of the VSWR for values less than or equal to 5 is of 18 percent, for the center element. Figure 2.44 presents the reflected power for the patch array and displays that there is a high probability of having a reflected power between -2dB and -3dB. Over time, on average, the center element reflects 55 percent of the power back to the transmitter, while for the first and last element is of 56 percent and 57 percent, respectively. It is possible to conclude that the patch array is inappropriate for this configuration. Some possible reasons for the patch array to perform so poorly could be that the distance between center points is less than 0.5λ causing more reflected power.

Lastly, the horn array is shown in Figure 2.45. The aperture of each horn is of

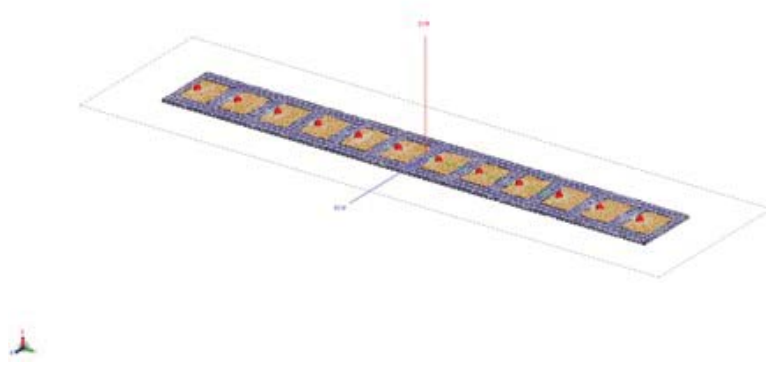


Figure 2.40: 3D view of patch antenna array model.

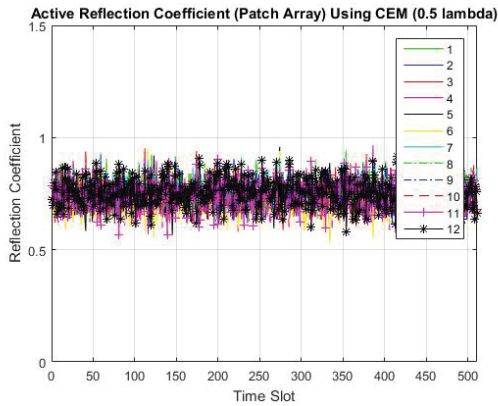


Figure 2.41: Active reflection coefficient of patch array.

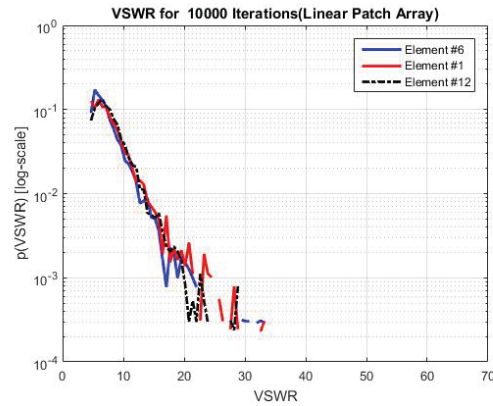


Figure 2.42: Probability of patch array.

size 2.34λ by 3.02λ with a flare of length equal to 2.52λ . The spacing between each element (from aperture's edge-to-edge) is 0.5λ . Each horn antenna is independently fed with a waveguide excitation of 1 Volt and 0 degrees of phase that excites only the fundamental mode. The waveguide size is 0.35λ by 0.71λ by 1.66λ . The active reflection coefficient, plotted in Figure 2.46, is the lowest of the three cases since a horn antenna is a more directive element and therefore does not couple as much energy into neighboring elements. Figure 2.47 shows the VSWR probability for the center, first and last antenna elements of the patch antenna array. The range of the

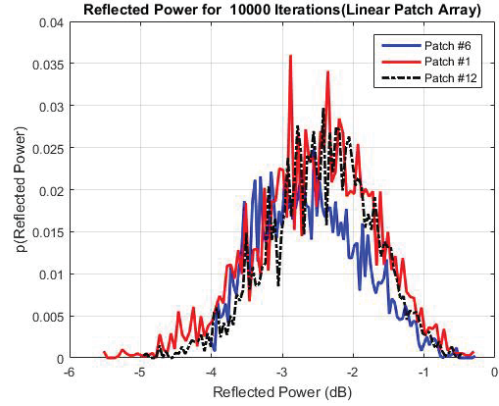
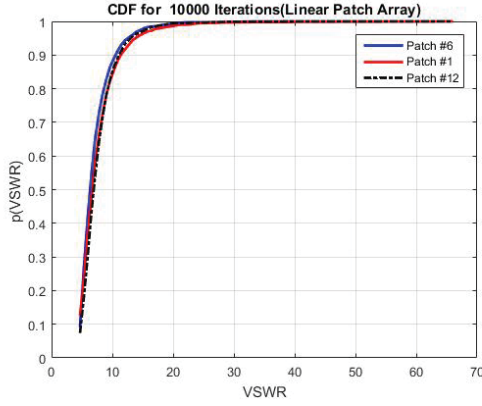


Figure 2.43: CDF of patch array model. Figure 2.44: Reflected power of patch array model.

