Antennas for detection of ADS-B signals at satellites and investigation on crosstalk between antenna elements

For detection of ADS-B signals

Master thesis

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Abstract:

This project investigates different antenna types for mounting on a cube satellite for reception of ADS-B. The report is split up in two parts, where the first part is a link-budget that sets the requirements for the antenna. The second part is where the antennas is investigated. This includes a reflector antenna, a quadrifilar antenna and a hemispherical antenna.

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STUDENTERRAPPORT

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Abstract:

I dette projekt er der blevet undersøgt hvilke antenner der kan bruges til at modtage ADS-B signaler på en cube satellit. Rapporten er delt op i to hvor den første del er opstillet som et linkbudget der beskriver kravende til en sådan antenne. Den anden del er selve undersøgesøgelsen af forskellige antenne typer. Disse inkluderer en parabol antenne, en quadrifilar helical antenna og en hemispherical antenne.

Contents

Todo list

Preface

Here is the preface. You should put your signatures at the end of the preface.

Aalborg University, May 14, 2019

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Chapter 1

Introduction

The goal of this project is to make an deployable antenna for Automatic dependent surveillance-broadcast (ADS-B) on a Low-Earth Orbit (LEO) satellite. ADS-B is a system in which aircraft continually transmit their identity and GPS-derived navigational information. ADS-B networks for air traffic monitoring have already been implemented in areas around the world, but ground stations cannot be installed in mid-ocean and are difficult to maintain in the Arctic, leaving a coverage gap for oceanic and high latitude airspace. Therefore a solution can be to monitor the signals with a low orbit satellite using an antenna matched to the frequencies of the ADS-B. This has already been done by the company Aireon which has 66 ADS-B receivers hosted on the new Iridium NEXT LEO satellite constellation. But this is a large satellite and a CubeSat would be better suited for the application. Therefore the antenna should fit in a 1U cubesat which can be deployed when in space.

Chapter 2

Amplifier Imperfections

2.1 Non-linearity

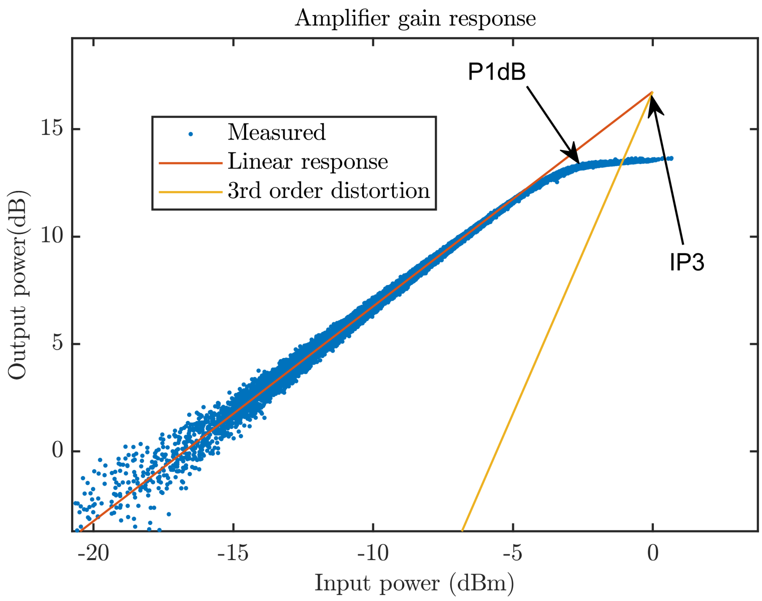

Figure 2.1: Amplifier non-linearity

An ideal power amplifier has an linear response over all frequencies and input power. This is depicted in 2.1 as Linear response. Unfortunately this is not true and therefore a measurement of a power amplifier has been done. The measurement shows that the amplifier at some level can be assumed linear, but at a point the amplifier will saturate due to the supply voltage and the gain will compress. The point where there is 1dB from the linear response to the real response is called the 1dB compression point (P1dB) which is also depicted in the figure. The non-linear gain response causes a distortion at the output which can be described by equation 2.1 [National

Instruments, 2019]. If a input-signal using two tones is considered then there will be a difference and a sum of the frequencies presented at the output which is caused by the cubic term in equation 2.3.

$$V_{out} = a_0 + a_1 V_{in} + a_2 V_{in}^2 + a_3 V_{in}^3 + a_4 V_{in}^4 + ... \tag{2.1}$$

Where V_{out} is the output signal from the amplifier, $a_1, a_2, a_3..$ is coefficients describing the ratio of the distortion and V_{in} is the input signal. If a single tone input is presented, then the output will consist of purely odd and even harmonic distortion.

$$V_{in} = sin(\omega_1 t) + sin(\omega_2 t) \tag{2.2}$$

$$V_{out} = a_0 + a_1(sin(\omega_1 t) + sin(\omega_2 t)) + a_2(sin(\omega_1 t) + sin(\omega_2 t))^2 + a_3(sin(\omega_1 t) + sin(\omega_2 t))^3 + ... \tag{2.3}$$

This is also called Two-Tone Third-Order Intermodulation Distortion and is also depicted in figure 2.1 as 3rd order distortion with a slope of 3:1. It can bee seen that when the output power increases then the 3rd order distortion increases 3 times. A measurement of this is called the third-order-intercept-point (IP3 or TOI). However, the intercept point it not directly measurable since the amplifier reaches compression way before. It can bee seen from figure 2.2 that the distorted component are spaced too close in frequency to be effectively filtered. This will cause distortion into nearby channels and is measured as Adjacent Chennel Power Ratio (ACPR).

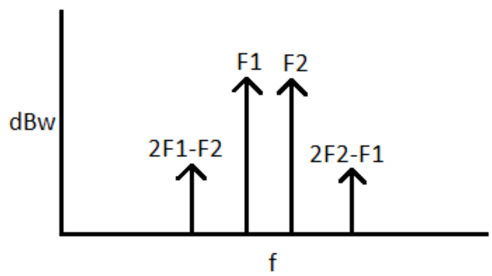

Figure 2.2: Two-Tone Third-Order Intermodulation Distortion

2.1.1 Distortion due to non-linearity

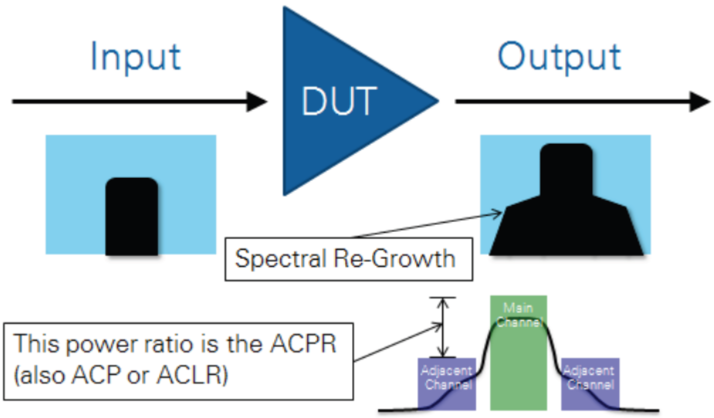

Figure 2.3: Graphical Depiction of ACPR in the frequency domain [National Instruments, 2019]

Due to the non-linearity of the PA described before, spectral regrowth will occur which will affect nearby channels. The Adjacent Channel Power Ratio (ACPR) is a measure of the power of the distortion components, caused by the non-linearity of the PA, that are leaked into the adjacent channel see figure 2.3. The formula for the ACPR is given by equation 2.4 and is used after a Fourier transform has been performed at the output of the PA.

$$ACPR = \frac{\int_{adjch} |Y(f)|^2 df}{\int_{mainch} |Y(f)|^2 df} \tag{2.4}$$

Where $Y(f)$ is the Fourier transform of the signal, adjch is the adjacent-channel and mainch is the main-channel.

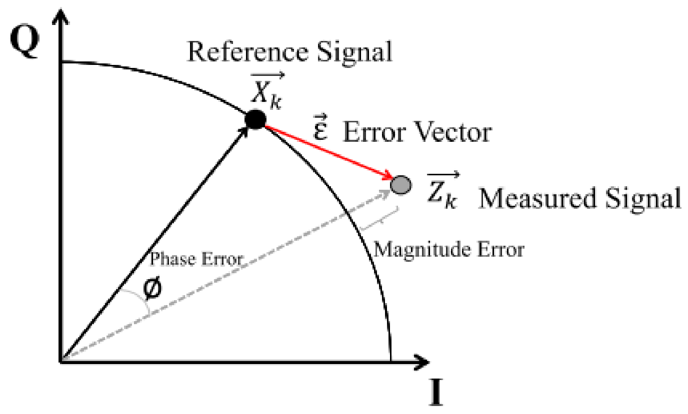

Figure 2.4: Graphical view of the EVM

Another measure of the error is the Error Vector Measurement (EVM) or Relative Constellation Error (RCE) which both is a measure of the error due to the constellations points in a IQ plot. If a signal is sent through an amplifier with a given IQ value, then the amplifier will distort those IQ values. The EVM and RCE is a measure of the power of the error vector divided by the power of the reference vector. [Ali Cheaito, et. al, 2016]

$$EVM = \frac{P_{error}}{P_{reference}} = \frac{E[|z(t) - x(t)|^2]}{E[|x(t)^2|]} \tag{2.5}$$

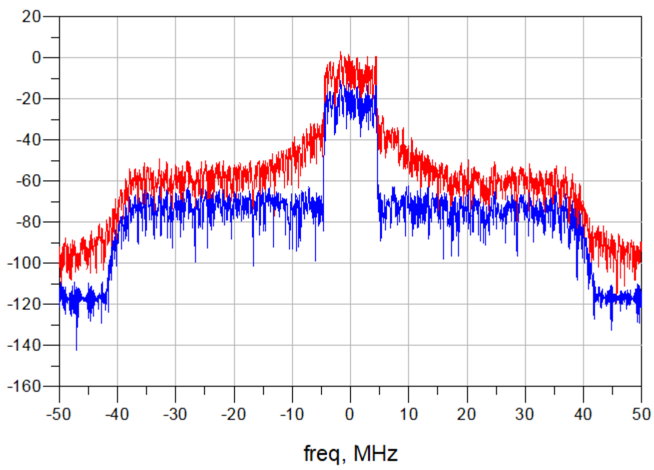

Figure 2.5: Destortion simulated in ADS, where blue is input-signal and red is output-signal. The simulation is made with a single amplifier connected to a 50Ω resistor. It is clearly that the output-signal is distorted. The ACPR becomes -45dB with a BW at 100MHZ

