MULTIDIMENSIONAL MEASUREMENTS

On RF Power Amplifiers

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Abstract

Measurements are important to specify and verify properties for components, modules and systems. The specifications for a certain figure of merit are usually given in a numerical value or a two dimensional plot. However, there are some devices, like power amplifiers with certain figure of merits that depends on two or more working conditions, requiring a three dimensional plot.

This thesis presents a measurement method including graphical user interface of three parameters gain, efficiency and distortion when two-tone or WCDMA signals are used as an input to the PA. The proposed method is substantially faster than the currently used methods.

An automated measurement system using digital signal processing techniques for improvements in speed and accuracy has been implemented. The measurement system consists in a vector signal generator, a vector signal analyzer, an oscilloscope, a current probe and a computer.

The two test signals two-tone and WCDMA are generated by a computer program in Matlab, these signals are swept in frequency and power in predefined steps. The signal is sent to the power amplifier through the vector signal generator, and then the output is sent back to the computer through the vector signal analyzer. The generated signal and the received signal are correlated and synchronized and the information required is extracted.

Results show that the presented method is fast and efficient when two or three dimensional plots are required in the analysis on the behavior of the power amplifier. However the range of frequency and power is limited.
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1 Introduction

1.1 Background

Power Amplifier (PA) is the key element to build a wireless communication system successfully, since this handle the highest power level on the system and introduce nonlinearities when it operates near the maximum output power.

The main objective of this thesis is to implement a measurement method and a graphical user interface (GUI) to measure, analyze and plotting three parameters, gain, efficiency and distortion in a three dimensional plot when two signals are applied to the input of the PA.

Characterization on PA has always been a challenge for the designers of PA. In order to design a good PA parameters like gain, efficiency and distortion need to be considered, being the efficiency and distortion one of the most challenging design problems. Even with all the sophisticated equipments and all the experience that designers of PA have, the process of analyze and verification of the different properties of the PA is quite slow.

This thesis intend to provide them an easy tool to measure, analyze and verify in a fast way the different parameters and problems that can be presented in the design and production of PA. With this method is possible to visualize the sweet spots [1] presented when the PA is operated in the nonlinear region. They can deeply visualize the behavior of the PA.

This work is done in partnership with Hibah Altahir [2].

1.2 Previous research


This thesis work shows the dependency between three parameters gain, efficiency and distortion on PA in a three dimensional plot. So far there has not
been a method to represent this dependency in a three dimensional plot. However, this thesis is based in the previous researches that were mentioned before.

1.3 Problem Statement

To implement a method and a GUI of three parameters gain, efficiency and distortion in order to get a three dimensional plot when two-tone or WCDMA signals are used as an input to the PA using essentially a vector signal generator (VSG), a vector signal analyzer (VSA) and an oscilloscope. Measurement setup considerations and knowledge about digital communication system, digital signal processing and PA shall be used.

1.4 Goal

The main goal is to develop a measurement method and a GUI for three parameters gain, efficiency and distortion, for the design, verification or production on PA. The method should be able to do the measurements as fast and efficient as possible.

1.5 Thesis Outline

The thesis is outlined as follows:

**Chapter 1: Introduction** - gives a brief introduction describing the background, problem statement and the goal of this thesis as well as an overview of the contents of this thesis work.

**Chapter 2: Theory** - presents basic theory on PA that is needed throughout this thesis. Two-tone signal, WCDMA signal and digital signal processing techniques are also presented for the derivation of the method proposed.

**Chapter 3: Measurement System** - gives the technical and theoretical information of the measurement system used along this thesis as well as some trade-offs caused for the used of this measurement system.
Chapter 4: Measurement Techniques - explains the methodology that is implemented in order to obtain the three dimensional plot of the different parameters of the PA. The GUI is also presented in this chapter.

Chapter 5: Results - presents the results obtained in two and three dimensional plots from the different parameters of the PA.

Chapter 6: Conclusions - presents the conclusions from analysis of the results shown in chapter 5 and ends with some suggestions for the future work.
2 Theory

This chapter gives an overview of the theory used along this thesis. In Section 2.1 a briefly definition of PA is introduced. The definition of gain, efficiency and distortion is given in Section 2.2, 2.3 and 2.4 respectively. Section 2.5 describes the test signals. Digital signal processing techniques like coherent sampling, synchronization as well as the definition of root raised cosine filter are given in Section 2.6.

2.1 Power Amplifier

The purpose of the PA is to convert a low power signal into a significant power for transmission from the transmitter to the receiver. It is used in the final stage of the transmission chain. Important considerations for PA are the gain, efficiency and linearity. Unfortunately there is a trade-off between efficiency and linearity. They can not be achieved simultaneously.

