Beam-steered Modulation in Advanced Antenna Systems

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Beam-steered Modulation in Advanced Antenna Systems

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Abstract

The newer spectral bands in millimeter-wave (mm-Wave) spectrum over the last few years have made higher data rates possible and improved quality of service for the users, but it possesses new challenges to design spectral agile radios. Power Amplifiers (PA) are a crucial analog component connected to Multiple input multiple output (MIMO) antennas which inherits non-linear effects. In addition, PA's can experience strong load impedance mismatch conditions alongside mutual coupling effect in an antenna array when operating across varying beam angles over wide range of 5G bands. This thesis investigates development of a simulation technique for comprehensive analysis of nonlinear and dynamic characteristics of multi-antenna transmitters (Tx). The analysis is implemented by developing various antenna array models which takes joint consideration of antenna crosstalk and mismatch effects in multi-Tx system and capable of reflecting their behavior to developed load sensitive PA models. Further the dynamic behavior is studied with several experiments performed to analyze the beam steered modulation effects and factors contributing to it.

Popular Science Summary

The modern wireless system is evolving in fast pace with advent of technologies like Internet of Things (IoT) and 5G. With huge demand for mobile data rates increasing each year and newer connected devices entering market because of different use cases there is increase demand for data rates. Streaming videos on wireless devices with high definition 4K 3D videos like examples clearly shows the demand for higher data rates. Mobile services are expected to be fast, reliable and cheap. Apart from this, the number of connected devices is growing exponentially, and three times more devices are expected to be connected in the next 5 years With in consequence with these changes, there is advancement in Antenna technologies like Multiple-Input-Multiple-Output(MIMO) part of Advanced Antenna systems (AAS). Design of these antenna systems requires modelling the transmitter-receiver chain components for system design parameters. As distance between elements in these MIMO antenna array is small, there are minute effects of non-linearities.

For wireless cellular communications(5G systems), there are several methods on how to improve the network performance.The important aspect is to model these non-linearites in tangible manner. When using MIMO antennas in a base station these undesirable effects causes significant impact on performance. At higher frequencies the magnitude of non-linearities increases. This master thesis addresses modelling of these problems associated MIMO systems and characterisation of these systems.

List of Abbreviations

AAS Advanced Antenna Systems
ACLR Adjacent Channel Ratio
BS Base Station
CRLB Crammer-Rao Lower Bound
CSIN Cauchy-Schwartz Inequality
DL Down-link
DMR Deviation-to-mean Ratio
DSP Digital Signal Processor
DUT Device Under Test
DPD Digital pre distortion
DIDO Dual Input Dual Output
EVM Error Vector Magnitude
FDD Frequency Division Duplexing
FPGA Field-Programmable Gate Array
FF Fast Fourier Transform
GMM Generalized Method of Moments
IMD Inter Modulation Distortion
IID Independent and Identically Distributed
IFFT Inverse Fast Fourier Transform
LMS Least Mean Squares
LLS Linear Least Squares
MIMO Multiple Input Multiple Output
mm-wave Millimetre Wave
MCAC Mutual Coupling Antenna Calibration
NF Noise Fig.
NR 3gPP 5G Standard
PA Power Amplifier
RLS Recursive Least Squares
LS-PA Load Sensitive Power Amplifier

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Chapter 1

Introduction

The newer spectral bands in millimeter-wave (mm-Wave) spectrum over the last few years have made faster data rates possible and improved quality of service for the users, but it posses new challenges to design spectral agile radios.[1]

Wireless antennas are crucial component in transmit-receive (Tx-Rx) chain in base station transceivers. Switching from single to multiple wireless antennas was the important transition in the technology, This multiple antennas system is called multiple-input multiple-output (MIMO). MIMO systems has lot of advantages in terms of improved quality and link reliability.

As multiple antennas are being used in MIMO, it is necessary to study the affects caused by these antennas in the system. The data transmitted and received through these antennas should be of higher quality so to increase the strength one of the important component used is Power Amplifiers (PA). The PA is used to amplify the signal power levels. The quality of wireless communication system is dependent on PA, it is critical in transceiver design.

This thesis will investigate different advanced antenna system design options in MATLAB such as phased antenna array, embedded antenna array and rectangular antenna array modelling approaches with comprehensive analysis for different dynamic characteristics of multi-antenna transmitters(Tx) at 2.4Ghz and mmWave. In consonance with the findings, analysis of mmWave(28Ghz) operating frequency in active antenna systems is carried in the same way as sub at 2.4Ghz experiments.[2]

1.1 Background & Motivation

The radiation pattern of antennas shows a pattern of "lobes" at various angles, directions where the radiated signal strength reaches a maximum, other direction by "nulls", angles at which the radiated signal strength falls to zero. The lobe in that direction which has a larger field strength than the others, this is the "main lobe". The other lobes are called "side lobes".Undesirable energy loss due to individual antenna spacing within an array causing radiation in undesired direction (side lobes) and mutual coupling in antenna pattern are the key factors that reduces spectrum efficiency . In order to model these antenna effects and transmission chain effects modelling the transmission chain is important.The strong need is for solving load modulation variations along with the traditional PA non-linearities which can be done in analog or digital. Advanced techniques like directing energy to individual user by beam-forming through array of antennas is another important advancement looking into in the thesis.

This electromagnetic interaction between the two or more antennas when placed in an array structure is called mutual coupling[3]. Another bigger problem is nonlinearity. A non-linear system is a system in which the output and input are not directly proportional to each other. To solve the problems of mutual coupling, non-linearities, Mutual Coupling Antenna Calibration(MCAC) modeling can be used by changing antenna weights in digital domain. MCAC modeling is a new technique which is yet to be explored for multi-antenna transmitter systems. Thesis work consists of three main functionalities in the transmitter chain i.e. antenna array models, s-param model and PA Models to focus on load modulations effects. This work mainly focuses on modelling transmission characteristics of downlink chain. Further, antenna cross talk and mutual coupling effects has to be modelled to calibrate antenna weights[4] with the aim to study the antenna load modulation effects.

1.2 Previous Work

To increase the speed and performance, the modern wireless communication system cannot only rely on bandwidth, as usable frequency spectrum is getting crowded is investigated in this thesis[4]. Advanced antenna system, i.e Multiple input multiple output (MIMO), multi-user MIMO, massive MIMO modelling is continuation of the the thesis[4]. This is also listed as future work in [4].

These advanced antenna systems rely on the modelling of multi-antenna transmitter, using radio frequency (RF) power amplifiers (PAs) to form an antenna array is explored in[5], [6]. Related to DPD thesis from [6] is very important for this thesis which models the Single Input Single Output(SISO), Dual Input Dual Output (DIDO) models in Matlab. Simplified model is used from[5]. Mutual coupling modelling is explored in[5] and its extended to be modelled in tx-Rx chain model in Matlab™.

Several antenna design techniques from[3] is taken and used in Matlab™ to be model both memory and memory-less DPD in conjunction[6] with patch antenna array. Several experiments are conducted at sub 6Ghz and mmWave.[7]. All the above thesis explores several aspects, the unique thing that is concentrated in this thesis is to model load modulation and antenna tx chain in one single model.

1.3 Thesis Aim and Goals

The aim and goal of this thesis:

1. Investigate different antenna[8] models for AAS systems.
2. Analyze beam-forming[10] modelling in AAS.
3. Use embedded and phased array models to experiment on coupling effects.
4. Model and analyze effects of antenna spacing in array.
5. S-Param model for rectangular antenna array to analyze load modulation effects.
6. Model load sensitive PA model and integrate it to AAS model.

Chapter 2

Background & Theory

2.1 Antenna Arrays

A radio base station has antenna arrays connected in a definite fashion to achieve the required coverage. Antenna array is a part of transmitter or receiving module. It can exist in different geometrical shapes such as rectangular, circular, spiral and other shapes which are arranged in specific format. The individual antenna in an array is termed as element. A linear array is set of antenna elements arranged in form of row.

A radio base station is studied with a load modulation effects considered which is called as Power Amplifier Dual Input Dual Output(PA DIDO) model to achieve a desired performance with undesired effects like antenna mismatch, cross-coupling, non-linear and memory effects of the PA.[9]

The most difficult task is the dynamic load affected PA linearization by DPD. In order to use any DPD techniques and to visualize their performance we need to be able to model an integrated load sensitive PA model and interfaced with coupling and variable the non-linearities. Another challenge in 5G Advanced Antenna Systems (AAS) is to model, mutual coupling due to antenna spacing and antenna performance analysis due to beam steering and di-electric variations.

With the background [4], this thesis herein models a solution that carries out the task of modelling radio transmission chain for characterization of transmitter with PA-AAS model. For this purpose we first investigate below, the antenna array design options available in MATLAB.

2.1.1 Patch Rectangular Antenna Array

A rectangular linear array is set of linear rows of antenna elements where it forms a matrix of antenna elements. The array can be used to electronically form beams to direct the energy towards one direction. This concept is called as electronic beamforming. Beamforming concept can be extended to monitor the user equipment and steer the beam towards user dynamically which is termed as beam steering.

In a linear array if elements are arranged with uniform distance between them its called uniform linear array. If number of rows are increased then it is called uniform rectangular array. One important aspect is to arrange these elements closely packed to achieve greater directivity. When antenna elements are arranged closely[6] it bring two side effects (1) spatial correlation (2) mutual coupling.[3]

Patch micro-strip antenna is PCB etched antenna with dimensions length, width, height, antenna feed point as parameters as shown in figure 2.1. Multiple of patch elements can be used to form a patch rectangular antenna array. When array is formed distance between patch antenna element is one of the important aspect. Its commonly used in mobile and radio applications.[7]. As shown in figure 3.2 patch antenna is analysed with E/H patterns drawn, representing directivity in elevation (El) and azimuth(Az).

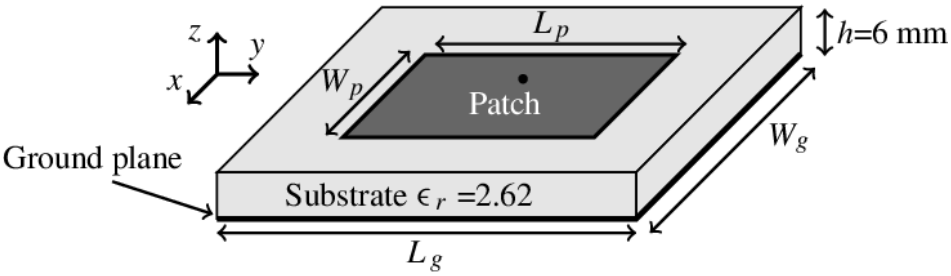

Figure 2.1: Patch Antenna Element in MATLAB [10]

2.1.2 Phased Antenna Arrays

Phased array antenna created by array elements with beam-forming systems embedded in wireless communication using Matlab is described in this section. Antenna arrays can be used to

(i) Increase the overall gain
(ii) Steer the beam to particular direction
(iii) Determine mutual coupling between antennas by concept of embedded antenna element

Each antenna element within the array have different ways to change the phase of the Tx or Rx signal. These are generally sensor based antennas.[3]. With phased array antenna, one can change the shape of the radiation pattern(beam) in more diverse way or change the direction of the beam electronically without physically moving the antenna . Its more explained as how this is used in chapter3.[11].

