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Linearizing a Power Amplifier Using Predistortion

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Problem Description

As the demand for higher bit rates over wireless radio networks increases, the manufacturers make use of new modulation techniques to utilize the frequency spectrum better. These techniques requires very linear radio equipment and drives research towards linearization and predistortion.

A power amplier (PA) in a radio link for NATO band III is to be linearized using predistortion. Prerequisites for the system and further details are included in appendix A on page 43. The PA needs to be characterized with a model including fifth degree intermodulation (IM) products. As the third order IM products dominates the distortion, these are of greatest concern.

A literature study of up to date linearization methods should give an overview over relevant alternatives. Based on this study, a model suitable for this PA needs to be made. The model needs to take into account the wide bandwidth and temperature range of the PA. Thorough familiarization of the simulation tool AWR Visual System Simulator (VSS) is necessary so that the model and predistorter can be simulated using this tool. Implementation of the predistorter in the current PA design should also be discussed.

Assignment given: 25. February 2009
Supervisor: Morten Olavsbråten, IET

Preface

This master's thesis has been prepared during the spring of 2009 at the Norwegian University of Science and Technology. The assignment was given by the Department of Electronics and Telecommunications while the work was done at Kongsberg Defence & Aerospace. A digital predistorter for a power amplifier has been created and simulated.

I would like to thank my supervisor Associate Professor Morten Olavsbråten at Department of Electronics and Telecommunications with NTNU for his invaluable support during this master's thesis. Also his Ph.d student Marius Ubostad has bin very helpful in setting up the measurements. In addition I am very grateful for the guidance from Senior RF and Analogue Designer at Kongsberg Defence & Aerospace AS Gaute Haga Andersen. My appreciations go also his department for including me and permitting me to use their instruments and devices for my measurements. I have enjoyed my stay and look forward to meet them again.

Abstract

Linear power amplification is important in radio communications to achieve high bitrates. Strong regulations of the frequency spectrum force manufacturers to use complex modulation schemes to increase the capacity. More linear amplifiers can use more complex modulation schemes like the 64Quadrature Amplitude Modulation (QAM). In addition will a linearized amplifier allow for increased output power and better efficiency.

Digital predistortion is one of the more successful methods of amplifier linearization. By distorting a signal before it reaches the power amplifier (PA), the nonlinearities of the PA may repair the distorted signal instead of damaging it.

A behavioral model is created using 16QAM modulated excitation signals. The PA model is based on empirical measurements. An open loop predistorter based on lookup tables corrects the I and Q channels in base band. The predistorter is created and simulated using AWR VSS.

A predistorter with a fairly small look-up table of 1008 entries shows an average reduction of third order intermodulation (IM) levels of 18,3 dB, and fifth order IM levels of 9,3 dB. Even when using mismatched lookup tables, an average reduction of 10,3 dB for IM3 and 4,4 dB for IM5 is achieved.

List of Figures

List of Tables

List of Abbreviations

ACP Adjacent channel power.

AGC Automatic gain control.

ALC automatic level control.

DAC Digital to Analog Converter.

DSP digital signal processing.

FM Frequency Modulation.

FPGA field-programmable gate array.

GaAs Gallium arsenide.

GMSK Gaussian Minimum-Shift Keying.

IM intermodulation.

IM3 third order intermodulation products.

IM5 fifth order intermodulation products.

IM7 seventh order intermodulation product.

IP3 Third order intercept point.

LUT lookup table.

MESFET Metal Semiconductor Field Effect Transistor.

MMIC Monolithic Microwave Integrated circuit.

P1dB 1 dB compression point.

PA power amplifier.

PAR peak to average ratio.

QAM Quadrature Amplitude Modulation.

QPSK Quadrature Phase-Shift Keying.

RMS root mean square.

VNA Vector Network Analyzer.

VSS AWR Visual System Simulator.

Contents

1 Introduction

Manufacturers of wireless communication systems experience an increasing demand of greater data rates. Since the strictly regulated frequency spectrum prevents the manufacturers of increasing the bandwidth, researchers are forced to better utilize the frequencies they already possess. Their solution is more complex modulation schemes which need very linear amplifiers.

Different aspects of the PA design are important for linear amplification. New materials for the transistors make more linear operation at higher and higher frequencies. A good bias circuit which matches the PA over the whole bandwidth is very important. The bias circuit controls the operating point, and if well designed, it will keep the PA in the linear region for all frequencies. An amplifier can achieve high degree of linearity by operating far below in the linear region, but this results in efficiencies down to a few percent and excess heat dissipation.

Several linearization methods exist to extend the linear region of an amplifier. Earlier analog linearization methods of the past have in the recent years been challenged by digital solutions, as the processing speed have increased. The predistorter retrieves corrections from lookup tables and add these to the signal before it reaches the PA. The nonlinearities of the PA will then restore the original signal before it is transmitted through the antenna.

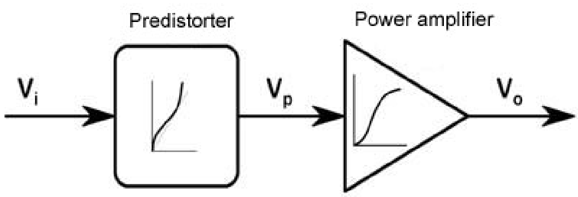

Figure 1.1: Conceptual predistorter

Wireless communication systems have traditionally used constant envelope modulation techniques such as FM or GMSK [1]. These techniques allow power amplifiers to be operated in the effective nonlinear region near saturation. The constant envelope ensures that no IM distortion is generated in adjacent channels.

National regulatory authorities divides the limited radio frequencies into frequency bands making sure all actors can use the air without disturbing each other. This thesis studies the radio link RL532A, which uses the "NATO BAND III" ranging from 1350-2690 MHz. Further specifications is found in appendix B on page 47. An operator in Norway spent 47 million NOK in 2007 for a license to build and drift a network using the 3G frequency band. These prices forces manufacturers to develop more complex modulation schemes to cram more bits into the transmissions. This have led to more spectrally efficient linear modulation methods such as QPSK with pulse shaping and 16QAM. [2]

The PA used in RL532A is divided into different stages, a driver stage followed by an end stage. The driver stage is based on commercial GaAs MMIC using MESFETs [3], while the end stage is based on discrete transistors. There are two such structures connected with a hybrid coupler. The two identical amplifiers works together as a balanced design. This nearly doubles the output power compared to a single stage and allows for the use of smaller transistors. Smaller transistors simplifies the matching of the amplifier to the rest of the radio circuit. This is because a smaller die size reduces the input impedance. However, the real advantage of this configuration is that any mismatch reflections from the amplifiers will be phase canceled at the coupler input or output [4].

In the following two chapters, an overview over relevant modeling and predistortion methods gives basis to the behavioral model chosen for the RL532A. Two characterization methods are carried out before the digital predistorter is simulated in AWR Visual System Simulator (VSS). The results are discussed in chapter 6 on page 33. For reproduction or further work, all the measurements and a small manual is found in the appendix section. The project files and spreadsheets will accompany the thesis digitally. For the reader's convenience, abbreviations and references are linked to their corresponding pages.

