The Impact of Thermal Noise, Phase Noise and Non-linear Distortion on the Performance of 4x4 MIMO System

David Bravo Brito

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Supervisors: Dr. ir. R. Mahmoudi  
ir. Tim Schenk

Group: TUE / ICS-MsM
Abstract

In this master thesis project a first study of a MIMO 4x4 simple stage amplifier has been carried out. The research method was following a *top-down approach*. Hereto, after the literature research, a 4x4 MIMO system simulation model was implemented. Later, several subsystems were developed in order to provide the final design with the desired characteristics.

Development of measurements and calibration techniques took an important role in this project reaching sometimes higher difficulty than the design itself.

One of the aims of this project was the study of the effect of correlation in combination with parameters like thermal noise, phase noise and the non-linearities of an amplifier stage.

The project has been carried out on system level. First, a MIMO 4x4 system simulation model was developed and tested. After that, some subsystems were designed and checked, independently. The goal of those subsystems is introducing certain effects -like different kind of noises and non-linearities of amplifiers- in the system. Afterwards they were put in the system model one by one and then analyzed. Finally, all the subsystems were placed together and the complete behavior was studied.

The followed procedure makes clear that the simulation of a complex system is not an easy task. Calibration can be a serious inconvenience for the designer. Also, measuring techniques have to be chosen carefully in order to achieve valid performance measures for the system, and then, right conclusions.

The results show that the phase noise dominates the performance of the system at the linear region but in the non linear region the non-linearities are the main drawback. As we expected, correlation among the streams has turned out as the most harmful parameter in the design. If the correlation reaches certain level the whole system performance collapses.

MIMO is a very good solution in applications where bandwidth efficiency really needs to be improved, which is especially true for systems with low carrier frequency if the frequency is not high. For high frequencies where a plenty of bandwidth is available, the drawbacks of MIMO make its use questionable.
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Chapter 1

Introduction

In this chapter a short introduction to this master thesis project is presented. First of all, the project background and the goal of the project are introduced. Afterwards, an overview of how the work has been structured is given.

1.1 Project background

Nowadays the evolution in the world of wireless systems claims for better and newer services in the devices. The development in electronics demands higher requirements in the telecommunication field. One of the main requirements is, obviously about bit rate. Companies are designing faster devices with lower power consumption and the main issue is turning out to be at the weakest link, the transfer speed. For instance, applications such as streaming video require radio transceivers that can support high data rates and throughput.

Improvements in bit rate can be achieved by several ways like increasing the constellation size or the bandwidth. Since increasing the constellation means important drawbacks like more strict signal to noise requirements, more complexity at the design of the front-ends and many more difficulties at the detection stage, the other option will be studied. Bandwidth is a valued resource which can not always be increased as much as the application needs, thus at this point, another option should be taken. Considering this, the solution will be increasing the bandwidth efficiency, which means with the same bandwidth, better bit rate is achieved. Due to that, new signal processing methods are required. It is right here where MIMO techniques arises.

MIMO is the acronym of Multiple Input - Multiple Output systems. The goal is increasing the bandwidth efficiency using the spatial dimension. The challenge in these techniques is sending information from a \( N_t \) number of transmitters to a \( N_r \) number of receivers with the same carrier frequency and without coding or time multiplexing. This concept is depicted in the following figure 1.1.
1.2. RESEARCH METHOD

This revolutionary concept is based in the knowledge of the channel (depicted in figure 1.1 as $H$ matrix). Assuming an accurate knowledge of that, the receiver should be able to distinguish the desired signal from the other ones.

When combining MIMO with broadband, generally OFDM modulation will be chosen. They will have to support multiple quadrature amplitude modulations (QAMs) with order of 64 or even 256 QAM. On one hand, such modulation levels demand a very high performance from the radio and require a highly linear architecture with very low spurious signal levels. High linearity is required in the entire signal path of both receiver and transmitter, imposing higher power consumption and the need for advanced design techniques.

On the other hand, phase noise arises as one of the main problems in synchronous systems like ours. Due to that, a particular study of this kind of noise is required.

Linearity is wanted and the thermal and phase noise will be studied. MIMO systems, however, will introduce an extra parameter which needs to be analyzed, i.e., signal correlation. The impact of the correlation in combination with the other effects can be extremely serious in this kind of systems.

1.2 Research method

As in every thesis, literature investigation is the first stage of the project. Due to the innovative aspect of this field, the literature investigation stage should be deeply accomplished regarding not only the challenging MIMO concept and its state of arts but also an overview of OFDM, the standard 802.11a, high frequency design concepts (like matching with Smith Chart) and, of course, a study of RF amplifiers and its design techniques.

The applied simulation tool was Advanced Design System (ADS) of Agilent Technologies which provides the RF simulator, which is very useful for this project. It requires an initial learning stage following a course of the tool (ref. [6]).
CHAPTER 1. INTRODUCTION

For the calculus and optimization of the channel algorithm, Mathematica 5 was used. The report has been written in Latex.

The development of the design had a first stage of a deep study of all the ADS component of the system. Sources, receivers, noise sources, measurement blocks, etc, were investigated. After getting to know the tool and its components doing simple simulations the study was focused on the amplifiers. Single, two and multitone simulations where done to introduce the project to the amplifiers design.

After the amplifier stage, phase noise was regarded. A study of the concept, an overview of the standard and simple simulations were done at that point.

Once the simple parts were studied, a MIMO system had to be implemented. Mathematica 5 was used for the algorithm and the channel was implemented with two blocks (Correlation and Decorrelation Block). After the implementation both blocks were checked and optimized.

When the system was ready, the phase noise block was placed and calibrated in the system and simulated in a MIMO environment. Afterwards, the same process was followed with the 4x4 amplifier stage.

At the end of this project, every block was settled in the system and a complete study was carried out.

1.3 Project Goal

The main goal of the project is a first study and implementation of a MIMO 4x4 simple stage amplifier. For that intention, the first goal is to develop a simulation model of a MIMO system. Some studies about MIMO should be done and finally a measurable system should be implemented. The second goal is the develop of testing blocks in order to see the impact of several parameters in the system. The last goal is the incorporation of the amplifier stage and measuring all its effects.

1.4 Thesis Outline

The report is divided into several chapters which will be explained next.

- Chapter 2 introduces several concepts about digital transmission like QAM signals, the used wireless standard IEEE 802.11a, etc.
- Chapter 3 is focused on the study of amplifiers, one of the most important parts of this lines. The first simulations are done in this chapter.
1.4. **THESIS OUTLINE**

- Chapter 4 presents the theoretical idea of MIMO and describes several important aspects of these techniques. Also a first idea about how the system is going to be is given on this chapter.

- Chapter 5 describes all of the developed subsystems of this project. They are independently analyzed in order to have a separate characterization of all of them.

- Chapter 6 shows the measuring methods and calibration techniques followed in the simulations of this project.

- Chapter 7 presents the most interesting obtained results of the simulations.

- Chapter 8 mentions the conclusions of the project and gives some suggestions for further investigations.
Chapter 2

Digital transmission concepts

During this study, several aspects of the digital transmission will be analyzed. Therefore, some remarks are made about this in this chapter.

Since the nineties the requirements about data rate and security have been increasing forcing the designers to focus the development in digital techniques. Because of that, different digital modulation schemes have been created and these schemes are classified into two different groups. On the one hand, there are schemes in which the information is only in the phase and not in the amplitude, hence they have constant envelope, such as QPSK, BPSK or FSK.

On the other hand, the other modulation schemes contain the information in both phase and amplitude, resulting in non-constant envelope signals. The principal advantage of this group over the first one is that they increase the data rate, but note that they are more sensitive to noise and they need linear amplification. Some examples of this category are QAM or OFDM.

In this chapter, Quadrature Amplitude Modulation and its most important properties will be studied. Furthermore a overview of OFDM and the IEEE 802.11a standard will be given.
2.1 QAM Basic Theory

**Quadrature Amplitude Modulation** is a digital modulation scheme that provides a higher data rate using the same bandwidth, namely increases the bandwidth efficiency if we compare that with BPSK for instance. Basically, QAM is a combination between amplitude modulation and phase shift (shift keying), so it combines analog and digital techniques. Quadrature modulation means that two carriers at the same frequency but phase-shifted 90° each other are modulated by two different signals, the I (in-phase) and Q (quadrature). In Figure 2.1 the general model of a QAM modulator is depicted.