2.2 Beam-forming Concepts- Why do we need a beam?

By wave nature we know that transmission of signal depends on wavelength and wavelength is a function of frequency. When we use low frequency we can transmit in all directions (one and two radiating element) as shown in figure 2.2 but when we use high frequency one does not have a choice other than using large antenna array to direct beam to particular user. Once the antenna array is formed, beam can be generated. We need to further understand how to steer this beam to particular user and then as user moves how to switch the beam direction over time to keep the connection established which is further described in 3GPP NR standards.[12]

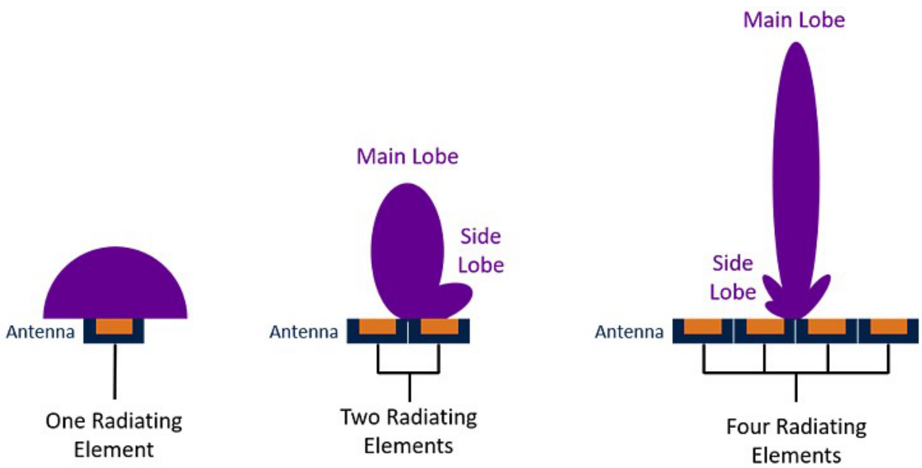

Figure 2.2: single and multi antenna array radiation pattern [13]

2.2.1 Beamforming by Antenna weights

A beam forming in antenna array is formed by using several antenna elements which control the direction of a wave. Once calculated and applied the changes to the phase of the each individual signals from an antenna array, the beam can be formed and directed in the required angle and direction as shown in figure 2.2.

The array's individual elements have varying distances to the target user equipment antenna when directing the resultant beam towards it. The path length difference for each signal is $dcos(\theta)$,as shown in figure 2.3 ϕ is the antenna with applied phase shift, d is the distance from each element of the array and θ is angle of arrival for the individual signal which is different and has to be calculated. To offset these difference so that each signal arrives at the same phase, phase shift is applied to each element from which a coherent beam is formed in the far-field. This is called coherent combining of the signal to particular direction[15].

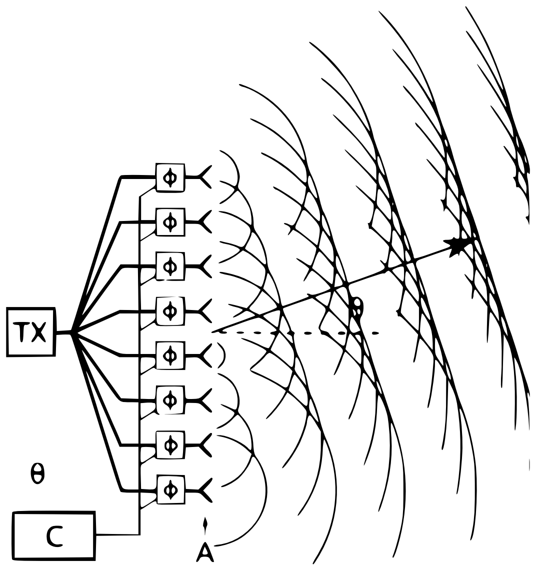

Figure 2.3: Antenna array radiation pattern [14]

The radiation pattern obtained by combining the individual signals from the directional antenna array will have many lobes with differing field strengths at different angles as a result of the constructive and destructive effects of the signal combining. The strength of the signal reaches to maximum, separated by no radiation in certain directions also called nulls. The main lobe is the intended beam with highest power, while the smaller side lobes which are usually unwanted as they radiate undesired radiation pattern in unnecessary directions.

2.2.2 Types of Beamforming

There are three main type of beam-forming (a) Analog (b) Digital (c) Hybrid beam-forming

Digital beamforming: In this method, every antenna has its own ADC/-DAC and transmit-receive circuits. Henceforth it makes it possible to generate many sets of signals and transmit them through antenna elements. The antenna array is able to handle multiple data streams from which multiple directed beams are formed at the same time. With this type of beam directing ability , array can transmit data at the same time to multiple receivers, by serving multiple users with high spectral efficiency. Digital antenna beam-forming is generally more adaptable with sign processing resources and extra hardware.

Analog beamforming: This method involves using a single set of ADC/DAC for the entire antenna and a single data stream, which allows for the formation of only one beam per set of antenna elements. The data stream path is divided into multiple paths, with each signal data path passing through a phase shifter and being transmitted to the corresponding individual antenna element. This technique offers the advantage of increased gain for the antenna array, resulting in broader coverage. However, the drawback of analog beamforming is that the beam direction for all frequency bands remains the same.

Hybrid beamforming: This method is the combination of both digital and analog methods. In this type of antenna array it consists of subarrays of analog beamforming with digital signals. This reduces energy consumption and design complexity, making it more cost-effective. Thesis basically explores digital beamforming method.

2.2.3 Beamforming weights

When multiple antenna's are placed in an array form, there will be constraint's in terms of controlling the shape and direction of the beam. Phase and gain controller is used to calculate the values needed to steer the beam pattern to a given direction as shown in figure 2.4

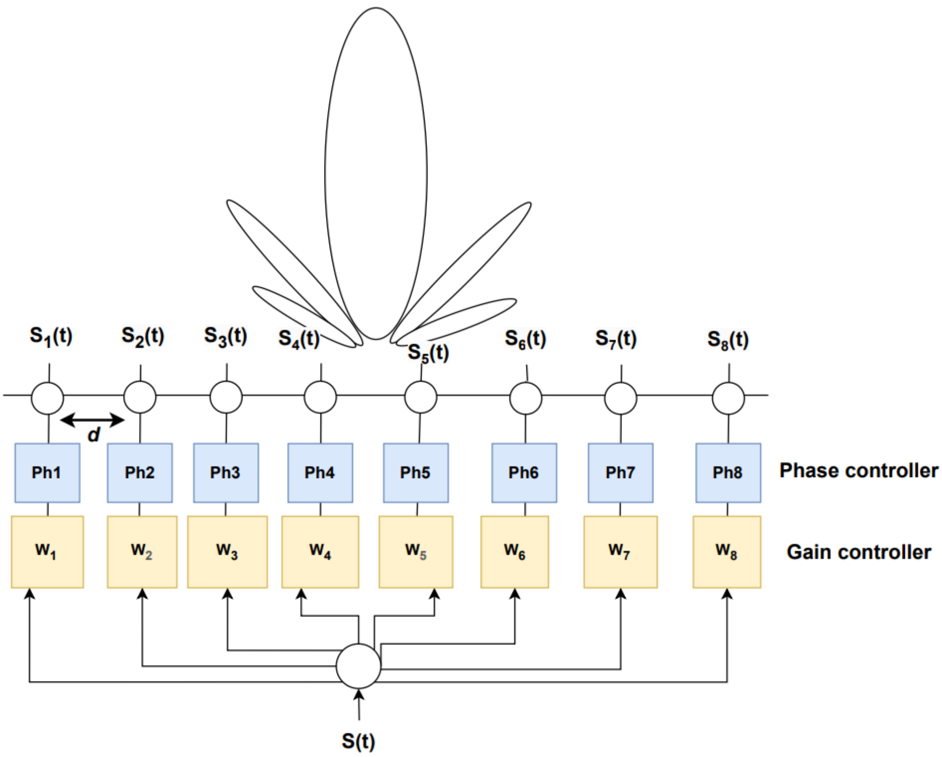

Figure 2.4: Single and Multi-dimensional array [16]

The pattern generated by each of the antenna in an array is added up to form a single beam pattern which can be represented by mathematical form as shown in the equation 2.1

$$\begin{aligned} |s(t)| &= |s_1(t) + s_2(t) + s_3(t) + s_4(t) + s_5(t) + s_6(t)s_7(t) + s_8(t)| \\ &= |(1.e^{-j(1.d.\Theta_1)} + w_2.e^{-j(2.d.\Theta_1)} + w_3.e^{-j(3.d.\Theta_1)} \\ &+ w_4.e^{-j(4.d.\Theta_1)} + w_5.e^{-j(5.d.\Theta_1)} + w_6.e^{-j(6.d.\Theta_1)} \\ &+ w_7.e^{-j(7.d.\Theta_1)} + w_8.e^{-j(8.d.\Theta_1)})s(t)| \end{aligned} \tag{2.1}$$

Further, this equation 2.1 can be simplified into a vector form as shown below. Theoretically, changing the gain and phase in the vector equation 2.2 we can obtain the required shape and direction of the beam pattern. Formula from equation 2.2 is used by Matlab function to calculate the weights for a given antenna array to steer the beam to particular direction as calculated by phase-shift[6]

$$|s(t)| = \left| \begin{bmatrix} w_1.e^{-j(1.d.\Theta_1)} \\ w_2.e^{-j(2.d.\Theta_2)} \\ w_3.e^{-j(3.d.\Theta_3)} \\ w_4.e^{-j(4.d.\Theta_4)} \\ w_5.e^{-j(5.d.\Theta_5)} \\ w_6.e^{-j(6.d.\Theta_6)} \\ w_7.e^{-j(7.d.\Theta_7)} \\ w_8.e^{-j(8.d.\Theta_8)} \end{bmatrix} s(t) \right| \tag{2.2}$$

2.3 Modelling Tx-Rx Chain

System modelling is one of the important steps in behavioral analysis of an antenna systems. A block diagram for system model is shown in figure 2.5. With AAS systems and increased complexities in MIMO antenna design such as spacing between elements in antenna array, undesired effects affecting antenna directivity becomes more important. In software environment we model these hardware effects.

Patch antenna element is modelled and tuned at a desired frequency. The dimensions of the antenna length, breadth, height , dielectric is calculated and chosen. Once the antenna elements are created azimuth(Az) and elevation(El) directivity patterns are observed to fine tune the side bands.

2.3.1 Undesired Effects in Antenna Arrays

Mutual coupling is a negative effect observed when there are large MIMO antennas. Mutual coupling is defined as an electromagnetic interference caused by the radiation pattern of individual antenna elements affecting neighbouring elements. Coupling redirects the energy that needs to be radiated towards free space back into the radio system.

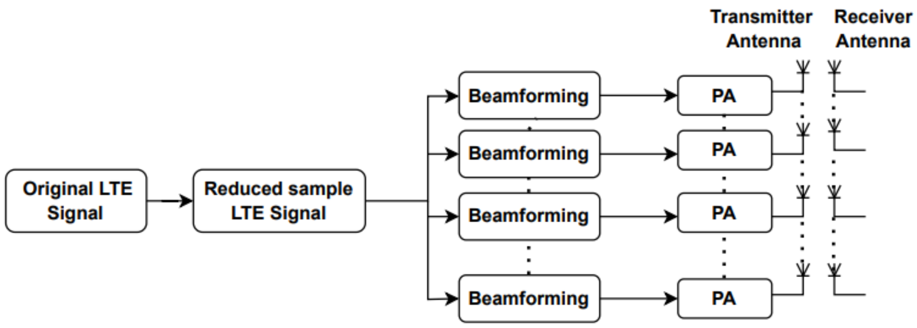

Figure 2.5: Tx Rx system model

Another cause of undesired effects is load modulation effects which is due to load mismatch affecting PA nonlinearity. Below are the list of effects that we have modelled and considered in Tx-Rx modelling.

(i) Mutual coupling between antenna elements.
(ii) Dielectric constant affecting directivity.
(iii) Beam steering effects on directivity.
(iv) PA non-linearity and load mismatch effects.

2.3.2 Spacing between elements

Designing an antenna with proper dimensions and inter-element spacing is important to eliminate unwanted grating lobes in a rectangular array. Broadside array is the one that gives a radiation pattern perpendicular to antenna placement. By arranging elements with respect to wavelength we can create antenna patterns directed towards user. Mutual coupling effects also depends on the antenna array element spacing. By rule of thumb the spacing between elements are arranged as function of wavelength. Optimal arrangement is between $\lambda/2$ to λ [17]. If the wavelength crosses the λ, then grating lobes and mutual coupling effects increase. For large antenna arrays mutual coupling effects the antenna pattern significantly with spacing and general rule of thumb cannot be applied.

Beam-width of the main lobe , the size and position of side lobes also depend on the distance between the array elements because the fields add up differently for different antenna spacing. Further the distance between elements, the narrower the beam-width due to increase in total.

Antenna wavelength is inversely proportional to its frequency of operation. Lower frequency antenna has shorter wavelength and higher frequency has longer wavelength. Mutual coupling effects can affect severity levels affecting performance and link distance to Tx-Rx. On longer run if not addressed it would damage the sensitive radio components like Low noise amplifiers (LNA). Most importantly coupling effects distorts antenna radiation pattern and gain. So it is important to calculate the optimal spacing in-order to increase performance of antenna arrays.