[1] Frequency Modulation (FM), Gaussian Minimum-Shift Keying (GMSK)

[2] Quadrature Phase-Shift Keying (QPSK), QAM

[3] Gallium arsenide (GaAs) Monolithic Microwave Integrated circuit (MMIC) Metal Semiconductor Field Effect Transistor (MESFET)

2
Modeling

2.1 Measures

This section defines some of the measures by which power amplifiers are categorized.

2.1.1 Adjacent Channel Power

The spectral region next to the fundamental signal is known as the adjacent channel. The integrated power which lies inside this region is named Adjacent channel power (ACP). The closest distortion to the fundamental are the third order IM levels. There are different definitions of the ACP bandwidth corresponding to modulation systems and regulations. However a logical limit would be a frequency offset of three times the bandwidth of the fundamental signal [4]. Reduction of the distortion in this region is the main focus in this thesis.

2.1.2 Third order intercept point

The Third order intercept point (IP3) is the intersection between the 1:1 slope of the fundamental gain and 3:1 slope of the third order intermodulation products (IM3)s. A 1 dB increase of the fundamental signal results in a 3 dB increase of the IM3. The fundamental signal and the distortion coming from IM3 have the same amplitude at this theoretical point. It is a single-point specification which have been used to compare PAs to each other. Any amplifier will suffer from saturation or destruction before actually reaching the IP3. If, however, both extrapolations are done from well inside the linear region, IM3 levels can be calculated at different signal levels based on the IP3. The higher intercept point, the less IM3 to worry about. When mea-

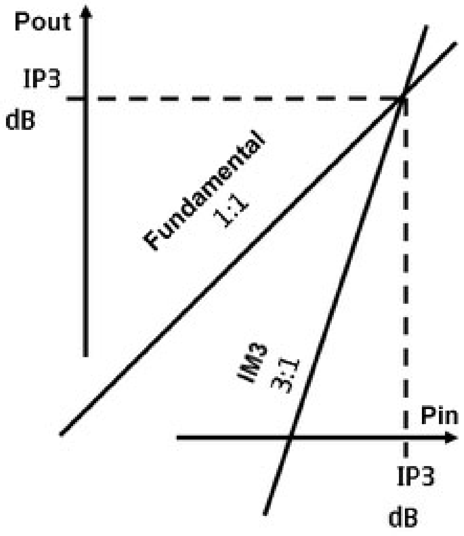

Figure 2.1: Third order interception point

suring distortion, the actual IM3 data points may wander substantially from the extrapolated line. These deviations are caused by higher IM products and increase with input power [4]. IM3 are still accurate enough to model receivers, which normally receive signals so small that third degree distortion dominate all of the nonlinear behavior. As higher order nonlinearities are significant in a power amplifier [3], it is not as much of use for power amplifiers.

2.1.3 1 dB compression point

When input power increases enough, the amplifier will suffer from compression. The point where the actual gain is 1 dB below a linear gain, is defined as the 1 dB compression point (P1dB). The P1dB lies about 10 dB lower than the IP3. Cripps, [4] p238-239, has calculated this relationship to be about 9,6 dB considering only IM3. Because higher order distortions also affects the output power, this can only be used as a rule of thumb. The P1dB is a popular measure of how high the linear region stretches. PAs are often compared by how much they are backed off from this point.

2.1.4 Peak to average ratio

The peak to average ratio (PAR), or crest factor, is the peak amplitude of a waveform divided by the root mean square (RMS) value of the waveform.

$$PAR = \frac{|x_{peak}|}{x_{rms}} \tag{2.1}$$

The waveforms with high PAR have more power locked up in the high peaks. The clipping of these peaks mainly determines the IM levels. Even if the average power lie beneath the P1dB, the peaks might bring the PA into saturation. A QAM signal will have a variable PAR, while a two-tone signal limits the PAR to approximately 3 dB. The PAR grows with the number of constellation points for the QAM scheme. An upgrade to 64QAM will therefore require the operation point to be further backed off from the P1dB.

2.2 AM/AM and AM/PM

AM to AM distortion is deviation from an ideally linear gain. This typically takes place as a compression as the amplifier goes into saturation. This effect visualizes itself as a shrinking of the constellation diagram or a downwards bend in a diagram showing output power as a function of input power.

AM to PM distortion is a change in the phase of the transfer characteristic as the input power level is increased towards and beyond the P1dB. This causes the constellation diagram to slew. It is challenging for physical models to include AM/PM effects as they depend on physical effects in many components. These effects are both interactive and complex. If AM effects are ignored completely, even one degree of AM/PM distortion can cause IM3 at a level of -53 dBc[1]. To reduce IM3 levels by any more than about 10 dB, a linearization device must correct AM/PM as well as AM/AM effects[4].

2.3 Behavioral models versus physical models

The physical model is a "bottom up" approach where all the components in PA and their relationships are put together. With knowledge of the theoretical rules describing their interactions, a set of nonlinear equations relating the terminal voltages and currents is formed. These models achieve high accuracy at the prize of longer simulation times [5]. The necessary extensive knowledge of the internal structure of the PA can often be a problem.

[1]dBc = decibels below the channel level

Behavioral models considers the PA as a "black box", considering only the input and output. There are nonparametric models based on for example a frequency plot or an impulse response on one side, and there are a number of parametric models using polynomials.

The greatest challenge for the behavioral model is to reduce the complexity while preserving high accuracy of modeling. For the empirical models this means reducing the number of measurement points. Cavers demonstrates in [2] that the IM products of optimum spacing are only 1-4 dB lower than that of equal spacing by amplitude. Tables equispaced by amplitude are simple, independent of amplifier, modulation format or backoff from P1dB. This makes equal spacing by amplitude a good choice from an engineering standpoint when entries for the lookup table is to be found.

Reducing complexity for polynomials is all about reducing the number of coefficients [7]. A ninth degree model consisting of a power series with nine complex coefficients have shown to have sufficient complexity to model most PA characteristics [4]. Several polynomial models are thoroughly presented in [5] for the interested reader. As the PA in RL532A is modeled by a behavioral model based on empirical measurements, these will not be discussed in detail here.

2.4 Characterization by two tones

The traditional two-tone test visualizes the theory behind distortion products. Two sine waves spaced close together in frequency is sent through the PA to see which frequency components turn up at the output. IM products comes as a result when two fundamentals or harmonics are mixed together. When these two signals lie close enough together, odd order IM products will appear too close to be filtered out. Even order IM products, on the other hand are easily filtered out together with the harmonics.

Using a power series as model, output voltage can be related to input voltage as

$$v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + a_4 v_i^4 + a_5 v_i^5 + ... \qquad (2.2)$$

Both v_i, v_0 are small, time varying quantities representing the input and output signals. This series characterizes one operation point of the amplifier.