![Modulator for generalized QAM signal](image)

**Figure 2.1:** Modulator for generalized QAM signal

The general QAM signal is:

\[
s(t) = x(t) \cdot \cos(\omega_c t) - y(t) \cdot \sin(\omega_c t)
\]  

(2.1)

It has been shown that a QAM signal has two different components, one in phase and the other in quadrature. From another point of view, this can be seen as a simple amplitude modulation of a complex signal, therefore:

\[
g(t) = x(t) + j \cdot y(t) = I(t) + j \cdot Q(t) = R(t) \cdot e^{j\theta(t)}
\]  

(2.2)

where

\[
R(t) = \sqrt{I^2(t) + Q^2(t)} \quad \text{and} \quad \theta(t) = \arctan\left(\frac{Q(t)}{I(t)}\right)
\]  

(2.3)

Moreover, these baseband signals (I and Q) can be multilevel signals, hence QAM modulation scheme increases the data rate keeping the same bandwidth. With 4QAM, which is the simplest...
QAM scheme, is transmitted twice the number of bits with respect to a typical amplitude modulation, notice that two signals are transmitted instead of one. Also depending on the number of symbols, different QAM schemes can be achieved. For example, if $I$ and $Q$ signals have both two levels, 4QAM is obtained; if they have four levels each one, 16QAM. The Table 2.1 shows the different QAM modulation schemes and the multiplication factor of the bit rate with respect to a normal amplitude modulation ($K$).

<table>
<thead>
<tr>
<th>I/Q levels</th>
<th>QAM type</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4QAM (QPSK)</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>16QAM</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>64QAM</td>
<td>6</td>
</tr>
<tr>
<td>16</td>
<td>256QAM</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2.1: QAM type and $K$ according to its $I$ and $Q$ levels

Usually, digital modulations are represented by constellations (also known as IQ diagrams), which show the valid locations for all the permitted symbols. For example, if two levels are used for $I$ and $Q$, 4QAM is achieved. These two possible levels are $-1$ and $1$, the possible symbols of the 4QAM constellation would be $(-1,-1), (1,-1), (-1,1)$, and $(1,1)$, as shown in Figure 2.2. For the rest of QAM modulation schemes the process is similar, the only difference is in the number of symbols.

![4QAM constellation diagram](image)

Figure 2.2: 4QAM constellation diagram

As stated before, QAM represents a powerful technique that multiplies the data rate without increasing the bandwidth. Despite of this, there are some problems to mention.

First at all, if a large number of symbols is needed the separation between contiguous levels is quite small, so different technological problems can appear. The baseband processing must be very accurate to generate these signals in the transmitter and to recover the bits properly in the receiver.

Another problem is the noise like in every communication system. As mentioned before, when
2.2. PROBABILITY DENSITY FUNCTION (PDF) AND COMPLEMENTARY
CUMULATIVE DENSITY FUNCTION (CCDF)

The number of symbols is huge the contiguous levels are closer, so QAM can accept only a finite
amount of noise power. This noise power is inversely proportional to the number of levels, so the
schemes with less number of symbols present more robustness to noise, and the schemes with
large number of symbols are more sensitive to noise.

A further disadvantage is the need of linear amplification, because otherwise it is not possible
to recover the information in the receiver properly.

2.2 Probability Density Function (PDF) and Complementary
Cumulative Density Function (CCDF)

These properties of the signal gives an idea about how the power of a signal is distributed.
The PDF and CCDF depend on the signal modulation. They are both mathematical operations,
but in this thesis we only explain their application in the signal processing.

The PDF represents the probability that the signal has a determined power value, and nor-
mally it is shown with a histogram diagram, where the x-axis represents the different power
values and the y-axis the probability of these values. It is usually given by 2.4:

$$PDF = \text{histogram} \left( \frac{V_i^2(t)}{2R} \right) \quad \text{with} \quad i = 1 \ldots N$$

(2.4)

where $V_i$ is the instantaneous voltage levels of the signal. The $R$ is obviously the impedance
and $N$ is the last signal value in the signal taken into account for the PDF. It is important
to notice that the histogram is calculated from the power so the result will be the PDF of the
power. Generally, the signal PDF is calculated regarding the average power of the signal, in
order to make the PDF independent of power levels 2.5:

$$PDF_{\text{norm}} = \text{histogram} \left( \frac{V_i^2(t)}{\frac{1}{N} \sum_{i=1}^{N} V_i^2(t)} \right) \quad \text{with} \quad i = 1 \ldots N$$

(2.5)

The CCDF represents the probability of exceeding a specific power value. For example, it is
useful to check the probability of how many power levels can be above the average power.

$$CCDF = 1 - \sum_{k=1}^{M} PDF = 1 - \sum_{k=1}^{M} \text{histogram} \left( \frac{V_k^2(t)}{\frac{1}{N} \sum_{i=1}^{N} V_i^2(t)} \right)$$

(2.6)

where $M$ is the number of lines of the histogram.
CHAPTER 2. DIGITAL TRANSMISSION CONCEPTS

2.3 Adjacent Channel Power Ratio (ACPR)

Due to the scarcity of the spectrum, most of the times it is necessary to share the communication channel with other users. The communication channel is divided into several smaller channels, and in each one of these smaller channels exist independent transmissions. The ACPR is defined as the ratio of the total power inside a certain bandwidth out of the transmission channel (usually coinciding with the channel adjacent to the transmission one), to the total power inside the transmission bandwidth. The ACPR gives an idea of the linearity of the system. If the system has non-linearities, the spectral regrowth is higher, and the power inside the adjacent channel too.

2.4 OFDM overview

A short definition for frequency division multiplexing (FDM) is a multiplexing technique that uses different frequencies to combine multiple streams of data for transmission over a communications medium. FDM assigns a discrete carrier frequency to each data stream and then combines many modulated carrier frequencies for transmission. Orthogonal Frequency Division Multiplexing is an FDM modulation technique for transmitting large amounts of digital data over a radio channel. OFDM works by splitting the radio signal into multiple smaller sub-signals (see figure 2.3) that are then transmitted simultaneously at different frequencies to the receiver.

![Basic structure of FDM](image)

Figure 2.3: Basic structure of FDM

The most relevant characteristic of this technic is that it uses specific orthogonality constraints between the subcarriers. Hence, subcarriers are partly overlapping but orthogonal with respect to each other. At the peak of each subcarrier, the amplitudes of the other subcarriers have zero crossings (see figure 2.4)
2.5 Error Vector Magnitude (EVM)

There are different techniques to determine the distortion and noise contribution in QAM systems, such as Bit Error Ratio (BER), Signal to Noise and Distortion Ratio (SNDR), Adjacent Channel Power Ratio (ACPR), Eye Pattern, Error Vector Magnitude (EVM), etcetera.

EVM is a powerful technique used to determine errors in digital systems and their cause. EVM is a very simple measurement which gives a very visual impression of how noise affects to the signal. In figure 2.5 is shown how a vector is calculated as the difference between the measured vector and the reference vector. The measure is the actual signal and the reference is an ideal signal based on the knowledge of data, for example number of symbols, bit rate, filtering, etc.

The EVM result is defined as the square root of the ratio of the mean error vector power to the mean reference power expressed as a percentage. The calculation of the error vector is done for each symbol. The measured symbol is denoted as \( Z_n \) and consists of a signal which has been corrupted by noise, frequency offsets and other impairments. The ideal reference signal is denoted as \( S_n \), it is a signal free of noise whose magnitude has been normalized to one. \( \tilde{Z}_n \) is referred to as the modified version of the measured signal where the frequency, absolute phase, absolute amplitude and chip clock timing have been selected to have the minimum error vector. Each complex element is represented as \( S_n, Z_n \) and \( \tilde{Z}_n \) respectively. The instantaneous error vector is obtained by subtracting the ideal reference from the modified version of the measured
waveform. The root mean square EVM is defined by 2.7

\[ EVM_{RMS} = \sqrt{\frac{\sum_{n \in N} | Z_n - S_n |^2}{\sum_{n \in N} | S_n |^2}} \] (2.7)

2.6 IEEE 802.11a

The 802.11 is the family of IEEE of standards related to the wireless LAN technology. 802.11 specifies an over-the-air interface between a wireless client and a base station or between two wireless clients. There are several specifications in the 802.11:

- **802.11** — applies to wireless LANs and provides 1 or 2 Mbps transmission in the 2.4 GHz band using several coding techniques.

