Multidimensional Measurements

on RF Power Amplifiers

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Abstract

In this thesis, a measurement system was set to perform comprehensive measurements on RF power amplifiers. Data obtained from the measurements is then processed mathematically to obtain three dimensional graphs of the basic parameters affected or generated by nonlinearities of the amplifier i.e. gain, efficiency and distortion. Using a class AB amplifier as the DUT, two sets of signals – both swept in power level and frequency - were generated to validate the method, a two-tone signal and a WCDMA signal. The three dimensional plot gives a thorough representation of the behavior of the amplifier in any arbitrary range of spectrum and input level. Sweet spots are consequently easy to detect and analyze. The measurement setup can also yield other three dimensional plots of variations of gain, efficiency or distortion versus frequencies and input levels. Moreover, the measurement tool can be used to plot traditional two dimensional plots such as, input versus gain, frequency versus efficiency etc, making the setup a practical tool for RF amplifiers designers.

The test signals were generated by computer then sent to a vector signal generator that generates the actual signals fed to the amplifier. The output of the amplifier is fed to a vector signal analyzer then collected by computer to be handled. MATLAB® was used throughout the entire process.

The distortion considered in the case of the two-tone signals is the third order intermodulation distortion (IM3) whereas Adjacent Channel Power Ratio (ACPR) was considered in the case of WCDMA.
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<td>2-D</td>
<td>Two Dimensional</td>
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<td>3-D</td>
<td>Three Dimensional</td>
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<td>ACLR</td>
<td>Adjacent Channel Leakage Ratio</td>
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<td>ACPR</td>
<td>Adjacent Channel Power Ratio</td>
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<td>BW</td>
<td>Bandwidth</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>DFT</td>
<td>Discrete Fourier Transform</td>
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<td>DLL</td>
<td>Dynamic Link Library</td>
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<td>DUT</td>
<td>Device Under Test</td>
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<td>ETSI</td>
<td>European Telecommunication Standards Institute</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>GSM</td>
<td>Global System for Mobile communications</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<td>GPIB</td>
<td>General Purpose Interface Bus</td>
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<td>IM3</td>
<td>Third Order Inter-modulation Distortion</td>
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<td>LDMOS</td>
<td>Lateral Double-Diffused MOSFET</td>
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<td>PA</td>
<td>Power Amplifier</td>
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<td>PAE</td>
<td>Power Added Efficiency</td>
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<td>PAR</td>
<td>Peak to Average Ratio</td>
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<td>PEP</td>
<td>Peak Envelope Power</td>
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<td>PRBS</td>
<td>Pseudo Random Binary Sequence</td>
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<tr>
<td>R&amp;S</td>
<td>Rohde and Schwarz ®</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>SDSSS</td>
<td>Selectable Direct Sequence Spread Spectrum</td>
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<td>VSA</td>
<td>Vector Spectrum Analyzer</td>
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<td>VSG</td>
<td>Vector Signal Generator</td>
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<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
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Chapter 1
Introduction

1.1 Introduction

This project was conducted in partnership with Edith Graciela Condo as a part of a master thesis [1]. The main objectives of the project are to implement a user friendly measurement system that is capable of performing measurements on RF power amplifiers and plotting gain, efficiency, and distortion in three dimensions. Then analyze the amplifier under test based on the results of the measurements. Finally, implement a graphical user interface for commonly used applications of the measurement system.

The motive to the project is to give a better visualization to the amplifier behavior. Designers usually have measurement results in the form of tables. Even though tables are informative, they do not give the visualization provided by figures. Other merits of the method are ease of measurements and time efficiency. The user specifies the measurement boundaries in terms of frequency and power levels then obtain a full set of measurement results about the amplifier in a relatively short time. Sweet spots can also be detected easily in three dimensional graphs.

This chapter will give a general background on RF amplifiers, amplifiers classes, the technology used for the transistor under test (LDMOS) and the thesis outline.

1.2 Measurements of RF amplifiers

Characterization of RF power amplifiers has always been a challenge for RF engineers. Several parameters are significant when characterizing an amplifier; however, some parameters are commonly of interest. Efficiency, for example, is an important parameter of an amplifier, however, to obtain the maximum efficiency the amplifier is usually pushed into its non-linear region. This, in turn, induces intermodulation products. The non linear region is the region where the gain of the amplifier does not increase linearly with the increment of the input. One common measure of nonlinearity is the 1dB compression point. The 1dB compression point, as the name implies, is the point where the signal gain has dropped 1 dB [2]. Figure 1.1 illustrates 1 dB compression point.
The relation between these parameters is usually plotted in two dimensions. The drive to this project was to test if a three dimensional plot will give more insight to the behavior of the amplifier. Finding sweet spots should also be easier with three dimensional plots.

**1.3 Classes of Amplifiers**

Since a class AB amplifier is used in this project, a brief definition of power amplifier classes can be useful to get a general idea about class AB in relation to other amplifier classes.

In class-A amplifiers, the transistor is in the active region during the entire input signal. The drain voltage and current waveforms are sinusoidal (for a sinusoidal input) hence; the result is a linear output signal. DC-power input is constant which results in a maximum efficiency of 50% at peak power envelope (PEP).
Class B amplifiers have the gate bias set at the threshold of conduction so that the transistor is active half the duration of the input signal and the drain current is a half-sinusoid. Class B provides linear amplification with maximum theoretical efficiency of 78.5% at PEP.

The gate in class C is biased to conduct in less than half the duration of the input signal. Linearity is lost but efficiency is increased significantly to reach practical values up to 90%. Since the output signal is strongly distorted, tuned circuits are often used to reconstruct the signal.

Class-D power amplifiers use at least two transistors as switches to generate square drain–voltage waveforms. A series-tuned output filter is used to pass only the fundamental frequency component to the load. For an Ideal class D power amplifier, the efficiency can reach up to 100%.