The input signal v_0 is substituted with the two sines of equal amplitude and with frequencies ω_1 and ω_2, as used in the two-tone test. The spacing between the sines is much smaller than either of the carrier frequencies.

$$v_i(t) = vcos(\omega_1 t) + vcos(\omega_2 t) \qquad (2.3)$$

The output voltage in equation (2.2) becomes

$$\begin{aligned}
v_0(t) = & a_1 \cdot v \cdot (cos(\omega_1 t) + cos(\omega_2 t)) \\
& + a_2 \cdot v^2 \cdot (cos(\omega_1 t) + cos(\omega_2 t))^2 \\
& + a_3 \cdot v^3 \cdot (cos(\omega_1 t) + cos(\omega_2 t))^3 \\
& + a_4 \cdot v^4 \cdot (cos(\omega_1 t) + cos(\omega_2 t))^4 \\
& + a_5 \cdot v^5 \cdot (cos(\omega_1 t) + cos(\omega_2 t))^5 \\
& + ...
\end{aligned} \tag{2.4}$$

Each line of 2.4 represents a degree of distortion. Each one of these generate a number of distortion products of either the same or lower orders.

For example, the second degree term produces second order products at frequencies $2\omega_1, 2\omega_2$ and $(\omega_1 + \omega_2)$.The fourth degree term produces fourth order products at $\omega_1, 4\omega_2, (2\omega_1 + \omega_2)$ and $(3\omega_1 + \omega 2)$, but also second order products at $2\omega_1, 2\omega_2$ and $(\omega_1 + \omega_2)$ [4].

Table 2.1 on the following page shows the results of expanding out equation 2.4 up to the fifth degree. IM products will appear at all the frequencies listed in the first column. The third order IM products appear at $(2\omega_1 - \omega 2)$ and $(2\omega_2 - \omega_1)$. Next to these, fifth order IM products will appear at the frequencies $(3\omega_1 - 2\omega_2)$ and $(3\omega_1 - \omega_2)$

2.5 Characterization by a modulated signal

A modulated excitation signal gives a more realistic characterization of the PA. The signal generator modulates the signal using 16QAM and low pass filter it before sending it through the PA. The constellation diagram of 16QAM is shown gray coded in figure 2.2 on the following page. The Gray code make sure that two adjacent points in the constellation only differs by one bit. Other codes may as well be used.

The spikes from the two-tone test turn into sidebands when a modulated signal is used. Figure 2.3 on page 9 shows how the IM3 also consist of contributions from fifth order intermodulation products (IM5). A portion of each order of distortion lies within the original band limits of the undistorted signal. This is not a problem as far as measurement is concerned, but becomes a problem when the signal is demodulated and information is retrieved from it.

	$\alpha_1 \cdot$ v	$\alpha_2 \cdot v^2$	$\alpha_3 \cdot v^3$	$\alpha_4 \cdot v^4$	$\alpha_5 \cdot v^5$
1(DC)		1		9/4	
ω_1	1		9/4		25/4
ω_2	1		9/4		25/4
$2\omega_1$		1/2		2	
$2\omega_2$		1/2		2	
$\omega_1 \pm \omega_2$		1		3	
$2\omega_1 \pm \omega_2$		3/4			25/8
$2\omega_2 \pm \omega_1$		3/4			25/8
$3\omega_1$		1/4			25/16
$3\omega_2$		1/4			25/16
$2\omega_1 \pm 2\omega_2$				3/4	
$3\omega_2 \pm \omega_1$				1/2	
$3\omega_1 \pm \omega_2$				1/2	
$4\omega_1$			1/8		
$4\omega_2$			1/8		
$3\omega_1 \pm 2\omega_2$					5/8
$3\omega_2 \pm 2\omega_1$				5/8	
$4\omega_1 \pm \omega_2$				5/16	
$4\omega_2 \pm \omega_1$				5/16	
$5\omega_1$					1/16
$5\omega_2$					1/16

Table 2.1: Two-Carrier distortion products up to fifth degree [4] p.234

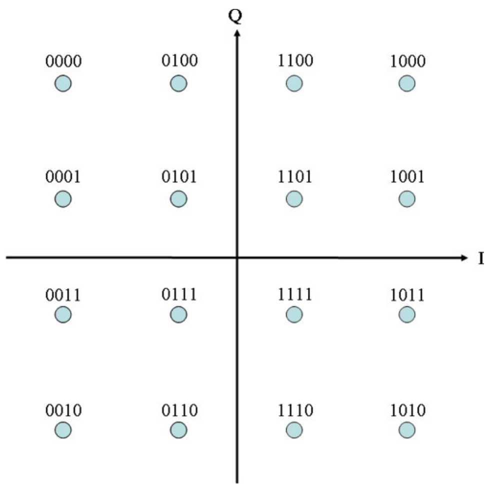

Figure 2.2: Gray coded IQ diagram of 16QAM

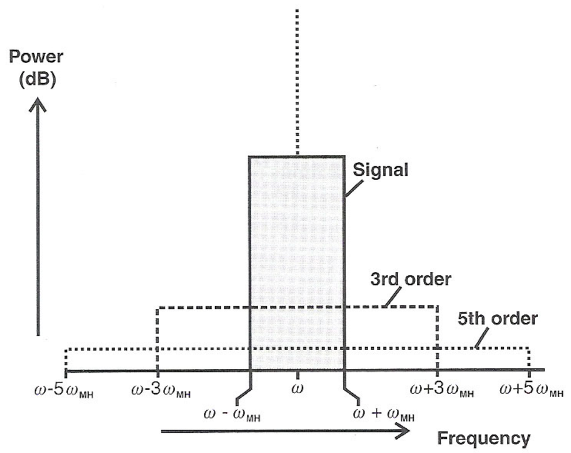

Figure 2.3: Intermodulation spectrum for a modulated signal. [4] page 235.

3

Predistortion

The two sides, consisting of analog enthusiasts challenged by digital radicals, are evident in the realm of predistortion. As the processing speed increases, analog solutions are already being replaced by better digital inventions.

Most PA linearization techniques compares the amplitude and phase at the output with the input and generate appropriate corrections. Memoryless techniques base the correction on static data previously measured, while techniques with memory updates the corrections on the fly while the PA is in operation. The two ways of realizing this is to use either a feedback structure or a feedforward structure.

3.1 Analog Predistortion

These techniques have been used by commercial manufacturers in the past years. The simple ones can be a configuration of one or more diodes. These can handle signal envelopes which vary at speeds up to less than an order of magnitude down from the RF cycle time. The more complex analog predistorters can in principle synthesize whatever required nonlinear characteristics by using separate sections to generate the various degrees of distortion[3].

3.1.1 Feedback

A feedback loop records the output of the amplifier and use this information to alter the input. Direct feedback is prone to oscillation problems, and is rarely used at microwave frequencies.