2.3.3 Effects of Mutual Coupling

The electromagnetic fields radiated from a driven antenna element will generally affect the electromagnetic pattern of an array. This is specially true when resonant element is the effected conductor (in multiples of half-wavelengths) in around similar frequency the active or passive array is where where all conductors are part of. Due to the placement of affected conductors in the near-field, antennas cannot be treated as transmitting and receiving signals in accordance with the Friis far-field transmission formula. Instead, mutual coupling effects must be considered by calculating the mutual impedance matrix. By utilizing the mutual impedance computed for a particular configuration, it is possible to determine the radiation pattern of a patch antenna or the currents and voltages for each element in a phased array.

Near-field pattern of such array of antennas interactions are undesired and not good for antenna array pattern. Characteristics of antennas gets unpredictable causing loss of RF power when antenna is near metallic objects. In addition, for high band antennas ($>$ 6GHz) and MIMO antenna arrays, magnitude of these effects increases many folds. Therefore with a careful design, it is possible to reduce the electrical interaction between nearby antenna elements.There can be distance between antenna elements that can be adjusted to reduce the mutual coupling effects[18]

2.3.4 S-Param to model Mutual Coupling

Scattering parameters or S-param represents the input-output relationships between ports in a antenna array. At high frequency it is important to describe a given network in terms of waves than in the form of S-param matrix. S-parameters are very useful to model antenna behaviour in terms of equations. S-param matrix formed represent the incident and reflected wave phenomenon from the equations which is useful to modelling mutual coupling[3]. A two port network with S-parameters is shown in figure 2.6.

S11 is reflection coefficient of input port
S12 is the reverse voltage gain
S21 is the forward voltage gain.
S22 is Reflect coefficient of output port.

The value of S11 provides a method to measure matching network condition, that is, S11= 1 represents an open circuit; S11= -1 represents a short circuit; and S11= 0 represents a perfectly matched circuit. Electromagnetic waves transmitted from each element of array has interference from its neighbouring elements and can be modelling by reflection co-efficient values. Using the matrix values its easier to model the phenomenon of mutual coupling.

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

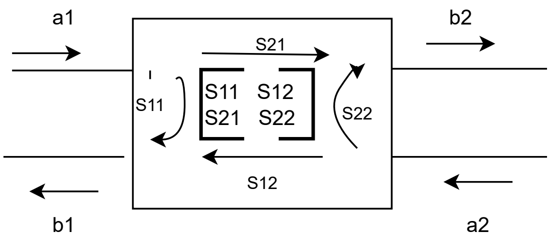

Figure 2.6: Two port Network S-param Model

2.4 Power Amplifier

An amplifier is a crucial component in transmitters as it amplifies the input voltage to increase the amplitude of the signal. The desired outcome is to implement a straightforward mathematical function, such as f(x) = a.x. However, in practice, the behavior of the power amplifier (PA) is not linear, and it exhibits second and third-order functions, which are undesirable, as shown by the red curve in the figure2.7.

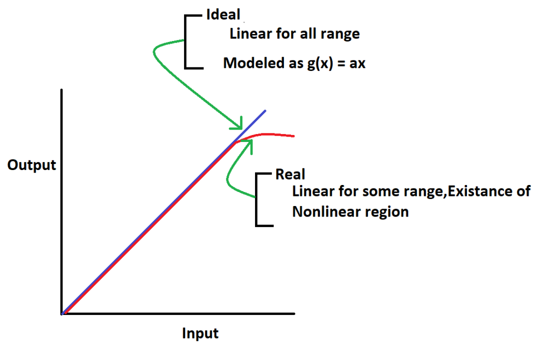

Figure 2.7: Ideal and Real Curve of PA [16]

Non-linear behavior in power amplifiers (PA) can be a problem because it distorts the signal being amplified. In a linear amplifier, the output signal is a scaled version of the input signal. However, in a non-linear amplifier, the output signal can be distorted due to the non-linear relationship between the input and output signals. This can cause unwanted harmonics, inter modulation distortion (IMD), and other nonlinear effects.

IMD is particularly problematic because it can cause interference with other signals in the frequency spectrum. Nonlinear distortion can also limit the amount of power that can be transmitted without distortion.

2.4.1 How to avoid Non-linearity in PA's?

There are several methods commonly used to reduce or eliminate the non-linearities in power amplifiers (PAs). These methods are explained as below:

(i) Using a PA of wider linear region: A power amplifier with a wider linear region can help reduce non-linearities. However, such PAs may have lower efficiency and higher cost due to the need for higher linearity.

(ii) Drive the input to the linear region of the PA: This can be achieved by increasing the input power level or using a lower signal bandwidth. However, this method may not be always practical and achievable to the desired level of linearity.

(iii) Using filters in the frequency domain: This method involves filtering the output signal to remove the spectral components that result from the non-linearities in the PA. However, this approach may not always be effective, especially when the non-linearities are severe and/or vary over time.

(iv) Using advanced smart designing like pre-distortion: This method involves designing a pre-distortion circuit that can be used to compensate for the non-linearities of the PA. The pre-distortion circuit can be trained using an appropriate algorithm, such as the Least Mean Squares (LMS) or the Recursive Least Squares (RLS) algorithm. This approach can be effective but requires careful design and implementation.

In summary, the choice of the method to reduce or eliminate non-linearities in power amplifiers depends on various factors, such as the specific requirements of the application, the available resources, and the trade-offs between linearity, efficiency and cost.

2.4.2 Saleh Model for PA

Memory-less non-linearity modelling is one of the way to model PA non/linearity effects. For simplicity, this work focuses on approach of memory-less Saleh model for PA modelling unlike other complex methods such as Volterra series. For a baseband signal this kind of modelling is useful to integrate in Tx-Rx chain modelling. The amplitude distortion is amplitude-to-amplitude modulation (AM/AM) and the phase distortion is amplitude-to-phase modulation (AM/PM) is introduced as parameters to this memory-less modelling. Below are the steps for modelling Saleh model further details of experiments are discussed in chapter3[19].

(i) Multiply the input baseband signal normalised gain factor.
(ii) Split the complex signal into its magnitude and angle components.
(iii) Apply an AM/AM distortion to the magnitude of the signal, according to the

selected model method, to produce the magnitude of the output signal.
(iv) Apply an AM/PM distortion to the phase of the signal, according to the selected model method, to produce the angle of the output signal.
(v) Combine the new magnitude and angle components into a complex signal. Then, multiply the result by an output gain factor.[4]

2.5 ACPR

In a wireless communication system, ACPR (Adjacent Channel Power Ratio) or ACLR (Adjacent Channel Leakage Ratio) refers to the power ratio between the primary frequency channel and the adjacent channel. This phenomenon may arise due to nonlinearities in the power amplifier (PA), which leads to distortions and spectral leakage. This results in the transmission of higher levels of unexpected or unwanted power in the sideband compared to the main channel, leading to interference with devices operating in neighboring bands.[4]

A poor ACLR also reduces the efficiency of transmission. Load modulation also affects ACLR. The ACLR is given by,2.3, [4]

$$ACLR_{db} = 10log_{10}\frac{\int_{adjch}|Y(f)|^2 df}{\int_{mainch}|Y(f)|^2 df} \tag{2.3}$$

where, Y(f) is the fourier transform of the signal, adjch is signal bandwidth of adjacent channel and mainch represent the signal bandwidth of main channel.

2.6 EVM

EVM (Error Vector Magnitude) is a metric that gauges the accuracy of symbol transmission within the constellation of a radio. This parameter reflects the signal quality, which depends on factors such as noise, nonlinear distortion, interfering signals, and radio load. The EVM value is usually expressed in decibels (dB) and occasionally as a percentage.[18].

2.7 Directivity

Directivity refers to the directional nature of the radiation pattern of an element or antenna array. A higher directivity means that more radiation is transmitted in a particular direction. Specifically, directivity is the ratio of the radiant intensity transmitted in a given direction to the radiant intensity that would be transmitted by an isotropic radiator (a theoretical antenna that radiates uniformly in all directions) with the same total transmitted power.Mathematically show as 2.4,[20]

$$D = 4\pi * \frac{U_{rad}(\theta, \phi)}{P_{total}} \tag{2.4}$$

where $U_{rad}(\theta, \phi)$ is the transmitter radiant intensity in the direction of (θ, ϕ) and P_{total} is the isotropic radiator total transmitted power. When converted to decibels, the directivity is denoted as dBi.

Chapter 3

Methods- Modelling Advanced Antenna Systems

Before creating a simulation model, we need to look at system considerations and define system model and requirements for which simulation model must be built. In this chapter we therefore look at various steps involved in the modeling process for the system model shown in figure 3.1. First step involves analysis of antenna array design options in MATLAB. For this purpose three different options have been explored. Further Tx/Rx model is developed along with the considerations of PA model.

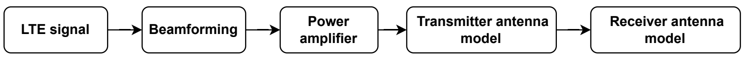

Figure 3.1: General Tx-Rx block diagram

Input is the LTE signal. A band-limited time domain LTE information signal is generated. In order to model the antenna array we need to feed the LTE signal to antenna. Filters have been used to filter out noise from the LTE signal.

3.1 Massive MIMO Channel Model

Due to the high frequency nature of 5G (mm Wave), the antenna size and the aperture will be reduced. Enormous number of antennas are used to solve this issue of reduced or small aperture. Single transmitter and receiver antennas are separated with R distance then the received power is given as in eqation 3.1 [3],

$$P_{rx} = \frac{P_{tx}}{4\pi R^2} \tag{3.1}$$

The equation above simplistically models the transmit receive condition and does not take into account the frequency and gain of Tx-Rx antennas. If the transmit and receive antenna gain are taken into consideration it becomes as in equation 3.2[16]

$$P_{rx} = \frac{P_{tx}}{4\pi R^2}\frac{\lambda^2}{4\pi}G_{rx}Gtx \tag{3.2}$$

The equation suggests that doubling the frequency, which results in halving the wavelength, will cause a fourfold decrease in received power. Therefore, when using millimeter-wave technology, which operates at higher frequencies and shorter wavelengths, the received power is significantly lower. For example, In current communication if we have 2GHz and 20GHz frequency in 5G, then the wavelength in 20GHz frequency will be 10 times shorter than the wavelength of 2GHz. It means that the power received at 20GHz will be 100 times lower than the power received at 2GHz.[21]

In other words, the question is "how we can make receive power larger?" Mathematically it is simple, one can get larger receive power by setting the parameters as follows.

1. Increase transmit power
2. Reduce the distance between the transmit and receive antenna
3. Increase wavelength (use low frequency)
4. Increase receiver antenna gain
5. Increase transmitter antenna gain

In the above list, option 1 is infeasible as transmitter power cannot be increased as much as we require. Option 2, cannot be the solution since we cannot change the distance as it depends on the use case of mobile equipment. Option 3 cannot be the solution. Once we (standard organization and each network operator) decided to use a particular frequency, we need to follow the requirements and those cannot be changed. Option 4 is not feasible and reduces battery life of user equipment. Option 5 can be a doable solution. It may not be easy to increase the antenna gain, not controlled by standard organization, network operator does not prevent us from trying to increase the antenna gain[3].

Then how can we increase the antenna gain? By design antenna gain can be increased (e.g, shape, material etc), but the amount of gain increased by design cannot compensate the huge amount of the reduced power cause by the increased frequency. The best approach is by using number of Tx/Rx antennas part of AAS system. With this introduction to need of massive MIMO further the chapter highlights the design of the patch element and later design with patch antenna array.

3.1.1 Designing Patch Element Matlab

On dielectric surface a patch of conductive is etched patch antenna. As the ground plane supports the complete structure of antenna,dielectric material is mounted on it as shown in figure 3.2. The signal to the antenna is provided using feed lines

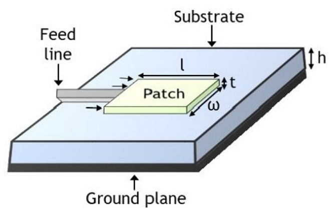

Figure 3.2: Patch Element Design [22]

connected through the patch.