A single transistor is operated as a switch in class E amplifiers. The drain voltage waveform is the sum of the DC and RF currents charging the drain-shunt capacitance. Ideal efficiency of class E can reach up to 100%. Class E can be used for high-efficiency amplification at frequencies as high as K-band.

In Class F amplifiers, a resonator circuit is used to shape the drain waveform. The drain voltage includes odd harmonics resulting in a semi-square waveform, while the current includes even harmonics resulting in half-sine wave. As the number of harmonics included increases the efficiency increases towards 100% [3].

The waveforms of drain currents and voltages of all ideal amplifier classes are shown in Figure 1.2(a). Figure 1.2(b) demonstrates the conduction area of different amplifier classes.

1.4 Class AB amplifiers

Class AB amplifier has been a focus of many power amplifiers designers because of its compromise between the linearity of class A and the efficiency of class C amplifiers in addition to a wider dynamic range than either class A or B.

Nevertheless, a class AB amplifier has usually large memory effects [4]. A classical circuit schematic of a class AB amplifier is shown in Figure 1.3.
The shunt resonant circuit has a resonance at the fundamental frequency. The capacitor should have a value high enough to shunt all the harmonics while allowing only the fundamental to be delivered to the load.

The RF “choke” works as the name implies, that no RF reaches the power supply. The DC block is a capacitor used to ensure that no DC will be present at the load [5].

Theoretically, Class AB has maximum efficiency that is lower than the maximum theoretical efficiency of a class B amplifier (i.e. 78.5%). The practical efficiency is usually much less than the theoretical value.

A driver amplifier of class A was used to drive the DUT to the saturation level. Considering the high linearity of class A (ensured by selection of suitable input levels), the DUT could be driven without nonlinear components resulting from the driver disturbing the measurements.

1.5 LDMOS Technology

Since the transistor in the PA used in this project is designed with Lateral Double Diffused MOS (LDMOS) technology, a brief definition of the technology is given in this Section.

The increasing usage of wireless communication created a demand for a linear, cost effective and a high gain power transistor technology in base station applications where peak power requirements can be as high as 120 watts in single carrier applications; hence, there was the LDMOS technology [6].

LDMOS is a majority carrier transistor based on the lightly doped drain concept. The schematic cross section for LDMOS technology is illustrated in Figure 1.4. Cutoff frequency for LDMOS as function of gate length is not as strong as for other MOS technologies such as CMOS [7]. Also, The LDMOS transistor has better thermal and gain bandwidth performance than the VMOS transistor because the Beryllium Oxide (BeO)
isolation layer has been eliminated. Moreover, LDMOS does not require a temperature compensating biasing circuit for protection [8].

RF performance of the LDMOS is greatly affected by the inherent output parasitic capacitance. The parasitic affect brings down device performance parameters such as efficiency, gain and noise figures of the power amplifier. It also makes the output match difficult. Several methods however, have been used to reduce this inherent parasitic capacitance [9].

![Schematic cross section for LDMOS technology](image)

Fig 1.4: Schematic cross section for LDMOS technology [7]

### 1.6 Thesis Outline

The second Chapter of this thesis discusses the basic theory of the main topics involved in the project such as: the test signals, distortion, Gain, efficiency, sampling, FFT and correlation.

The third Chapter discusses the method and approach used to conduct the project. The approach includes: signal generation and collection, current measurements, device under test characterization and the measurement system limitations. It also includes a discussion about some phenomena present in the measurements distortion asymmetry.

In the fourth Chapter, test settings are listed and the results are displayed.

The fifth Chapter gives a discussion about the results presented in Chapter 4. Conclusions are presented in this Chapter as well as future work.
Chapter 2

Theory

2.1 Introduction

Several parameters can be considered when characterizing an RF power amplifier. In a class AB amplifier, nonlinear operation is usually of interest. Consequently, characteristics of non-linear operation such as distortion, gain reduction and efficiency improvement are to be studied. In this Chapter these parameters will be discussed theoretically along with some other parameters and functions addressed in the project; e.g. memory effects, coherent sampling and Fourier transform.

2.2 Test Signals

The simplest yet very informative stimulus to characterize nonlinearities in nonlinear devices is the two-tone signal. Such kind of characterization is becoming increasingly important for evaluating different aspects of nonlinearity such as in-band distortion or spectral re-growth [10].

2.2.1 Two-tones Signals

A multi-tone signal is represented as:

$$u(t) = \sum_{k=1}^{N} a_k \sin(\omega_k t + \psi_k)$$  \hspace{1cm} (2.1)

Where $a_k$ are the amplitudes, $\omega_k$ are the angular velocity with $0<\omega_k<\pi$ and $\psi_k$ are the phases.

To obtain a signal with only the positive frequencies, $u(t)$ is multiplied with the unit step.

$$U_+(f) = 2U_{\text{step}}(f)U(f)$$  \hspace{1cm} (2.2)

The time domain representation of equation (2.2) is:

$$u_+(t) = \int_{-\infty}^{\infty} U_+(f)e^{j2\pi ft} df$$
\[ F^{-1} \left[ 2U_{wcp} (f) \right] * F^{-1} \left[ 2U (f) \right] \]  

(2.3)

Where \( F^{-1} \) is the inverse Fourier transform. Hence,

\[ u_s(t) = \left[ \delta(t) + \frac{j}{\pi t} \right] * u(t) \]

\[ = u(t) + j \frac{1}{\pi t} * u(t) \]  

(2.4)

The second term of equation (2.4) is equivalent to the Hilbert transform of \( u(t) \). Then the low pass equivalent of signal \( u(t) \) is:

\[ u(t) = u_s(t) e^{-j2\pi f_s t} \]

\[ = I(t) + jQ(t) \]  

(2.5)

Where \( I(t) \) is the in phase component and \( Q(t) \) is the quadrature phase Components.