Indirect feedback techniques involve envelope detectors at both the input and output of the PA. A differential amplifier forms an error correction signal

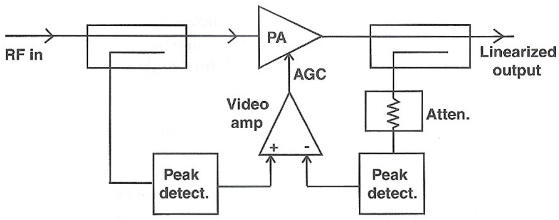

Figure 3.1: An indirect feedback system. [4] p421

which is fed into a Automatic gain control (AGC) on the PA. This technique have been common in the mobile communications industry, but gives only a few decibels of IM reduction [4]. Since this technique provides no extra effect to the output signal, it will suffer from the saturation of the main PA. This is the main reason to the low efficiency, as the effect decreases markedly as the PA swings into the compression region. At much lower power levels, the gain required from the error amplifier becomes much higher if any useful effect is to be obtained, which leads to bandwidth and stability problems. AM/PM effects are not corrected with this technique [4].

The Cartesian Loop offers up to 30 dB of IM reduction for signal modulation bandwidths lower than about 100 kHz [4]. This technique feeds the I and Q channels into separate differential correction amplifiers, before a vector modulator forms the actual signal sent into the PA. This technique reduces time difference between the AM/AM and AM/PM processes which are a prime cause of asymmetrical IM sidebands.

The Polar Loop is another successful method showing efficiencies greater than 50% and IM3 reduction of 25 dB.

3.1.2 Feedforward

Feedforward is the technique where a corrective signal is applied to the output of the PA. Output correction needs to generate a significant amount of power to perform its function, but will physically increase the power capability of the PA. Feedforward offer the same benefits as feedback without the instability and bandwidth limitations. The feedforward loop provides dynamically extra power needed to compensate for the gain compression of the main PA. It is capable of reducing the IM distortion of any PA by at least 30 dB, with no signal bandwidth or video delay restrictions [3]. The extra amplifier might decrease the overall efficiency, and the nonlinear contributions of the error amplifier must be taken into consideration. Feedforward techniques also have problems tracking the phase and gain for large bandwidths [4].

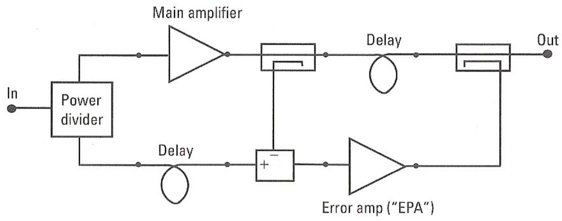

Figure 3.2: A basic feed forward loop. [3]

3.2 Digital Predistortion

With predistortion, the correction is applied at the input. This implies that the corrected input signal will be subject to the nonlinearities of the PA. The digital predistorter is cheap, is not locked to modulation formats and can be used in combination with many existing techniques. A digital signal processing (DSP) unit calculates the inverse function of the PA and stores the corrections in lookup tables. DSP speed is still a limitation for signal bandwidths above about 20 MHz. The radio in this thesis have a signal bandwidth of 3,1 MHz staying well inside this limit.

Lookup tables containing direct corrections for the I and Q channels have the advantage of fast operation. Polynomials demand less table size as only the coefficients are stored. Instead a more complex, and hence slower, process of solving the polynomial is required. Both alternatives are based on approximations. The lookup table (LUT)s are constrained by the number of bits available and the table sizes. Polynomials suffer from approximations during the calculation. First the model has been truncated to a fixed order. Inverting this polynomial to find the inverse characteristics of the PA, results in another infinitely long polynomial which needs to be truncated again. On top of the two truncations, the designer runs a risk that the polynomial is unsolvable. This predistorter uses linear interpolation to map the correct input to the output from the PA. An intermodulation scheme may also be used between two neighboring entries in the LUT to keep its size down.

Predistortion alleviates the distortion from a device, by driving it harder. But as with feedback, it adds no extra power to compensate for the saturation of the main PA. It may seem that it has a "gain", but in practice the "gain" is achieved by reducing the predistorter attenuation.

The predistorted signal emerging from an ideal predistorter will necessarily contain harmonics of the baseband modulation signal. This means that the DSP drivers will have to work at a speed corresponding to maybe an order of magnitude faster than required of the original signal.

3.3 Bandwidth of predistorters

A predistorter will create distortion products in addition to those of the PA. Using a third order model for both the PA and the predistorter, the output of the PA becomes

$$v_0 = a_1 v_p + a_3 v_p^3 \tag{3.1}$$

The input voltage v_p is the output of the predistorter giving

$$v_p = b_1 v_{in} + b_3 v_{in}^3 \tag{3.2}$$

Substituting for v_p gives the PA output

$$v_0 = a_1(b_1 v_{in} + b_3 v_{in}^3) + a_3(b_1 v_{in} + b_3 v_{in}^3)^3 \tag{3.3}$$

Expanding this gives

$$v_0 = a_1 b_1 v_{in} + (a_1 b_3 + a_3 b_1) v_{in}^3 + 3a_3 b_1^2 b_2 v_{in}^5 + 3a_3 b_3^2 b_1 v_{in}^7 + a_3 b_3^3 v_{in}^9 \tag{3.4}$$

A third order predistorter creates additional distortion extending all the way up to the ninth degree. A digital predistorter based on LUTs will probably create even higher degree distortion. The spectrum of a predistorter output will therefore have an equal, or in most cases a significantly larger bandwidth than the original PA for the same operation point. Predistorters may therefore exceed regulatory spectral distortion masks at higher frequencies, which may have originally been met by the uncorrected glsPA[4].

3.4 Performance requirements

The figures 3.3 on the facing page and 3.4 on the next page gives an idea of the performance required from a predistorter. These curves are based on a two-tone signal envelope having a PAR of 3 dB. The predistorter has to reduce gain compression down to 0,01 dB and phase distortion to less than 1 degree in order to reduce IM levels down to -60 dBc [4].

3.5 Mapping predistorter

The predistorter created in this thesis uses a mapping principle. Appendix F on page 87 explains the model in a greater detail, while this section presents the principle using the following scenario:

Using an input of -10 dBm, the PA output shows 16 dBm. For the PA to be linear, the output needs to be 17dBm. Intuitively 1dB is added to the input

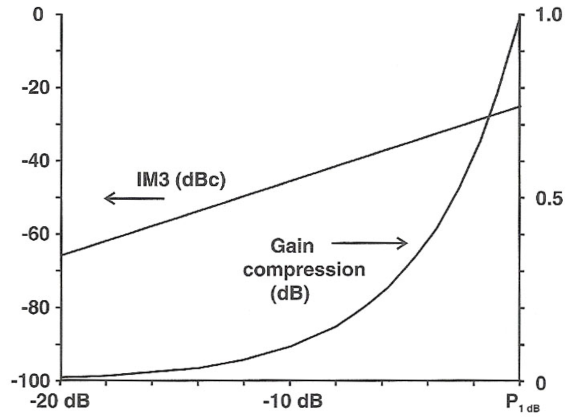

Figure 3.3: Two-carrier IM distortion and single carrier gain compression as a function of of input power [4] p401

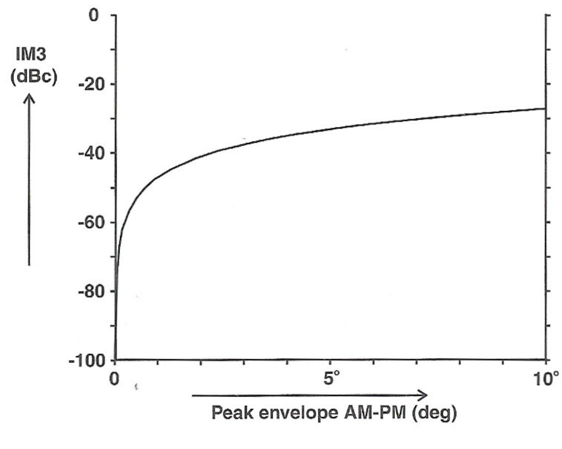

Figure 3.4: Two-carrier IM distortion as function of peak AM/PM.[4]p401

to compensate for this loss. This time the output shows 16,5 dBm, still 0,5 dB short. 1dB correction at the input does evidently not correspond to 1dB correction at the output.