2.2 AM/AM and AM/PM distortion

If the input signal to the PA is modelled as equation 2.6

$$x(t) = a(t)e^{j\phi(t)} \tag{2.6}$$

Where $a(t)$ is the envelope of the signal and $e^{j\phi(t)}$ is the phase of the input signal. Then the distorted output of the amplifier will be that of equation 2.6 where $g(t)$ is the amplitude distortion and $f(t)$ is the phase distortion also called Amplitude to Amplitude (AM/AM) and Amplitude to Phase (AM/PM) distortion. AM/AM distortion can be defined as the deviation from the constant gain when PA is operated in compression region. On the other hand, the increased phase change at compression region can be termed as AM/PM distortion.In presence of wideband signals having non constant amplitude, PA behaves as nonlinear system and exhibits two types of non-linearities which is static distortion and memory effects.

$$y(t) = g(a(t))e^{j\phi(t)+f(a(t))} \tag{2.7}$$

2.2.1 Memory effects

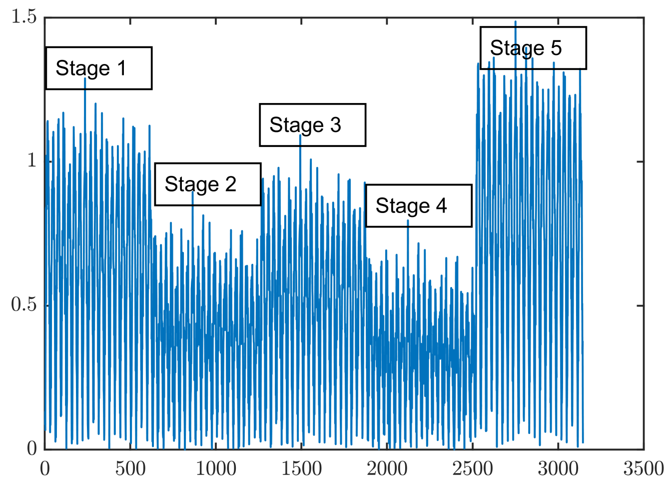

Figure 2.6: Example of amplitude changes at the input of a PA

In modern communication systems, the input power to the PA may be adjusted corresponding to the needs by the network. This makes a suddenly increase or decrease in the power as depicted in figure 2.6 which makes the PA work in the transient stage [Yan Guo, et.al, 2015] [Taijun Liu, et.al, 2007]. The transient stage is where the power suddenly increases or decreases to another mean power, whereas the steady state is when the PA operates under stable conditions where the mean power is constant. When the PA is operated in steady state under a high mean power, the amplifier will begin to dissipate heat. This will cause the internal transistors to operate under a hot state where the characteristic of the transistors will change due to a colder state. If the mean power suddenly is decreased the amplifier will still be hot, but with time the amplifier will cool down and the characteristic will change. This can be called slow memory effects whereas fast memory effects is when the amplifier is driven in its steady state and the parasitics of the components distort the signal. Also antennas at the output of the amplifier has an important role specially if several antennas are connected to form an array. The electrical field will couple to each other and cause fields that will affect the memory effects in the system.

2.3 Efficiency

An important measure of an amplifier is its efficiency, specially when the amplifier is located in a battery powered application. The efficiency of a amplifier is given by equation 2.8

$$\eta = \frac{P_{out}}{P_{amplifier} + P_{out}} = \frac{P_{out}}{P_{DC}} \tag{2.8}$$

Where P_{out} is output power from the amplifier, $P_{amplifier}$ is power dissipated in the amplifier and P_{DC} is the power DC consumption. A more common way to express the efficiency is in terms of power added efficiency (PAE) which is a measure of the difference of power between the output and the input signals versus the DC power consumption.

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \tag{2.9}$$

2.4 Antenna Diversity and MIMO

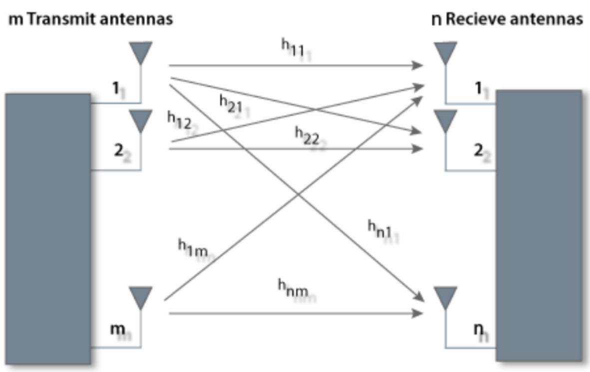

Figure 2.7: Concept of MIMO [Silvus Technologies, 2019]

MIMO (Multiple Input Multiple Output) systems are systems with Multiple Element Antennas at both link ends. The antenna elements of a MIMO system can be used for four different purposes: beamforming, diversity, interference suppression, and spatial multiplexing which is transmission of several data streams in parallel that allows improvement of capacity.[Andreas F. Molisch, 2011] A MIMO system is modelled as in equation 2.10 and is also depicted in figure 2.7.

$$\mathbf{y} = \mathbf{H}\mathbf{x}+\mathbf{n} \tag{2.10}$$

Where $\mathbf{y}$ is the received vector, $\mathbf{H}$ is the channel matrix, $\mathbf{x}$ is the transmitted vector and $\mathbf{n}$ is noise. If the full channel matrix is known then the transmitted vector can be obtained by the receiver like equation 2.11.

$$\mathbf{x}+\mathbf{n} = \mathbf{H}^1\mathbf{y} \tag{2.11}$$

The principle of MIMO is to ensure that the same information reaches the receiver on several statistically independent channels. In MIMO systems, several transmits paths is archived by use of several antennas, which gives a spatial separation if they are separated enough to give a correlation factor ρ that is below $0.5 - 0.7$ [Andreas F. Molisch, 2011]. The formula for the envelope correlation factor between two antennas is given by equation 2.12. The formula assumes that the WSSUS (Wide-Sense Stationary Uncorrelated Scattering) model is valid, no LOS exists, the power delay profile has an exponential shape, the incident power is isotropically distributed in azimuth and only propagates in the horizontal plane, and an omni-antenna is used.

$$\rho = \frac{J_0^2(k_0 v\tau)}{1 + (2\pi)^2 S_\tau^2 (f_2 - f_1)^2} \tag{2.12}$$

Where J_0 is the Bessel function of the first kind and S_τ is the delay-spread of the channels. If the correlation between two antennas is investigated for the same frequency, then the formula can be rewritten as equation 2.13 because $f2 - f1 = 0$.

$$\rho = J_0^2(2\pi d)^{-1} \tag{2.13}$$

Where d is the element spacing given in wavelengths. A plot of this can bee seen in figure 2.9.

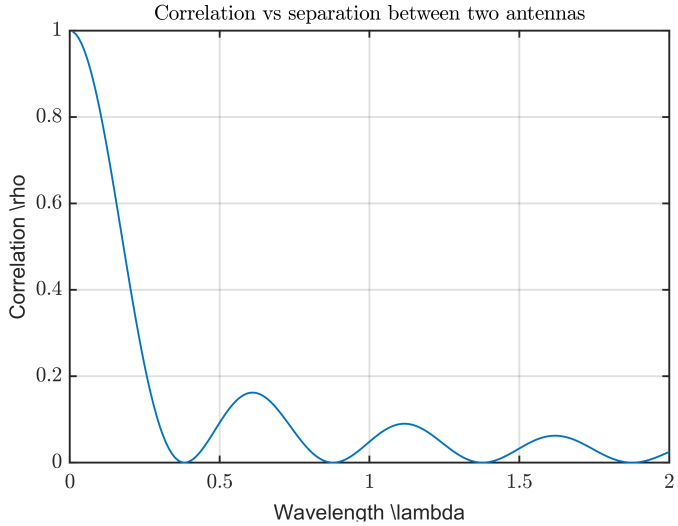

Figure 2.8: Correlation factor for two antennas versus distance

Another method to calculate the correlation factor is to use measured or simulated S-parameters as shown in equation 2.14 [Xuan Wang, et. al, 2011] where k is the propagation constant and d the distance in meters.

$$\rho = \frac{A + BJ_0(kd)}{B + AJ_0(kd)} \tag{2.14}$$

$$A = -2Re(S_{12}^*(1 - S_{11})) \tag{2.15}$$

$$B = |1 - S_{11}|^2 + |S_{12}|^2 \tag{2.16}$$

A simulation has been made in CST studio with 4 antennas separated 0.1λ at $f = 3.5Ghz$ or 8.6mm, see figure 2.9. The simulated S-parameters has been imported to MATLAB and the formula is used to generate the correlation plot in figure 2.10. From the figure it can bee seen that when the frequency increases the correlation becomes lower.

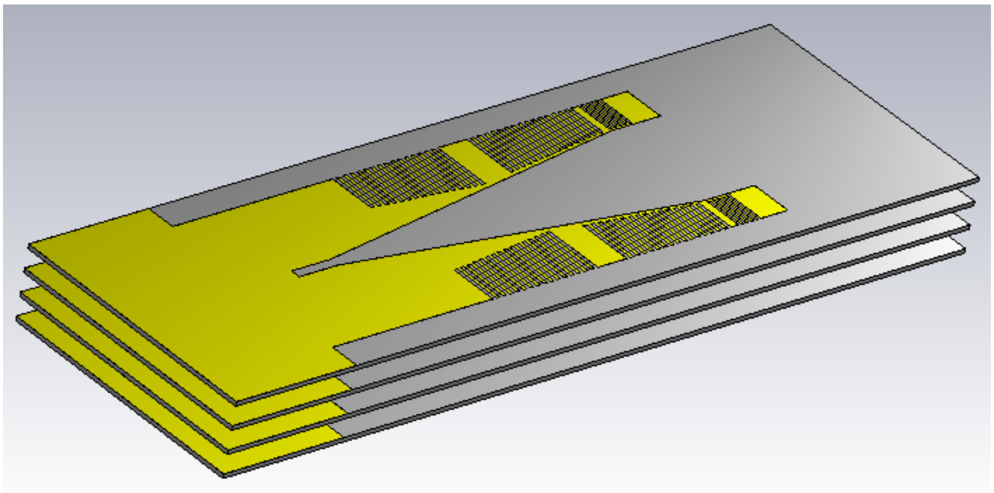

Figure 2.9: 4 wideband PCB antennas separated 8.6mm

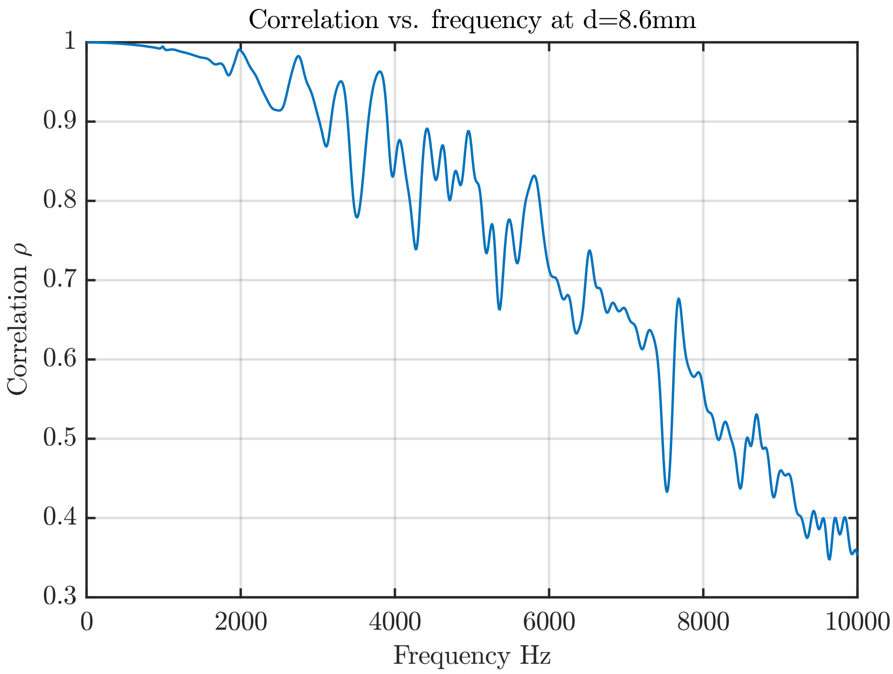

Figure 2.10: Correlation between antenna 1 and 2

2.5 Array factor

When several antennas are spaced relatively close to each other it is called an antenna array. If the antennas are isotopic and are spaced with a quarter wavelength then the array will radiate twice the energy in the direction perpendicular to the array, thou the gain along the array will become zero. A mathematical expression of this is called the array factor (AF).