PA is usually optimized to have high efficiency, high 1dB compression point, and good gain. Amplifiers are divided according to their method of operation into different classes [7], [8]. It is necessary to define Class A and AB. They are used throughout this thesis.

2.1.1 Class A amplifiers

Class A amplifier has the highest linearity over the other classes but does not give maximum efficiency. It is assumed to be perfectly linear in the region between cut-off and saturation [7]. This class of PA is commonly used in small signal stage.

2.1.2 Class AB Amplifiers

Class AB amplifiers show a solution for a trade-off between efficiency and linearity. The device is biased typically to a quiescent point which is somewhere
in the region between the cut-off point and the class A bias point, see Figure 2.1. Class AB has higher efficiency, larger memory effect and higher nonlinearity than class A [9].

![Figure 2.1 Class A and AB of PA](image)

### 2.2 Gain

There are different definitions of gain like available gain that is the ratio between the power available from the output and the power available from the source. Another definition is the transducer gain which is the ratio between the power delivered to the load and the power available from the source.

The definition that is taken into account in this thesis is the power gain that is the ratio between the output and the input power, and is usually measured in decibels.

\[ G = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]  

### 2.3 Efficiency

Efficiency is one of the most important considerations in PA, as well as leads to the different classes of PA. It represents the ratio of RF output power to DC input power:
\[
\eta = \frac{P_{\text{out}}}{P_{\text{dc}}} \tag{2.2}
\]

One drawback of this definition is that it does not take into account the drive power required, which in an RF PA is quite important [5], [7]. A better measure that includes the drive power required is the power added efficiency (PAE), defined as:

\[
\text{PAE} = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{dc}}} \tag{2.3}
\]

where, \(P_{\text{in}}\), is the RF drive power. PA is usually optimized to provide high efficiency.

### 2.3.1 Efficiency and Linearity

An ideal PA would be a linear device, but real PA is only linear within certain limits. Usually PA is designed to achieved good efficiency at the expense of linearity, after the linearity requirements can be achieved by external techniques for linearization such as feedback, feedforward and predistortion [7], [9], [10], the treatment of these techniques are out the scope of this thesis.

### 2.4 Distortion

Distortion will be generated if a band limited signal is passed through a nonlinear PA [6], [11]. It usually increases when PA operate at or near saturation. There are different types of distortion like third order intermodulation and adjacent channel power ratio.

#### 2.4.1 Third-Order Intermodulation

Third-order intermodulation (IM3) is the measure of the distortion products produced by a nonlinear device like PA. The IM3 products have the maximum effect on the signal since they are close to the carrier that it is almost impossible to filter out and can cause interference in another system.
When two signals at frequencies $f_1$ and $f_2$ are input to a nonlinear PA, then IM3 product will occur at frequencies of $2f_1 - f_2$ and $2f_2 - f_1$, as indicated in Figure 2.2. The IM3 products appear either side of each carrier, at the frequency spacing equal to that of the two input carriers.

![Figure 2.2 Two-Tone Intermodulation](image)

### 2.4.2 Adjacent Channel Power Ratio

Adjacent Channel Power Ratio (ACPR) or Adjacent Channel Leakage Ratio (ACLR) is commonly used for WCDMA signals, where the channel bandwidth is 3.84 MHz with 5 MHz spacing between channels. ACPR compares the power in an adjacent channel to that of the signal, see Figure 2.3, and is normally measure in dBC. In PA design, the ACPR is the most commonly used figure-of-merit to describe linearity [7].
2.5 Test Signals

The test signals used in this thesis for characterization of the PA are two-tone and WCDMA signals.

2.5.1 Two-tone

Two-tone measurements are the most used technique to characterize the nonlinear distortion in amplifiers.

The general form of the signal is given by [12]

\[ s(t) = \text{Re}\{r(t)e^{j(\omega_c t + \phi(t))}\} \]  \hspace{1cm} (2.4)

\[ s(t) = r(t)\cos(\omega_c t + \phi(t)) \]  \hspace{1cm} (2.5)

where \( \omega_c \) is the carrier frequency and \( r(t) \) and \( \phi(t) \) are the envelope and the phase of the signal respectively, given by

\[ r(t) = \left( x^2(t) + y^2(t) \right)^{1/2} \]  \hspace{1cm} (2.6)

\[ \phi(t) = \arctan \left( \frac{y(t)}{x(t)} \right) \]  \hspace{1cm} (2.7)

where \( x(t) \) and \( y(t) \) are the in-phase (I) and quadrature-phase (Q) signals respectively, given by
\begin{align}
  x(t) &= \sum_{k=1}^{N} A_k(t) \cos(\omega_k t + \phi_k(t) + \lambda_k) \\
  y(t) &= \sum_{k=1}^{N} A_k(t) \sin(\omega_k t + \phi_k(t) + \lambda_k)
\end{align}

where $A_k(t), \phi_k(t), \omega_k$ and $\lambda_k$ are the amplitude, phase, relative frequency and initial phase of the $k$:th sub-carrier and $N$ is the number of sub-carriers. The subcarriers are referenced to the RF carrier frequency $f_c$, i.e., if $f_c = 2.14GHz$, $f_1 = -2MHz$, and $f_2 = 2MHz$, there will be one tone at $2138MHz$ and one at $2142MHz$ at the RF output.