- **802.11a** — an extension to 802.11 that applies to wireless LANs and provides up to 54 Mbps in the 5GHz band. 802.11a uses an orthogonal frequency division multiplexing encoding scheme rather than FHSS or DSSS.

- **802.11b** (also referred to as 802.11 High Rate or Wi-Fi) — an extension to 802.11 that applies to wireless LANs and provides 11 Mbps transmission (with a fallback to 5.5, 2 and 1 Mbps) in the 2.4 GHz band. 802.11b uses only DSSS. 802.11b was a 1999 ratification to the original 802.11 standard, allowing wireless functionality comparable to Ethernet.

- **802.11g** — applies to wireless LANs and provides 54 Mbps in the 2.4 GHz band.

In this project an acceptable value for the EVM could be around 10% for the received signal. A concrete mask is defined in the standard for the ACPR and it is depicted in the following figure.3.6
2.6. IEEE 802.11A

![IEEE 802.11A Diagram](image)

Figure 2.6: 802.11a standard spectral mask

In the following figure 2.7 an overview of existing and future wireless data communication standards is presented.

![Overview of Wireless Standards](image)

Figure 2.7: Overview of wireless standards [1]

This project will use 802.11a because 5.2 GHz band provides more spectrum space than the 2.4 GHz band. In addition, there are already few devices on the market operating at 5.2 GHz.

However, not everything is perfect with this standard, there are also some drawbacks of using it. Higher frequencies have higher path losses. 802.11a base stations have to be deployed more densely than 802.11b/g base stations. But this drawback could be interpreted as an advantage because in this case, more channel reassignment can be done.
Chapter 3

Amplifiers

In wireless systems, the element which converts -increasing it significantly- the power used by the device to the transmitted power level is the RF amplifier. Since the goal of this report is the study of an amplifier stage, some theoretical concepts will be shown here. Moreover, with the aim of using it in the future, first simple simulations about amplifiers will be done as well.

3.1 Power Amplifiers basic theory

In this section some concepts about RF power amplifiers will be presented.

3.1.1 Average Output Power

The output power of an RF power amplifier is defined as the total power of the RF signal, within the band of interest, delivered by the power amplifier to the load. The load is usually an antenna with an input impedance of 50Ω. It should be notice that the output power does not include the power contribution of the harmonics or any other unwanted spurious signal generated by the amplifier.

The output power directly depends on the chosen modulation scheme. For a typical sine wave signal, the output power is given by the equation (3.1):

\[ P_{\text{out}} = \frac{V_{\text{out}}^2}{2R_L} \]  

(3.1)

If the signal is modulated, the power varies as a function of the time, and then the formula (3.1) is only valid for the instantaneous power. So it is possible to calculate the average output
3.1. POWER AMPLIFIERS BASIC THEORY

power if the instantaneous power is known at any time:

\[ P_{\text{out, average}} = \frac{1}{N} \sum_{i=1}^{N} \frac{V_i^2}{2R_L} \]  

(3.2)

In the frequency domain, it is also feasible to calculate the average output power, by applying the Parseval relation, which is defined for time and frequency domain:

\[ P_{\text{out, average}} = \frac{1}{N} \sum_{i=1}^{N} \frac{V_i^2}{2R_L} = \sum_{f=-\infty}^{\infty} \left| \frac{V_f^2}{2R_L} \right| \]  

(3.3)

3.1.2 Power Gain

The power gain of an amplifier is the ratio of the output power to the input power, and it is given by (figure 3.4):

\[ \text{PowerGain} = \frac{P_{\text{out}}}{P_{\text{in}}} \]  

(3.4)

The power gain fits with the voltage gain if the loads in the input and in the output are identical. As for the non-linear power amplifiers, the power gain is mainly the one in the linear region.

3.1.3 Power amplifier compression curve

Every power amplifier has a non ideal active device. Because of being non ideal, this device has a nonlinear operation region and this fact is the reason of many studies in our field. A linear amplifier is called this way because its behavior is linear. That means that the gain remains constant for every value of the Power input, the Power output has the same gain. In a real environment there is a power level in the input that makes the amplifier saturate. From this value the active device enters in the saturation region.

A plot of the output power of a real power amplifier as function of the input power is called power amplifier's compression curve. A curve of a typical power amplifier is shown in figure 3.1. Note that there are three well different regions: linear, compression and saturation.
3.1.4 Output One dB Compression point

A measure commonly used to determine the power amplifier non-linearity is the output 1 dB compression point. This point is defined as the point where the output power of the amplifier has dropped 1 dB below the level extrapolated from the linear small-signal region, as shown in figure 3.2.

![Figure 3.2: 1 dB compression point](image)

3.1.5 Third-Order Interception Point (TOI)

The third-order interception point measure is also used to evaluate the power amplifier non-linearity, and it is based on the third-order spurious signal in the output voltage. To determine it, a two-tone measurement has to be done, and it is the point where the third-order intermodulation at the output equals the magnitude of the fundamentals. The third-order interception point is typically determined by extrapolating the values measured at low signal levels, as shown in figure 3.3.

As a rule of thumb, the TOI is calculated as the point which is about 10 dB above the 1 dB compression point (ref. [2]).
3.1. POWER AMPLIFIERS BASIC THEORY

3.1.6 Adjacent Channel Power Ratio and Spectral Mask

The non-linearity in a power amplifier often tends to widen the bandwidth of the transmitted signal and raise the power density level in the frequency regions surrounding the transmission channel. This phenomenon is referred to spectral regrowth (figure 3.4). Thus, it is possible to evaluate the non-linearity using a metric called the adjacent channel power ratio (ACPR). The ACPR is defined as the ratio of the total power inside a certain bandwidth out of the transmission channel, usually coinciding with the channel adjacent to the transmission channel, to the total power within the transmission bandwidth.

Another way to evaluate the non-linearity is by using spectral masks. The spectral masks, defined by the standards, set a limit on the spreading of the power density spectrum, as well as any out-of-band emissions, such as harmonics of the carrier frequency, or any unwanted spurious signals generated by the amplifier. An example of a spectral mask is in the following figure 3.5.
The mask defined for the specifications of the standard 802.11a is depicted in the following figure 3.6.

Thus, the signals of this standard whose spectrum exceeds the spectral mask are not valid, because the spectral regrowth spoils the linearity of the system. An example of the signal what this study will deal with -802.11a standard- is depicted in red in figure 3.7. The blue line is the mask defined by the designer, usually, the mask of the standard.
3.2 First designs

For the beginning of the amplifiers study some simple simulations setups are studied. The first one is single tone simulation. In this case the design will concern a simple tone and a fixed frequency. Later on the study will concern two tones in order to check the effect of harmonic components and intermodulation products. Finally this section will finish with the analysis of a typical 802.11a signal which will give more accurate impression about what will happen in a wireless environment.

3.2.1 Single tone simulation

One tone simulation is the very beginning of the simulations in this project. This will give an introduction and also a first impression about the behavior of a RF amplifier. Figure 3.8 shows the design. It will be as simple as an N Tone source - which will provide only one tone-, an RF Amplifier - which will be the object of this first study- and the load - 50 ohms-.

![One tone RF analysis diagram](image-url)
CHAPTER 3. AMPLIFIERS

The frequency of this first design will be around 5.2 GHz (figure 3.9) because that is the value of the carrier of the standard 802.11a, that will be used next. The power levels are not relevant because the main information is given by the parameters of the amplifier. In this case a sweep between -70 and 40 dBm will be done.