$$AF = \sum_{n=1}^{N} e^{(nJ2\pi d\cos(\alpha)+JB(n))} \tag{2.17}$$

Where N is number of antennas in the array, d is the distance between the antennas, α is the azimuth angle from $0..2\pi$ and B is the feeding phase of a single antenna. In figure 2.11 and 2.12 the array factor for 2 and 4 antennas spaced $[0.1, 0.2, 0.3, 0.4, 0.5, 0.6]\lambda$ are plotted respectively. It is seen that the energy doubles in the 90° for all distances in figure 2.11 while it becomes 4 times greater in figure 2.12.

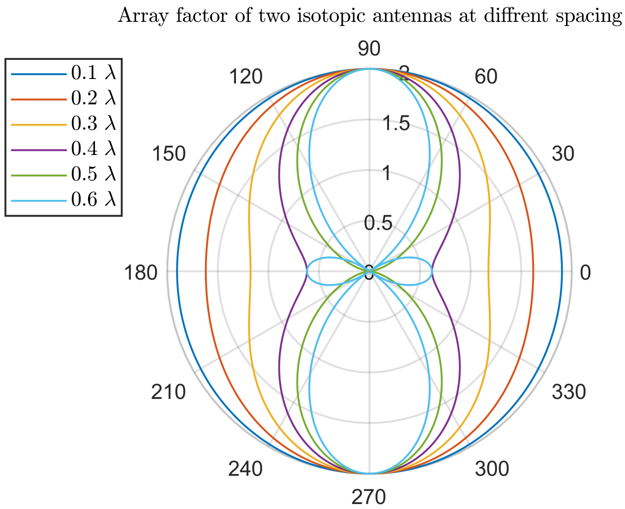

Figure 2.11: Array factor of two antennas with diffrent spacing

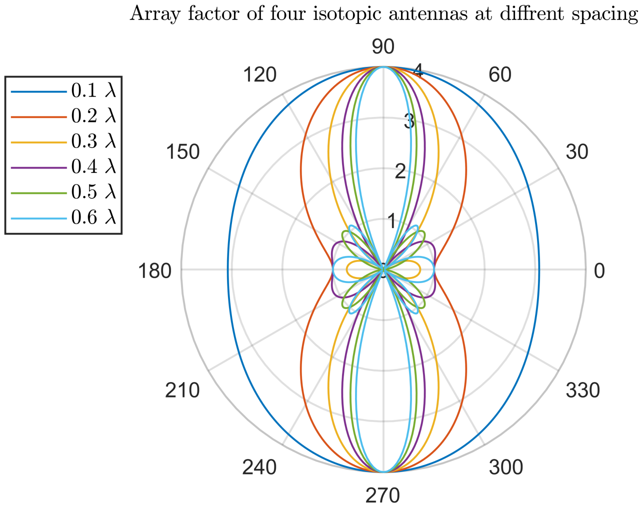

Figure 2.12: Array factor of four antennas with diffrent spacing

Chapter 3

Amplifier modelling

3.1 Pre-distortion

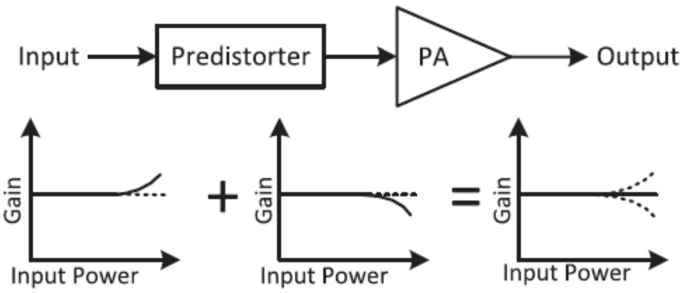

Figure 3.1: Consept of predistortion [Yan Guo, et.al, 2015]

In figure 3.4 the consept of Digital Pre-Distortion (DPD) is depicted. DPD is a way to "distort" the incomming signal with the inverse transfer-function of the amplifier. For example the gain of the amplifier is ideally linear in the small-signal region and gets non-linear at higher signal levels. To overcome this, a block called the predistorter inverses this non-linear curve which is the exact inverse of the PA, then a linear amplification can be achieved at the final PA output. But to archive this inverse of the PA all the non-linear effects has to be accounted for including memory effects.

3.2 DPD models

Weiner

A simpel model to include memory effects is the Weiner model, which consists of a linear filter $h(m)$ followed by a_k which is the polynomial coefficients of the non-linearity. The model is given by equation 3.1

$$y_{wiener}(n) = \sum_{k=1}^{K} a_k [\sum_{m=0}^{M-1} h(m)x(n-m)]^k \tag{3.1}$$

It is seen that the output consists of the sum of the non-linear response multiplied with the sum of the input with the former input multiplied with a filter. The Weiner model is one of the simplest ways to combine memory effects with non-linearity but unfortunately it does not provide good results for modelling a power amplifier.

Hammerstein

Another simple model is the Hammerstein model which is given by equation 3.2

$$y_{hammerstein}(n) = \sum_{m=0}^{M-1} g(m) \sum_{k=1}^{K} a_k x^k(n-m) \tag{3.2}$$

Which is formed by a non-linearity followed by a linear filter. It is seen that the output consist of the sum of the linear filter $g(m)$ multiplied with the sum of the filter coefficielts a_k multiplied with the input signal and the former input signal in the power of k. Yet this filter is simple it does also have it's limitations when it come to modelling of power amplifiers.

Memory Polynomial

A more used and general model is the memory polynomial given in equation 3.3. The model is a deviation of the Hammerstein model which has proven effective for predistortion of actual power amplifiers under typical operations.

$$y_{mp}(n) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x(n-m)|x(n-m)|^k \tag{3.3}$$

where a_{km} is the filter coefficients, $x(n)$ is the input, M is the memory debt and k is the envelope order.

Estimation of coefficients

A way to calculate the coefficients for a DPD algorithm is by use of the least-square-type algorithms. The reason for this is that the coefficients are linear weighting of non-linear signals. The easiest way to formulate such a problem is to first collect the coefficients into one $J \times 1$ vector denoted $\boldsymbol{w}$, where J is the total number of coefficients. The input can then further be assembled in to a vector denoted $\boldsymbol{X}$ which dimensions is $N \times J$. The model output can then be expressed by:

$$\hat{\boldsymbol{y}} = \boldsymbol{X}\boldsymbol{w} \tag{3.4}$$

where $\hat{\boldsymbol{y}}$ is an $N \times 1$ vector which is an estimate of the real output $\boldsymbol{y}$. The inverse of this model used for predistortion is then:

$$\hat{\boldsymbol{x}} = \boldsymbol{Y}\boldsymbol{w} \tag{3.5}$$

where the input now is being estimated from the output samples. It is then possible to use the least-squares solution to minimize the estimation error:

$$\boldsymbol{w} = (\boldsymbol{Y}^{\boldsymbol{H}}\boldsymbol{Y})^{-1}\boldsymbol{Y}^{\boldsymbol{H}}\boldsymbol{x} \tag{3.6}$$

where $\boldsymbol{Y}$ is a $J \times N$ matrix where N is number of samples. The equation can further be rewritten as:

$$\boldsymbol{Y}^{\boldsymbol{H}}\boldsymbol{Y}\boldsymbol{w} = \boldsymbol{Y}^{\boldsymbol{H}}\boldsymbol{x} \tag{3.7}$$

This equation can easily be solved by MATLAB using the "backslash" operator (\) by Cholesky decomposition and forward/backward substitution.

Estimation in MATLAB

If an input and output signal is measured and imported into MATLAB and called $\boldsymbol{x}$ and $\boldsymbol{y}$ respectively, then a for-loop can do the $\boldsymbol{Y}$ matrix. Next we need to remove M sampels from $\boldsymbol{x}$ because of the time delay, then the substitution to find $\boldsymbol{w}$ using the (\) operator can be done. The code is given below:

```
K = 5;%envelope order
M = 8;%memory debth

Y = [];%init matrix
for m = 1:M
    for k = 1:K
        Y(:,end+1) = (y(m:end-M+m).*abs(y(m:end-M+m)).^(k-1));
    end
end

x2 = x(M:end);%Remove M samples
w = Y\x2;%Do the regression
x_est = Y*w;%
error = mean(abs(x2-x_est))
```

Now equation 3.5 must be used to obtain the inverse model:

```
X = [];%init matrix
for m = 1:M
    for k = 1:K
        X(:,end+1) = (x(m:end-M+m).*abs(x(m:end-M+m)).^(k-1));
    end
end
```

```
x_inv = X*Coeff;%inverse model
```