To summarize the two tone signal generation: it is the low pass equivalent of the summation of the signal \( u(t) \) and its Hilbert transform [11].

### 2.2.2 WCDMA

Wide Code Division Multiple Access (WCDMA) is a 3G standard that employs selectable direct sequence spread spectrum (SDSSS) technique and has been designed for an (always –on) packet based wireless condition. WCDMA supports a packet data rate of 2.048 Mbps per user. Therefore, allowing effective sound and multimedia traffic.

WCDMA requires 5 MHz of spectrum which is much higher than GSM; making changes in base stations RF equipment inevitable. Using such a wide channel enables WCDMA to have bit rates up to 2Mbps and carry simultaneously 100-350 voice calls depending on antenna sectoring, antenna polarization, propagation conditions and user velocity. The SDSSS chip rate of WCDMA can exceed 16 Mchips per second per user. A rule of thumb that WCDMA provides at least a six times increase in spectral efficiency over GSM compared on a system wide basis [12].

True WCDMA includes a number of embedded messages corresponding to the number of users served by the channel which is not easy to generate in the lab. Therefore, it is common to generate WCDMA either by generating a multiple tones signal or a noise like signals that have the same properties of a true WCDMA signal.

In case of the multiple tones, the signal is generated with equal tone spacing and can be represented as:

\[ s(t) = \sum_{k=0}^{N-1} A_k e^{j(\omega_k t + \phi_k)} \]  

(2.6)

Where \( N \) is the number of samples, \( A_k \) is the amplitude, \( \omega_k \) is the frequency and \( \phi_k \) is the phase.
If all initial phases are set to zero then the peak to average ratio (PAR) is given by:

\[ PAR = 10 \log_{10} N \]  

(2.7)

The multiple tones signal is usually suitable for studying the compression of an amplifier; however, for a large value of N, the peak to average ratio is high enough to cause nonlinear products to appear at frequencies of other tones; making the multiple tones with equal phases method ineffective in describing the linear behavior of the amplifier. A multiple tones signal with random phases can achieve lower PAR but it is still high compared to the noise like signals.

The noise like signals are usually represented as follows [13]:

\[ W(m) = \sum_{i=0}^{N-1} w_i(m) \]  

(2.8)

Figure 2.1 shows the channel and adjacent channels of a WCDMA signal.

![Figure 2.1: WCDMA signal](image)

WCDMA signal generation will be discussed in details in the next Chapter.

### 2.3 Distortion

Two sets of signals are used in this study: Two-tone and WCDMA. With both sets many sources of distortion are present, however, intermodulation distortion (IM3) and adjacent channel power ratio (ACPR) are the ones studied in this project.

#### 2.3.1 Third Order Intermodulation Products

When an amplifier is excited by multiple tones at different frequencies and power levels high enough to push the amplifier to the nonlinear region, it generates numerous mixing products. These mixing products are generated at the base band and at the harmonics of the excitation as well as at the excitation frequencies themselves. In addition to that even more mixing products can be generated between the excitation and the harmonics creating intermodulation products. If an excitation of two tones at
frequencies $f_1$ and $f_2$ is applied to an amplifier then the third order intermodulation products will occur at $2f_1-f_2$ and $2f_2-f_1$. The designation of “third order” comes from a common representation of the transfer function of the amplifier as a simple power series; where the third term arises from gain compression and includes the frequencies $2f_1-f_2$ and $2f_2-f_1$ [14].

A detailed mathematical description of the IM3 distortion can be found in [14], [15].

### 2.3.2 Adjacent channel power ratio

Adjacent channel power ratio (also referred to as Adjacent Channel Leakage Ratio (ACLR)) is a distortion usually associated with WCDMA signals. ACPR is defined as the ratio between total linear power in one channel and the total linear power leaking from the adjacent channel. The ACPR is referred to as upper ACPR if the leakage is from the upper adjacent channel and lower ACPR if the leakage is from the lower adjacent channel.

The ETSI specifies that the ACLR should not be below 45dB within 5 MHz below the first or above the last carrier frequency [15].

### 2.3.3 Memory Effects

Memory effects are usually introduced by changes made in bandwidth of the input signal. If two-tones are introduced to an amplifier, the difference between the frequencies represents the bandwidth of the signal and therefore, memory effects are present when a two-tone signal is applied [16].

### 2.4 Gain

When designing an amplifier, the gain can be represented in several ways, such as transducer power gain, power gain and available power gain. The equations for these gains are given below [17]:

\[
G_{\text{Transducer}} = \frac{P_L}{P_{AVS}} \quad (2.9)
\]

\[
G_{\text{Power\_Gain}} = \frac{P_L}{P_{IN}} \quad (2.10)
\]

\[
G_{\text{Available\_Gain}} = \frac{P_{AVN}}{P_{AVS}} \quad (2.11)
\]

Where $P_L$ is the power delivered to the load

$P_{AVS}$ is the power available from the source

$P_{IN}$ is input to the network

$P_{AVN}$ is the power from the network

As the equations show, the transducer gain is the ratio between the power delivered to the load and the power available from the source. Whereas the power gain is the ratio between the power delivered to the load and the input power the network. The available
gain is the ratio between the power provided by the supply and the power at the input of the amplifier.

In this project only the power gain is of interest. A driver amplifier is used to obtain power high enough to push the DUT to compression. The gain of the system will be a combination of the gains of the two amplifiers. If the driver has an impulse response of $H_1(\omega)$ and the DUT has an impulse response of $H_2(\omega)$ then the total gain of the system $H(\omega)$ is equal to $H_1(\omega) \times H_2(\omega)$ in the linear scale. This is equivalent to $H_1(\omega)_{\text{dB}} + H_2(\omega)_{\text{dB}}$ in logarithmic scale.