VSWR is from 1.1916 to 1.1934. Figure 2.48 displays the CDF for this case. Figure 2.48 implies these type of elements will experience a VSWR less than 2. This should not be a surprise, since horn antennas are directive antennas. Figure 2.39 depicts the probability of the reflected power for individual elements. Over time and on average, the probability of the reflected power for the horn array is the lowest of all three cases, averaging of 0.7 percent for the center, first, and last elements.

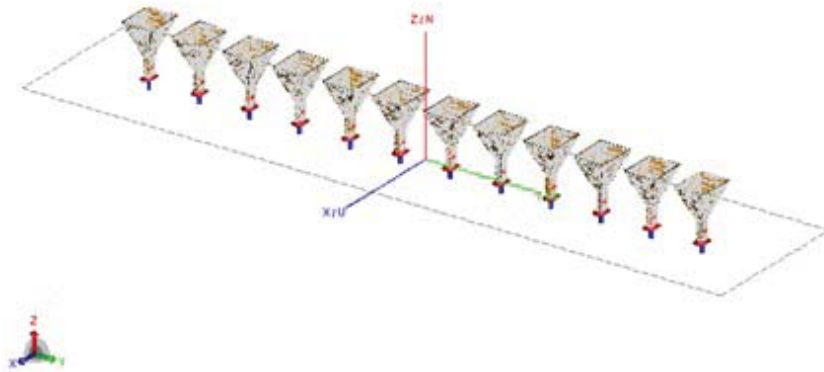


Figure 2.45: 3D view of a horn array model.

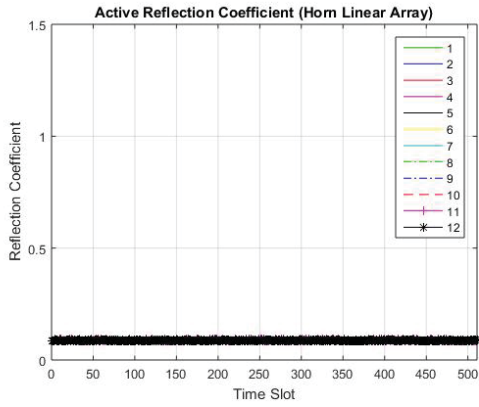


Figure 2.46: Active reflection coefficient of patch array.

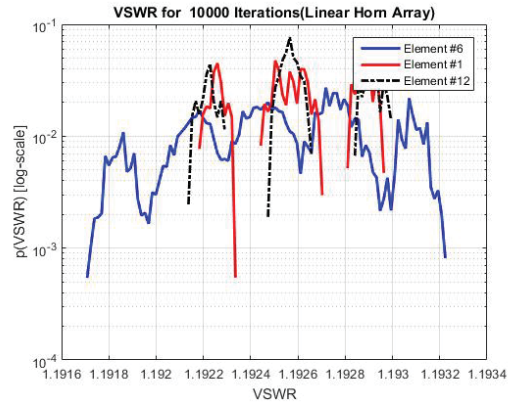


Figure 2.47: Probability of horn array model.

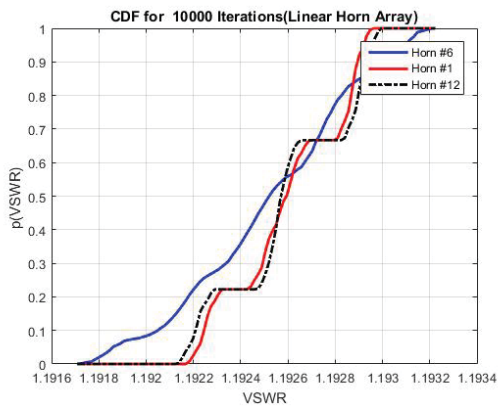


Figure 2.48: CDF of horn array model.

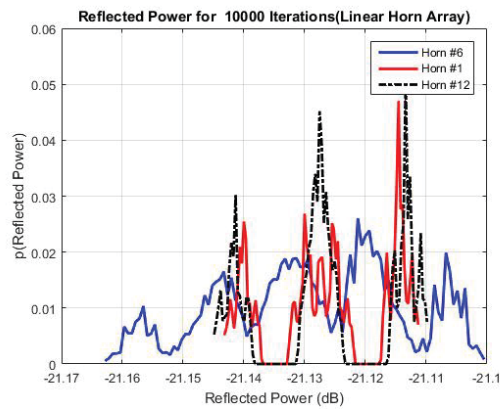


Figure 2.49: Reflected power of horn array model.

2.5 Summary

This work presents a technique that predicts the active impedance of a MIMO array that transmits orthogonal phase coded waveforms. This work will become the stepping stone to prove that the selection of the antenna element plays an important role in co-located MIMO radar transmissions. The effects on mutual coupling when different antenna elements are used was explored. The analysis was conducted for three cases: a uniform array of dipole antennas, a uniform array of patch antennas, followed by the analysis of a uniform array of horn antennas. It was shown that the best performance was from the horn array. The return losses of the elements of the dipole array were degraded, while the patch array seemed inappropriate for this configuration. These results can be important for MIMO waveform optimization processes and can be utilized to identify co-located MIMO radar performance degradation bounds.

In Chapter 3, validation of the novel methodology discussed in Chapter 2 is expanded. Measurements obtained from dual directional couplers to obtain a direct measurement of the ARC will be presented.

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