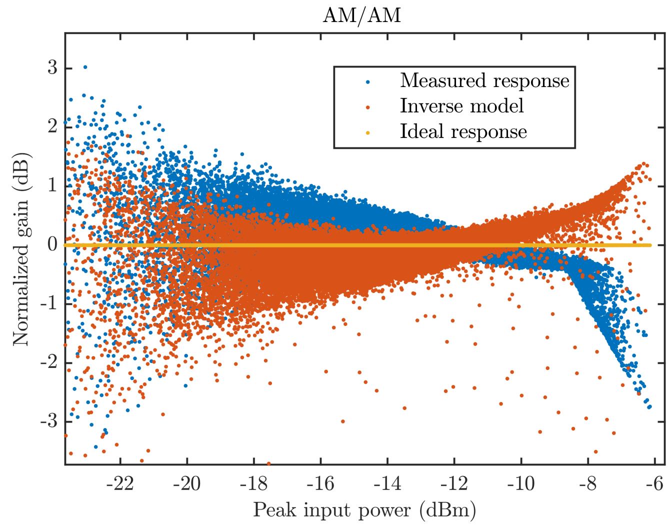

Figure 3.2: AM/AM plot of measured response and inverse model

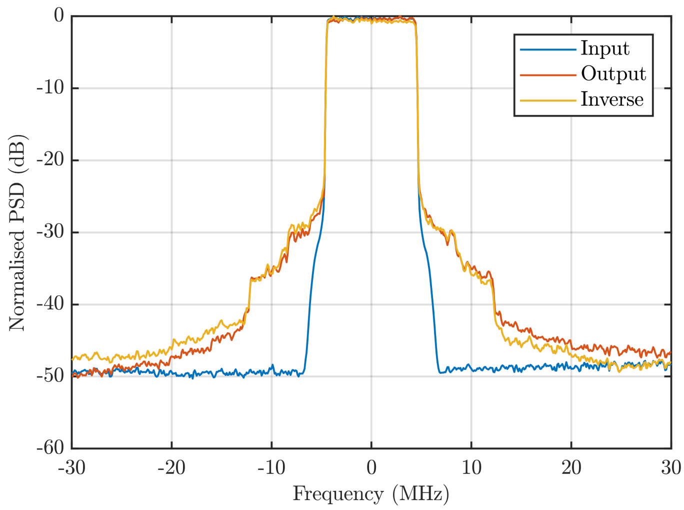

Figure 3.3: PSD of output, input and inverse model

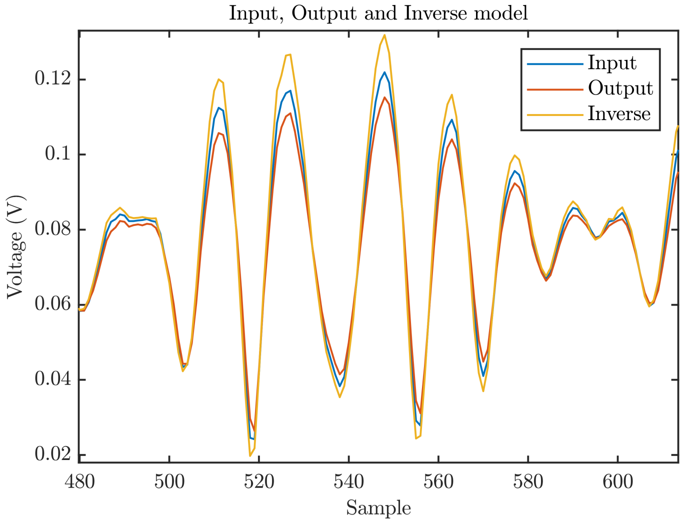

Figure 3.4: Baseband signal of input, output and inverse model

3.3 Crosstalk

Crosstalk is coupling from one branch to another branch. When only a signal is present on a single branch, no crosstalk would appear to this branch. On the other hand if a signal is presented at two branches then crosstalk would appear to both of them. There exist three types of crosstalk which is: Crosstalk before the PA's, see figure 3.5, Crosstalk after the PA's, see figure 3.6 and Crosstalk on the antennas and mishmash due to coupling. Crosstalk before the PA is also called nonlinear since it is amplified by the non linear PA. The nonlinear crosstalk and the PA nonlinear response should be jointly compensated by a predistorter to get a reliable system performance [Zahidul Islam Shahin, et. al, 2017] denoted $\mu_k(.)$. The output from the branches would become that of equation 3.8.

$$Y_{1k} = fk(uk(X_{11}, X_{12}, X_{13}, X_{1k})) \tag{3.8}$$

Where X is the input signal, Y is the output and fk is the PA response.

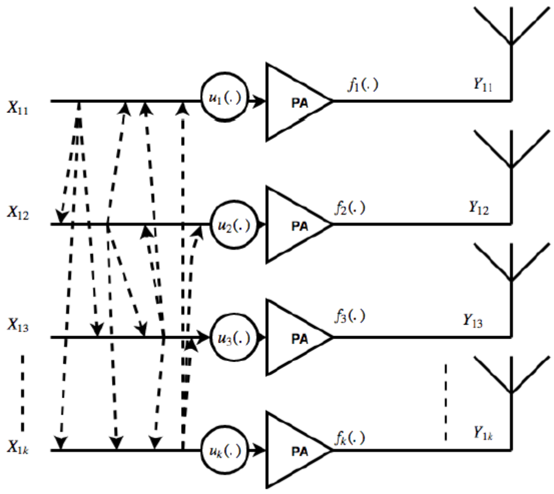

Figure 3.5: Crosstalk before PA [Zahidul Islam Shahin, et. al, 2017]

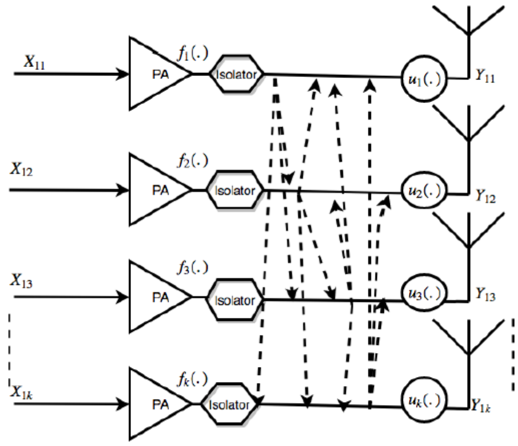

Figure 3.6: Crosstalk after PA [Zahidul Islam Shahin, et. al, 2017]

Crosstalk after the PA is called linear since it has an linear impact. In figure 3.6 the output of the amplifier is connected to an isolator, which makes the output unaffected by reflections. A linear model can therefore be used which is shown in equation 3.9.

$$Y_{1k} = \mu_k(f1(X_{11}), f2(X_{12}), f3(X_{13})..fk(X_{1k})) \tag{3.9}$$

When no isolators is presented the output will now be affected by the crosstalk or mutual-coupling between the antennas. A sketch of this is depicted in figure 3.7 where a_{1k} is the incoming signal to the amplifier, b_{2k} is the output from the amplifier and a_{2k} is the reflected signal form the antenna array at the k'th branch [Katharina Hausmair, et. al, 2017]. The relation between a_{2k} and the output signals b_{2k} is determined by the characteristics of the antenna array. The system model of the multi-antenna transmitter can, therefore, be split in to a crosstalk and mismatch model (CTMM). This block can further be used together with a dual-input-DPD which holds the model for the PA, see figure 3.8.

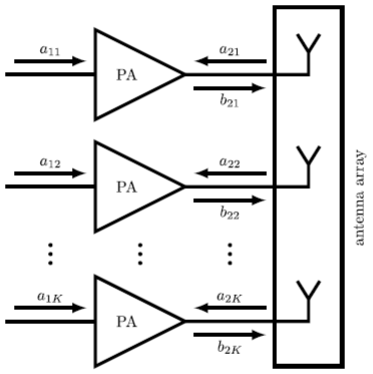

Figure 3.7: Model of the antenna crosstalk [Katharina Hausmair, et. al, 2017]

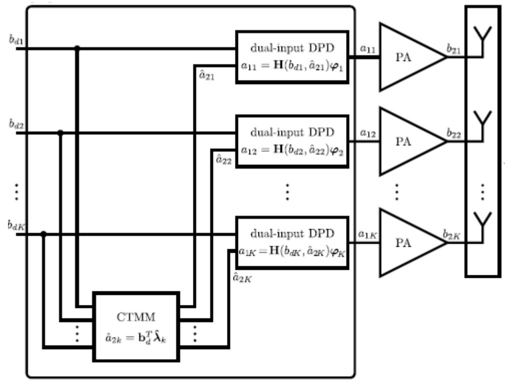

Figure 3.8: The predistortion method consists of two main blocks: one linear CTMM block for the whole transmitter and a dual-input DPD block in every transmit path. [Katharina Hausmair, et. al, 2017]

Chapter 4

Measurement

The purpose of this section is to characterize a power amplifier for its ACPR and AM/AM distortion and afterwards measure the impact of the crosstalk from the antennas.

4.1 Simulation of PCB antenna

The antenna used for measurement is a PCB antenna that measures 100x300mm on standard 1.6mm FR-4. The antenna has a S_{11} below -10dB from 2.5GHz to 6.0GHz and only gets as high as -7.5dB all the way up to 10GHz. The antenna is linear polarized and has a transmit and receive gain at 11.4dB. On the front of the PCB a large copper area is presented. This copper area is feed from the backside of the PCB where a small track is feed with a sma connector. In the simulation this track is feed with a wave guide port.