2.5 Efficiency

Obtaining the maximum efficiency of power amplifiers is a major goal for RF amplifiers engineers. In order to meet the linearity requirements, the amplifier is usually backed off. This causes the efficiency to drop drastically i.e. there is always a trade-off between efficiency and linearity [16].

Three definitions of efficiency are commonly used. Drain efficiency, power added efficiency and instantaneous efficiency. Drain efficiency is defined as: ratio of RF-output power to DC-input power. Mathematically, drain efficiency is defined as:

$$\text{EFF} = \frac{P_{\text{out}}}{P_{\text{in,DC}}}$$  \hspace{1cm} (2.12)

Whereas Power Added Efficiency (PAE) is defined the difference between the output power and the input power divided over the DC input power, PAE is given by:

$$\text{PAE} = \frac{(P_{\text{out}} - P_{\text{in}})}{P_{\text{in,DC}}}$$  \hspace{1cm} (2.13)

PAE can be negative for very low gains. The instantaneous efficiency represents the efficiency at every instant of time. The highest instantaneous efficiency will occur at the peak of the input [3].

2.6 Sampling Theorem

The Sampling theorem basically states that the analog signal to be sampled should be sampled at a rate at least twice its highest frequency component. If this condition is satisfied, then the analog signal can be reconstructed from the sampled signal. In practice, the original signal can not be exactly recovered from the sampled signal due to the fact that the $\text{sinc}$ function ($\sin(\omega t) / \omega t$) is infinite. Nevertheless, the analog signal can still be recovered with acceptable accuracy.

For a signal with restricted bandwidth a special exception of the sampling theorem can be applied so that the signal can be sampled at a rate equal to the difference between the highest frequency component and the lowest frequency component. E.g. if a signal has a band of $f_1 < f < f_2$, the minimum sampling frequency can be reduced from $2f_2$ to the
rate f2-f1, which is the bandwidth of the signal. The exception is only applicable if the samples are generated as in-phase and quadrature-phase components.

In practical applications a low pass filter (commonly called an anti-aliasing filter) is used ahead of the digitizer to eliminate under sampling. Since the ideal rectangular cutoff characteristics are unrealizable, the sampling rate is usually chosen to be even higher than twice the highest frequency component of the analog signal. Over sampling also eliminated the need for sophisticated interpolation techniques in most of the cases, making the reconstruction of the signal much easier [18].

In addition to satisfying the sampling theorem, coherent sampling should be applied.

### 2.6.1 Coherent Sampling

Coherent sampling is a method of sampling periodic signals where the sampling window fits an integer number of full periods of the periodic signal. Mathematically, coherent sampling is expressed as:

\[
\frac{f_{in}}{f_s} = \frac{N}{M}
\]  

(2.14)

Where,

- \(f_{in}\): Frequency of the periodic input signal.
- \(f_s\): Sampling frequency.
- \(M\): Number of cycles within the sampling window (should be an odd integer).
- \(N\): Number of points in the sampling window and is a power of two.

Coherent sampling provides higher spectral resolution when used with FFT.

According to IEEE standard 1057: “For an ideal transfer characteristic in the absence of random noise, the minimum record sue that will ensure a representative sample of every code bin is \(2\pi M^2\), with the following restriction: The input frequency is chosen such that the number of cycles per record is an integer that is prime relative to \(M\) so that there are no common factors” [19].

### 2.7 Fast Fourier Transform (FFT)

The basic idea behind all fast algorithm computation of discrete Fourier transform is to divide the sequence into smaller segments and perform the discrete time Fourier transform (DFT) on them. FFT provides reduction in the computation complexity. FFT is used in this project to extract the frequencies of the input tones from the signal received from the spectrum analyzer. Detailed explanation of FFT and DFT can be found in [20].
2.8 Correlation

Correlation is used in this project to compare and synchronize the input signal to the collected signal. Assume a pair of signals \( x[n] \) and \( y[n] \). The cross correlation is given by:

\[
r_{xy}[l] = \sum_{n=-\infty}^{\infty} x[n]y[n-l], l = 0, \pm 1, \pm 2, \ldots \quad (2.15)
\]

Where \( l \) is the lag, and represents the time shift between the pair. If \( l \) is positive then \( y[n] \) is said to be shifted by \( l \) samples to the right of \( x[n] \) and to the left of \( x[n] \) if \( l \) is negative.

The ordering of \( x[n] \) and \( y[n] \) indicates that \( x[n] \) is the reference signal. If \( y[n] \) was taken as the reference, then the correlation is given by:

\[
r_{yx}[l] = \sum_{n=-\infty}^{\infty} y[n]x[n-l], l = 0, \pm 1, \pm 2, \ldots = r_{xy}[-l] \quad (2.16)
\]

Therefore, \( r_{yx}[l] \) is obtained by reversing the sequence \( r_{xy}[l] \) in time [20].

2.9 Geometric Representation of Modulated Signals

If a modulation signal set \( S \) includes \( M \) possible waveforms then \( S \) can be represented as:

\[
S = \{s_1(t), s_2(t), \ldots, s_M(t)\} \quad (2.17)
\]

If the elements of \( S \) are viewed as points of vector space, then from a geometric point of view, any finite set of physically realizable waveforms in a vector space can be expressed as a linear combination of \( N \) orthonormal forms which forms the basis of that vector space. If a signal is to be represented in the vector space, then the signals that form the basis of the vector space must be found. Once that is done, any point in that vector space can be represented as a combination of the basis signals \( \{\Phi_j(t), j = 1, 2, \ldots, N\} \) such that [12]:

\[
s_i(t) = \sum_{j=1}^{N} a_{ij} \Phi_j(t) \quad (2.18)
\]

The basis signals are orthogonal to one another in time such that:

\[
\int_{-\infty}^{\infty} \Phi_i(t) \Phi_j(t) dt = 0, i \neq j \quad (2.19)
\]

Each of the basis signals is normalized to have unit energy i.e.

\[
E = \int_{-\infty}^{\infty} \Phi_i^2(t) dt = 1 \quad (2.20)
\]

Since a binary modulation scheme is used in this project, the binary information bit is mapped directly to the signal.
The axes of the vector space are commonly referred to as I and Q. Figure 2.2 represents a typical IQ modulator.