The reason is as follows. What happens when adding 1dB to the input, is that the PA is driven a little harder. As the PA's operating point moves closer to the P1dB, it suffers a little more from compression. The correction must take into consideration that the PA is going to run in a more nonlinear operation point. Usually a stronger correction is needed as the PA goes into saturation.

Returning to the scenario: Since an increase of 1dB at the input resulted only in 0,5 dB increase at the output, a stronger correction seems necessary. The input is therefore increased by 2 dB to -8dBm. This time the output shows 17dBm, which is the correct output for a linear PA.

4 Measurement setup

The excitation signals must take the bandlimited structure of the amplifiers into consideration. Single-tone, two-tone and multisine (>4 tones), are excitations which have been frequently used in addition to noise signals and digitally modulated signals. Classical test signals such as the step function or pseudo-random binary sequences are rarely used to characterize high frequency amplifiers, as these must be low-pass filtered and then modulated onto a carrier signal. [5]

A single-tone measurement gives no IM products, and nonlinearities results only in gain compression. A single tone measurement can be used to measure phase data with a network analyzer. Of the other alternatives, two-tone is one of the most common giving IM products, but no phase data.

The PA in RL532A is characterized using the traditional two-tone test, and a modulated signal. The two sines were swept across the input power, while the modulated signal have a power sweep included in the modulation. The modulated signal includes the necessary power sweep in the modulation, saving lots of time.

4.1 Two-tone characterization

This excitation signal consists of two sines of equal amplitude. The two tones have to be spaced close enough in frequency so that the odd IM products appear not too far out in the frequency spectrum. This is important to maintain the assumption that all of the IM products have the same gain as the fundamentals. However, the two tones must maintain a spacing so that the spectrum analyzer are able to separate them from each other. Ideally should the two tones be generated from two separate signal generators connected by a coupler. This would make sure the two sines would not affect

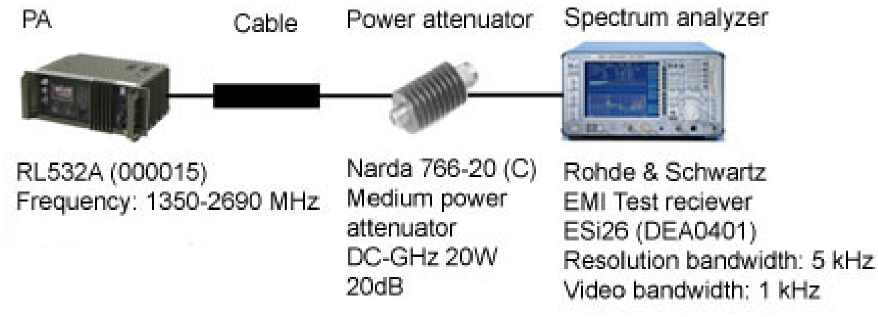

Figure 4.1: Measurement setup of the two-tone test

each other, and that the two have exact equal amplitudes. It is important that the signal sources are stable and accurate in frequency, with very low noise to avoid ambiguity when measuring very low levels of IM distortion. Also, the signal sources must be closely matched in amplitude to avoid variations due to the test setup. Unequal amplitude sources will create unequal amplitude distortion products. [1]

In lack of two signal generators, the internal modem in the radio was used as signal generator. The PA design includes an automatic level control (ALC) which controls the output power level of the PA. The input stage provides the end stage with a signal of constant power. The power sweep is then performed by adjusting the ALC. It divides the power output into 16 levels of 1,5 dB intervals. The duplex filter is disconnected so that only the two stages of the amplifier is included in the measurements.

To include phase measurements in the two-tone test, a reference is needed. One could include a third signal generator to mix down both the input and output to a lower frequency. This will conserve the phase, and measurements could be done to the down-mixed signals to find the phase difference. A third generator was also not available at the time of this measurement, instead phase measurements were captured from the measurement of a modulated signal.

4.2 16QAM signal

The modulated signal from the signal generator is a pseudo random bit sequence which is unknown to the Vector Network Analyzer (VNA). This signal is looped over and over. The signal is modulated with 16QAM using a root raised cosine low pass filter with a roll-of factor $\alpha = 0,34$. The roll-off factor states how many percent into the ideal low pass filter the lean should begin. The signal amplitude then falls as a cosine, crosses the imaginary line of an ideal low pass filter at the midpoint, and extends out of the ideal low pass filter with the same percentage. This makes the original sequence come out as a trajectory in the IQ diagram. The I and the Q value represent components of a signal vector with amplitude $A = \sqrt{I^2 + Q^2}$ and a certain phase angle.

The symbol rate of 2,304 Msym/s, the 16QAM modulation, the root raised cosine filter and the roll-off factor are all specified in the signal generator as well as the VNA.

The signal is sent directly to the end stage of the amplifier before reaching the VNA. The attenuator is just a measure to protect the sensitive input connector of the VNA. The VNA acts as a receiver and demodulates the signal. The trajectory is oversampled 8 times and put on top of a IQ diagram with the 16 ideal points of QAM. The VNA samples the trajectory based on the symbol rate, and finds the sample points closest to the ideal constellation points. This might be sample number 3, and 16+3 and so on. This bit sequence is then assumed to be the one sent from the signal generator.

A demodulated 16QAM signal tends to look more like in figure 4.2. The slew is a result of phase distortion, while the gain compression make the constellation shrink. The demodulated bit sequence suffers from bit errors. When the trajectory lies closer to a wrong point on the IQ diagram, the VNA will assume this point to be part of the bit sequence. These bit errors will typically represent less than 0,1 dB of the IM levels.

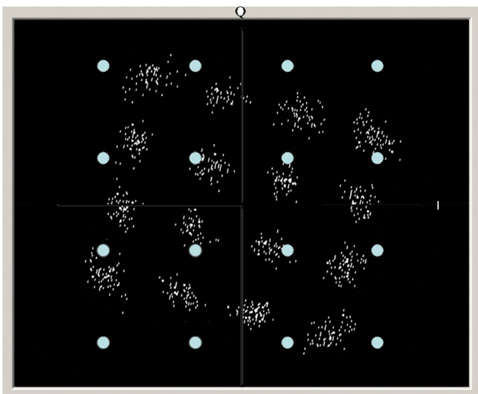

Figure 4.2: Typical constellation diagram of 16QAM

Because it knows the type of filter, the roll-of factor, the modulation and the symbol rate the VNA is able to create an ideal trajectory based on the demodulated signal. It will then compare the ideal trajectory with the demodulated one to find AM/AM and AM/PM effects.