Below are the key characteristics considered for patch antenna design based of previous antenna studies:-

- Thin conductive region, $t << \lambda$ 0 (where $\lambda 0$ is free space wavelength)
- The ground plane must have comparatively very large dimensions than the patch
- A thick dielectric substrate with dielectric constant within the range of 2.2 is used
- Arrays of microstrip elements in the antenna configuration provide greater directivity.[3]

Microstrip antennas generally provide provide high beam-width. A very high-quality factor is offered by a patch antenna. A large Q implies a narrow bandwidth and low efficiency. This can be countered by increasing the thickness of the substrate. The increase in thickness beyond a certain limit will cause an unwanted loss of power so there has to be compromise. Matlab tool is used to design these antenna elements.

3.1.2 Antenna Designer Matlab

Antenna designer is a application in Matlab that can be used to design, visualise and analyze antennas. GUI can be opened with a Matlab license which can be used to tune antennas to design parameters that are needed. Antenna Toolbox™ has functions and applications for the design, analysis, and visualization of antenna elements and arrays. Element antennas and build arrays of antennas using existing elements with parameterized geometry, arbitrary planar structures. [20]

The Antenna Toolbox™ employs electromagnetic solvers, near-field and far-field radiation patterns, and efficiency calculations to aid in antenna analysis. Additionally, it allows for the visualization of geometry and analysis results in both 2D and 3D. The impedance analysis results can be used for S-params for integration with the RF front-end. Antenna performance including mutual coupling can be modelled. Matlab™ antenna designer tool is used to create antenna element with Az and El patterns as shown in figure 3.3. An example of elevation azimuth and 3D patterns generated for single patch element at 2.4GHz is as shown in figure 3.3.

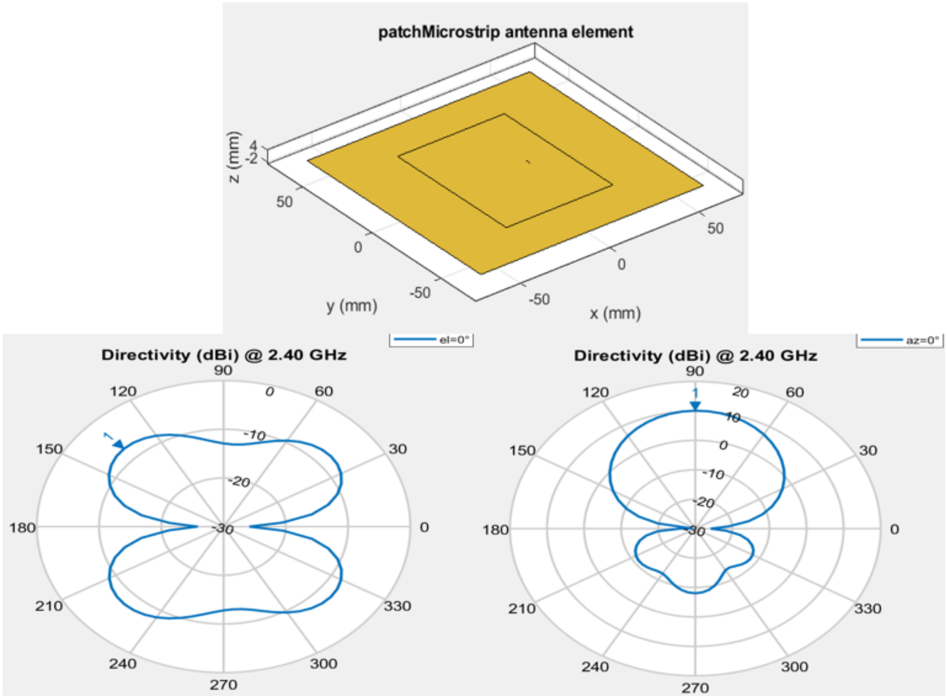

Figure 3.3: Patch element design, Az and El

After getting single element, design array of element 2x2 rectangular array is created and Az, El and 3D patterns are generated as shown in the figure3.4

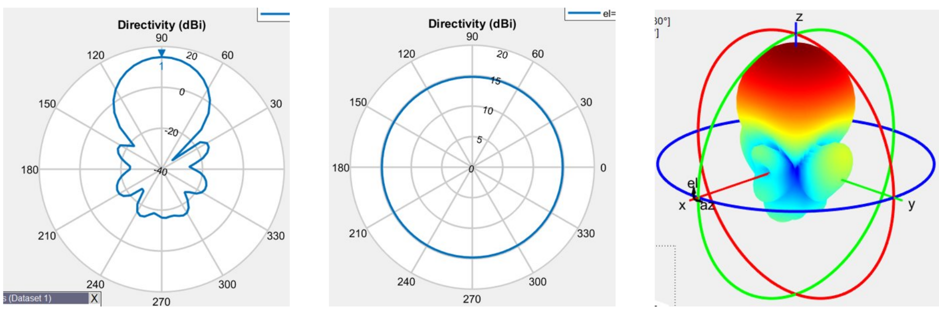

Figure 3.4: Rectangular antenna array El, Az and 3D pattern

3.1.3 Phased Array Antenna

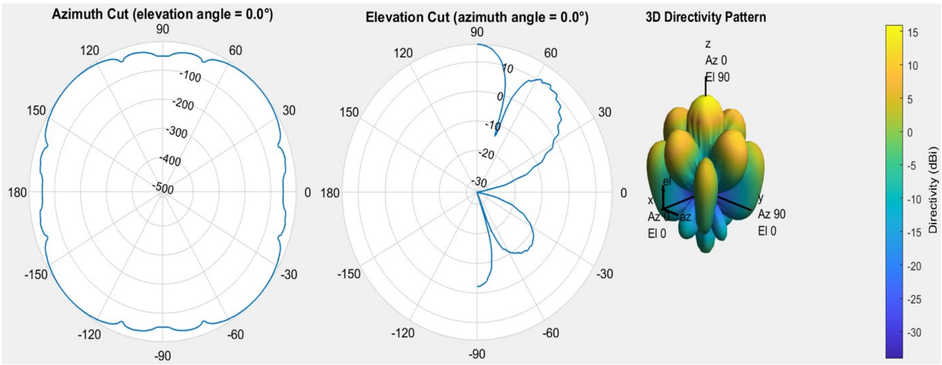

Figure 3.5: Phased antenna array Az, El and 3D patterns

Antenna array which is electronically steered is termed as 'phased array antenna'. The phase shift can be changed for a specific value by a fixed electric circuit or for arbitrary value by variable phase shift or digital signal processing. Azimuth, elevation and 3D pattern of a phased array are shown in figure 3.5.

Phased array antenna can be of two main types. **Dynamic phased arrays**: use variable phase shifters to direct the beam to a required angle. **Fixed phased arrays**: Here beam position is stationary but antenna can be moved. This are mostly used in radar applications. Dynamic and fixed can be further classified as, **Active phased arrays** which consists of arrays with amplifiers or processors which are in each phase shifter element and **Passive phased arrays**: contains huge mid or central amplifier with attenuating phase shifters. Phased array antennas of dynamic type can be fundamentally classified as,

1. Time domain beamformer
2. Frequency domain beamformer

Time domain beamformer works by introducing time delays. The basic operation is called "delay and sum" so the incoming signal are delayed from each element in an array by a certain amount of time, and then added together. In frequency domain beamformer signal is categorised by DFT to different frequency bins. Each bin uses different delays and added together.

Some key design parameters provided in MATLAB based on frequency of operation are width, length, height, dielectric material, feeder distance and sidelobe reduction techniques.

3.1.4 Embedded Antenna Array

The embedded element pattern is a pattern of a single element which is embedded in the finite array and is calculated by driving the central element in the array and terminating all the remaining elements of the array into a reference impedance.

The pattern of the driven element is referred as the embedded element, which considers the effect of coupling with its neighboring elements. Central region/element of the array is chosen commonly for the embedded element pattern generation, depending on even or odd number of elements in an array. Due to the presence of mutual coupling the pattern generated from the isolated element changes when it is placed in an array. Hence, this disprove the use of pattern multiplication, in which it is assumed that all elements have the same radiation pattern. To generate the pattern from total array radiation using pattern multiplication and to improve the accuracy of the analysis, we replace the isolated element pattern with the embedded element pattern this method models the mutual coupling effects.

3.2 LTE Signal Modelling

LTE signal is generated with 20MHz bandwidth with QPSK modulation and filtering with band-limited filters. A PSD of LTE signal with OFDM modulation 16-QAM ,FFT-512 and a filter bandwidth of 20MHz is shown in the figure 3.6.

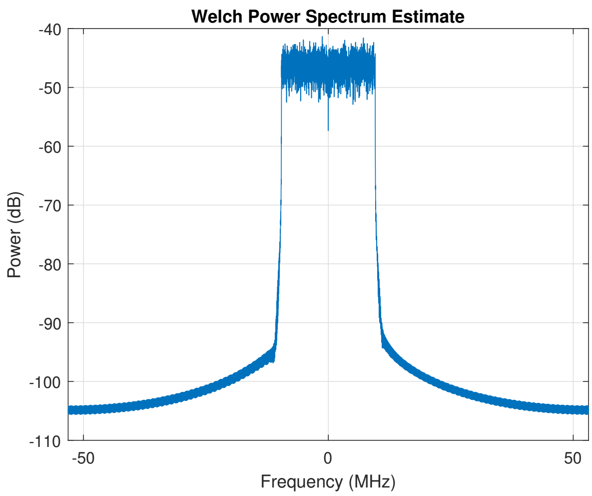

Figure 3.6: LTE signal

3.3 Tx-Rx Modelling

Tx-Rx modelling in this work considers usage of different antenna schemes and PA models in Tx-Rx chain shown in figure 2.5. These include:

(i) Rectangular array to be used for S-Parameters model.
(ii) Embedded antenna model to model self coupling.
(iii) Phased array antenna model to use for beam steering and distance between elements effect on load modulation.

(iv) Memory based SISO and DIDO PA model in transmission chain.
(v) Load sensitive PA Model in Tx Chain.

3.3.1 Beamforming in Specific Direction

A matrix to illustrate digital beamforming is as written in the below equation.[4] X(t) is the input signal which is multiplied by a complex weight in the processor.To form the output Y(t) array weights are summed as,

$$Y(t) = \sum_{n=1}^{N} W_n^* X_n(t) \tag{3.3}$$

In equation 3.3, W represented as weight vector, is given by $[W_1, W_2, W_3........W_N]T$, N is the number of antenna element and $X(t) = [X_1(t), ..., X_N(t)]T$ is the input signal for all the elements. By changing the W which is the weight matrix, beam can be directed towards the required direction as seen in figure3.7. Beam steering can be done by keeping the amplitudes same for all the elements and changing the phases in required direction. θi.

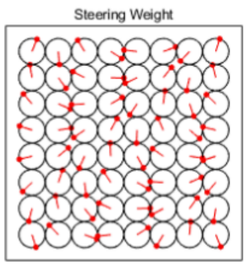

Figure 3.7: Steering Weight [16]

Once the beam-forming weights are calculated Tx-Rx model can be used to steer the beam in different angles so that effects of mutual coupling can be observed. Further adding on, distance between elements can be changed to observe load modulation effects [6]. The receiver part shown in the chain is to ensure transmitter chain works as intended. The focus is however on the transmission part, which can be seen in figure 3.8

3.4 PA Model and Integration

PA modelling is a complex problem. Generally PA's can be modelled as memory based or memoryless models. Block diagram of the multi-antenna TX with a PA model is shown in 3.9. The MIMO antennas TX has 'L' parallel transmit paths. Each path operates in the same frequency band and consists of an RF PA, which is connected to one antenna element in the transmit array.