Fig 2.2: IQ modulator
Chapter 3

Method

3.1 Introduction

The project involved different stages with several methods. The device under test was a class AB amplifier and the whole test setup was in a 50 ohm environment. To drive the DUT, a driver of class A was used. MATLAB® was utilized to handle all the communication with the vector signal generator (VSG) and the vector spectrum analyzer (VSA) through GPIB port. An oscilloscope was used to measure the drain current. The test signals and all the mathematical computations were handled in MATLAB®.

In this Chapter, the setup of the project is explained in details as well as the data collection and processing.

3.2 Test Setup

The project set up is shown in Figure 3.1

![Test Setup Diagram](image)

**Fig 3.1: Test setup**

Before getting into the details of the test setup, it is important to mention that a behavioral model was used to model the DUT. A behavioral model (also referred to as a black box model) characterizes an amplifier by relating the sampled output and input...
signals and can effectively characterize the nonlinearities and memory effects in an amplifier [21].

3.3 System Operation

The system is expected to work with basically any RF PA. The user should specify the frequency range, number of frequency steps, the input power levels range and the power steps size. The step size defines the rate at which the power or frequency are to be swept.

3.4 Signal Generation

This Section describes the generation of the test tones used in the project and the practical limitations of generation. Two types of signals were used in this project to validate the method: two-tone and WCDMA signals. The method should be applicable to any kind of signal since it is universal, however, changes in the code might be required to handle other types of signals. In both cases of two-tone and WCDMA, the data was sent as I-Q data (for more details about I-Q modulation see Section 2.9). 

As mentioned before, a class A driver was used to provide the DUT with adequate input power level. The gain of the driver (47.3 dB), was later compensated for in the characterization of the DUT.

3.4.1 Two-tone signals

Both test signals were generated initially in MATLAB® then R&S® SMU200A vector signal generator was used to generate the actual RF power. The center frequency was 2.14 GHz with sampling frequency of 40 MHz. The maximum measurable range of frequency around the carrier is 9 MHz due to the limitation of IQ bandwidth of the vector spectrum analyzer. An IQ bandwidth of 28 MHz was used giving the possibility to measure in a range of 14 MHz at each side of the carrier. Since the IM3 products are to be measured, calculations showed that the maximum allowable frequency should not exceed 9 MHz (i.e. 4.5 MHz at each side of the carrier) e.g. if a range of 9 MHz is set, the highest IM3 frequency is calculated as follows (2*4.5 MHz - (-4.5 MHz)) = 13.5 MHz which is still covered with the IQ bandwidth. However, changing the carrier frequency enables measurements on any arbitrary range of the spectrum.

The two-tone baseband signals where generated in such a way that only the positive frequencies are present. The user then specifies the ranges of frequency and power as well as the steps. The result from this specification is a set of two-tone pairs in blocks. Each block contains all the power levels (in steps) of a specific two-tone frequency pair.

Coherent sampling was used to ensure higher spectral resolution (i.e. avoiding spectral leakage), therefore, the tones spacing can be slightly different (within tens of Hertz).
Special attention should be paid when setting the power levels of the two-tone signals. First, a reference level is set at the signal generator. All the power levels are calculated in relation to that reference level e.g. if the reference level is set to -4 dB and the power level is set to -5, then the power at the signal generator is -4-5=-9dB.

Since the power set in MATLAB® refers to the average power, the peak power will always be 3dB (since the two tones generated are of equal amplitude and zero phase difference)

Referring the previous example, the -9 will be the average power and the peak will be -6dB.

Figure 3.2 shows a 14 power-step two-tone signal at 2.14GHz with Δf= 250 KHz.

Fig 3.2: A 14 power-step two-tone signal at 2.14GHz with Δf= 250 KHz

3.4.2 WCDMA

It is useful to give a brief description about raised cosine filter and the roll – off factor before discussing the WCDMA generation. A raised cosine filter is one of the most popular pulse shaping filters in the area of mobile communication. The transfer function of the raised cosine filter is given by:

\[
H_{RC}(f) = \begin{cases} 
1 & 0 \leq |f| \leq \frac{1-\alpha}{2T_s} \\
\frac{1}{2} \left[1 + \cos\left(\pi |f| 2T_s - 1 + \alpha\right)\right] & \frac{1-\alpha}{2T_s} \leq |f| \leq \frac{1+\alpha}{2T_s} \\
0 & |f| > \frac{1+\alpha}{2T_s}
\end{cases}
\] (3.1)

Where \(\alpha\) is the roll-off factor and can range between 0 and 1 [12]. The magnitude transfer function of a raise cosine filter is shown in Figure (3.3).
A true WCDMA signal consists of a number of embedded message signals corresponding to the number of users which is not practical to generate in the lab. It is easier to generate a noise like signal that bears the same shape and characteristics of a true WCDMA signal and behaves in the same way. This noise-like signal is first generated by summing up a number of pseudo random Binary sequence (PRBS) of length $M$. The number of PRBS is selected to represent different users of the system. Mathematically:

$$W(m) = \sum_{i=0}^{N_c-1} w_i(m)$$  \hspace{1cm} (3.2)

Where $N_c$ is the number of PSBS and $m$ is the chip number, $m = 1, 2, ..., M - 1$. The sequence is then clipped to achieve a certain peak to average ratio (PAR). The clipped sequence is then applied to root raised cosine filter with an over sampling ratio of $R$ and a roll-off factor of 0.22 as specified for WCDMA. The final signal has a length of $M \ast R$ and a sampling frequency of $R \ast C$, where $C$ is the chip rate and is equal to $3.84 \times 10^6$ as specified for WCDMA [13].