![Figure 3.9: Spectrum](image)

Several simulations regarding to the amplifier have been studied. It is important to notice that in this model of the amplifier it is possible to determine which parameters have influence on the behavior of this device. That is the task of GCTYPE parameter. Figure 3.10(a) shows a simulation considering only the 1dBc point and TOI (see the parameter GCTYPE). In that figure is clear to see how the amplifier goes into saturation region for higher values of Pin. Also that effect is shown in the figure 7.12(b) where there is the gain subgraph which drops down. In the next figure 3.11(a) and figure 3.11(b) there are the results at the input and the output and it's quite easy to see how the higher values of the output are saturated. The device is in saturation region because it's forced by the designer in the previous settings of 1dBc and TOI (in this case).
3.2. FIRST DESIGNS

Figure 3.10: Saturation effects

(a) Pin vs Pout  
(b) Gain

Figure 3.11: Saturation effects

(a) Vin  
(b) Vout

Also the study has been done for all the parameters of the amplifier each one independently and all together as well. The aim of this simulations is just to know what the behavior of the RF amplifier is and, in this previous designs, only with simple tone.
3.2.2 Two tone simulation

In this section the design will be the same but using an extra tone (see figure 3.12(b)). With this new change the study of third order interception point will be possible. Now it is needed to pay attention to the power because it is delivered in two tones so each them should be 3 dB below the delivered power.

![Figure 3.12: Two tones source](image1)

On the first hand a comparison between first order gain and third order component is done. As has been explained before, if both graph are dragged out of their linear region there will be a point where both dotted lines come together, this is the IP3 point in figure 3.13

![Figure 3.13: TOI](image2)
3.2. FIRST DESIGNS

3.2.3 Multitone simulation.

Now the amplifier will work with a typical 802.11a RF source in order to check how it will behave in a normal wireless environment. For that intention it is needed to use a whole wireless design which will be formed not only by the previous components but also by source, receiver and a EVM block for checking the error (see figure 3.14).

![Figure 3.14: WLAN 802.11a RF Source test](image)

Then all the measurements will be redone but in the previous case, most of the power was only in one or two certain points. Now the power is spread in a bandwidth of 20 MHz, the simulations should take care of this characteristic.

Figure 3.15(a) shows the results of this simulation, including results for one and two tones. Apparently they are the same, but when zooming into the compression region it is possible to see some differences between them. That’s because the crest factor is much higher here (for more details see ref. [3]).
CHAPTER 3. AMPLIFIERS

Besides, regarding the input/output relations it is important to study parameters like probability density function (PDF) and the error vector magnitude (EVM). The PDF of the power of the signal based on the IEEE 802.11a standard will look like figure 3.16(a). It is important to see that the PDF is normalized, that means that the average power is placed in zero. From the zero (average power), the probability function is spread around 9 dBs above the average power (see figure 3.16(b)), that means that if linearity is desired, the average should be 9 dB below the saturation region, otherwise part of the signal will be no longer linearly amplified. For this kind of applications where linearity is a requirement, the designer should take care about keeping the whole distribution of the power in the linear region.

If the average power increases, the spectrum goes partially or totally into the saturation region so it will not be like the spectrum at the input of the device. Now it will be different. In figure 3.17 is clear how the PDF is changing when the average power comes close or into the saturation region. Obviously the EVM becomes higher there.

Figure 3.15: One, Two and multitone signals

Figure 3.16: PDF, Instantaneous and Average power
3.2. FIRST DESIGNS

![Figure 3.17: PDF comparison](image)

Notice that the PDF is a very useful tool to see how the power is distributed during the transmission. In the figure 3.18(a) there is another comparison of PDF but now the signal is even more inside the saturation region. In this situation, the power at the output will be concentrated in a very narrow zone. That effect is clear in the corresponding constellation diagram shown in the figure 3.18(b). There is easy to see how, instead of the expected 64 QAM constellation, most of the values of the signal have almost the same power level, which means, the same distance to the center of the diagram.

![Figure 3.18: PDF and Constellation diagram](image)
CHAPTER 3. AMPLIFIERS

At this moment the behavior of the device has been modeled for each configuration, one, two and multitone doing a study of its parameters as well. Since now the study will concern only the multitone simulations, that means the 802.11a wireless signal.

Depending on the GCType variable, the amplifier will consider one or more parameters which will make it more real. Also is possible to do the opposite interpretation, regarding only one parameter is possible to check only the effect of that consideration separately, which makes the study more systematic.
Chapter 4

MIMO systems

MIMO is the acronym of Multiple Input - Multiple Output systems. It is based in the use of the spatial dimension for increasing the bandwidth efficiency. In a MIMO system information is sent synchronously by multiple transmitters and is received by multiple receivers. Now it will be studied more deeply.

4.1 The concept

We consider a MIMO wireless communication system with $N_t$ transmitting antennas (TX) and $N_r$ receiving antennas. The idea is to transmit different data streams for all the $N_t$ transmitters at the same carrier frequency. In this model the stream from the $p$-th transmitting antenna as function of the time will be denoted by $s_p(t)$.

Making the assumption that the time delay between the fastest and the slowest path of the wireless multipath channel is really smaller than $1$/Bandwidth, the system can be called a narrowband system. In that case, all the multipath components between the $p$-th TX and $q$-th RX can be joined in one term, say $h_{qp}(t)$.

It is important to notice that since all the signals are sent at the same carrier frequency, the $q$-th antenna will receive not only the signal from $p$-th but also from all $N_t$ transmitters. This will be denoted by 4.1.

$$x_q(t) = \sum_{p=1}^{N_t} h_{qp}(t)s_p(t) \quad (4.1)$$
4.2. CHANNEL ESTIMATION

Gathering all the signals together, the matrix notation will be:

\[
x(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_{N_r}(t) \end{pmatrix}, \quad s(t) = \begin{pmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s_{N_t}(t) \end{pmatrix}
\]  

(4.2)

\[
H(t) = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{pmatrix}
\]  

(4.3)

Therefore it will be:

\[
x(t) = H(t)s(t)
\]  

(4.4)

This equation is modeling the following basic MIMO scheme:

![MIMO basic scheme](image)

Figure 4.1: MIMO basic scheme.

4.2 Channel estimation

It has been mentioned that \( H(t) \) models the channel matrix. Each row of this matrix models each parallel transmission so finally there will be an equation system. Hence, in order to solve the equation system for recovering the \( s(t) \), in 4.5 the solution will be reached multiplying both sides of the equation with the inverse of \( H(t) \):

\[
H(t)^{-1}x(t) = H(t)^{-1}H(t)s(t) = I_{N_t}s(t) = s(t),
\]  

(4.5)
where $I_{N_t}$ is the $N_t \times N_t$ dimensional identity matrix. Thus to estimate the transmitted signals at the receiver, the vector $x(t)$ must be multiplied by the inverse of the channel matrix $H(t)$. That means that the channel matrix has to be known at the receiver. This can be done in several ways like, for instance sending a training sequence, that is known to the receiver, to train the channel. This process is called channel estimation and is probably the main issue in MIMO studies but due to that is not the goal of this project it will not have many attention in this report.

Anyhow, after studying what is the concept of channel estimation, is not difficult to see that doing a good estimation of the channel is crucial to develop a valid system.
4.3 MIMO channel modeling

Previously it has been mentioned that each antenna will receive several signals which come from the several transmission antennas but that is not a complete description of the fact. Also it is very important to take care about the reflections. These are the components of the desired signals but reflected in different elements like walls, floor, etc. So when a transmission occurs, the transmitted signal from the p-th TX antenna will arrive at the q-th by several ways or paths. Those are a direct path and the reflected paths. This will be called multipath principle (see figure 4.2).

Due to constructive and destructive interference or the multipath components, the received signal can vary as a function of frequency, location and time. Those variations are called fading.

In a MIMO system, all TX antennas transmit simultaneously and on the same carrier frequency. Because of that, the received signal on a given RX antenna q consist of a linear combination of contributions from all the $N_t$ transmitters. Moreover, it necessary to consider the multipath effect which gives a sum of scaled an phase-shifted copies of the original TX signal in the q-th RX antenna with a time delay in respect of the original one. See ref. [1] for a more detailed reference of this situation.

4.3.1 Scattering, noise and channel estimation

From all the literature about MIMO one fact is clear: A MIMO system is more robust in rich-scattering environments. Also, if white gaussian noise is introduced in the system it is shown that the pure-LOS case -no multipath- suffers severely from the additive noise. For that case, the columns of the H matrix have a strong resemblance -correlation- which introduce an important
error. In a richly scattered environment the channel matrix is highly orthogonal so when noise is added at the H matrix, the effect is not that relevant.

4.4 The design

In this project, MIMO is considering in a typical wireless environment. That means that the signal, after being split in several ways and before being transmitted, should be amplified. For that intention, usually the designers use several independent power amplifiers (see figure 4.3) in the front-end of the transmitter, one for each stream.