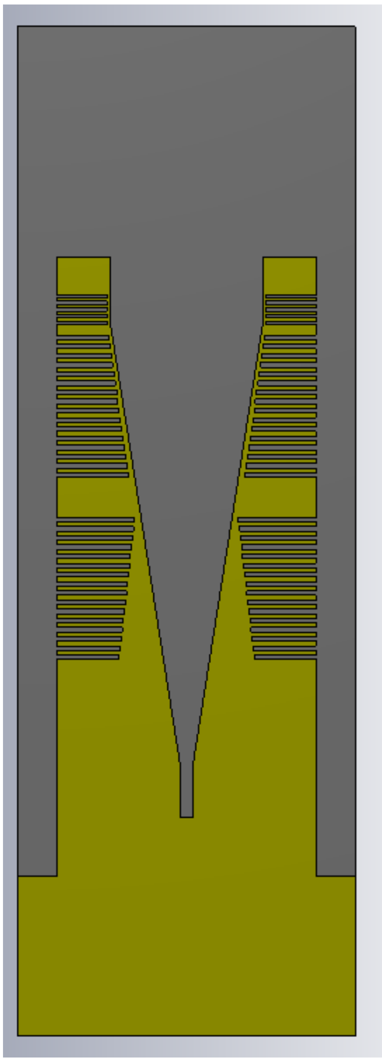

Figure 4.1: Front of PCB antenna

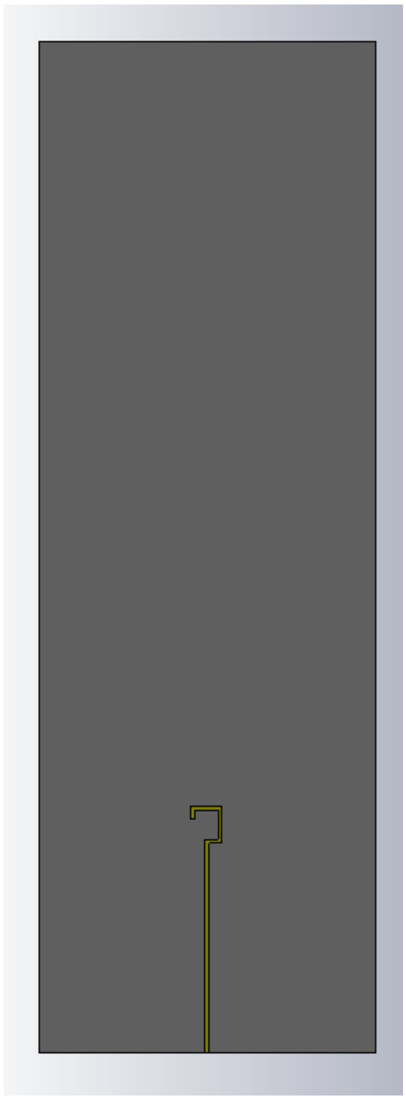

Figure 4.2: Backside of PCB antenna

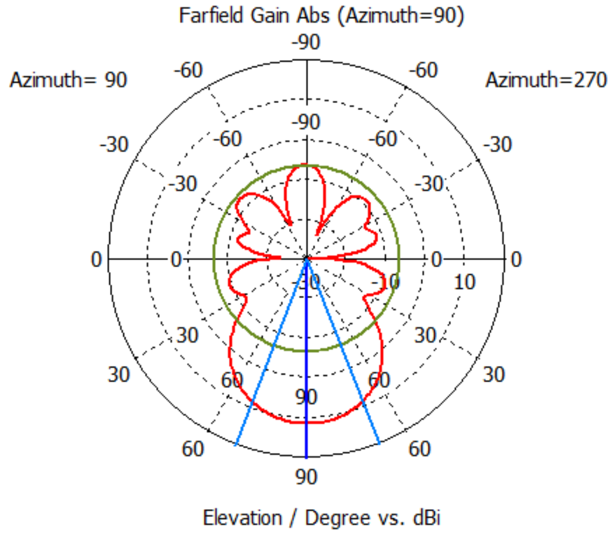

Figure 4.3: Farfield of the antenna

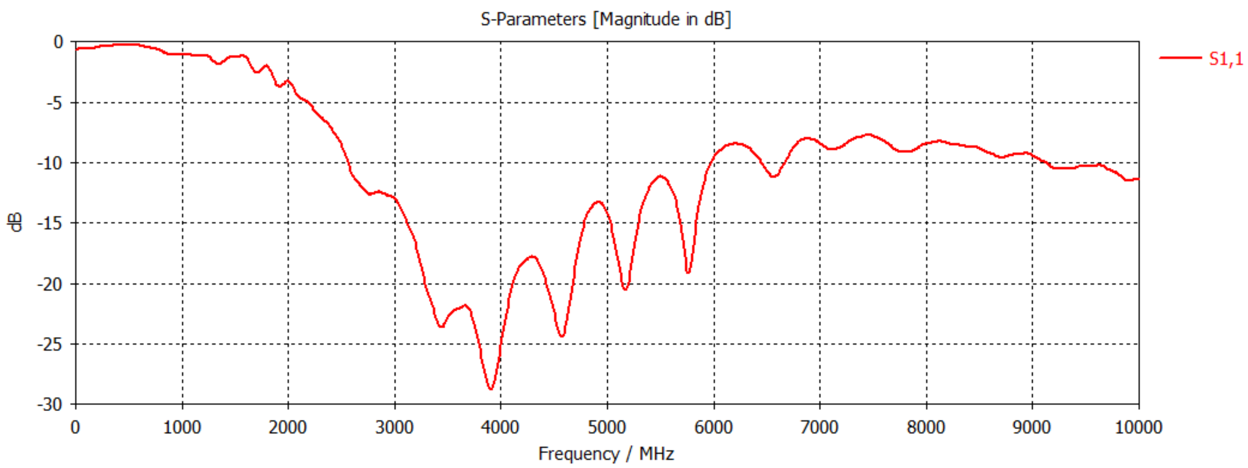

Figure 4.4: S_{11} of the antenna

4.2 Power Amplifier

The *ZX60-6013E+* amplifier is a small buffer-amplifier with a BW from 20MHz - 6GHz. It has an output-power at maximum 11.16dBm at 3.5GHz (1 dB compression). The gain is 13.85 dB and the noise figure is 3.42dB. In figure 4.6 and 4.7 curves for the amplifier gain and output power versus frequency it depicted respectively. The amplifier is shown in figure 4.5

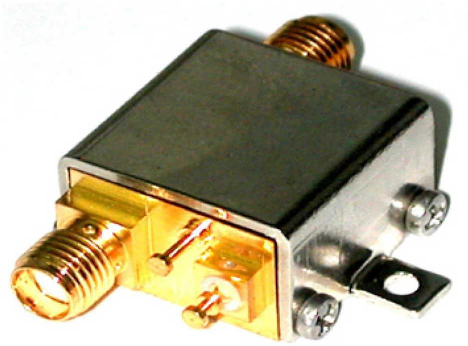

Figure 4.5: The *ZX60-6013E+* amplifier

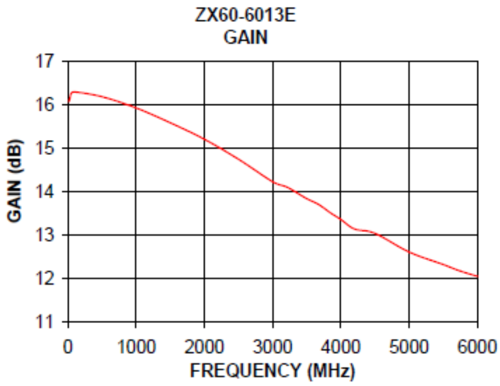

Figure 4.6: Gain versus frequency

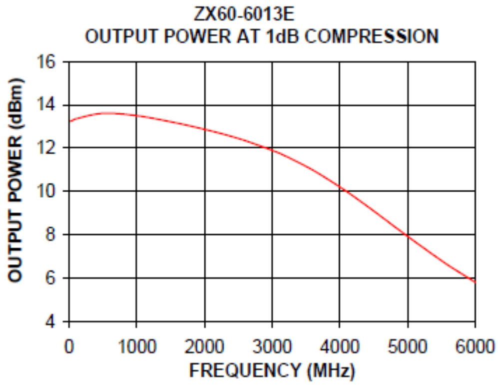

Figure 4.7: Output power versus frequency

4.3 Measurement setup

To measure the impact of the antenna crosstalk, several measurements must be done at different setups. The first setup is shown in figure 4.8. In this setup only the amplifier is measured. The signal generator is generating a 10MHz LTE signal at 3.5GHz where the output is connected to the input of the amplifier. The amplifier is supplied with a 12.0VDC signal from the power supply and the output of the amplifier is connected to a 6dB attenuator to protect the input stage of the spectrum analyser, which measures the output signal from the amplifier.

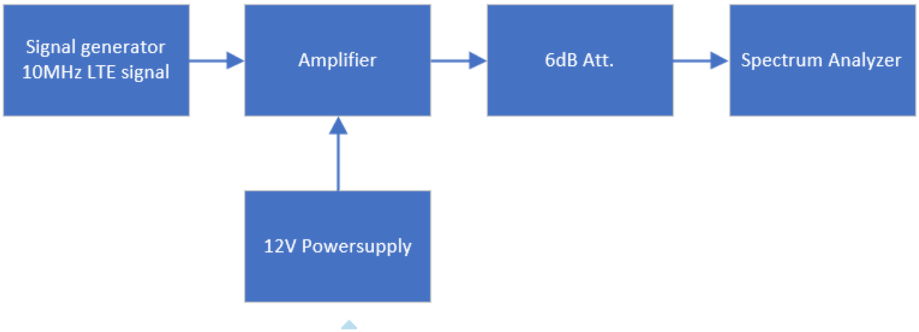

Figure 4.8: Block diagram of measurement at amplifier

In figure 4.9 the second measurement setup is shown. In this setup the antennas are now introduced. The Tx antenna is connected to the output of the amplifier. The Rx antenna are spaced 1 meter apart from the Tx antenna (measured from feed to feed). The 6dB attenuator is removed and the antenna is connected to the spectrum analyzer.

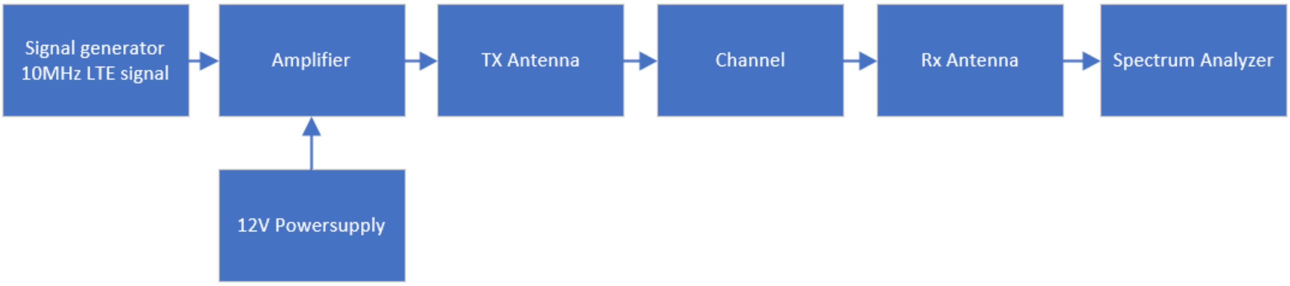

Figure 4.9: Block diagram of measurement using one antenna

In setup three a power-divider is now introduced together with a second amplifier and second antenna. The received power will now increase 3dB but because the amplifiers has to be driven in the same power levels as before, one must add another 3dB to the input of the power divider. Be aware that in the measurements a 1:4 power divider was used and therefore the power was increased 6dB. The unused ports was terminated to a 50Ω load. Also measurement using 4 antennas has been done in the same way. The only diffrence from the measurement was that the terminations was removed and an other 2 amplifiers and 2 antennas was added. See figure **??**.