WCDMA specifications require that the ACPR should be measured 5MHz below the first and above the last carrier used. Therefore, only one WCDMA signal could be sent to the amplifier at a time due to the limitation of the IQ bandwidth of the VSA. I.e. since the IQ bandwidth of the VSA is 28 MHz, then with a WCDMA signal having a band of 3.84 MHz and another 5MHz at each side for the ACPR measurements, there is not enough range to measure another WCDMA signal.

The user specifies the range of frequency to be measured and the frequency step size as well as the input power range and the power step size. The frequencies generated will represent the carrier frequencies of the WCDMA signals. For each carrier frequency, the entire specified power range will be swept in steps and each power step will be sent
separately to the amplifier. The reference level of the VSG will be set individually for
every power level. This yields more time consumption compared to two-tone
measurements. The power levels set by the user are the actual power levels to be sent to
the amplifier. Again, these power levels represent the average power levels. PAR in the
generated WCDMA signals is 10 dB therefore; the peak value is always 10 dB higher
than the average values.

3.5 DUT

DUT is a class AB amplifier provided by freescale semiconductor®. The amplifier is
a single stage amplifier and the transistor is implemented using LDMOS technology. The
transistor (freescale® MRF7S21150H) operates at 28V drain voltage and 5.33V gate
voltage. The quiescent drain current is 1.35A. The amplifier has a gain of 17.5 dB at
2.14GHz and its return loss at the same frequency is -40dB.

3.6 Data collection and synchronization

3.6.1 Two-tone Signals

Data collected from the VSA is in I-Q form. If a sequence of \( N \) samples is sent to the
VSA, then at least \( 2N \) must be collected to ensure that at least one full sequence will
start at the beginning of the first step. To be able to extract that full sequence, the
collected data is correlated to the sent signal. Correlation is used to detect the point at
which the received signal is most similar to the sent signal. That point has the highest
value in the correlation result. The desired signal is then extracted from the received
sequence using the highest value of the correlation as the starting point. Once that is
done, FFT is then applied to the correlated data to get its spectral representation. The FFT
will give the spectral representation of the entire band covered with the IQ bandwidth,
However, only four points are of interest: the two-tones and their third order
intermodulation products. Hence, these four points are located and their corresponding
power levels are recorded.

3.6.2 WCDMA

Data is also collected in the form of I-Q modulated signals. The procedure is quite
similar to collecting two-tone signals with few exceptions. First, there is no need for
synchronization since the spectrum represents a single signal. Also, the definition of
distortion has changed; now it should be the average of distortion in the channels above
and below the carrier. To cover that channel, a Hanning window is used. The loss of
energy due to the Hanning window is compensated for by adding the energy of the same
Hanning window (i.e. same length) to the data.
3.7 Current Measurements

The Drain current of the amplifier is needed to calculate the power added efficiency.

Current measurements were performed using Agilent® 54610B digitizing oscilloscope. The oscilloscope has a bandwidth of 500 MHz and sampling rate of 20MHz/second. Agilent® current probe N2783A was used with the oscilloscope. The probe measurements appear in the oscilloscope screen as voltage where each volt represents 10 Amperes.

Fig 3.4: Current waveform in two-tone measurements

The current measurement method differs slightly depending on the test signal. In the case of two-tone, the accuracy of current measurement depends strongly on the choice of the number of samples per power step (N).

In order to view the current corresponding to each power step, N should be large to provide enough time for the current to settle before rising to the next level. If N is too small, the current will appear as a straight line instead of the correct current waveform (shown in Figure 3.4).
Nevertheless, \( N \) cannot be chosen to be unlimitedly large, since higher number of samples yields more computation time and usage of memory.

The choice of \( N \) is also affected by the tone spacing. The narrower the tone spacing, the higher the \( N \) needed to measure the current correctly.

The number of samples that achieved the best compromise between the above mentioned criteria was found to be \( N = 2^{14} \), which is relatively high. With \( N = 2^{14} \) the total number of samples sent per a power sweep is given by the multiplication of the number of power steps by the number of samples per power step i.e. the number of steps \( \times N \).

Due to a limitation in the software used to collect the data, the number of samples to be collected from the VSA was limited to 500000 samples. Combining this limitation with the choice of suitable \( N \), the maximum number of steps allowed per two-tones was 15.

The oscilloscope was set to get the average of 8 measurements before sending the readings. The next task was to precisely extract one full sweep starting from the lowest step to the highest. A code was implemented to extract the required sequence. Each value of the current was recorded with its corresponding power step.

In the case of WCDMA, current measurements were simpler since the data collected each time corresponds to a single WCDMA signal. The oscilloscope data was read and the average of the readings was taken and recorded.

### 3.8 Asymmetry

Asymmetry in amplitude of lower and upper IM3 is often observed in microwave power amplifiers subject to two-tone or multitone stimulus. In case A WCDMA signal is applied, the asymmetry appears as a difference between the power level of the lower adjacent channel and the higher adjacent channel.