![Figure 4.3: Typical MIMO design.](image)

The reason of using those different amplifiers is simple, the frequency of the signal. The operation with high frequency signals involve many drawbacks in the electronic design. The common wireless signals are usually of 2.4 GHz or 5.2 GHz -our case- and they are quite difficult to isolate within a chip. For that reason, until now the amplifier stage have been placed independently for each transmitter.

Moreover is easy to see that, if the design has several different signals of 5.2 GHz so close to each other, the effect inside the chip will be similar than in a MIMO channel without reflections. That means having components of undesired signals in each stream.
4.4. THE DESIGN

The challenge of this project is to be a first study and implementation of a simple stage amplifier chip for a MIMO 4x4 application. This design will implement the previous amplifiers within a unique chip (see figure 4.4, the figure has been done with a 3x3 configuration for clearness reasons).

Figure 4.4: Our MIMO design.
Chapter 5

Subsystem Blocks

The simulation system model developed in this project is a MIMO 4x4 with several blocks which should be studied independently. This design will have primitive -basic- blocks given by ADS for this kind of projects. In this case most of them will be concerning the 802.11a standard, namely sources, receivers and measuring blocks.

Since this project is done at system level, besides the primitive blocks, this project should implement particular blocks in order to achieve the desired design. At this point, three kind of blocks must be distinguished: Matrix blocks, testing blocks and the amplifier stage. The first class is about blocks concerning to the design itself. Blocks which are part of a MIMO system and concerning the behavior of the channel and the receiver. That blocks will be the correlation matrix block, and the inverse matrix block.

The second class is a removable block, used for checking the design in several scenarios. Those blocks are thermal noise and phase noise blocks. They are going to be tested separately for checking the impact of noise and phase noise independently.

The last class is the amplifier stage. It will illustrate the behavior of an amplifier stage in that environment, checking how will be affected by the noise previously mentioned and the correlation of the other streams.
5.1 PRIMITIVE BLOCKS

5.1 Primitive blocks

There are several simple blocks given by ADS, in this section. The most relevant will be studied next.

5.1.1 Wireless 802.11a source

This MIMO 4x4 system will make use of the WLAN 80211a RF source (see figure 5.1)

![Figure 5.1: Wireless 802.11a source](image.png)

It provides the system of a 802.11a signal and also gives the designer the chance of configuring the properties of that signal. It can be done through the twenty one configurable parameters that it has. Those parameters are about used frequency and power, bandwidth, impedances, gain, phase characteristics, IQ characteristics, guard intervals, etc. For a proper knowledge of the tool, they were studied at the initial stage of the project.

The internal design of the source is given in figure 5.2 and figure 5.3 but it will be not studied in this lines. For more details see ADS design guide specifications and [5].

![Figure 5.2: Wireless 802.11a source scheme](image.png)
5.1.2 Wireless 802.11a receiver

The used receiver will be the WLAN 80211a RF RxFSync receiver (see figure 5.4)

With fourteen configurable parameters, its working is corresponding to the source and also have required a previous study.

The internal design of the source is given in figure 5.5 and figure 5.6 but, as previously with the source, it will be not studied in this section. For more details see the ADS design guide specifications and ref. [5].
5.1. PRIMITIVE BLOCKS

Figure 5.5: Wireless 802.11a receiver scheme

Figure 5.6: Wireless 802.11a receiver scheme 2

5.1.3 SDC Crossing components

The next section of this chapter will study two of the main blocks of the final design, i.e., the Correlation Block and the Correlation Inverse Block. Inside those blocks -as is shown in the figure 5.10 and figure 5.12- per in each stream, the four signals are taken and mixed up following an algorithm. The result will be the crossed or decrossed signal. That crossing process will be done by the following SDC block shown in the figure 5.7).

It is important to notice that ADS can provide only two versions of this block. One with real output and another one -the chosen one- with complex output. Due to the fact that our signal is timed signal and it is not possible to do the desired signal processing in a proper block its necessary to do it with the complex one and incorporate to the system the next studied block, the converters.
CHAPTER 5. SUBSYSTEM BLOCKS

Figure 5.7: SDC crossing block

5.1.4 Converters

As has been explained before, the mix of the streams has to be done with complex blocks so, for introducing external timed components like noise sources, local oscillators, amplifiers, etc. certain converters should be used (see figure 5.8).

Figure 5.8: Timed-to-complex and complex-to-timed converters
5.2 Matrix Blocks

MIMO can be regarded as a baseband technique, where the transmitted signals are recovered by advanced signal processing. This requires a total redesign of the ADS 802.11a receiver, which was out of the scope of this project. Therefore influence of the channel and channel correction was modeled using the following correlation and decorrelation blocks. Although, that does not model the fading MIMO channel, it does indicate the influence of channel correlation and allows the use of the standard 802.11a ADS receiver blocks.

Hence for designing a MIMO system, some undeveloped blocks should be done first. Those blocks are about building a MIMO channel and for recovering back the signal from the channel. For that intention the next two blocks are presented.

5.2.1 Correlation

The correlation block (or correlation matrix block, see figure 5.12) will take all the signals from the sources and mix them with each others.

![Figure 5.9: Correlation matrix block](image)

This block has four inputs, one for each stream and 6 outputs, one per stream and two for testing.

The correlation block builds the pseudo channel matrix previously explained in the theoretical chapter of this report. At the output of this block each stream will be formed by of all signal
CHAPTER 5. SUBSYSTEM BLOCKS

streams. Hence, this block is implementing the following matrix.

\[ H(t) = \begin{pmatrix} \alpha & \rho_1 & \rho_2 & \rho_3 \\ \rho_1 & \alpha & \rho_1 & \rho_2 \\ \rho_2 & \rho_1 & \alpha & \rho_1 \\ \rho_3 & \rho_2 & \rho_1 & \alpha \end{pmatrix} \] (5.1)

So, at the output of the block, for the first stream for instance, there will be:

\[ A = \text{Source}_1 \cdot \alpha + \text{Source}_2 \cdot \rho_1 + \text{Source}_3 \cdot \rho_2 + \text{Source}_4 \cdot \rho_3 \]

But several considerations are taken about this H matrix. The first one is concerning the path losses, the \( \alpha \). In this case they are not considered so the \( \alpha \) will be equal to one because any signal component is lost. The other assumption done is that the influence of the non desired streams in the desired one is equal for all streams, which means: \( \rho_1 = \rho_2 = \rho_3 \) and called simply \( \rho \). Usually used to be a percentage value.

After those considerations the H matrix will be like the following.

\[ H(t) = \begin{pmatrix} 1 & \rho & \rho & \rho \\ \rho & 1 & \rho & \rho \\ \rho & \rho & 1 & \rho \\ \rho & \rho & \rho & 1 \end{pmatrix} \] (5.2)

Using the previous example and a correlation value of 20\%, the first stream will be

\[ A = \text{Source}_1 + 0.2 \text{Source}_2 + 0.2 \text{Source}_3 + 0.2 \text{Source}_4 \]
The internal scheme of the correlation block is shown in the figure 5.10.

This block presents 4 inputs and 6 instead of 4 outputs. That is because there will be 4 normal (namely crossed) outputs and two for measuring. A remark should be done about the upper two measuring outputs.

The first normal output is just the signal of the first source with a certain correlated component coming from the other sources. From this point there will be impossible to separate the correlated component -called distortion- from the desired signal. Due to that, two extra (and equal) ports are used. In those ports the desired signal will be suppressed and only the distortion will pass by. After this block noise will be added to one of those paths (exactly the same added noise of the first stream).

That two measuring paths will be used for measuring the signal to distortion (SND) and the signal to noise and distortion ratio (SNDR).
5.2.2 Decorrelation

The correlation matrix inverse block or decorrelation block (see figure 5.11) will take the 4 streams at its input and recover the transmitted signal from them. Thus, it is doing the same task as the channel estimation block in a MIMO receiver. Mathematically this is the inverse matrix of the H matrix, namely, inverting the Correlation block.