The complex envelope of the input signal in (2.5) is [11]

\begin{equation}
  s_j(t) = r(t)e^{j\phi(t)} = x(t) + jy(t)
\end{equation}

If the phase is set to zero, the peak-to-average power ratio (PAR) becomes

\begin{equation}
  PAR = 10 \log_{10} N
\end{equation}

### 2.5.2 WCDMA

Wideband Code Division Multiple Access (WCDMA) is a guide band digital radio communications technology, which provides new service capabilities. It is used in the third generation (3G) telecommunication system. WCDMA requires a minimum spectrum allocation of 5MHz, which is important distinction from the other 3G standards [13].

True WCDMA signals are not practical to generate instead they can be generated by noise-like signals from pseudo random binary sequences (PRBS)

\begin{equation}
  W(m) = \sum_{i=0}^{N-1} \omega_i(m)
\end{equation}

where $\omega_i(m)$ is the $i$:th PRBS.
2.6 Digital Signal Processing Techniques

2.6.1 Coherent sampling

Coherent sampling is one of the most common techniques for evaluating the performance of data converters and other sampled systems. This method increases the spectral resolution of a Fast Fourier Transform (FFT).

It describes the sampling of a periodic signal and its relationship between input frequency $f_{in}$, sampling frequency $f_s$, number of cycles $N_{cycles}$, in the sampled set and number of samples $M_{samples}$ in the FFT. Mathematically is represented by

$$\frac{f_{in}}{f_s} = \frac{N_{cycles}}{M_{samples}}$$

(2.13)

where $f_{in}/f_s$ must be relative prime, which is fulfilled if $M_{samples}$ is a power of 2 and $N_{cycles}$ is an odd integer number [14].

Figure 2.4 shows a spectral leakage caused by non-coherent sampling. For example, if $M_{samples} = 2^{14}$, $f_s = 40MHz$ and $f_{in} = 1MHz$, then $N_{cycles} = 409.6$ but $N_{cycles}$ must be an odd integer number, then $f_{in} = 1.023MHz$. This is an input frequency that satisfies the definition of coherent sampling, see Figure 2.5.
2.6.2 Root Raised Cosine Filter

The Root Raised Cosine (RRC) filter is frequently used to shape pulses and limit Intersymbol Interference (ISI) in communication systems. The frequency response of the filter is given by [12]
\begin{equation}
    h(t) = \text{sinc} \left( \frac{t}{T} \right) \cos \left( \frac{\pi \beta t}{T} \right) \frac{1}{1 - \left( \frac{4 \beta^2 t^2}{T^2} \right)}
\end{equation}

\[ 0 \leq \beta \leq 1 \]

where \( \beta \) is the roll-off factor. The frequency response of RRC is specified by the roll-off factor, which varies from 0 to 1.

In many systems the transmitter and the receiver are specified as a RRC filter [15], with a certain roll-off factor \( \beta \) (e.g. in WCDMA the roll-off factor is \( \beta = 0.22 \)).

**2.6.3 Synchronization**

When two signals are measured in different time instants, then synchronization is needed in order to find the delay between both signals. Synchronization is based in the definition of cross-correlation. Consider \( x(n) \) as an input and \( y(n) \) as an output signals, then the cross-correlation between both signals is given by

\begin{equation}
    r_{xy}(m) = \sum_{n=m}^{N+m-1} x(n) y^*(n-m)
\end{equation}

where \( m \) is the delay and \( N \) is the number of samples.
3 Measurement System

This chapter gives an overview of the measurement system, internal structure and configuration of the different instruments that have been used during this thesis is introduced.

The measurement system that has been implemented and used in this thesis is shown in Figure 3.1, this measurement system consists of a Rohde & Schwarz SMU200A VSG, a Rohde & Schwarz FSQ 26 VSA, a Driver Power Amplifier (DPA), a PA, an Oscilloscope, a Current Probe and a Personal Computer (PC), which is interconnected with the Oscilloscope and VSG through a General Purpose Interface Bus (GPIB) as well as is interconnected to the VSA through a Local Area Network (LAN) connection.