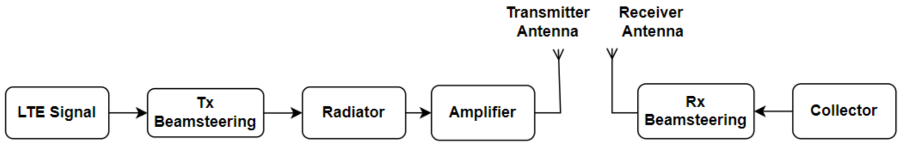

Figure 3.8: Block diagram of Tx Rx blocks

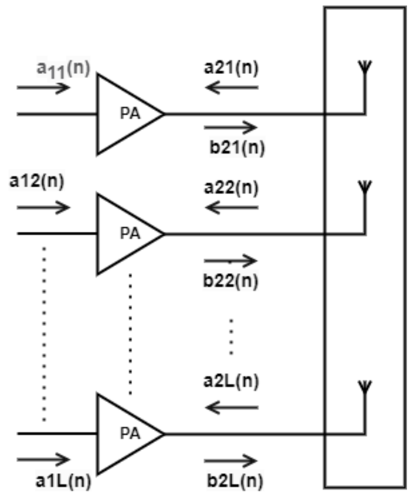

Figure 3.9: Multi-antenna Tx system [23]

In our system model, we consider such a multi-antenna TX system with PA's operating at 2.4MHz[3]. The signal $b2i(n)$ describes the PA output voltage wave of the i^{th} TX path at time step n. The forward wave $a1i(n)$ is the input signal to the PA of the i^{th} branch. The signal $a2i(n)$ is a wave incident to the output of the i^{th} PA. $b2i(n)$ is modelled to include antenna crosstalk and mismatches[6].

$$b(n) = \sum_{p=1}^{p} \sum_{m=0}^{m} \theta_{pm} \alpha(n-m)|\alpha(n-m)|^{p-1} \tag{3.4}$$

3.4.1 PA Model - DIDO Modelling

A memory based full volterra series modelling of PA leads to extremely high model complexity and is therefore infeasible. In this thesis we therefore considered a reduced memory polynomial structure. In this structure, cross terms between a signal and terms of the same signal with different delays are not considered from volterra model. Hence, the final pruned model is given below.[6]

$$b_{2i}(n) = \sum_{m1=0}^{M_1} \sum_{p=0}^{(p_1-1)/2} \alpha_{m1}^{(2p+1)} \alpha_{1i}(n-m1) * |a_{1i}(n-m1)|^2 p \tag{3.5}$$

$$+ \sum_{m2=0}^{M_2} \beta_{0_{m2}}^{(1)} \alpha_{2i}(n-m2) + \sum_{m3=0}^{M3} \sum_{m4=0}^{M4} \sum_{p=1}^{(p_2-1)/2} \beta_{m_4 m_3}^{(2p+1)} * \alpha_{2i}(n-m_3)|\alpha 1i(n-m4)|^2 p \tag{3.6}$$

$$+ \sum_{m5=0}^{M5} \sum_{m6=0}^{M6} \sum_{p=1}^{(p_3-1)/2} \gamma_{m_6 m_5}^{(2p+1)} * \alpha_{2i}(n-m_5) * \alpha_{1i}(n-m6)^{p+1} (\alpha_{1i}(n-m6)^{p-1}) \tag{3.7}$$

Following the memory polynomial approach, terms such as $m1 = m2 = m3$ are considered. The terms in equation 3.5 describe the behavior of the PA due to the amplification of $a1i(n)$ and are the same as in a SISO memory polynomial model equqtion 3.4. In equation 3.6 and 3.7, the negative implications of coupling and mismatch and the mixing of these effects with PA nonlinearity are described, where in equation 3.6 all terms containing $a2i(n)$ are combined, and in 3.7 all terms containing its conjugate, i.e., $a * 2i(n)$, are combined. It can be observed that the nonlinear orders P1, P2, and P3, and the memory tap lengths M1, M2, M3, M4, M5, and M6 that are necessary to obtain a good model which helps in reaching closer to real behaviour of PA.[23]. SISO and DIDO models presented here with these equations are further used in phased array antenna module to model PA non-linearities and used for evaluations in chapter 4.

3.4.2 Load Sensitive Memoryless PA Model

Memoryless nonlinearity model is a way to create less complex PA model. The memoryless impairment can be demonstrated and visualized by levels applied in this model are exaggerated and not representative of typical levels for modern radios. An ideal power amplifier can be model as a linear amplitude (AM/AM) gain, signal can be boosts to the desired level with zero phase (PM/AM) gain. Therefore, its effect on the system is to intensify the signal without distorting it, possibly by adding a permanent and stable delay/phase shift.

The Load sensitive PA model represents the nonlinearity of an amplifier by two gain factors: amplitude-amplitude AM/AM as in equation 3.8 and amplitude-phase PM/AM as in equation 3.9. These factors model the AM and PM error generated by a given input signal with known amplitude. Here is it observed that both transfer functions have the input magnitude as a denominator,which is a characteristic of load sensitive PA nonlinear model.

The amplitude-amplitude and amplitude-phase factors are extracted by the unique behavior of the amplifier and are represented by defines 'Alpha','Beta' including scan angle variations and S-parameters as in equation 3.10 and in equation 3.11,[18] obtained from antenna, given the operating conditions, and are related to the AM/AM and PM/AM factors by the equations below [4]. where u is the magnitude of the scaled signal. The α and β parameters for AM/AM and AM/PM are similarly named but distinct,Z_{ARC} = S-parameters from antenna array, f is the frequency and θ is the scan angle variations.[20]

$$F_{AMAM}(u) = \frac{\alpha(f,\theta)_{AMAM} * u^2}{(1+\beta(f,\theta)_{AMAM} * u^2)} \tag{3.8}$$

$$F_{AMPM}(u) = \frac{\alpha(f,\theta)_{AMPM} * u^2}{(1+\beta(f,\theta)_{AMPM} * u^2)} \tag{3.9}$$

$$\alpha(f,\theta) = a_0 + a_1(1 - \frac{(|Z_{ARC}|(f, A_{ii}, S_\theta)}{|Z_0|} \tag{3.10}$$

$$\beta(f,\theta) = b_0 + b_1(1 - \frac{(\angle(|Z_{ARC}|(f, A_{ii}, S_\theta))}{\angle|Z_0|} \tag{3.11}$$

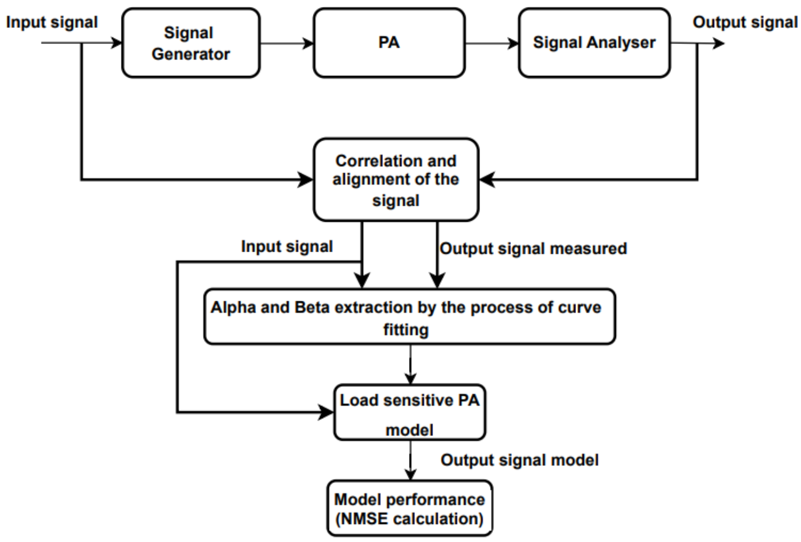

Figure 3.10: Load sensitive PA modeling process

Figure 3.10is the Load sensitive PA modelling flowchart. From the flowchart mathematical expression for extracting α and β by the process of curve fitting method is given by equations 3.12, 3.13

$$\sum_{\theta_j}^{\theta_n} \sum_{f_k}^{f_n} \alpha_{\theta_j, f_k} = \frac{(\sum r_{i,j,k^2}) - m(\sum r_{i,j,k^4})}{(\sum r_{i,j,k^2})(\sum w_i r_{i,j,k}) - (\sum ri, j, k^4)(\sum w_i)} \tag{3.12}$$

$$\sum_{\theta_j}^{\theta_n} \sum_{f_k}^{f_n} \beta_{\theta_j, f_k} = \frac{(\sum r_{i,j,k^2})(\sum w_i) - m(\sum w_i r_{i,j,k^2})}{(\sum r_{i,j,k^2})(\sum w_i r_{i,j,k}) - (\sum ri, j, k^4)(\sum w_i)} \tag{3.13}$$

3.5 Designing Antenna Array for 28GHz

Within the 3GPP standard frequency bands, there are two distinct categories: sub-6GHz, and millimeter-wave. Subcarrier spacing and the maximum bandwidth varies depending on the ranges. In millimeter wave range and in sub(6GHz) the maximum bandwidth is 400Mhz and 100Mhz respectively. So the previous section antenna and models of PA and LTE signal was generated for sub 6GHz frequency. When it comes to higher frequencies the lambda becomes further smaller in mmWave. Its important for this thesis to model non-linearaties in higher frequencies. The goal is to repeat the modelling for 28GHz by designing the antenna array with L,W,H and optimal spacing then generating Az,El patterns which is also called called as n258 band according to 3GPP[7].

3.5.1 Challenges at 28GHz

The baseline path loss between transmitter and receiver increases. One would notice that the path loss gets over 80dB at 28Ghz and over 88 dB just 10m away from transmitter. The loss difference between 5m and 10m is around 6dB as shown in reference [21]. Free space path loss is important factor at higher frequencies.

One of the another factors is about utilizing mmWave in wireless communication has been poor penetration (high transmission loss) on materials that surrounds us generally. We can infer from results from different experiments that the penetration loss would be different on the characteristics of the material through which the mmWave passes and the thickness of the material. Like example with wood vs dry wall, the losses are different and penetration factor comes to picture. Thesis studies about factors affecting these parameters and experiments with different dielectric materials while designing antenna. However thesis scope is not to expand on path-loss factors. Thesis is more in direction towards getting transmitter modelled for load modulation variations[4].

Chapter 4

Experiments and Results

Modelling load modulation variation is one of the key goals of this thesis. In this regard several models developed in Matlab are taken into consideration and experiments are performed to model and observe the effects of load modulation in 2.4Ghz and 28Ghz.

This chapter explains about the experiments performed in three different antenna models. ie; (i) rectangular array (ii) phased antenna array (iii) embedded antenna array. Later in chapter further explanation is given how PA model is integrated to phased antenna array Tx model(ii).

4.1 Rectangular Array

A rectangular array (2x2) model is designed in MATLAB. El, Az and 3D patterns are generated and observed which is as shown in the figure 4.1 below are the patterns[3]. This rectangular array model created is further used to extract S-parameter to check reflection coefficient effects[11].

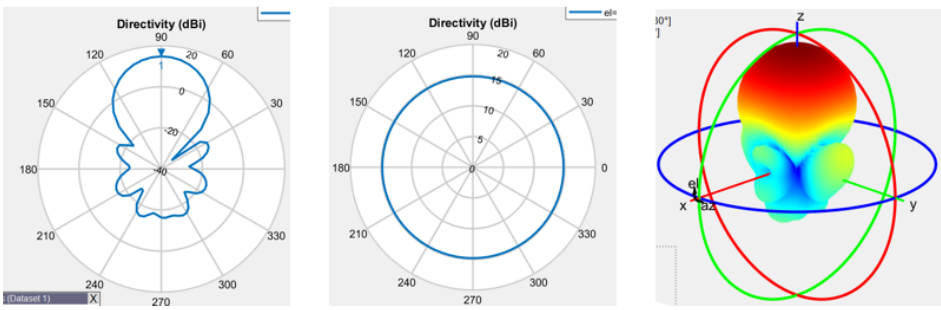

Figure 4.1: Rectangular array 2x2 pattern

4.1.1 Eliminating Side Lobes

Matlab antenna designer tool is used to calculate effective distance between elements to eliminate grating lobes as seen in the figure 4.2 black dot is the main lobe, green circle is the grating free area as it is not overlapping on the pink circles which are the grating areas.

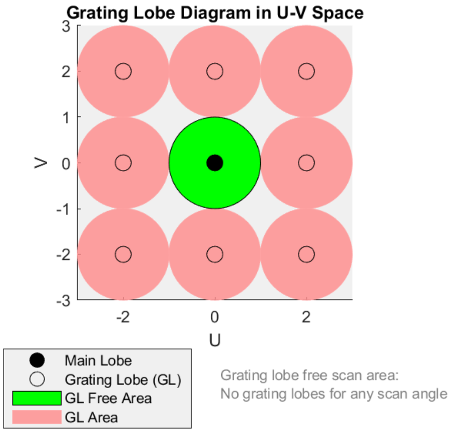

Figure 4.2: Side band reduction

4.2 Phased URA design

A phased.URA antenna model is designed in MATLAB. El,Az and 3D patterns are generated and observed as shown in figure 4.3. Using this model more diverse ways of analysing load modulation variation can be analyzed.