![Correlation matrix inverse block](image)

Figure 5.11: Correlation matrix inverse block

It is important to notice that this block is done after doing a channel estimation. With that process, the system "knows" the channel (H matrix) and then design this correlation matrix inverse according with that estimation for extracting the signal. Although it is one of the main issues of the study of MIMO systems, and due to the fact that it is not the aim of this project, this lines will not pay attention to how is the channel estimation done.

So at this point is placed this block, done after the channel estimation process. Each stream will be extracted from the total signal received in each antenna. If there is no correlation between those streams at the same antenna, this extraction would be perfect but, obviously in the real world it never happens. That is the intention of the next blocks. They will introduce non-linearities, noise, correlation, etc in order to build a more real design.
Returning to the actual block, the following figure 5.12 is the internal design. The used algorithm have been calculated first and optimized afterwards with Mathematica 5.

**CorrMatInv4_dist**

Figure 5.12: Correlation matrix inverse diagram

The four lower inputs/outputs are for each stream. The upper two are for measuring signal-to-noise ratio and signal-to-distortion ratio respectively (see Measurement Techniques chapter).
CHAPTER 5. SUBSYSTEM BLOCKS

5.3 Testing Blocks

As told before, for achieving a more realistic MIMO system, it is necessary to introduce external elements which will have influence in the behavior of the system. In this section two blocks are developed: the thermal noise and the phase noise block.

5.3.1 Uncorrelated Thermal Noise Block

Thermal noise appears in every communication system. In this project it will be implemented in its most simple way. A random noise source per each stream (see figure 5.13). Its important to remark that each stream will be affected by different Thermal Noise block, so the noise will be different for each case and, of course uncorrelated with the other noise sources.

Figure 5.13: Thermal noise

5.3.2 Uncorrelated Phase Noise Block

The contribution of the phase noise in a synchronous communication system is extremely rough. Because of that, standards like the used 802.11a have specifications about the values of that kind of noise. In wireless systems it can be caused by several aspects like multipath interferences, synthesizers or, like in our considerations, PLL's of the local oscillators. For that reason this project has a block (see figure 5.14) which reproduces this noise.

Figure 5.14: Phase noise block
5.3. TESTING BLOCKS

The internal circuit of the block is depicted in figure 5.15. There is shown how the signal of each stream is modulated in a local oscillator using a carrier which has a configurable value of phase noise. The final signal is located at the desired frequency but exhibits phase noise.

Figure 5.15: Phase noise circuit
CHAPTER 5. SUBSYSTEM BLOCKS

It is important to notice that, as is shown in the figure 5.14, the value of the phase noise is introduced in that block by four parameters: two for the frequency and two for the amplitude of the mask. Those parameters just set the value of the mask for the phase noise. In this case they have as a default values the same ones specified in the requirements of the 802.11a standard. The mask of that requirements is shown in the figure 5.16.

A last remark about correlation should be made. Figure 5.15 depicts the internal circuit of this block. There we see four different noise sources added to each stream. Those noise sources are fully independent and different. That is because the phase noise introduced will be fully uncorrelated.
5.4 Amplifier Stage

The amplifier stage is one of the main topics of this project. In the final design it will be placed just before the correlation matrix inverse. That is because the effect of the non-linearities of the amplifier will cause serious problems.

The used model will be the GainRF amplifier of ADS (see figure 5.11). This model have been chosen because it is very configurable trough eleven parameters such as Gain, impedances, noise figure, one dB compression point, TOI, etc.

![GainRF diagram](image)

**Figure 5.17: RF Amplifier**

A first study of this power amplifier was needed in order to get familiar with the characteristics of the device and the concept of designing the amplifier stage. Some results of that study are presented in the RF amplifiers chapter of this report.

Hence, the amplifier stage will be a block with five inputs and five outputs (see figure 5.18). One per stream and two for measuring purposes. From outside of the block is possible to make modifications in parameters like one dB compression point, TOI point and saturation point.

![Amplifier stage diagram](image)

**Figure 5.18: Amplifier stage**
In the figure 5.19 its simple diagram is depicted.

**4x4 Amplifier Block**

![4x4 Amplifier Block Diagram]

Figure 5.19: Amplifier stage circuit

This design has 4 inputs and 4 outputs for each stream but also has two ports for measuring purposes.
5.5 Complete design scheme

The whole design of this project is given in the figure ??; there are all the blocks that form the final design.

Figure 5.20: MIMO 4x4 entire design

But first, more simple simulations will be studied in order to have a better idea of the effect of each block.
CHAPTER 5. SUBSYSTEM BLOCKS
5.5. COMPLETE DESIGN SCHEME
Chapter 6

Measurement techniques

A design with these characteristics (see figure 6.1) has to be measured in several places under several conditions. In this section the main measuring points will be explained.
6.1 Constellation

The most obvious measurement is probably the received constellation. Depending on the study will be measured in the source or, more often, at the receiver. The internal diagram will not be shown in this section. For more references consult ref. [5].

An example of typical placement of this block is given in figure 6.2.

In this case this block is showing the QAM constellation at the receiver. In the following figure 6.3 an example of a 64QAM constellation with 1.5% of EVM is given.

![Figure 6.2: Constellation block](image)

![Figure 6.3: Example of received 64 QAM constellation with 1.5% EVM](image)
6.2 EVM

In previous chapters the EVM mathematical concept has been explained. For its measurement in RF environments ADS provides a block called WLAN-80211a-RF-EVM depicted in the *figure 6.4.*

![Figure 6.4: EVM 802.11a block](image)

It gives the value of EVM during a certain number of frames (configurable number, typically 90 in our study). For comparing different EVMs in this project usually the used method has been comparing the EVM sample of the 90th frame.

It also important to notice that in its internal scheme (see *figure 6.5*) there is already receiver so, it is not necessary to place another receiver block in front of this block, differently than the case of constellation measurements.

![Figure 6.5: EVM 802.11a internal scheme](image)
6.3 Power, SNR and SNDR

Measuring the power is crucial in every communication system, for that reason some power measurements procedures will be explained in this section.

6.3.1 Power measurements

There are several ways of measuring the power. The most used way in this project is making use of a WLAN RF Power measurement block attached to a timed sink (see figure 6.6).

![Figure 6.6: WLAN power measurement](image)

6.3.2 SNR

The signal to noise ratio (SNR) is one of the most significant measurements in a communication system. In our case, for doing that measurements the input power and the noise power have been measured at the output of both devices (see figure 6.7). Those measurements are done in dBw or dBm so, for calculate the SNR, we just have to do the substraction.

![Figure 6.7: Signal and noise power measurement](image)
6.3.3 Signal to Distortion Ratio (SDR). Distortion measurement

The signal at the receiver will usually be formed by three components. The transmitted signal, the additive noise and the undesired signals coming from the other sources, i.e. distortion. Usually distortion and noise are called just noise but, in our case sometimes the exact value of the distortion has to be known. Due to the fact that it is impossible to distinguish the signal from the distortion in the receiver, the implemented solution was an extra output in the correlation matrix block.

As is explained in the Correlation Matrix section of Subsystem Blocks chapter, there is a path where the main signal is canceled and only the contribution of the others streams is taken. That is the distortion signal which we will measure. Also a filter has been added to extract the power of the harmonics. It is very important to notice that this path does not have any kind of noise contribution, just the correlated signals.

In the figure 6.8 the measurement device and the used path are depicted.

Figure 6.8: Distortion power measurement

Once the power of the distortion is measured, is easy to obtain the signal to distortion ratio which, of course, has influence in the final performance of the design.
6.3.4 Signal to Noise and Distortion Ratio

Although signal and distortion is an important tool to analyze the system, the whole "undesirable" components have to be measured. That means not only distortion but also noise. For that measurement another special path has been implemented in the blocks. This is similar the previous path but also takes into account the thermal noise (exactly the same source as used for the first stream). In the figure 6.9 the measurement device is depicted.
6.4 Amplifier measurements

An RF amplifier is a complex device which can be subjected to many variations and can be configured in many ways. Due to that, it is very important to measure the input and the output of that component in order to check that its behavior is the expected, for instance in the calibration process. For that intention, two extra ports have been implemented in the concerned block (amplifier stage). These ports bring measurable points outside of the block (see figure 6.10).