![Figure 3.1 Measurement System](image)

3.1 Implemented Measurement System

Figure 3.1 shows the implemented system that has been used in this thesis and part of the system has been presented elsewhere [4], [11], [16], [17].
The system works as follows: A signal is generated in the PC as I and Q, data files and downloaded to the Arbitrary Waveform Generator (AWG). As can be seen in Figure 3.1 the AWG generates the analogue I and Q signals at baseband then these signals are fed to the IQ modulator in the signal generator, which produces the desired modulated signal at the desired RF given by Eq. (3.1) or on complex envelope form by Eq. (3.2)

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

\[ s_i(t) = r(t)e^{j\phi(t)} = x(t) + jy(t) \]  

This signal is then amplified by a DPA before entering to the PA. The output signal of the PA is measured and compared to the reference signal, \( s(t) \).

The VSA down-converts and digitise the signal and sends it back to the PC. This data is then processed by the PC, which then is used to calculate the parameters of the PA.

An oscilloscope and a current probe are part of the measurement system; these instruments are used to measure the drain current in order to calculate the PAE of the PA. The output signal of the PA is measured with the current probe then the oscilloscope digitizes the signal and sends it back to the PC. The signal measured to the output of the PA is compare with the input signal, \( s(t) \), that was generated in the PC, both signals have the same behaviour. The data of these signals is then evaluated and processed by the PC, which then is used to calculate the current values of the PA. The oscilloscope was set to execute an averaging of eight measurements in order to get accurate results.

### 3.2 Vector Signal Generator

The VSG used in the presented measurement system is the R&S SMU 200A from Rohde & Schwarz. It presents different functions, one of the most important function used in this measurement system is the IQ modulator.

The SMU 200A has two digital-to-analogue converters (DAC). Each DAC has a clock frequency up to 100 MHz and is used to up convert from baseband to RF.
3.3 Vector Signal Analyser

A VSA of the model FSQ26 from Rohde & Schwarz has been used in the present measurement system. It has a sampling rate from 10 KHz to 81.6 MHz and an IQ bandwidth of 28 MHz. One of the main characteristics of this VSA is the IQ demodulation bandwidth.

The VSA down-converts the signal through the analogue-to-digital converter, then the signal is digitised and sent to the PC. Most of the functions in the VSA can be set from a suitable program in the PC, like Matlab.

In the R&S FSQ26 the total power of the entire signal must be taken into account because if levels are expected or are possible to be higher than 30dBm then an attenuator must be inserted before the RF input of the R&S FSQ.

3.4 Driver Power Amplifier

A driver power amplifier of class A was used in order to drive the PA under test to the saturation level. One of the main characteristics of PA class A is that can be assumed to be perfectly linear. The gain of the DPA used in this thesis is 47.3 dB.

3.5 Power Amplifier under test

The output of the PA was connected through an attenuator to the VSA in order to reduce the signal level as explained in Section 3.3.

A RF PA of class AB operation from Freescale Semiconductor has been used in order to accomplish the measurements. Class AB has a large memory effect and high nonlinearity [9].

The PA under test is a single stage amplifier. It has a band from 2100 MHz to 2700 MHz. The peak output power at the 1 dB gain compression point is greater than 150 W (= 51.76 dBm) and the gain is 17.5 dB. The operational average output power is 44 W with WCDMA signal input. The transistor of the PA is made using LDMOS technology. It operates at 28V drain voltage and quiescent drain current of 1.35 A.
3.6 Oscilloscope and Current Probe

The Oscilloscope used is 54610B from Agilent. It has 2 channels and a bandwidth of 500 MHz. This instrument can be programmed over a GPIB interface. The functions of the oscilloscope were controlled by the PC and it was programmed in Matlab.

The input of the oscilloscope is connected to the N2782A current probe from Agilent, which is connected to the output of the PA in order to measure the current. The current probe used a power supply from Agilent. One of the characteristics taken into account in the current probe is the output voltage rate which is 0.1 V/A (10:1). Figure 3.2 shows the current probe used in this thesis.

![Current probe and some of its parts](image)

Figure 3.2 Current probe and some of its parts

One of the drawbacks with the oscilloscope used in this thesis is the number of samples that is approximately 1800 samples. This value is too small in compare with the number of samples of the generated signal. This limitation is taken into account in this thesis.
4 Measurement Techniques

In this section the methodology to measure the gain, PAE and distortion on the PA in order to get the data for multidimensional plots will be described. In Section 4.1 two-tone signal is described, Section 4.2 describes WCDMA signal. In both cases signal processing techniques have been used i.e. coherent sampling of the sampled signal and synchronization. A short description of the GUI is given in Section 4.3.

The phase is not measured because is out the scope of this thesis. However, some results on phase measurements are presented in [3] and [18].

The methodology developed in this chapter follows the theory explained in Chapter 2.