A better VNA could use this data to expand the demodulated trajectory with the AM/AM and AM/PM data. This would reconstruct a more correct version of the original trajectory sent from the signal generator. This would reduce the number of bit errors.

The trajectory runs through all amplitudes from zero to the highest peak. This ensures that the modulated signal has a swept power range equivalent to the dynamic range of the desired signal [3]. By comparing the incoming trajectory with an self produced ideal one, the VNA can compute AM/AM and AM/PM diagrams. All samples are used to create the AM/AM and AM/PM curves showing up as clouds. Most data points are found around the average power level as a result of the modulation. This makes the model less accurate at other power levels.

The losses in the attenuator, the junction and the cables are measured separately for the frequencies used, and subtracted from the measurement results. This measurement is a lot more realistic than the two-tone test and is used as basis for the predistorter. The measurement was set up as in figure 4.3 with the help of Ubostad [6].

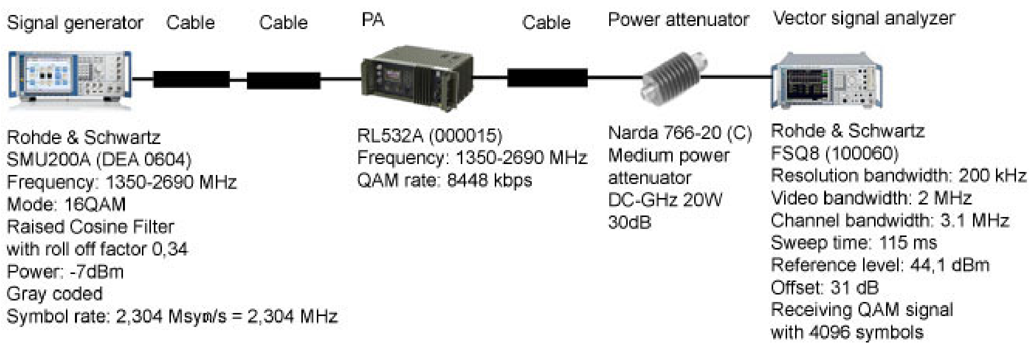

Figure 4.3: Measurement setup using a modulated signal

5

Results

5.1 Two-tone test

The measured power spectrums shows how the IM products vary for different frequencies. A leak from the local oscillator in the radio modem is observed at all measurements, but it is not observed higher than -20 dBc.

There is unfortunately used a slightly too small resolution bandwidth in the spectrum analyzer. The resolution bandwidth of 5 kHz, with a video bandwidth of 1 kHz, results in that only part of the signal power is included in the measurement data. A resolution bandwidth covering the whole signal bandwidth shows a gain of 43.42 dB at power level 16, while the results show a gain of approximately 36 dB.

The actual loss in the cables and the attenuator is also not measured. As the error sources becomes too many, it is realized that the results is accurate enough anyways. They are still included to enlighten the theory behind IM products and to give a picture of how much the IM levels change at different operating points.

Figure 5.1 on the next page, 5.2 on the following page and 5.3 on page 23. show the power spectrums at 1350 MHz, 2400 MHz and 2690 MHz. As seen from the frequency axis, the IM products appear for every 582 kHz, the same distance as the spacing between the fundamentals. Closest to the two fundamental sines lies the IM3, followed by IM5. A more accurate model can also include seventh order intermodulation product (IM7) and so on if desired.