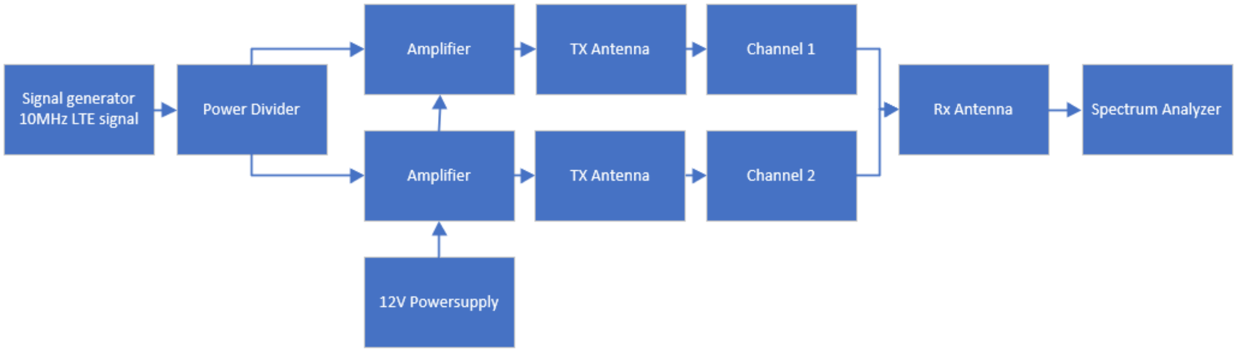

Figure 4.10: Block diagram of measurement using two antennas

In figure 4.11 a picture of a real measurement setup is shown. The antennas are spaced 1 meter apart from the input terminals and are pointing directly towards each other. The PA is mounted on a aluminium sheet with a tool grip to keep it at a constant temperature. The PA is supplied with 12.0VDC from the power supply and draws 40mA of current. The signal generator is connected to the input of the amplifier and the output of the amplifier is connected to the Tx antenna. The spectrum analyser is connected to Rx antenna. In figure 4.12 a measurement with 4 antennas is depicted. The antennas is mounted in a piece of flamingo with slots at at distance of 0.1λ. This way the antenna can be moved to make the desired measurement.

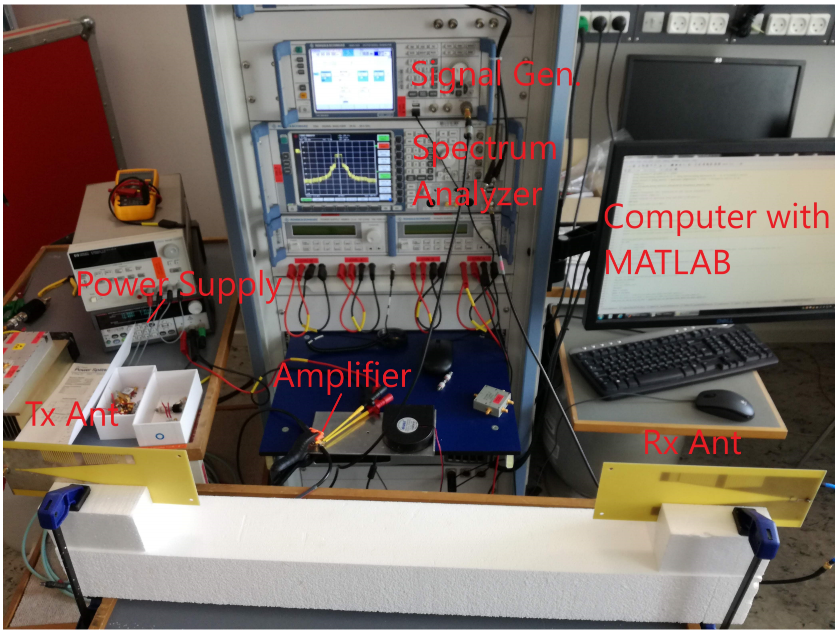

Figure 4.11: Measurement setup using one transmit antennas

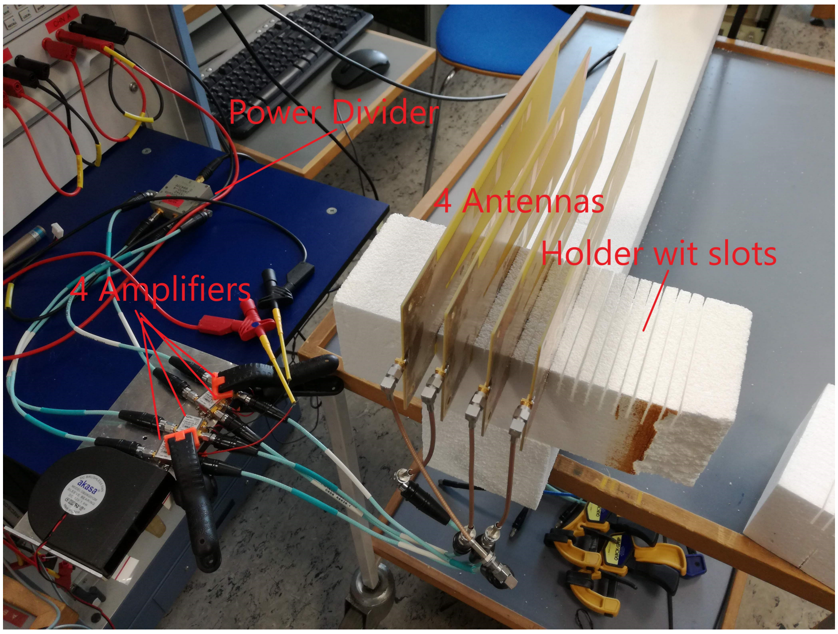

Figure 4.12: Measurement setup using four transmit antennas

4.3.1 Measurement of AM/AM distortion

Measurement has been done using the methods described in section 4.3. The results in figure 4.13 is a measurement of only the amplifier. It is seen that at an input of -2.5dB the amplifier starts to decrese its gain. This is expected due to the compression point. The mean gain of the amplifier is measured closly to 13.8dB as expected. It is further seen that the spreading of the signal is highest at low signal levels. When introducing one Tx antenna and one Rx antenna the free space loss must be accounted for. This is done by use of equation 4.1 [Constantine A. Balanis, 2005] which gives 20.5dB in loss. In the measurement 19.5dB was measured, the difference is might caused by the antenna them self, since the used antenna gain is only simulated, and the antenna are spaced relativity close, or it can be reflections from the table or room that are causing the difference. Cable loss and connector loss has been measured and accounted for.

$$Pathloss(db) = 10 * log10(G_r G_t (\frac{4\pi d}{\lambda})^2) = 20.5dB \tag{4.1}$$

The measurement using one Tx antenna and one Rx antenna shows that the gain of the system now becomes close to 6dB, this is also expected since the gain of the system is:

$$G_{system}(dB) = G_{amplifier} + G_{antenna} - Pathloss = 13.85dB + 11.4dB - 19.5dB = 5.75dB \tag{4.2}$$

It can be seen from figure 4.14 that the antenna system makes the AM/AM distortion wider at the compression point, but smaller at lower power levels. In figure 4.15 to 4.20 the results from measurement setup three is shown. The results are made with two transmit antennas and therefore the system gain is increased by 3dB. The results shows small variations due to AM/AM distortion between, but a significant change in AM/AM at compression point in the pre-sentence of two antennas instead of one. Also AM/AM at lower power levels seems to decrease with two antennas compared to one.