4.1 Two-tone Signal

One of the signals for nonlinear characterization of power amplifier is two-tone signal which is swept in frequency and amplitude in predefined steps. The data file for frequency sweep also contains the power sweep. This method makes it possible to store the amplitude matrices of the IM3 products over tone spacing and power for a PA in a short time. The time depends on the number of frequency steps, power steps and the number of samples.

Figure 4.1 shows two-tone signal sweeping in frequency and amplitude. The vertical axis represents the power that is given in dB and the horizontal axis represents the frequency that is given in MHz. The start and stop of the power as well as the frequency depends of the specifications on the PA.
A two-tone signal is defined, symmetric around the carrier frequency $\omega_c$, with zero-phases, equal amplitudes and frequencies $\omega_1$ and $\omega_2$. From the equations (2.8) and (2.9) $x(t)$ and $y(t)$ becomes $s(t) = A\cos(\omega_0 t)$ and $y(t) = 0$. Using trigonometric identity the RF signal becomes

$$s(t) = (Ae^{j\omega_1 t} + Ae^{-j\omega_2 t})/2$$

This input signal is sent to the PA through the VSG and is sent back to the PC through the VSA as explained in Chapter 3. In order to apply the definition of coherent sampling the collected data must be twice the length of the number of samples that was sent to the VSG.

By sending repetitive signals synchronization can be applied to the input, $x(n)$, and output, $y(n)$, of the PA, this technique use the definition of cross correlation, see Chapter 2. When the input, $x(n)$, and output, $y(n)$, of the PA were synchronized the values of the power were computed with the FFT.

By sweeping in both frequency and amplitude a matrix of the IM3 upper and lower is obtained. From this matrix the properties of the power amplifier are then derived.

### 4.1.1 Current Measurement

The current is measured with the oscilloscope and the current probe as is explained in Chapter 3.
Once the input signal is generated in predefined steps and the output of the signal is measured with the current probe, then the current measured at the output of the PA approximates the staircase transfer curve shown in Figure 4.2.

![Figure 4.2 Current measured at the output of the PA. Six power steps have been performed in this measurement.](image)

This curve is compared to the generated signal that was sent to the PA; both signals have the same shape with different number of samples due to the limitation of the oscilloscope. The number of samples in the oscilloscope is approximately 1800 samples and the number of samples “N” selected in the generated signal is $2^{14}=16384$ per power step. This means if there are 5 power steps as shown in Figure 4.2, then the total number of samples in the generated signal is $2^{14} \times 5 = 81920$ samples. The value of, $N$, must be chosen carefully because if, $N$, is too small the current shape will not be visualize clearly on the other hand if, $N$, is too large the computation time will increase.

Since the number of samples in the oscilloscope is too small in compare with the number of samples of the generated signal, then computer calculation are required in order to get one period of the current measured to be comparable with the output signal on the PA.
4.2 WCDMA Signal

A WCDMA signal is swept in frequency and amplitude, here the signal is sent one at a time to the input of the PA and sent back to the PC, see Chapter 3. The method is as following

First, a WCDMA signal was generated, the procedure is described in [11]. In summary: A number, \( N_c \), of PRBS are generated and added together as is explained in Section 2.5.2. This sequence is hard clipped to obtain a certain PAR. The clipped sequence is then RRC filtered with a specified sampling ratio and a roll-off factor of 0.22, as specified for WCDMA. The final signal has a sampling frequency \( f_s = \rho \cdot 3.84 \cdot 10^6 \), where, \( \rho \), is the sampling ratio and \( 3.84 \cdot 10^6 \) is the chip rate used in WCDMA.

With this generated signal a frequency sweep and a power sweep are performed by changing the carrier frequency and the RF level in the VSG respectively. The generated signal does not need to be synchronized, since the signal is sent and collected one at a time.

The distortion used in WCDMA signal is the ACPR. ACPR is referred as an upper and lower adjacent channel. In order to calculate the distortion in WCDMA signals the average of the upper and lower adjacent channel is recorded.

In the case of WCDMA signal the current values are obtained straight from the oscilloscope, since the signal is sent one at a time. In order to get accurate results the averaging of those values are taken.

4.3 Graphical User Interface

Figure 4.3 shows the GUI. It has been designed in order to show the results obtained throughout this thesis. Two and three dimensional plots of the test signals are shown in the GUI.
4.3.1 Measurements

The user can decide what kind of signal is going to test as an input of the PA two-tone or WCDMA signal. In both cases frequency and power settings are required.

4.3.2 Settings for Two-tone Signal

The settings for two-tone signal are divided in frequency and power

4.3.2.1 Frequency Settings

- Carrier Frequency: or center frequency of the two-tone. In this thesis a carrier frequency of 2.14 GHz was used.
- Frequency range: this parameter represents the range of the signal around the carrier. In the present thesis the maximum measurable range was 9 MHz.
• Number of frequency steps: this parameter represents how many steps the signal is going to be swept. There is no limitation in the number of frequency steps in this thesis.