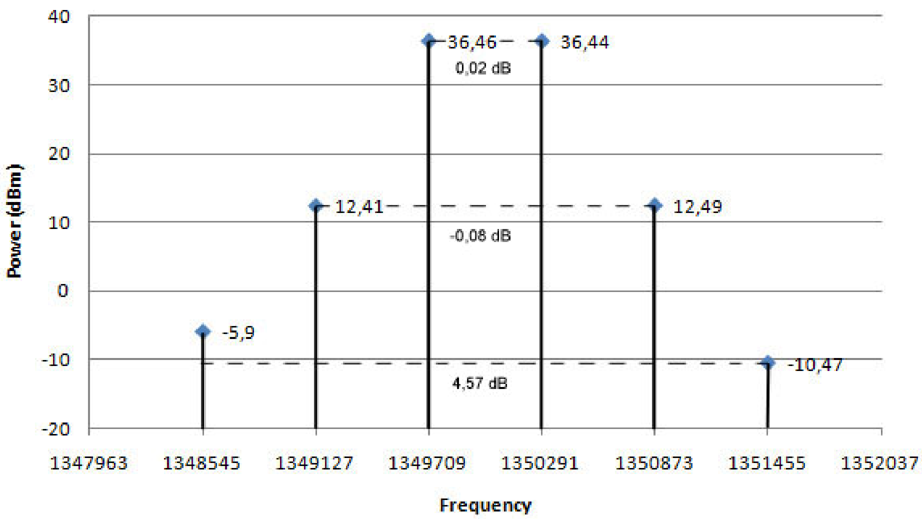

Figure 5.1: Power spectrum at 1350 MHz

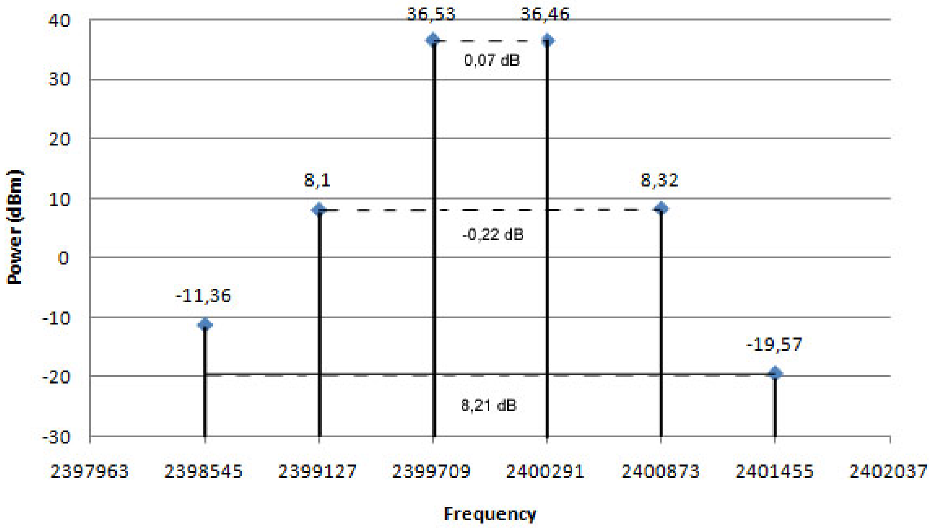

Figure 5.2: Power spectrum at 2400 MHz

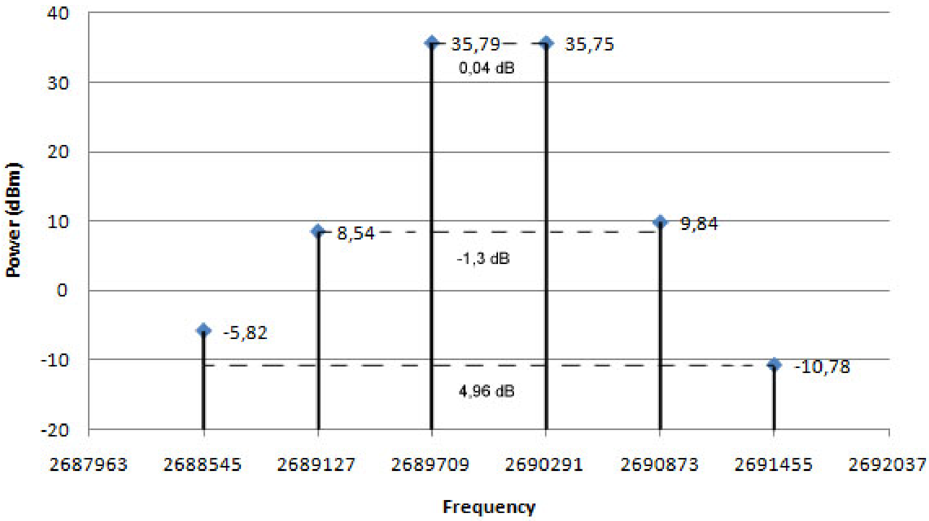

Figure 5.3: Power spectrum at 2690 MHz

5.1.1 Asymmetric intermodulation products

While the fundamentals stays fairly constant through the different frequencies, there are more changes with the IM products. The IM3 suffers from a slight asymmetry which increases with frequency. It reaches a maximum of 1,3 dB difference between upper and lower IM product at 2690 MHz. The fifth order IM products experience a stronger asymmetry, reaching its measured maximum of 8,21 dB at 2400 MHz.

5.1.2 Frequency dependence

Figure 5.4 on the following page and figure 5.5 on page 25 show how the IM products changes as a function of frequency. The two fundamental signals are very linear over the whole bandwidth, with the exceptions of 1350 MHz and 2400 MHz where it lies above 0,5 dB above the average.

Third order distortions are high in the lower part of the bandwidth. The difference flattens out for lower power levels, but about 8 dB separates the top and bottom at power level 16. Comparing the upper and lower IM5 graphs, one clearly see the asymmetry. At power level 16 the difference reaches 13 dB at 2250 MHz.

The complete spreadsheet containing these results is found in appendix C on page 51. The IM levels for 2nd and 3rd harmonic are also listed here. These lmeasured evels are much higher than the regulations allow because the duplex filter is disconnected