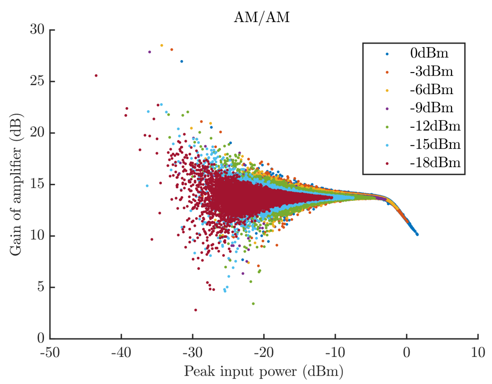

Figure 4.13: AM/AM distortion at amplifier

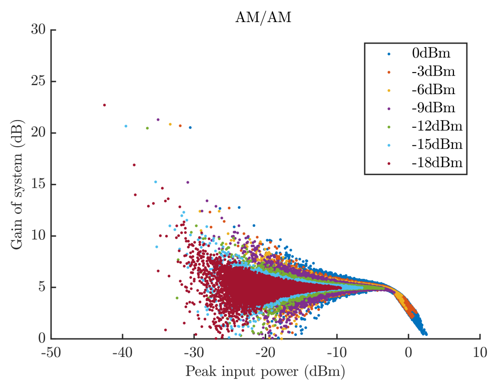

Figure 4.14: AM/AM distortion using one transmit antenna

Two transmit antenna

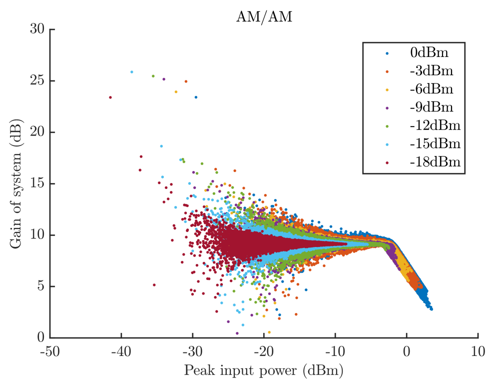

Figure 4.15: AM/AM distortion at 0.1 λ spacing between two antennas

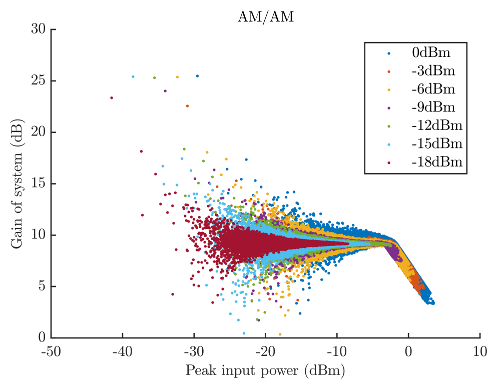

Figure 4.16: AM/AM distortion at 0.2 λ spacing between two antennas

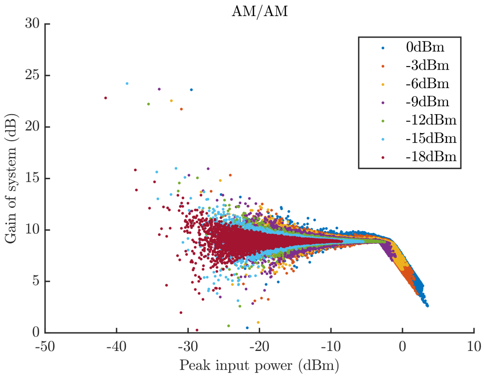

Figure 4.17: AM/AM distortion at 0.3 λ spacing between two antennas

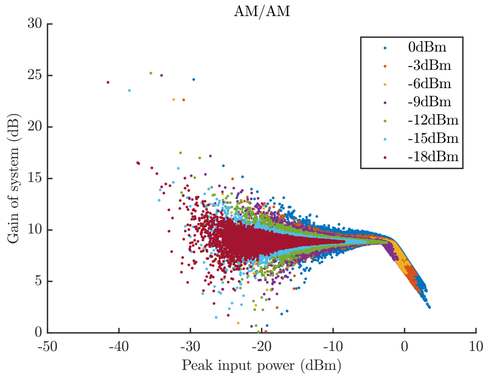

Figure 4.18: AM/AM distortion at 0.4 λ spacing between two antennas

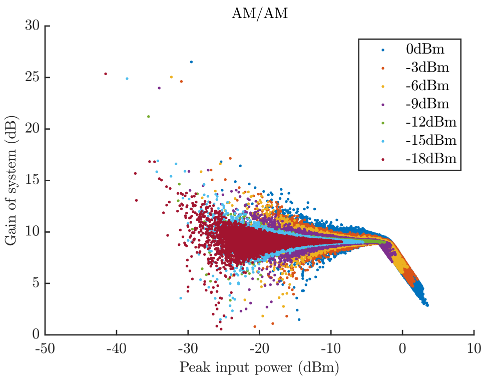

Figure 4.19: AM/AM distortion at 0.5 λ spacing between two antennas

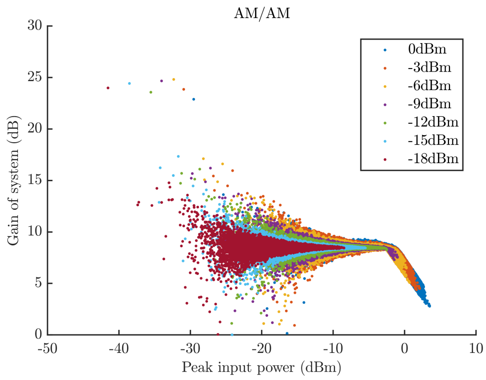

Figure 4.20: AM/AM distortion at 0.6 λ spacing between two antennas

Four transmit antenna

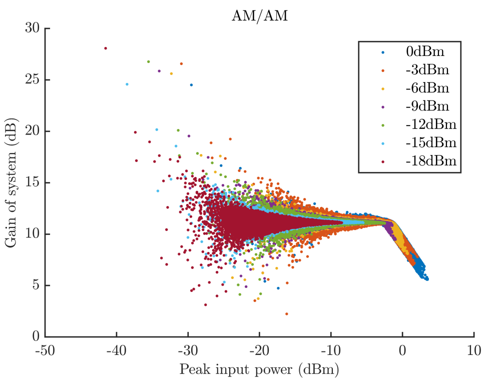

Figure 4.21: AM/AM distortion at 0.1 λ spacing between four antennas

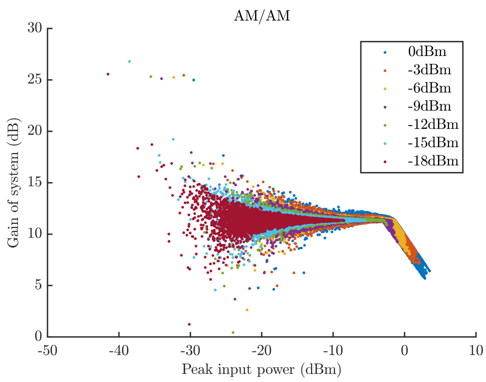

Figure 4.22: AM/AM distortion at 0.2 λ spacing between four antennas

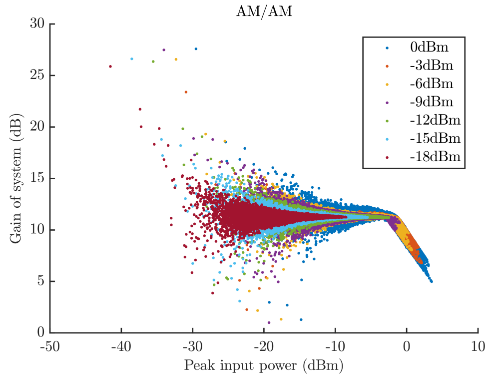

Figure 4.23: AM/AM distortion at 0.3 λ spacing between four antennas

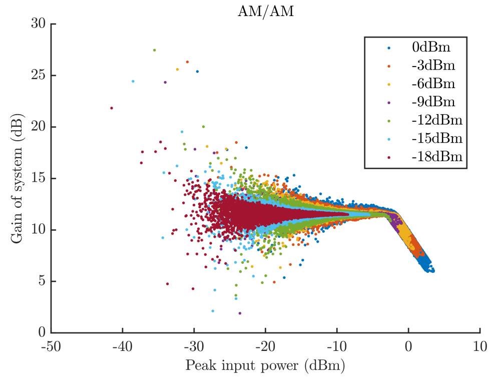

Figure 4.24: AM/AM distortion at 0.4 λ spacing between four antennas

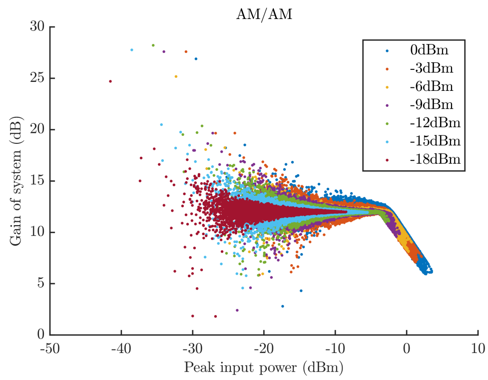

Figure 4.25: AM/AM distortion at 0.5 λ spacing between four antennas

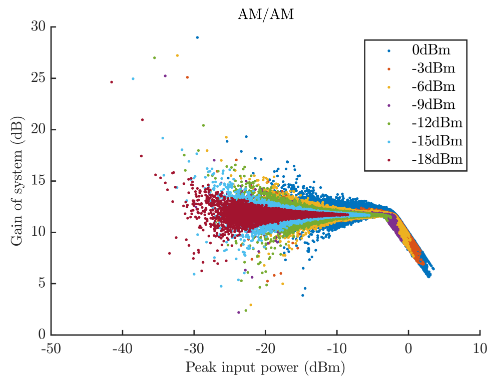

Figure 4.26: AM/AM distortion at 0.6 λ spacing between four antennas

4.3.2 PSD

The Power Sprectal Density (PSD) shown in figure 4.27 is measured directly at the amplifier. It shows that at a mean input-power at 0dBm the output of the amplifier is distorted, first at a input level at -9dBm the distortion becomes low. This is also expected since the input is mean power and therefore the peak of the signal would be closely to -3dBm (6dB backoff) which also is close to the compression point measured in section 4.3.1. Be aware that the noise floor increases due to the normalization of the signal. Also the reference-level at the spectrum analyser has an impact. When introducing the antenna system with one Tx antenna the distortion at -9dBm increases slightly. When introducing two antennas the distortion increases which is not a surprise due to the results from section 4.3.1.