4.3.2.2 Power Settings

Unless another characteristic is mentioned, the power settings depends on the PA to be measured.

• RF MAX Level: this setting is for precaution of the PA. It represents the maximum RF level that the PA can handle.
• RF_SG: it is the RF power reference level set on the VSG.
• Start Power: it represents from where the power sweep will start.
• Stop Power: it represents where the power sweep will stop. The maximum value is zero.
• Step Power: this parameter represents the number of steps between the start power and the stop power.

4.3.3 Settings for WCDMA signal

Power settings in WCDMA signal are the same that in two-tone signal. WCDMA signal differ from two-tone in the frequency settings.

• Carrier Frequency: or center frequency. In this thesis a carrier frequency of 2.14 GHz was used.
• Frequency start: it represents from where the signal is going to start to be shifted.
• Frequency stop: it represents where the signal is going to stop. In this thesis the PA under test has a frequency band from 2110 MHz to 2170 MHz.
• Frequency step: it represents how many steps the signal is going to be swept.
4.3.4 Plots

The results obtained in two-tone and WCDMA signal can be visualized in two dimensional plots or in three dimensional plots. The user can decide the test signal and the plots to be measured.

4.3.4.1 Plots for Two-tone Signal

The results of two-tone signal are given in two and three dimensional plots. The parameters to be plotted are gain, PAE, IM3, power input, power output, and frequency. Table 4.1 shows the options in the GUI.

<table>
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<th>Two-tone Signal</th>
<th></th>
</tr>
</thead>
<tbody>
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<td><strong>Three Dimensional Plots</strong></td>
</tr>
<tr>
<td>Gain as a function of frequency (for each tone)</td>
<td>Upper or lower IM3 in dBc or dB versus PAE and Gain</td>
</tr>
<tr>
<td>PAE as a function of frequency (for each tone)</td>
<td>Upper or lower IM3 in dBc versus frequency and input power</td>
</tr>
<tr>
<td>IM3 (upper or lower, in dBc or dB) as a function of frequency (for each tone)</td>
<td>PAE versus frequency and input power (for each tone)</td>
</tr>
<tr>
<td>Output power as a function of input power</td>
<td>Gain versus frequency and input power</td>
</tr>
<tr>
<td>Gain as a function of input power</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-1 Different options of two and three dimensional plots for two-tone signal

4.3.4.2 Plots for WCDMA Signal

As in the case of two-tone signal the results for WCDMA signal are given in two or three dimensional plots. The parameters to be plotted are gain, PAE, ACPR, input power, output power and frequency. Table 4.2 shows the different options that the user can chose in the GUI.
<table>
<thead>
<tr>
<th>Two Dimensional Plots</th>
<th>Three Dimensional Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain as a function of frequency (for each tone)</td>
<td>Upper or lower ACPR versus PAE and Gain</td>
</tr>
<tr>
<td>PAE as a function of frequency (for each tone)</td>
<td>PAE versus frequency and input power</td>
</tr>
<tr>
<td>Upper or lower ACPR as a function of frequency (for each tone)</td>
<td>Gain versus frequency and input power (for each tone)</td>
</tr>
<tr>
<td>Output power as a function of input power</td>
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</tr>
<tr>
<td>Gain as a function of input power</td>
<td></td>
</tr>
<tr>
<td>PAE as a function of input power</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-2 Different options of two and three dimensional plots in WCDMA signal
5 Results

This chapter presents part of the results obtained when the PA under test was measured. The evaluation measurements were done at a sampling frequency of 32 MHz and a RF carrier frequency of 2140 MHz using a sampling rate of 81.6 MHz, which is the maximum sampling rate of the FSQ can handle.

When the PA is operated at or near saturation the PAE improves compared to linear operation, but signal distortion is generally increased.

Measurements on two-tone signal are given in Section 5.1. The Section 5.2 presents the results of the measurements when WCDMA signal is used as an input of the PA. In Section 5.3 a comparative analysis of the test signals, two-tone and WCDMA is done.

5.1 Measurements on two-tone Signal

The measurement results of two-tone signal are presented in two groups. The first group shows relevant results in two dimensional plots and the second group shows the results in three dimensional plots.

5.1.1 Two Dimensional Plots

The different options of two dimensional plots when two-tone signal is used as an input on the PA are presented in Table 4.1.

In this example the amplifier is operated in the nonlinear region. The RF reference level on the VSG is -10 dBm. The number of samples per power step is \( N = 2^{14} \), the number of power steps is 14 with a power step size of 1 dB. The frequency range around the carrier is 6 MHz. The number of frequency steps is 10. The time it takes to perform this measurement is approximately 4 minutes.