![Figure 6.10: Amplifier measurement](image_url)
6.5 SYSTEM CALIBRATION

6.5 System calibration

Every study must have a continuous relation from one situation to another one. In every system that has components which are placed and removed, the calibration has an important role. What, at this point, is called calibration is just a technique by means of the effect of adding an element is null. So for instance when an ideal component is added to the system, no losses should be obtained from that, namely no effects of the new element arises. When and only when that component is no longer ideal its effect should be observable.

From the theoretical point of view, calibration is a very simple procedure. It is only comparing the results of placing an ideal component with the results without that component. In this project much time has been spent on this process, due to its relevance. In our system two calibration where find necessary, concretely for the testing blocks.

6.5.1 Amplifier calibration

For the amplifier calibration the followed method was placing an RF amplifier block with Gain = 1 and 1 dB compression point at 50 dB with means a very linear device. That is for avoiding the non linear region which could spoil the results.

Figure 6.11 shows the results without amplifier stage and with amplifier stage configured with the previously mentioned values.

![Amplifier calibration](image.png)

Figure 6.11: Amplifier calibration

It seems to be an only one line but that's because both lines are overlapped which is just what we were looking for. So if the amplifier is under certain conditions like has a gain of 1, is ideal or the working region is in the linear region and is matched, its influence in the system is utterly null.
6.5.2 Phase Noise calibration

For the phase noise calibration the procedure will be similar to the one of the amplifier one. In this case the ideal value for the phase noise will be setting a mask like the standard but with -1000 dB of attenuation. The obtained result is depicted in the following figure 6.12.

![Figure 6.12: Phase noise calibration](image)

At this case a variation between both curves arises but the value of that variation have been considered negligible, because it is lower than one dB and the introduced EVM is very small. At first this variation was not that small, in fact it was around 8 dB so we had to do an investigation into this effect. After trying with other noise sources, checking the matching and looking for isolating blocks, we found out that out of this block that effect was not that big. So we placed the phase noise stage right in the system, not inside a block. Eventually the better result as depicted above was achieved and it was considered valid.

The reason of this drawback has been supposed as a reflection problem because when an amplifier stage is also added to the system, this variation disappears. Anyway, that remains with the isolators so it should be investigated more.

The study of the reason of the problem was finally finished because the lack of time.
6.5. SYSTEM CALIBRATION
Chapter 7

Obtained results

After previous studies of several aspects of the design, it is time to place everything together. For that intention, the first step is to design and study the system itself, without any external influence. After that, some other blocks will be added to the design. Finally, the whole system will be tested.

7.1 4x4 Simple design

The final simulations serie will start with a study of the channel, which is introduced in this project as the correlation and decorrelation blocks. At this point the design will be a 4x4 MIMO design with no external influences as depicted in figure 7.1. No noises or non-linearities are in the system, purely the ideal case.
7.1. 4X4 SIMPLE DESIGN

Figure 7.1: Ideal 4x4 MIMO system setup

In those conditions the system is checked doing a sweep of the values of the $\rho$ parameter, therefore changing the correlation among the received streams. As we expected after reading ref. [8], the most interesting result in this study is shown in the figure 7.2. This figure depicts the values of the EVM for different values of the $\rho$.

Figure 7.2: 4x4 EVM without any impairments

Here we can see that the EVM remains almost at zero percent. That means that without any external influence, the system works properly. It will remain like this until correlation or noise will be introduced in the analyzed environment.
CHAPTER 7. OBTAINED RESULTS

At this point, it is proved that MIMO concept is working. A MIMO environment has been developed in ADS and its behavior is as it expected. Now external components will be introduced.

7.2 4x4 Simple design with Thermal Noise

Every communication system exhibits Thermal Noise. In our case additive white Gaussian noise (AGWN) has been introduced by independent and uncorrelated noise sources at each stream, in the correlated signal streams. Figure 7.3 the design is depicted.

![Figure 7.3: MIMO 4x4 with Thermal Noise](image)

The simulation is done by sweeping the power of the thermal noise sources and using a fixed value of the $\rho$. This is compared with the previous results without noise. In this case the impact of the noise can not be neglected, even more harmful when correlation appears ($\rho$ not zero). In the next figure 7.4 is shown how the noise affects the EVM.
7.2. 4X4 SIMPLE DESIGN WITH THERMAL NOISE

Figure 7.4: EVM with noise and $\rho = 0$ vs Thermal noise power in dBm

If correlation appears the EVM will increase as we can see in the following figure 7.5.

Figure 7.5: EVM with noise and $\rho = 12\%$ and $24\%$

In the first case ($\rho=0$) is shown that for a value of -20 dBm (-50 dBw) the resulting EVM equals 11%. That value for this standard is unacceptable because in that conditions the constellation is like figure 7.6. Extracting the signal from this constellation will introduce a high level of errors at the receiver.

Figure 7.6: Constellation with 11% of EVM

From now on, most of the simulations will be done sweeping the value of the thermal noise. Usually assuming a power for the source of 0 dBm.
CHAPTER 7. OBTAINED RESULTS

7.3 Thermal Noise and Phase Noise

This section will introduce phase noise in the system. For that intention the previously described Phase Noise Block will be placed in the channel. This block can be configured with the desired values of the mask for the phase noise. In the figure 7.7 the design is depicted.

![Figure 7.7: MIMO 4x4 with Thermal Noise and Phase Noise](image)

7.3.1 Phase Noise with standard mask

The mask of the standard 802.11a (previously shown in the figure 5.16 of the Subsystems blocks chapter) defines a value of the amplitude of the noise of -90 dBm (approximately, the exact value is -87 dBm).

In this first simulation is studied by means of the SNR vs EVM of the system but with a mask very much lower than the standard one. Notice that the EVM will be always in percentage and the SNR in dB. This case is simulated with an amplitude of -1000 dBm, which means no phase noise. Under this condition the system behaves like figure 7.8 and is almost coincident with the system without phase noise (see calibration section of measurements techniques chapter).
7.3. THERMAL NOISE AND PHASE NOISE

In the following simulation of the phase noise the value of the mask will be fixed to the standard and the $\rho$ parameter will be changed. Hence, figure 7.9 depicts a comparison of several values of the graph of SNR vs EVM. The straight black line represents the system with negligible values of the phase noise (so, figure 7.8). The dark pink line is representing the system with the specifications of the standard for the phase noise. The two upper lines (in light pink) represent the same of the dark pink but increasing the $\rho$. They are for a value of 10% and 20% of correlation ($\rho$) respectively.

Figure 7.8: Phase noise = 1000 dBm

This first analysis of the phase noise confirms the expectation that when the correlation appears in the environment, the phase noise become one of the most important problems of the designer. Just in the moment that the phase noise is introduced, a significant change in the EVM takes place. The more correlation ($\rho$) we have, the bigger EVM results.
7.3.2 Phase Noise comparison

Checking how serious the phase noise influence in the design is, it is important to have an accurate idea of what the parameter is that we are dealing with. For that intention, a modification of the value of the 802.11a standard will be done and compared with the last result. In this case, a value of the amplitude of -80 dBc/Hz has been selected instead of the previous -90 dBc/Hz.

*Figure 7.10* compares the results with both phase noise mask.

![Phase noise -90dBm vs -80dBm](image)

*Figure 7.10: Phase noise -90dBm vs -80dBm*

With that modification, for the simplest case ($\rho=0$, no correlation) of -80 dBm the value of the EVM is really close to the value for -90 dBm and $\rho=20\%$. That means a serious increment of the noise.

More simulations were done with higher values of the phase noise and all of them confirm that problem as expected.
7.3.3 Correlated Phase Noise

After checking the effect of increasing the phase noise mask another interesting point of view will be studied. The aim at this time will be to analyze a correlated phase noise. For that intention the phase noise block should be modified. As is presented in figure 7.11, instead of four different phase noise sources, the design will use only one source affecting all the streams. The phase noise in this case will be, obviously fully correlated.

![Figure 7.11: Correlated Phase Noise Block](image)

Doing the same previous uncorrelated simulations with this configuration the obtained results were the following depicted in figure 7.12.
If we analyze the obtained results a strange conclusion arises. In the figure 7.12(a) we see how the uncorrelated simulations have a certain level with \( \rho=0 \) and an increment of the EVM when the \( \rho \) increases, namely when correlation increases. When the simulation is redone with fully correlated phase noise, all the graphs come together to the same value which is coincident with uncorrelated phase noise with \( \rho=0 \). The same effects appears for a value of -80 dBm.