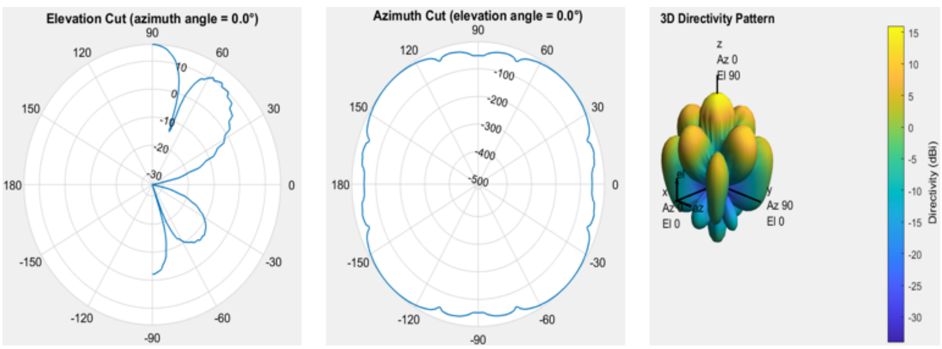

Figure 4.3: Phased URA array 2x2 pattern

4.2.1 Load Modulation Effects due to Scan Angle Change for Phased.URA

Scan angle is changed in the direction of the beam or the pattern generated from the antenna array. Varying the scan angles from 35°to 145° beams are directing toward the respective angle. When the beam is steered the shape of the main and side lobes beams are also changing both in Az and El angles which can be seen in figure 4.4. This shows that the change in direction also changes the beam shape which can overlap with the neighbouring antenna's beam causing load modulation effects.

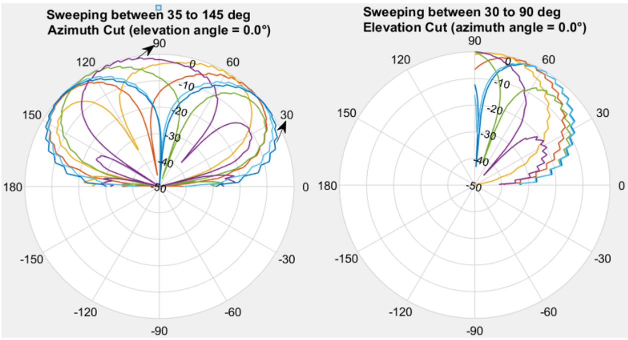

Figure 4.4: Beam scan

4.2.2 Crosstalk Effects with Beam Steering and Directivity for Phased.URA

In figure 4.5 for 2.4GHz, scan angle is varied with respect to directivity of the beam in the Az angle and El angle. We can see that maximum directivity is towards 130 ° and the maximum directivity is towards 90° in the Az angle. In figure 4.6 for 28GHz we can see that maximum directivity is towards 110 ° and the maximum directivity is towards 130° in the az angle. Purpose is to find crosstalk between the neighbouring antenna in zero degree directivity.

4.2.3 Load Modulation Effects of Antenna Element Spacing

One could see that just by arranging multiple antenna in an array with right distances we could create a beam with the directivity in a certain direction. It can be seen as in equation2.1 that distance between elements (d) places a critical role in the antenna pattern and further antenna pattern impacts direction due to mutual coupling effects so in this model we experiment about the relative separation between the elements.

From the figure 4.7 we can see that when antenna element spacing is varied from 0.1λ to 1λ, directivity in El direction is changing and at 0.5λ is the minimum

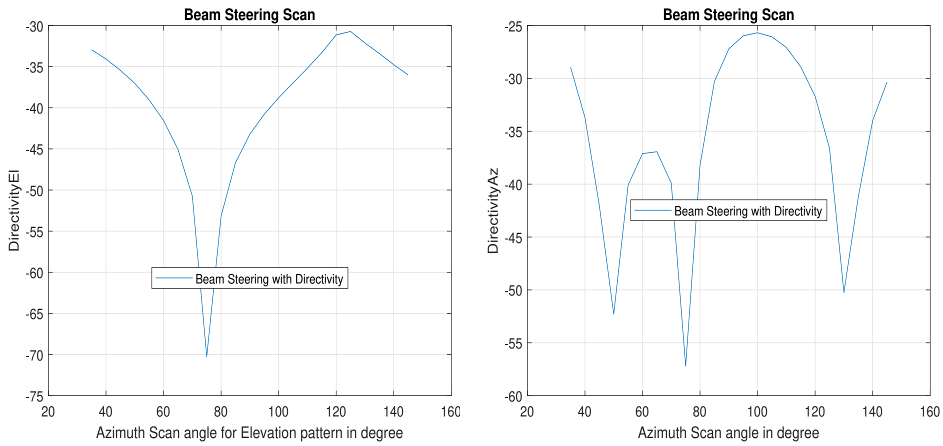

Figure 4.5: Scan angle - Directivity with respect to Az and El pattern at 2.4GHz

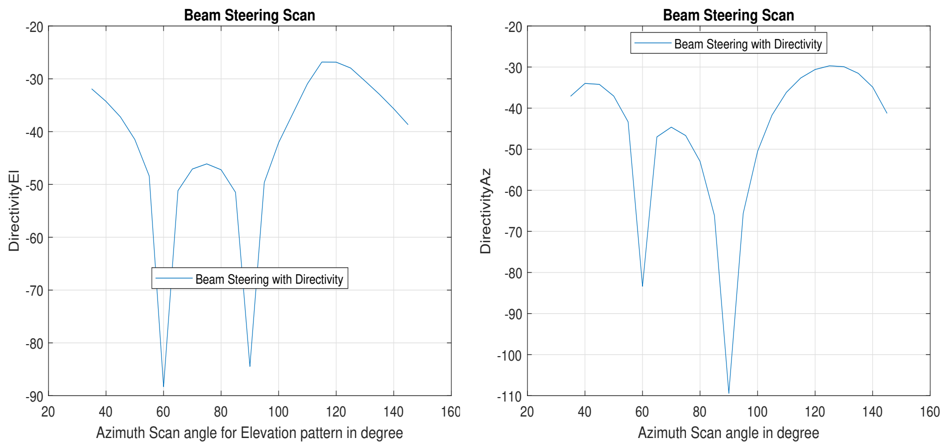

Figure 4.6: Scan angle - Directivity with respect to Az and El pattern at 2.8Ghz

directivity for 2.4GHz and from figure 4.8 for 28GHz, 0.3λ is having minimum directivity and at 1λ maximum directivity. This clearly implies that load modulation effects and mutual coupling cannot be ignored especially at higher frequencies.

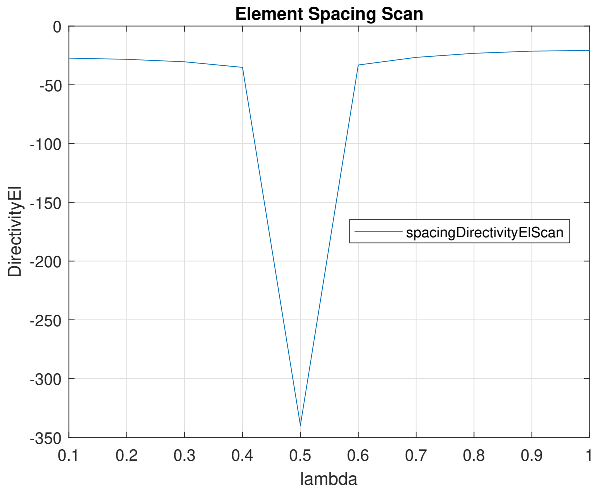

Figure 4.7: Distance variation at 2.4GHz

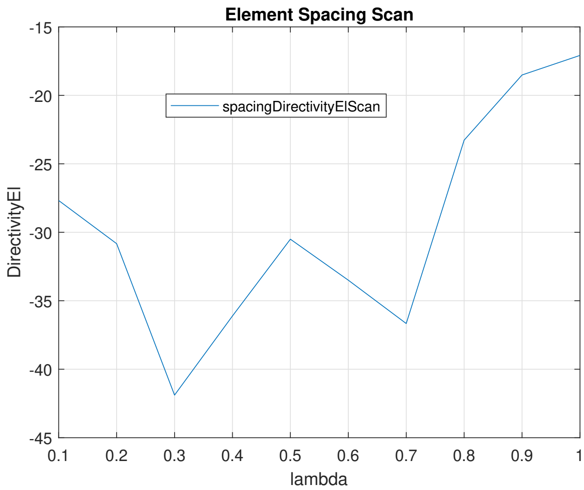

Figure 4.8: Distance variation at 28Ghz

4.2.4 Embedded Antenna Array Analysis

In this experiment we have considered three types of antenna arrays i.e. phase.URA, fullwave array (rectangular) and embedded element antenna array. First experiment is standalone embedded element pattern and its variation with respect to di-electric constant of substrate. It can be observed that teflon which has higher dielectric constant causes variation in pattern when steering of angles is done as shown in figure 4.9.

From the figure 4.10it can be seen that comparing phase.URA, rectangular

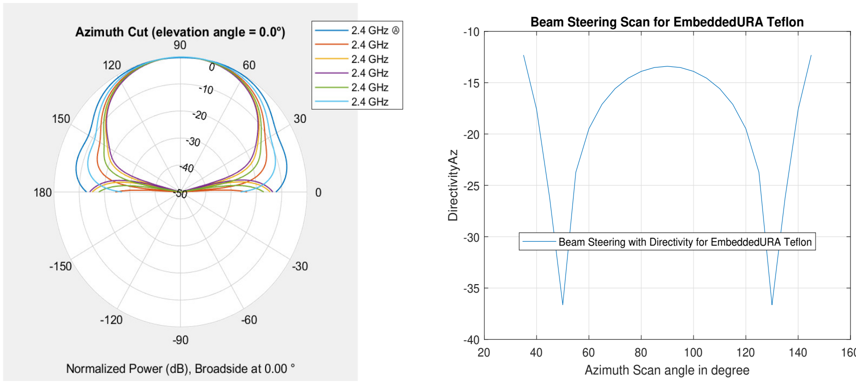

Figure 4.9: Embedded El pattern El, Az for teflon and air

and the embedded URA pattern. Embedded URA pattern is having maximum directivity both in Az and El direction. This experiment is done on 'air' substrate. The same experiment is done on 'teflon' substrate which has higher dielectric constant. embedded URA pattern is having the maximum directivity in comparison with others as shown in the figure 4.11.The change in substrate has effect on the pattern of antenna and mutual coupling.

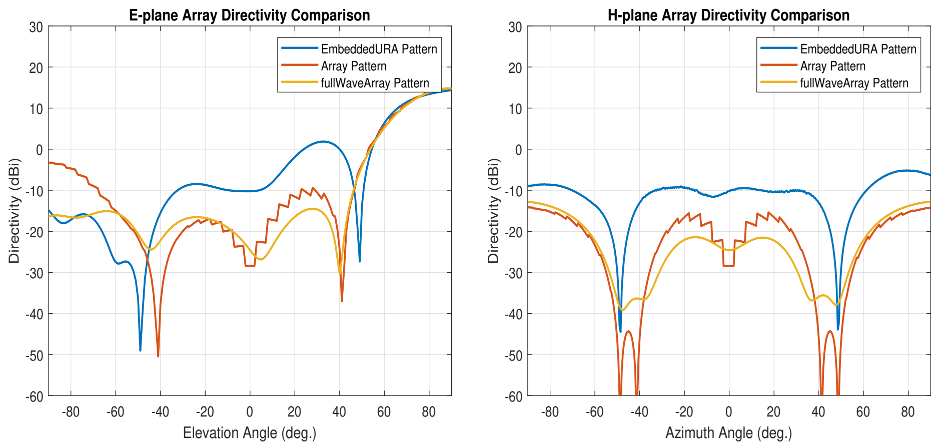

Figure 4.10: Embedded El pattern comparison with full wave

Scan angle is varied from 35°to 145° to observe the beam pattern of embedded antenna element and directivity are plotted as shown in the figure 4.12. Spacing between the antenna elements are varied and directivity is plotted as shown in figure 4.12 at 0.6 is having the maximum directivity.