Figure 5.1 shows the output power as a function of the input power. From the figure the maximum output power is 48.58 dBm with an input power of 37.3 dBm.
Figure 5.1 Output power as a function of input power

Figure 5.2 shows the upper IM3 as a function of frequency. The table in the right corner of the figure shows the input power levels in dBm. When the input power is 24.3 dBm the IM3 shows a strange behavior at the frequency of 2147 MHz. The different instruments and connections that were used in this thesis could be the cause of this phenomenon.

Figure 5.2 Higher IM3 as a function of frequency
Figure 5.3 shows the gain of the second tone as a function of the frequency. The table in the upper corner of the figure represents the input power levels on the PA. From the figure can be seen that the gain is almost stable with respect to the frequency at each power step. The exception is the point at 2142 MHz at which the input power has the lowest value.

![Figure 5.3 Gain second tone as a function of frequency](image)

5.1.2 Three Dimensional Plots

The dependency of gain, efficiency and distortion is presented in a three dimensional plot. In this thesis there are different options to be plotted in three dimensions, see Table 4.1.

The results that are given in Figure 5.4, 5.5, and 5.6 are when the PA is operated in the nonlinear region. In this case the settings in the GUI are the same as in two dimensional plots.

Figure 5.4 shows the upper IM3 products in dBc versus PAE and gain. The shape of the curve shows the dependency between IM3, PAE and gain. There is a trade-off between IM3 and PAE and also gain and PAE. When IM3 is high PAE is low and when PAE is low IM3 is high. A similar relation is between gain and PAE.
The markers in Figure 5.4 show with more details the values of PAE, gain, IM3 and also the values of power and frequency at each point. This figure is obtained in the latest Matlab version.

Figure 5.4 Higher IM3 versus PAE and gain with fourteen power sweeps and ten frequency sweeps.

Figure 5.5 shows the gain versus the frequency and input power. The markers on the figure show the relation between these parameters. The gain is high when the input power level is low and the gain is almost constant with respect to the frequency at each power step.
Figure 5.5 Gain versus frequency and input power levels with fourteen power steps and ten frequency sweeps.

The phenomenon that is presented in two dimensions in Figure 5.2 can be better visualized in Figure 5.6. Only one point presents a strange behaviour as can be seen in Figure 5.6.

Figure 5.6 Higher IM3 versus frequency and input power levels with fourteen power steps and ten frequency sweeps.
Figure 5.7 and 5.8 show the results of an example when the PA operates slightly in the non-linear region. When the PA operates at or near saturation the PAE improves compared to linear operation, but signal distortion is generally increased. This example is performed with a RF reference level on the VSG of -10 dBm. The number of samples per power step is $N = 2^{14}$, the number of power steps is 15 with a power step size of 0.5 dB. The frequency range around the carrier is 6 MHz. The number of frequency steps is 45. The time it takes to perform this measurement is approximately 30 minutes.

Figure 5.7 shows the dependency between higher IM3 measured in dBc versus the PAE and the gain measured in dB. From the figure the maximum PAE can be achieved when the IM3 is increased and the maximum gain can be achieved when the PAE is low.

![Figure 5.7 Higher IM3 versus PAE and gain with fifteen power steps and forty five frequency sweeps.](image)
Figure 5.8 shows the three dimensional plot of gain versus frequency and input power levels measured in dB on the PA. The gain is high when the input power is low.

![Figure 5.8 Gain versus frequency and input power levels with fifteen power steps and forty five frequency sweeps.]

5.2 Measurements on WCDMA Signal

The results obtained throughout this thesis when WCDMA signal is used as an input of the PA are given in two or three dimensional plots. There are different options that can be plotted, see Table 4.2. Relevant results are given in Section 5.2.1 and 5.2.2.

5.2.1 Two Dimensional Plots

The settings in the GUI are following given: the RF reference level on the VSG is -12 dBm. The number of samples per power step is \( N = 2^{14} \), the number of power steps is 11 with a power step size of 1 dB. The frequency sweeping range is
from 2 GHz to 2.3 GHz with a frequency step size of 50 MHz. The time it takes to perform this measurement is approximately 11 minutes.

Figure 5.9 shows the gain as a function of the frequency. The table in the right corner of the figure represents the input power levels. The gain is slightly constant in the frequency range from 2110 to 2170 MHz this is because the PA under test is designed to work within this range.

Figure 5.9 Gain as a function of Frequency. Eleven power sweeps are performed.

Figure 5.10 shows the PAE as a function of the frequency. The table in the upper corner of the figure represents the input power levels for each power step. The values of the PAE decrease when the frequency increases. There is an abrupt change when the power input is 25.4 dB at a frequency of 2100 MHz and PAE of 24.12.
Figure 5.10 PAE as a function of frequency. Eleven power sweeps are performed.