Asymmetry in general is a result of memory effects in the power amplifier. Several methods attribute the asymmetry to different kinds of memory effects e.g. biasing network, variations of low-frequency output impedance, out of band terminations, limitation of the modulation bandwidth, unbalance in two input signal drive level and thermal time constants of the power amplifier [22],[23].
Chapter 4

Results

4.1 Introduction

Measurement results of two-tone and WCDMA signals as well as the graphical user interface designed for the project are presented in this chapter. There are basically two test results shown: a two-tone test signal and two WCDMA test signals. Several graphs can be plotted using the measurement system. The table below shows the plots that can be obtained for each signal type.

<table>
<thead>
<tr>
<th>Signal</th>
<th>3-D plots</th>
<th>2-D plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Tone</td>
<td>● Efficiency versus gain versus distortion (high and low, in dB or absolute).&lt;br&gt;● Frequency versus input power versus efficiency (for each tone).&lt;br&gt;● Frequency versus input power versus gain (for each tone).&lt;br&gt;● Frequency versus input power versus distortion (high and low, in dB or absolute).</td>
<td>● Frequency versus gain (for each tone).&lt;br&gt;● Frequency versus distortion (both high and low, in dB or absolute).&lt;br&gt;● Input power versus efficiency (for each tone).&lt;br&gt;● Input power versus gain.&lt;br&gt;● Input power versus output power.</td>
</tr>
<tr>
<td>WCDMA</td>
<td>● Efficiency versus gain versus distortion (high and low, in dB or absolute).&lt;br&gt;● Frequency versus input power versus efficiency.&lt;br&gt;● Frequency versus input power versus gain.</td>
<td>● Frequency versus gain.&lt;br&gt;● Frequency versus distortion (both high and low, in dB or absolute).&lt;br&gt;● Input power versus efficiency.&lt;br&gt;● Input power versus gain.&lt;br&gt;● Input power versus output power.</td>
</tr>
</tbody>
</table>

Table 4.1: List of figures that can be plotted by the system

All power levels presented in the figures of this chapter are in dBm unless otherwise stated.
4.2 Graphical User Interface (GUI)

A graphical user interface was designed to facilitate the use of measurement system. In the GUI, the user may specify the test signal, the frequency range, the step size, the plot of interest, the RF power reference level, the carrier frequency and the maximum allowed input power for the amplifier (for protection). In the MATLAB® Version used throughout this project (MATLAB® 7.4 -R2007a), data markers in figures can not be set in the GUI, but in later versions of MATLAB® the markers can be set. In Figure 4.1, the designed GUI is shown. The markers on the figure are obtained using MATLAB® 7.6.

![Fig 4.1: GUI of the project](image)

The data markers in the figure can show the values of efficiency, gain and distortion. User then picks the point of interest and refers to a table created by the code. The table contains the values of all power levels and frequencies and their corresponding efficiency, gain and distortion values. A code was implemented to get a “smart marker” that is capable of showing directly the frequency and power level corresponding to each point in the plot. The smart marker is not supported by the MATLAB® version used in the Project; however, it was tested and found successful in version 7.6.1 of MATLAB®. Figure 4.2 shows the smart marker mentioned above.
4.3 Two-tone Measurements

The results of a two tone test are shown in figures 4.3-4.6. Figure 4.3 shows a 3-D plot of efficiency versus gain versus distortion (in dBC). Figure 4.4 shows the variation of efficiency as a function of input power and frequency whereas Figure 4.5 shows the variation of the gain as a function of input power and frequency.

Figure 4.6 is a 2-D plot of the input power versus the output power. The slope of the curve represents the gain.
Figures 4.3 to 4.6 have the following test conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of frequency steps</td>
<td>45</td>
</tr>
<tr>
<td>Frequency step size</td>
<td>66.67KHz</td>
</tr>
<tr>
<td>Frequency sweeping range (around the carrier)</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Reference RF level</td>
<td>-10dBm</td>
</tr>
<tr>
<td>Number of power steps</td>
<td>15</td>
</tr>
<tr>
<td>Power step size</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Power sweeping range (in relation to reference level)</td>
<td>-10 dB to -3 dB</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.14 GHz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Number of samples per power step</td>
<td>$2^{14}$</td>
</tr>
<tr>
<td>Gain of driver amplifier</td>
<td>47.3dB</td>
</tr>
</tbody>
</table>

Table 4.2: Test conditions (two-tone)

![Efficiency versus gain versus IM3 high](image)

Fig 4.3: Efficiency versus gain versus IM3_high
Fig 4.4: Frequency versus input power versus efficiency

Fig 4.5: Frequency versus input power versus gain
4.4 WCDMA Measurements

For WCDMA, there is no limitation on the number of power steps or frequency steps since a single WCDMA signal is sent to the amplifier at each step. Two test results are presented in this section. Figure 4.7 is a 3-D plot of efficiency, gain and ACPR (high). Figures 4.8 and 4.9 show the variation of gain and efficiency, respectively, as a function of input power levels and WCDMA carrier.

Figure 4.10 is a 2-D plot viewing the variation of efficiency as a function of WCDMA carrier; the different curves in that Figure represent different input power levels.

Figures 4.7 to 4.10 have the following test conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of frequency steps</td>
<td>6</td>
</tr>
<tr>
<td>Frequency step size</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Frequency sweeping range</td>
<td>1.9GHz to 2.4GHz</td>
</tr>
<tr>
<td>Number of power steps</td>
<td>11</td>
</tr>
<tr>
<td>Power step size</td>
<td>1 dB</td>
</tr>
<tr>
<td>Power sweeping range</td>
<td>-20 dBm to -10 dBm</td>
</tr>
<tr>
<td>Sampling frequency (VSA)</td>
<td>60 MHz</td>
</tr>
<tr>
<td>Number of samples per power step</td>
<td>$2^{14}$</td>
</tr>
<tr>
<td>Gain of driver amplifier</td>
<td>47.3 dB</td>
</tr>
</tbody>
</table>

Table 4.3 Test conditions (WCDMA)
Fig 4.7: Efficiency versus gain versus ACPR_High