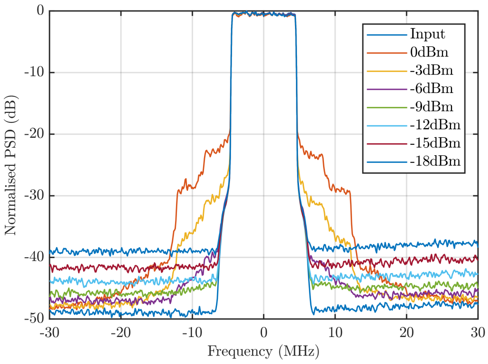

Figure 4.27: PSD at amplifier

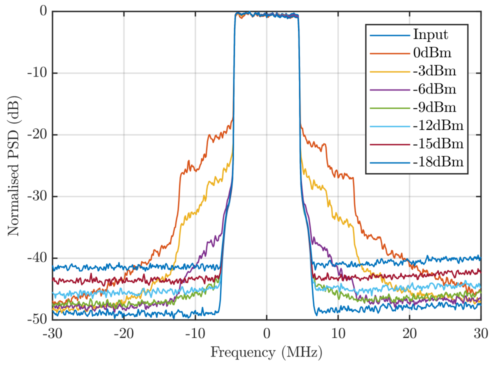

Figure 4.28: PSD using one transmit antenna

Two transmit antenna

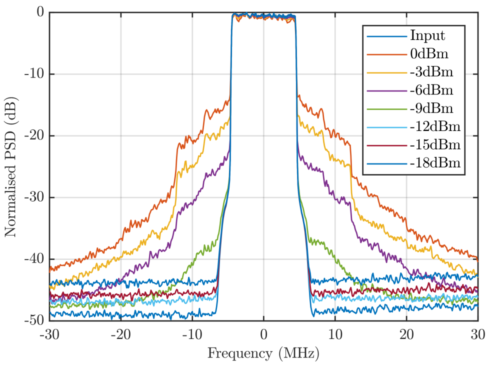

Figure 4.29: PSD at 0.1 λ spacing between two antennas

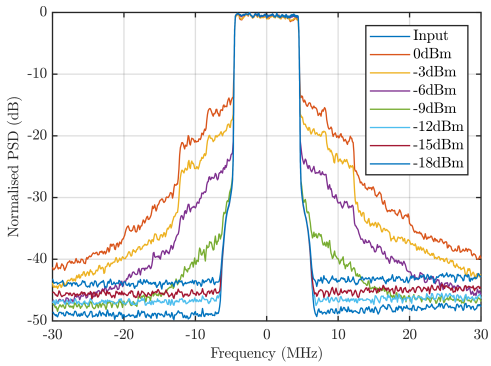

Figure 4.30: PSD at 0.2 λ spacing between two antennas

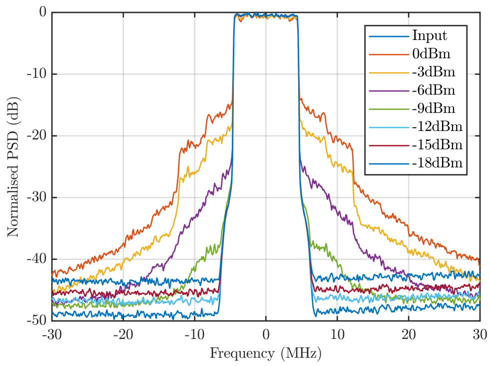

Figure 4.31: PSD at 0.3 λ spacing between two antennas

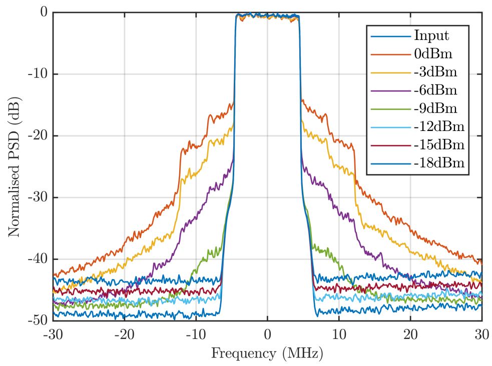

Figure 4.32: PSD at 0.4 λ spacing between two antennas

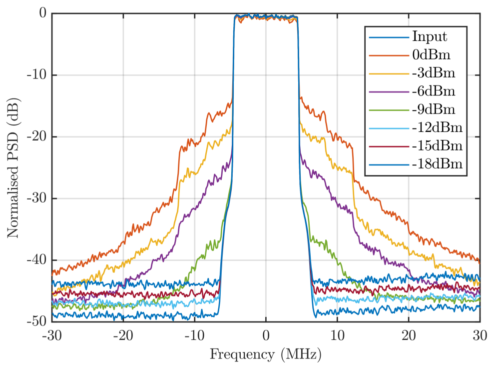

Figure 4.33: PSD at 0.5 λ spacing between two antennas

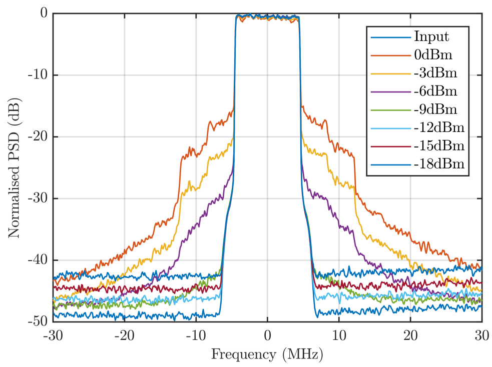

Figure 4.34: PSD at 0.6 λ spacing between two antennas

Four transmit antenna

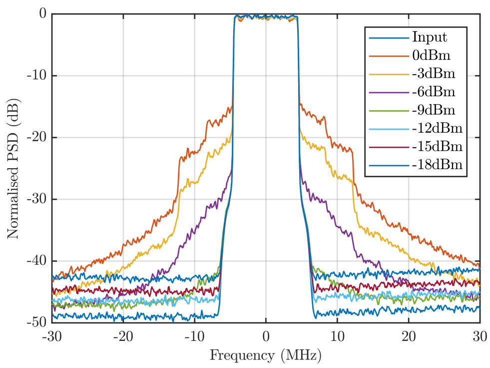

Figure 4.35: PSD at 0.1 λ spacing between four antennas

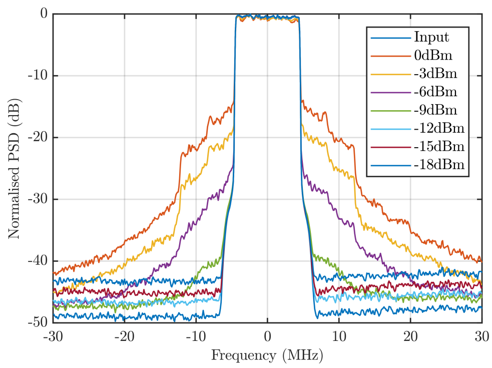

Figure 4.36: PSD at 0.2 λ spacing between four antennas

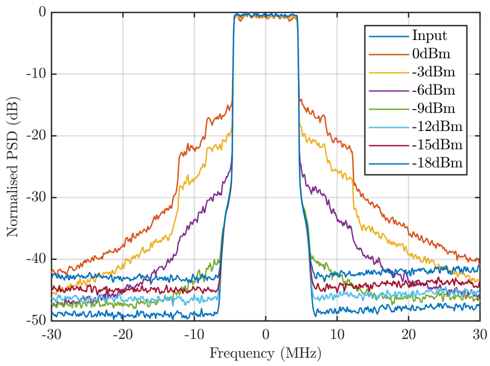

Figure 4.37: PSD at 0.3 λ spacing between four antennas

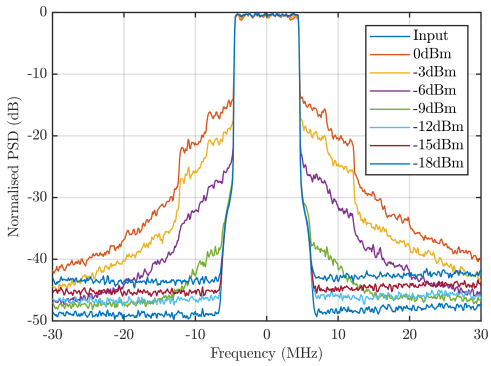

Figure 4.38: PSD at 0.4 λ spacing between four antennas

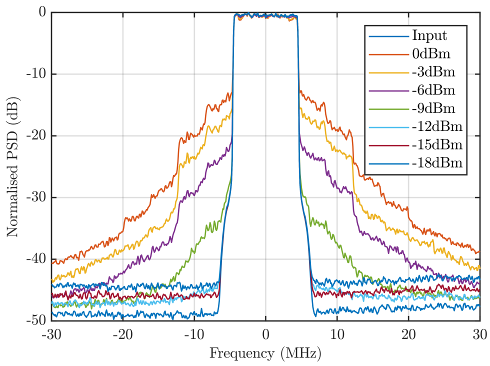

Figure 4.39: PSD at 0.5 λ spacing between four antennas

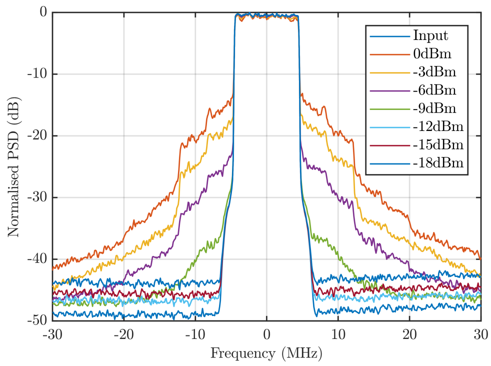

Figure 4.40: PSD at 0.6 λ spacing between four antennas

4.3.3 ACPR

Two transmit antenna

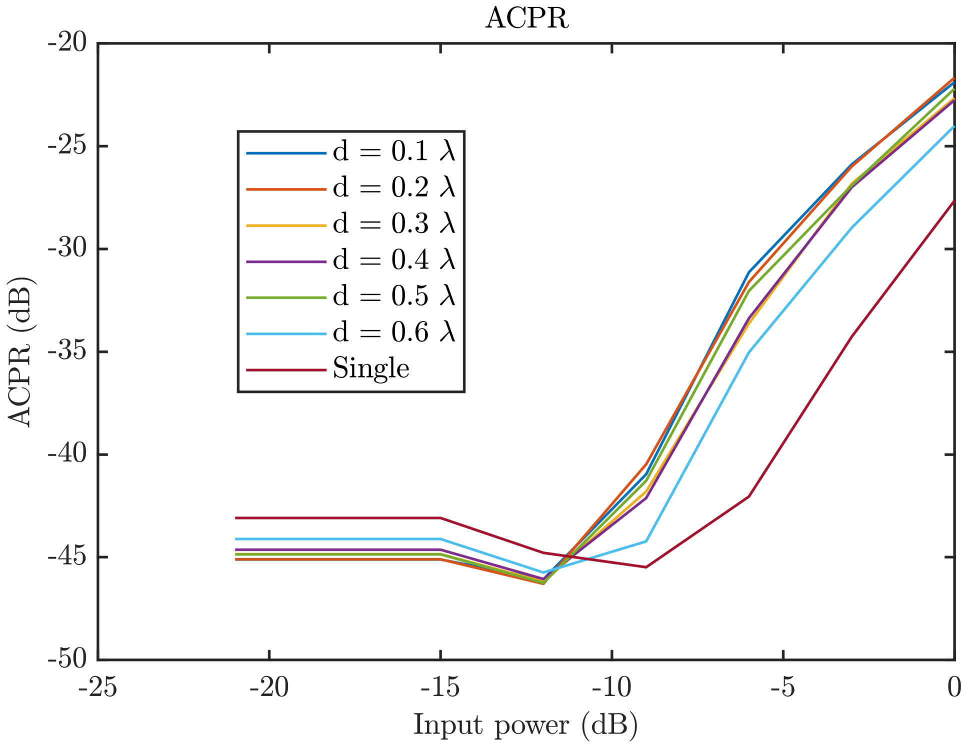

Figure 4.41: ACPR using two transmit antennas

Four transmit antenna

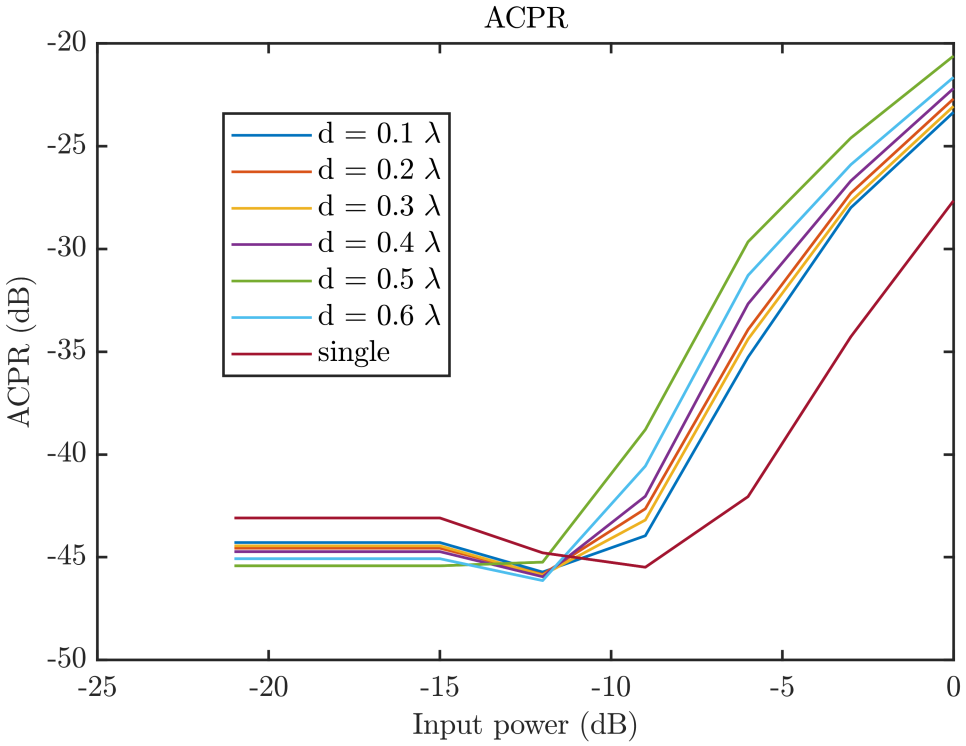

Figure 4.42: ACPR using four transmit antennas

Chapter 5

Conclusion

The purpose of this project was to development an antenna to receive ADS-B signals from aircraft's on a CubeSat. A link budget was made and it showed that there was a need for a radiation-pattern that could compensate for the increased length in the reception due to the angle of the earth. Another important requirement for the antenna was that it should be circular-polarized since the received signal was linear polarized but the angle of reception was not known. A reflector antenna, a quadrifilar helical antenna and a hemispherical antenna was investigated. None of these antenna could overcome those requirements in their basic forms and modifications to these was investigated. The reflector antenna had a high gain in one single direction and a large size compared to the wavelength which made it difficult to use on a CubeSat. The quadrifilar helical antenna showed that is was difficult to change in its radiation-pattern due to the common design and still keep it circular polarized. The hemispherical helical antenna was modified to have four arms and a stretched structure which showed good performance, but this design had no gain in the center. This could be improved by changing the feeding point, but this introduced a non-symmetry which made the antenna to become non circular polarized.

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Appendix A

Appendix A name

Here is the first appendix