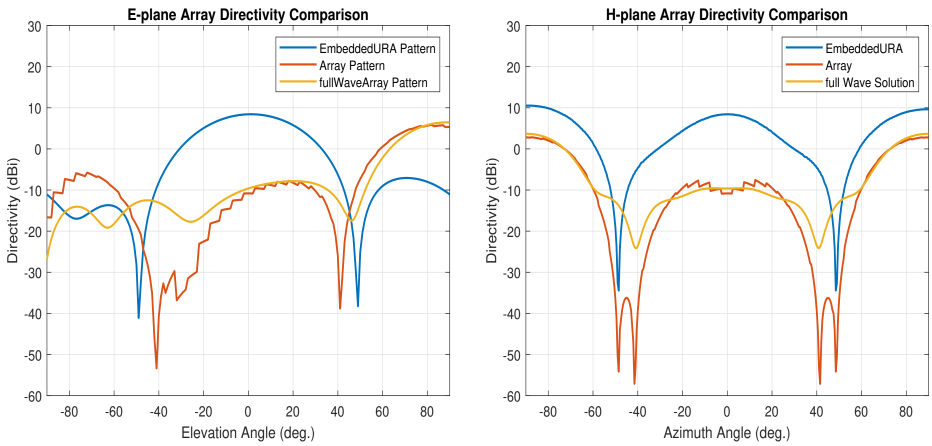

Figure 4.11: Embedded El pattern comparison with full wave with teflon as substrate

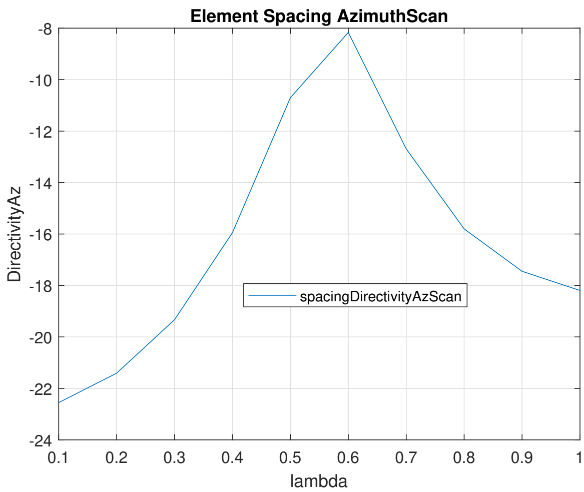

Figure 4.12: Embedded spacing scan of embedded URA

4.2.5 Rectangular Antenna Array S-Parameter Model

The rectangular antenna array(2x2) that we discussed in the beginning of the chapter is used to integrate S-parameter. The S21 factoring mutual coupling effects and S11 factoring load modulation and reflection coefficient effects are analysed[24].

S-Parameter for the (2x2) antenna array is calculated. The mutual coupling or self coupling effects are plotted as shown in the figure 4.13. As this experiment is done on 2.4GHz antenna array, at 2.4GHz frequency we can see the minimum coupling effect for first antenna and for second,third and fourth it is slightly varying but can be considered.

Further from figure 4.14 we can observe the mutual coupling effects for each antenna element across the angles ranging from 40° to 120° in steps of 10. Varying scan angle and observing S-param reflection co-efficient shows it has deviation for different elements of antenna in (2x2) array which infers us that load modulation variation with respect to distance and scan angle.

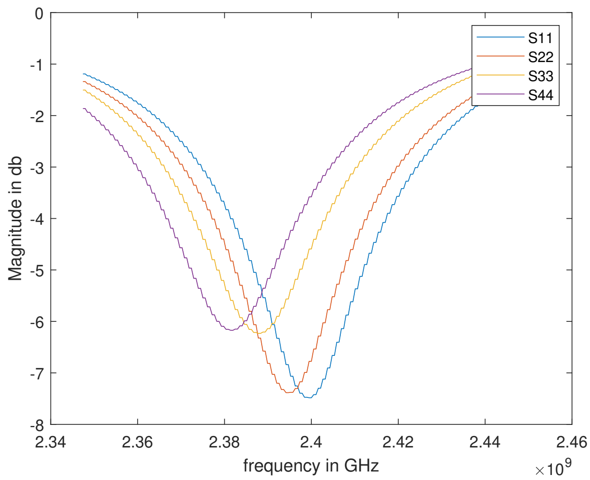

Figure 4.13: S-param for single angle by varying spacing between antenna elements

4.3 Power Amplifier Modelling

Previous chapter we have discussed about the concepts and theories related to PA. In this section we can see the results of implementing two memory based models (i) SISO (ii) DIDO and load sensitive memoryless model (modified Saleh's model) to accommodate the PA non-linearities[12]. SISO model equation is implemented as described in chapter3. Steps followed are

(i) Model PA from SISO equations.
(ii) Use LTE signal in rectangular antenna array model.
(iii) Use modelled s-param values to multiple with LTE input signal.
(iv) Use the resultant as input to PA before sending to antenna.

By doing above steps we will account for load modulation variations.
LTE signals is large samples and becomes complex for calculations hence reduced or decimated version of LTE signal is used for PA to decrease the run-time. From

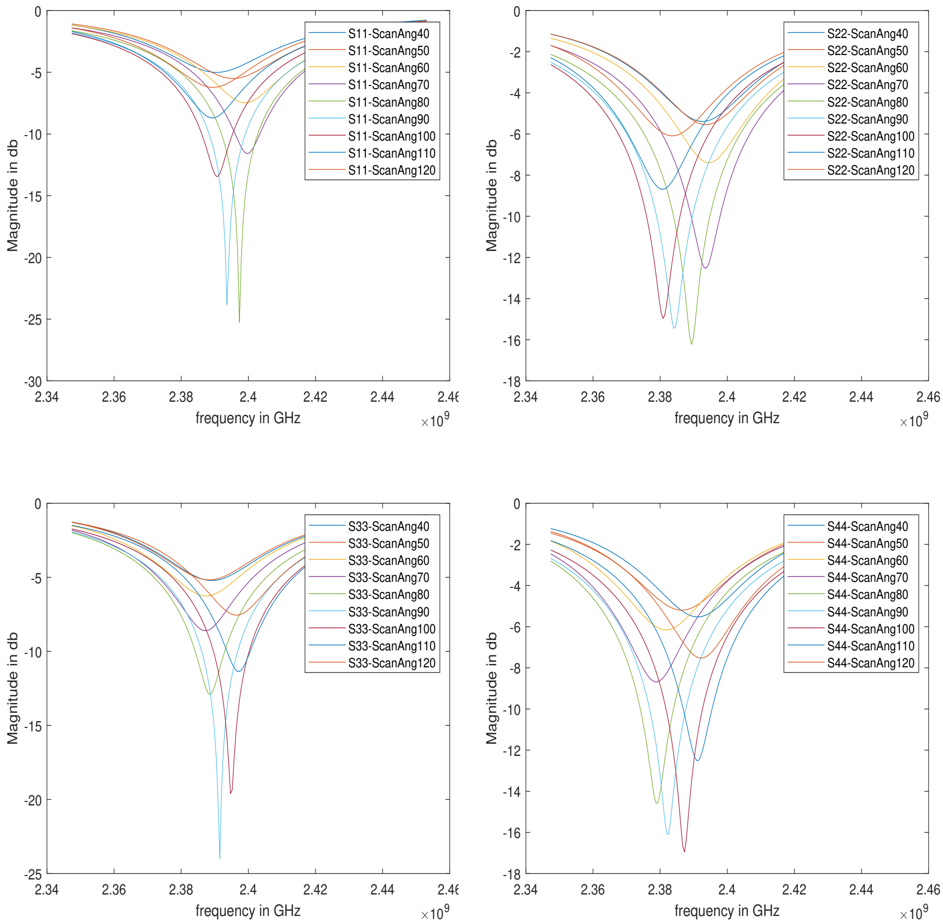

Figure 4.14: S-Param- antenna elements varied for different steering angles

the power spectral density graph as shown in the figure 4.15 we can see how original LTE signal has changed after passing through PA.

4.3.1 DIDO Model for PA

Based on fundamentals from chapter3 DIDO model accounts for load modulation variations from reflected signal as seen in figure 3.9 and that needs to be modelled, in SISO model we do not account for load modulation variation it only accounts for PA non-linearities.

From the figure 4.16 s_{in} is the input LTE signal and b1,b2,b3,b4 are obtained by multiplying the calculated s-parameters for antenna array by the input signal.

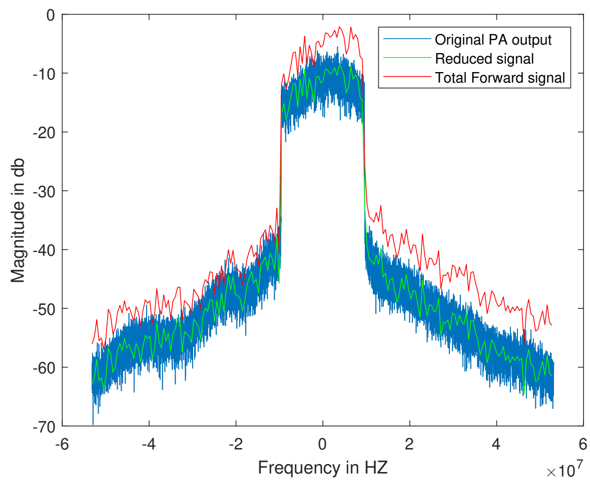

Figure 4.15: SISO PA

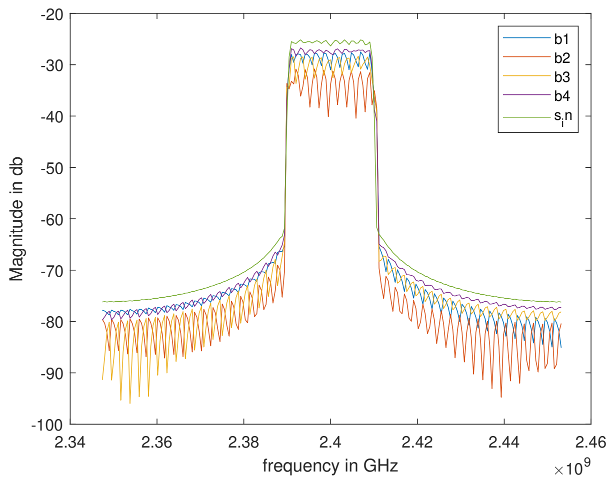

Figure 4.16: DIDO PA

It seen that b1,b2,b3 and b4 are the output signal which has distortion in it.

4.4 Load Sensitive Memoryless PA Model

PA memory based model needs recursive voltera series to be implemented and it creates hardware complexities. So in order to have less complexities we model PA by curve fitting method. In this method we find parameters required to model AM-AM and AM-PM distortions[21].

For different input voltage of PA amplitude and phase distortion is calculated and curve fitting looks like below. The curve fitting database is use to map our PA of desired distortion and characteristics to model load modulation variations.

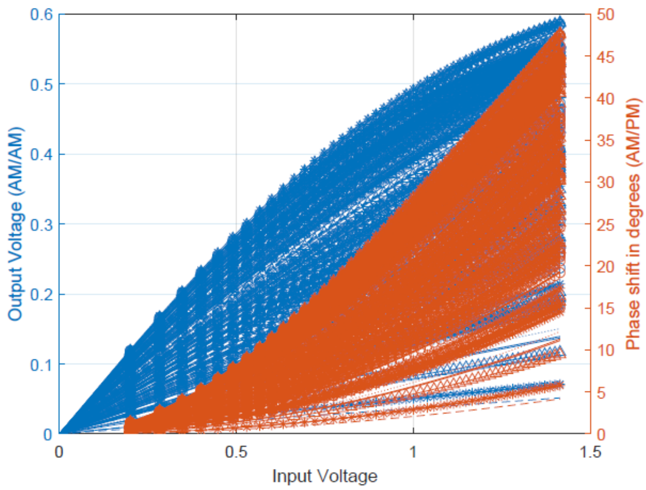

Figure 4.17: Saleh model AMAM AMPM

4.5 ACPR for 2.4GHz and 28GHz

In previous section we have experimented with S-param and PA-model integrated. For the output we calculate the ACPR[25]. Input and output PSD is used to calculate ACPR. ACPR/ACLR values for 2.4Ghz using phased array antenna model and over scan angle ACPR varies[8] can be seen in figure 4.18.