Fig 4.8: WCDMA carriers versus input power versus gain
Fig 4.9: WCDMA carrier versus input power versus efficiency

Fig 4.10: WCDMA carrier versus efficiency (legend = input power in dB)
Figures 4.11 to 4.13 are the results of another WCDMA measurement with more power and frequency steps under the following test conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of frequency steps</td>
<td>21</td>
</tr>
<tr>
<td>Frequency step size</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Frequency sweeping range</td>
<td>2.1GHz to 2.2GHz</td>
</tr>
<tr>
<td>Number of power steps</td>
<td>51</td>
</tr>
<tr>
<td>Power step size</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Power sweeping range</td>
<td>-20 dBm to -10 dBm</td>
</tr>
<tr>
<td>Sampling frequency (VSA)</td>
<td>60 MHz</td>
</tr>
<tr>
<td>Number of samples per power step</td>
<td>$2^{14}$</td>
</tr>
<tr>
<td>Gain of driver amplifier</td>
<td>47.3 dB</td>
</tr>
</tbody>
</table>

Table 4.4: Test conditions (WCDMA)

Figure 4.11 shows a 3-D plot of efficiency versus gain versus distortion of the WCDMA signal. The gain of the signal under various input power levels and with different carriers is shown in Figure 4.12. Figure 4.13 represents the efficiency of the signal as a function of input power level and carrier variations.

Fig 4.11: Efficiency versus gain versus ACPR_High
Fig 4.12: WCDMA carriers versus input power versus gain

Fig 4.13: WCDMA carrier versus input power versus efficiency
All results obtained from the system complied with the specifications provided by the amplifier manufacturer.

4.5 Measurement Time

Measurement time is an important factor in any measurement system. Since the method applied in this project is computer aided, the measurement time is considerably faster than any manual method. The time consumed for the measurement depends on the number of power and frequency steps. The measurement time for the two tone test displayed in this chapter was 30 minutes. In WCDMA tests, the measurement time for the first test (6 frequency steps and 11 power steps) was 8 minutes whereas for the second test (21 frequency steps and 51 power steps) the time was 80 minutes.

The time efficiency in WCDMA measurements is less than the one in two-tone measurement due to the fact that in two-tone measurement, all power steps for a single frequency step are sent collectively to the VSG and then collected collectively as well. In the case of WCDMA however, each power step is sent and received separately resulting in more time consumption. The advantage of sending each signal separately is that there is no limitation on the number of power steps or frequency steps whereas in the two-tone case, the maximum number of samples collected was 491520 samples due to a software limitation; taking into account that the number of samples per power step is $2^{14}$, the maximum number of power sweeps per frequency was found to be 15. The measurements can be repeated if more steps are needed.
Chapter 5

Discussion and conclusions

5.1 System Capabilities and Limitations

A measurement system was designed to perform measurements on power amplifiers. Several 3-D plots were obtained as well as traditional 2-D plots. 3-D plots can be useful in achieving a better understanding of amplifiers’ performance. It can also be used in other fields of amplifier measurements such as PA modeling and digital pre-distortion. It can also help PA designers detect sweet spots.

In the two-tone measurements presented in Chapter 4 (Figures 4.3-4.6), the plots showed clearly that when the amplifier was pushed to compression, the efficiency increased while the gain dropped; which is a well-known trade-off to amplifier designers.

The amplifier’s response to WCDMA signals did not significantly differ from its response to two-tone signals. The first WCDMA test signal (Table 4.3) covered a wide range of spectrum (500MHz). The figures show that the best point of operation is around 2.14GHz.

The second WCDMA test signal (Table 4.4) covered a narrower spectrum (100MHz) but in more power steps than the first WCDMA test signal. Again, the results complied with the specifications provider by the amplifier manufacturer. As the input level increased, pushing the amplifier towards compression, the gain dropped and efficiency improved. Results prove that the measurement method is successful.

Measurement time depends on the number of power and frequency steps. Time efficiency in two-tone measurements is more than one of the WCDMA since in a two-tone test, all power steps are sent to the amplifier collectively and obtained collectively whereas in WCDMA, each power step is sent separately.

Sending the signals separately in WCDMA enables sending any required number of power and frequency steps unlike the two-tone case where the maximum number of power steps is 15; due to the limitation of the maximum number of samples that can be collected.
Another limitation is the IQ bandwidth of the VSA. The IQ bandwidth of the used VSA is 28MHz, which limits frequency range that can be covered around the carrier to 9MHz (4.5MHz each side of the carrier).

Changing the carrier frequency, the user can sweep any arbitrary range of frequency supported by the VSA and VSG.

Results obtained from the system compiled with the specifications provided by the amplifier manufacturer.

Several parameters can be measured by the system, giving the possibility to plot even more plots than the ones presented in this report. The system is flexible and can be easily modified to measure even more parameters without essential adjustments.

5.2 Future Work

A limitation of the measurement system is the limited number of samples collected from the VSA. The VSA manufacturer specifies that the buffers can store up to 16 M samples. However, only 500K samples could be accurately collected using the software in the project. The limitation is either evolving form the codes provided by the VSA manufacturer or from MATLAB®. Troubleshooting of this limitation can result in extended system capabilities.

Another limitation is the IQ bandwidth of the VSA. That can be improved by either frequency stitching or by using a VSA with a higher IQ bandwidth.

Time efficiency wise, current measurements consumed most of the measurement time. Using another oscilloscope with a higher speed or even another current measurement method can improve the speed of the system considerably.

One interesting point will be to investigate the amplifier behavior as a function of the drain quiescent current while sweeping the input level and frequency.
References

19. IEEE Std 1057, IEEE Trial-Use Standard for Digitizing Waveform Recorders, section 4.1.3.3 - General Methods