From those graphs the conclusion would be for a fully correlated phase noise, the value of the EVM remains constant with different \( \rho \)'s so the phase noise is independent of the correlation among the streams, namely independent of the \( \rho \). That in our opinion is a very questionable result.

These results can partly be attributed to the common-phase-error (CPE) correction in the ADS WLAN receivers. These receiver can handle one CPE, which will be the case when all branches experience the same phase noise. However, in the case of independent phase noise, different CPEs will occur and it is impossible for the current ADS design to correct for it. The receiver in ADS should be modified for that.

Due to the lack of time no further investigations were done at this point but we insist in the doubts about these results.
7.4 Amplifier Stage

The amplifier stage is an important part of this study. For analysis of the non-linearities introduced in the system by this kind of stages the previously described Amplifier Stage Block is placed in the design. The schematic is depicted in the figure 7.19.

![Figure 7.13: MIMO 4x4 with Amplifier Stage](image)

With this block, like with the previous phase noise one, many studies have been done. Next, the most interesting results will be presented.

7.4.1 Preserving the output power level through 1dB compression sweep

Usually the amplifier designers analyze their systems changing the input power. By means of that, the non-linearities of the device will arise setting the 1dB compression point to a certain value. During this study a different way of working has been taken. In this project no concrete amplifier have been selected yet, so a particular value of TOI, 1dB
compression point or saturation power can not be fixed. Otherwise this study will be useful only for the selected value. Instead of the most common way of designing -varying the input power- in this project, the studied parameter will be the one whom is sweep. For instance, if the object of the study is the 1 dB compression point, this will be the sweep parameter, which means that the saturation region will change in every simulation. That will make this project practical for every kind of amplifier.

All this explanation will be more clear in the following figure 7.14 where the Gain vs $P_{in}$ are depicted.

![Figure 7.14: Sweep of 1 dB compression point shown in a gain curve.](image)

In this first case the most simple study of this stage have been done. This will be setting our common value for the input power, 0 dBm, a $\rho = 0$ and then make a sweep of several values of the 1 dB compression point. The results are shown in figure 7.15.

![Figure 7.15: Sweep of 1 dB compression point with $\rho = 0$](image)

The value of 50 dBm has been chosen in order to compare it with the linear (ideal) case.
7.4. AMPLIFIER STAGE

After that value some lower values like 25, 15 and 10 dB have been selected for studying how the EVM is influenced.

1dB Compression sweep with correlation

As we can see in figure 7.16, if the correlation among the streams appears ($\rho$ non-zero) the results become, obviously worse.

![1dB Compression sweep with correlation](image)

Figure 7.16: Sweep of 1 dBC with $\rho = 10\%$ and 20\%

Is evident that a value of 10\% and under certain conditions or for certain values of the 1dBC point may be can be neglected, not anymore with a value of 20\%.

In this figure we have seen that the difference between $\rho = 0$ and $\rho = 10\%$ is clearly not the same as $\rho = 10\%$ and 20\%.
Hence, we can conclude that the impact of the $\rho$ is not linear, so the medium has not a linear behavior.
CHAPTER 7. OBTAINED RESULTS

7.4.2 TOI and TOI+1dBc sweep

The studied RF Amplifier presents the opportunity of configuring it in order to consider certain parameters (see figure 7.17). Until now the shown results have been achieved considering only the 1dB compression point. Also an independent study of the TOI and TOI+1dB compression point have been accomplished.

Figure 7.17: RF Amplifier configured with TOI+1dB compression point

Theoretical concepts (see ref. [2]) of the amplifier design say that the TOI point should be at least 9.8 dB (namely 10dB) above the 1dB compression point. If the simulation is done below those 10 dB, ADS evidently presents an error. Above that 10 dB the device has a better behavior so for the designer the most interesting value is that 10 dB.

Due to the lack of relevance the simulations done with TOI and TOI+1dB compression point are not presented in this report.
Finally the system will be form by the channel -in this report introduced as correlation and decorrelation block-, the thermal noise block, phase noise and amplifier stage working at the same time. Hence the schematic will be the following figure 7.18.

The most interesting simulation results using this configuration will be presented next.
CHAPTER 7. OBTAINED RESULTS

7.5.1 Phase noise

Phase noise and the non-linearities of the amplifier stage have to be studied together, at this moment it will be done from the phase noise point of view.

In the following figures the value of the phase noise is fixed and the value of the 1dBc point is changed in the three most significant values: 25, 15 and 10 dB. The correlation at this point will be null.

![Figure 7.19: Complete system without phase noise](image)

![Figure 7.20: Complete system with different Phase Noise values](image)

The previous graphs show how the EVM turns worse when phase noise increases. If the phase noise remains in the values of the standard the change in the EVM is not drastic but if the phase noise doesn't fit the mask of the standard, the EVM increases significantly.
7.5. COMPLETE DESIGN

7.5.2 1dB compression point

At this time, the previous results will be shown from a different point of view. Now in the following figures there are presented, for each value of the 1dBc point, the obtained values for each phase noise.

![Graphs showing phase noise for different 1dBc points](image)

(a) 1dBc = 25 dB  
(b) 1dBc = 15 dB  
(c) 1dBc = 10 dB

Figure 7.21: Complete system with different 1dBc point

These graphs present how the value of the phase noise in combination with the non-linearities of the amplifier can bring the system to a very high value of the EVM. In figure 7.21(c) the EVM reaches the value of 9% which is very close to be unacceptable.
Chapter 8

Conclusions and recommendations

This master thesis project has been done following a *Top-Down* approach. Working at system level, particular subsystems have been used for implementing the final design, modeling different effects and testing the complete system. At the end of this report some conclusions and recommendations will be mentioned.

8.1 Conclusions

After this study some conclusions can be obtained:

- The impact of the correlation in this kind of systems is not linear. The damage caused by, for instance 20% of correlation is much higher than two times the damage caused by 10%.

- Correlation of the path acts as additional parameter, non linear and unpredictable parameter which stress the design procedure.

- It is well known that the impact of the phase noise in synchronous systems is very harmful. In MIMO systems -also synchronous- the phase noise use to appear in combination with correlation, which can easily collapse the system.

- Phase noise dominates the performance of the system at the linear region.

- Non-linearities dominate the performance of the system at the quasilinear region of amplifiers.

- Phase noise could be manipulated using higher power levels.

- Phase noise increases dramatically at higher frequencies, as we see in the first simulations with this kind of noise.
8.2 RECOMMENDATIONS

- Adaptive power control system is needed to adapt the performance of the system based on the non linear and unpredictable correlation path.

- Simulation of complex system is indeed not an easy task.

- MIMO introduces many complexities in the system with the aim of increasing the bandwidth efficiency. If this efficiency does not need to be improved other solutions should be considered. Implementation of MIMO systems in higher frequency range becomes questionable where a plenty of frequency bandwidth is available.

- MIMO is a good solution for mobile system such as GSM where the frequency is much lower and where the bandwidth cannot be increased so the bandwidth efficiency requires to be efficient.

8.2 Recommendations

For a possible future research continuing the present work, some suggestions will be given:

- In this project a simple and linear matrix was used for modeling the channel. It would be interesting change the values of that matrix and analyze the effect in the results. A not linear matrix could give a different vision of the system. Furthermore, a mapping of this correlation measure to the generally used correlation in communication theory has to be found.

- A simplified channel and receiver modeling was chosen in this report, enabling the use of basic ADS modules. It is recommended that in future research, however, a MIMO WLAN receiver block will be built which applies detection jointly over the receiver branches. This block could take out part of the influence of phase noise and thermal noise. The implementation of more realistic fading channels might also be incorporated here.

- MIMO systems are not always symmetrical, the number of antennas in transmission and in reception could be different. The idea of doing a study with asymmetrical matrices must be considered in further investigations.

- A first and generic study has been done using a generic amplifier. The next step in that field would be selecting a real device, place it in the system and analyze its behavior.

- Introduce the study of the AM to PM characteristic.

- Emphasize the calibration process.

- This study was done for the standard 802.11a which works at 5.2 GHz. It could be interesting to check the effect of changing the frequency or use another standard. For higher frequencies is possible that many more drawbacks could arise (nevertheless that affirmation requires to be probed) but for lower values may be some improvement can be achieved.
CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS
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