The same experiment is repeated for load sensitive-PA (modified Saleh model) at 28Ghz and over scan angle and ACPR is calculated as shown in figure 4.19. Similarly to consider effect of PA , we use LTE signal PSD to output of load sensitive-PA (modified Saleh model) PSD to calculate the ACPR and can be seen in figure 4.20.

4.6 EVM for 2.4GHz and 28GHz

EVM is calculated for 2.4GHz with LTE signal. Input and output PSD is used to calculate EVM and can been seen as in figure 4.21. EVM is calculated for 28GHz with LTE signal as input. Input and output PSD is used to calculate EVM[21] and is seen as in figure 4.22.

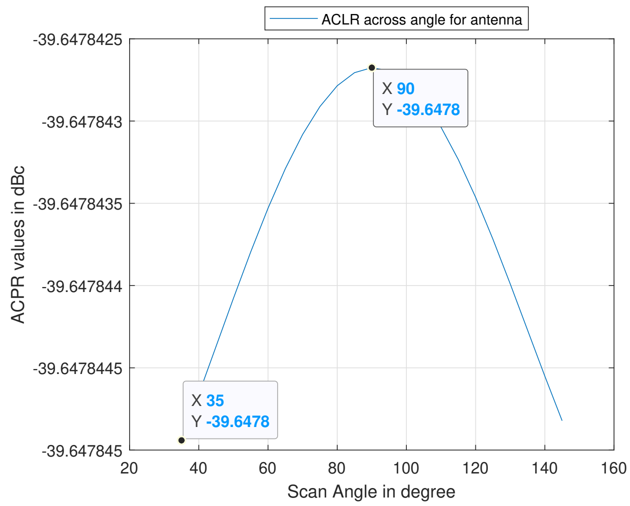

Figure 4.18: ACPR at 2.4GHz

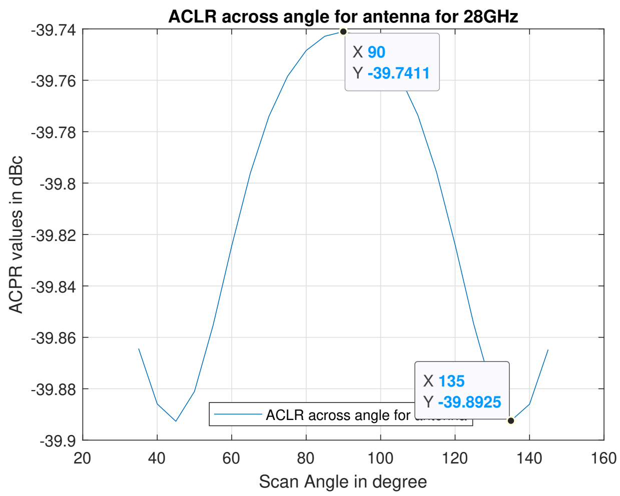

Figure 4.19: ACPR at 28GHz

EVM is calculated for load sensitive PA model at 2.4GHz with LTE signal as input. Input and output PSD is used to calculate EVM for different scan angles as seen in figure 4.23.

4.7 PSD for Antenna Model and Load Sensitive PA Model

LTE signal is used for 2.4GHz and output total combined forwarded PSD is calculated. Once output is calculated PSD is plotted for phased.URA antenna model[26]

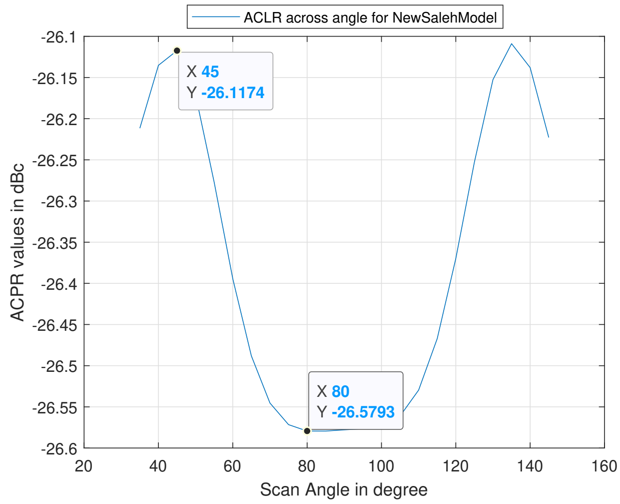

Figure 4.20: ACPR for load sensitive PA Model

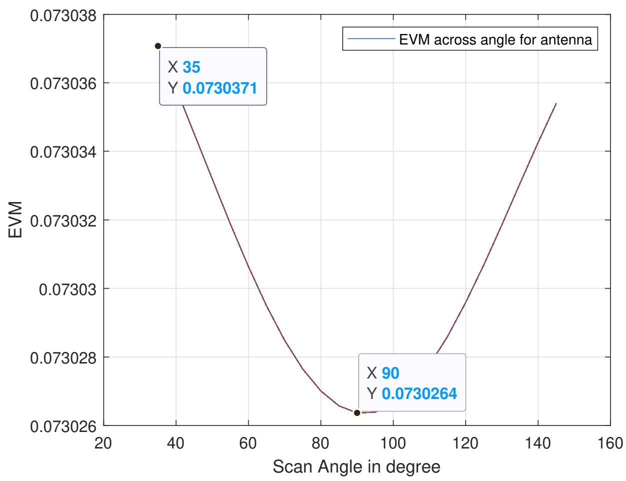

Figure 4.21: EvM at 2.4GHz

as seen in 4.24. Similarly PSD for input LTE and output of load sensitive PA model is plotted in figure 4.25 and can be easily seen that adjacent channel distortion when PA is introduced.

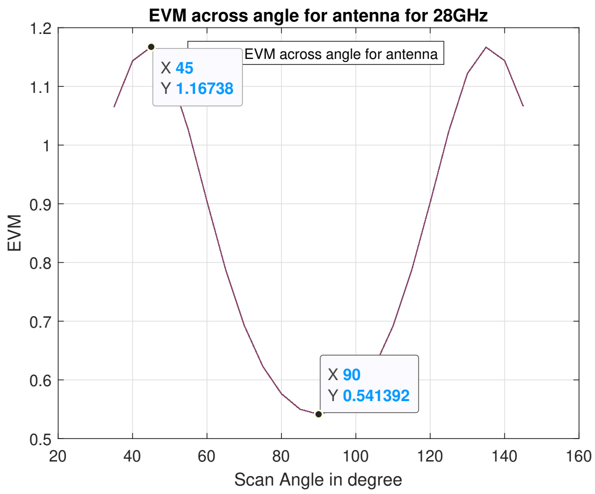

Figure 4.22: EVM at 28GHz

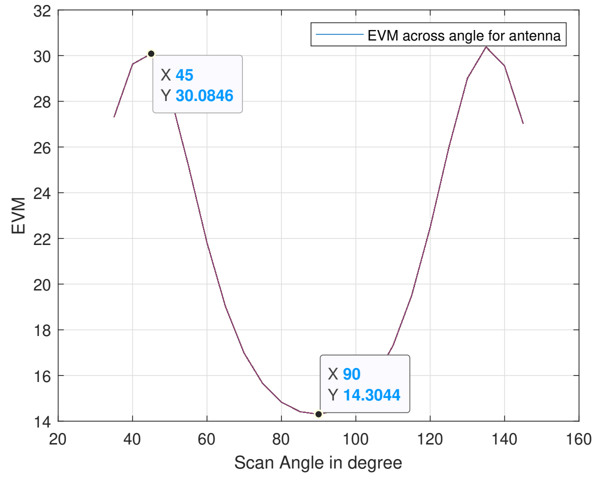

Figure 4.23: EVM for load sensitive PA model

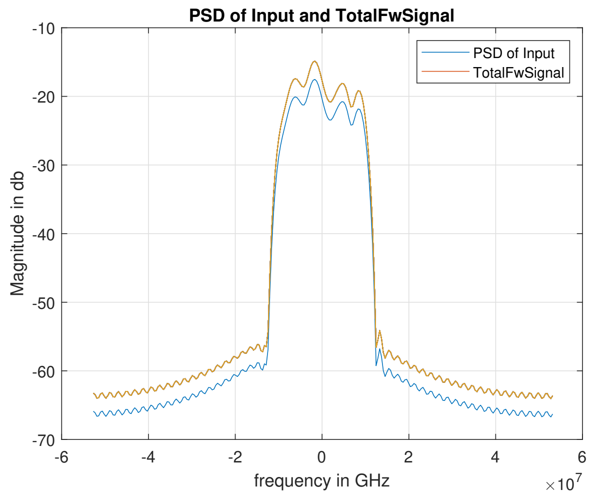

Figure 4.24: PSD for Tx antenna array at 2.4GHz without PA

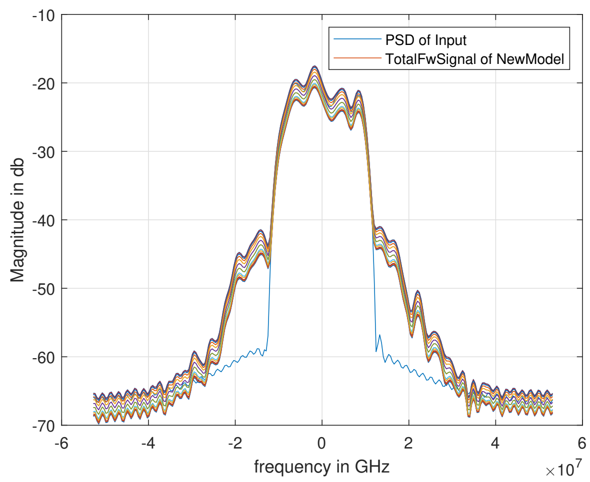

Figure 4.25: PSD of a load sensitive PA model

Chapter 5

Conclusion and future work

5.1 Conclusion

An analysis of load modulation effects focusing particularly on PA distortions on formed transmitted beam pattern of output signal was studied. Antenna design models for phased array, rectangular array and embedded rectangular array, SISO PA, DIDO PA and load sensitive PA model was built to account for different load modulation variations. To study the effects, a $2x2$-antenna transmitter array was developed in Matlab. The measurement was carried for 2.4GHz and 28GHz transmitting frequencies.

Antenna array was synthesized for digital beamforming and beam steering in a far-field scenario. These variations are seen with different scan or steering angles array was studied and load modulation variations at higher frequencies with distance between elements was evident. Beam scanning in different directions resulted in directivity variations showing the mutual coupling effects between antenna elements[5].

To investigate the cross-talk effects in detail for various cross-talk environments and to emulate solution design from a hardware perspective, phased array and rectangular array models were designed in antenna array tool.

Antenna array mismatch and coupling was modelled from the S-param model in rectangular array set up in the form to introduce cross-talk effects in the simulation models. Further to investigate coupling effects deeper distance and scan angles is varied in the model for 2x2 MIMO model. The coupling impact was studied on PA outputs i.e. without PA and then with PA. This degradation in ACLR is observed in scan angle changes for load sensitive PA model. From the table below its evident that ACLR and EVM having higher impact at 28GHz and it is observed from EVM values is degraded by order of 14db.

Models	Freq Band fc	Beam Scan	ΔEVM	ΔACLR db
Antenna array Tx	2.4 GHz	35-140	0.00001	0.00001
Antenna array Tx	28 GHz	35-140	1.13	0.11
Including PA model	28 GHz	35-140	15.78	1.40

Table 5.1: Table indicating increase in EVM,ACLR for higher frequency.

5.2 Future Work

The PA model is constant in nature which as they are extracted over the dynamic power range of signal generator but used at constant power in the simulation model. Thus, a closed loop adaptation is required between two systems at same time and throughput rate even when PA models are used to generate the pre-distorted signal. As a result, validation of the proposed method using measurement data could be done using script-based model rather than low throughput hardware model. The former approach will better synchronize with measurement setup and could be proposed as a future work. The future work suggestions can be listed as the following:

- Antenna array designing and analysis must be evaluated for a higher array like $64x64$ array pattern.
- Real-time hardware analysis for cross-talk design could be built and interfaced to approve and confirm simulation results.
- Hardware based DPD pre-distortion for cross-talk compensation could further be implemented based pre-distortion in a closed loop adaptation.
- Transform simulation-based hardware model to script-based model to run the algorithm in closed loop adaptation with physical PA and instruments.
- Load-pull measurement setup to extract PA model to test performance under load modulation effects on DPD.

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