Figure 5.11 shows the upper ACPR measured in dBc as a function of the frequency. As in the previous figure when the input power is lower the curve presents a strange behaviour. This behaviour could be due to the instruments or connections in the measurement system used in this thesis.
Figure 5.11 Upper ACPR as a function of frequency. Eleven power sweeps are performed.

5.2.2 Three Dimensional Plots

The dependency between gain, PAE and ACPR are presented in a three dimensional plots. There are different options to be plotted in three dimensions, see Table 4.2.

The results that are given in Figure 5.12, 5.13, and 5.14 correspond when the PA is set with the same values as Section 5.2.1. Figure 5.12 shows the upper ACPR measured in dBc versus the PAE and gain. As can be seen there is a dependency between these parameters.
Figure 5.12 Upper ACPR versus PAE and gain.

The results shown in Figure 5.9 can be better visualized in Figure 5.13. This figure shows the gain versus frequency and input power. The markers point out in what frequency range the gain is stable.

Figure 5.13 Gain versus frequency and input power
PAE versus frequency and input power levels are presented in Figure 5.14. This figure is the same that Figure 5.10 the only difference is that here is presented in a three dimensional plot.

Figure 5.14 PAE versus frequency and input power.

The results obtained when the RF reference level on the VSG is -15 dBm and the number of power steps is 12 with a power step size of 1 dB are presented in Figure 5.15 and 5.16. The frequency sweeping range is from 2.1 GHz to 2.3 GHz with a frequency step size of 50 MHz. The markers can not be visualized in these figures because they were plotted in an older version of Matlab.
Figure 5.15 Upper ACPR versus PAE and gain.

Figure 5.16 Gain versus frequency and input power.
5.3 Difference and Limitations

The difference between the method applied to two-tone and WCDMA signals is that in WCDMA signal, the signal is sent one at a time to the PA due to the bandwidth limitation on the VSA. Nowadays there are some techniques to increase the digital bandwidth of the VSA like frequency stitching [4], [19]. However this technique is out the scope of this thesis.

The difference between both methods is the time that does it take to perform one measurement. The time consumption in WCDMA is more than Two-Tone signal.

The behaviour of the PA in a certain point can be better visualize in the example presented in Figure 5.4, this figure shows the gain, efficiency, distortion, frequency and power at each point. Examples like the ones presented in Figure 5.7 and 5.8 do not show any kind of markers however, the data is stored in a table. The differences of these plots are due to the different Matlab versions that were used in this thesis.

In the present thesis there are two limitations in two-tone signal. The first one is that the maximum frequency range around the carrier is 9 MHz, i.e. 4.5 MHz at each side of the carrier frequency, due to the IQ bandwidth limitation of the VSA. The second limitation is that the maximum number of power steps is 15 due to the current measurements. If the current is not measured then there is no limitation in the number of power steps.

There is not limitation in frequency and power when the signal is sent one at a time as the case of the method applied to WCDMA signal. However the drawback in this method is the time that takes to perform one measurement in compare with two-tone signal.

The results presented in two and three dimensional plots when two-tone signal or WCDMA signal is applied to the input of the PA are according to the specifications on the PA under test [20].
6 Conclusions

6.1 Conclusions

This thesis has presented a fast and efficient measurement method and a GUI to evaluate and understand the dependency of three parameters, gain, efficiency and distortion when two-tone or WCDMA signal is used as an input on the PA. A completely two-tone and WCDMA signal analysis has been done in order to present in two and three dimensional plots how these parameters depend from each other.

The measurement system and the measurement techniques that were used for characterization of PA are considerably simpler than the traditional measurement technique that designers of PA have been using to analyze the behaviour of the PA. These techniques are based on signal processing techniques and programming codes on Matlab, which make the measurement method faster and efficient than traditional methods.

Two different signals and mainly three different parameters were evaluated. When a power sweep and a frequency sweep were performed on both test signals, the results on two-tone signal was obtained in a few minutes in compare with WCDMA signal that took much longer. This is due to the method applied on each signal was different. The time depends on the number of frequency steps, power steps and the current measurement. However, there is a limitation in the number of frequency range and the number of power steps on two-tone signal.

Results were presented in two and three dimensional plots in a GUI for both of the test signals. These results were validated by comparison with the specifications on the PA under test.
6.2 Future Work

On the signal generation side there are numerous sources of distortion and limitation, an interesting continuation of this work could be apply a digital predistortion technique to the VSG and to the DPA in order to generate an input signal to the PA with low distortion.

One of the main limitations to develop a method for each of the two test signals used in this thesis was the IQ bandwidth limitation on the VSA. In order to solve this problem frequency stitching technique could be applied to increase the bandwidth of the VSA.

If one is further interesting to measure more than two signals or measure in deep the characteristics of the PA as memory effect or analyze the PA by changing the bias point on the PA.
References