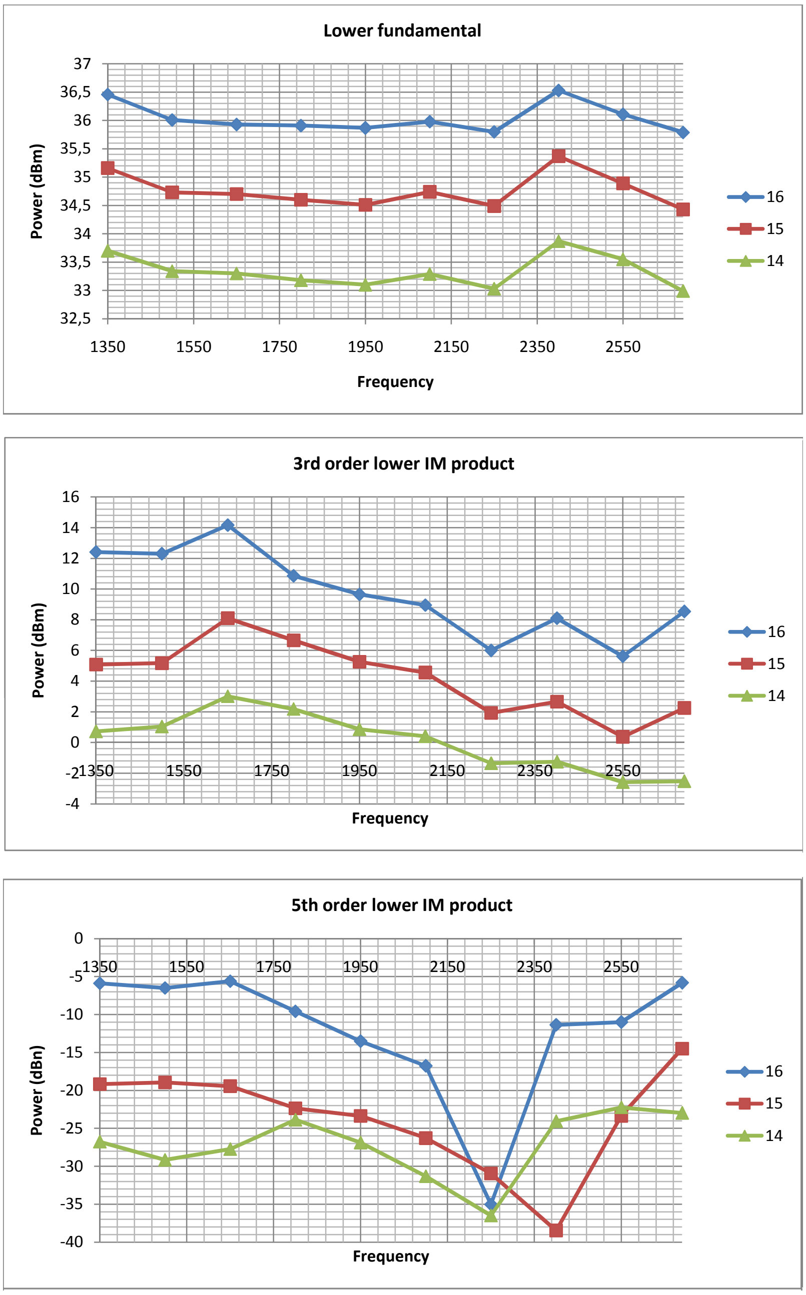

Figure 5.4: 1st harmonic lower IM products

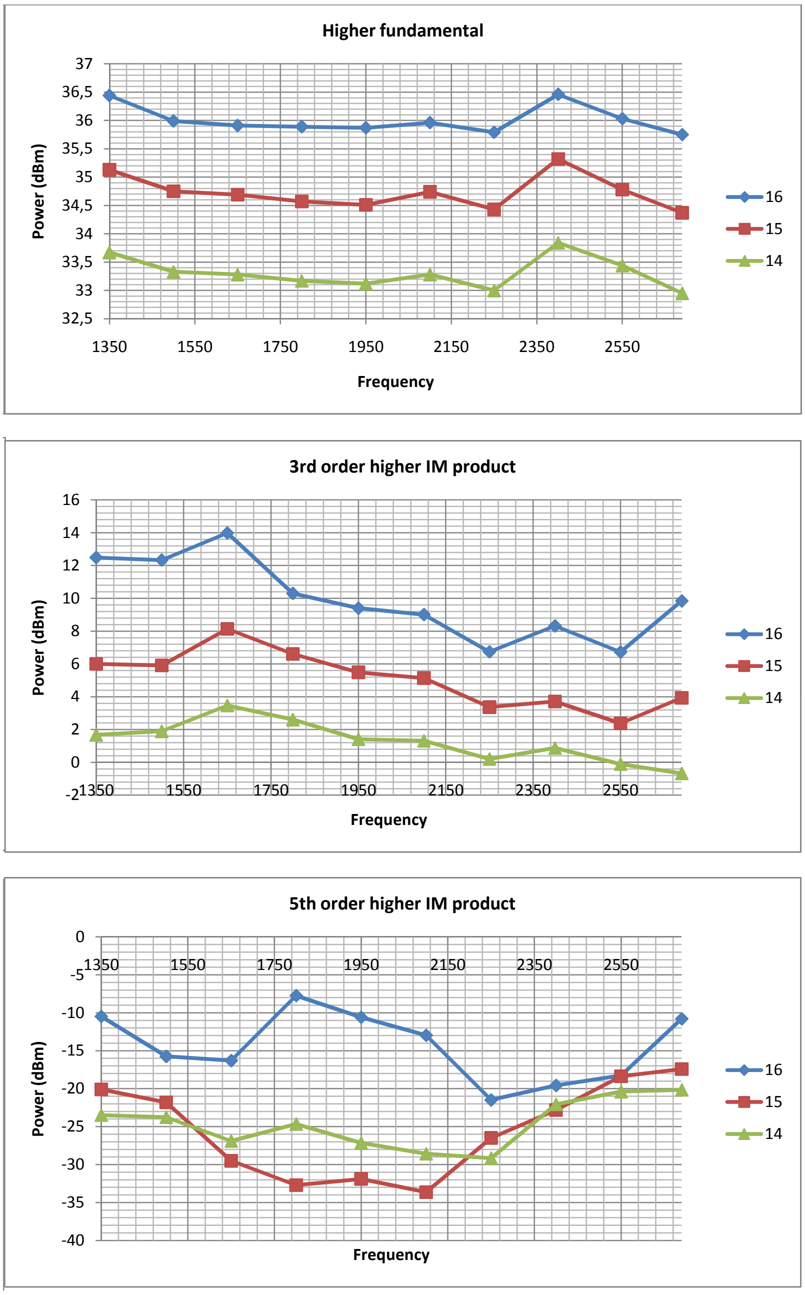

Figure 5.5: 1st harmonic higher IM products

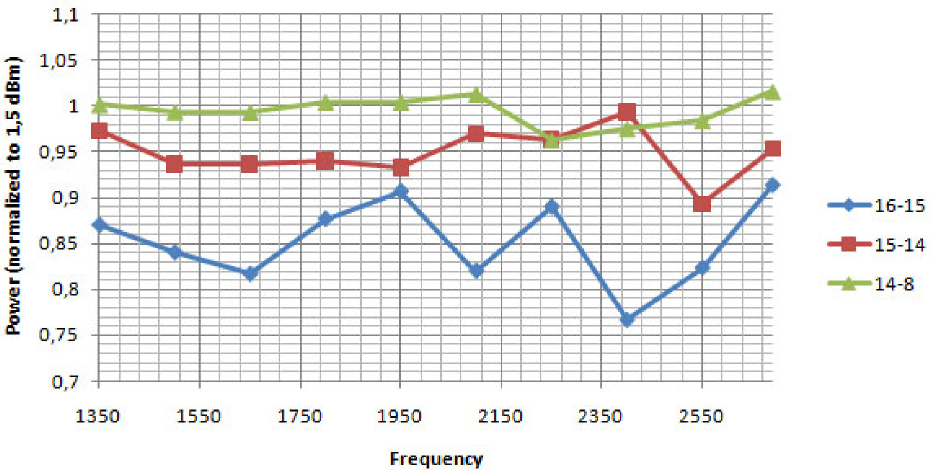

Figure 5.6: The power steps of the ALC normalized to 1,5 dB

5.1.3 Automatic Level Control

The ALC in the radio simulates the power sweep in the two-tone test. The accuracy of this function must be taken into consideration. As seen from figure 5.6 it is clearly most accurate for lower power levels. At maximum power, level 16, the step is as little as about 1,55 dB. This adds to the number of error sources this measurement suffers from.

5.2 Modulated excitation signal

Expanding the two sine waves from the first measurement to signals covering a frequency band will cause the IM products to expand in a similar way. Figure 5.7 on the facing page shows clear shoulders representing third order IM distortion levels. The test points corresponds to a two-tone test with a 20 dB bandwidth of 3,1 MHz, as used in the first measurement. The blue input signal is first amplified without predistortion, drawn in black. The same signal including predistortion results in the green power spectrum.

Figure 5.8 on the next page shows the gain compression of the amplifier. The blue line representing the predistorted signal lies very close to the linear curve dotted red. The black line shows the AM/AM curve of the PA without predistortion.

Figure 5.9 on page 28 shows the phase distortion without predistorter in black and with predistorter in dotted red.

Appendix E on page 67 lists the results of all the operation points included

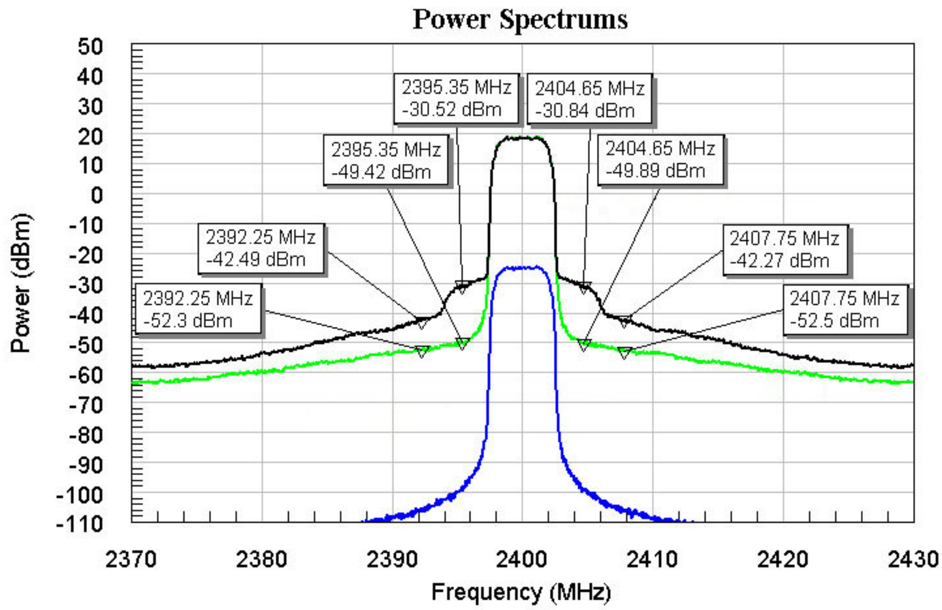

Figure 5.7: Power spectrum at center frequency 2400 MHz at 46 ℃

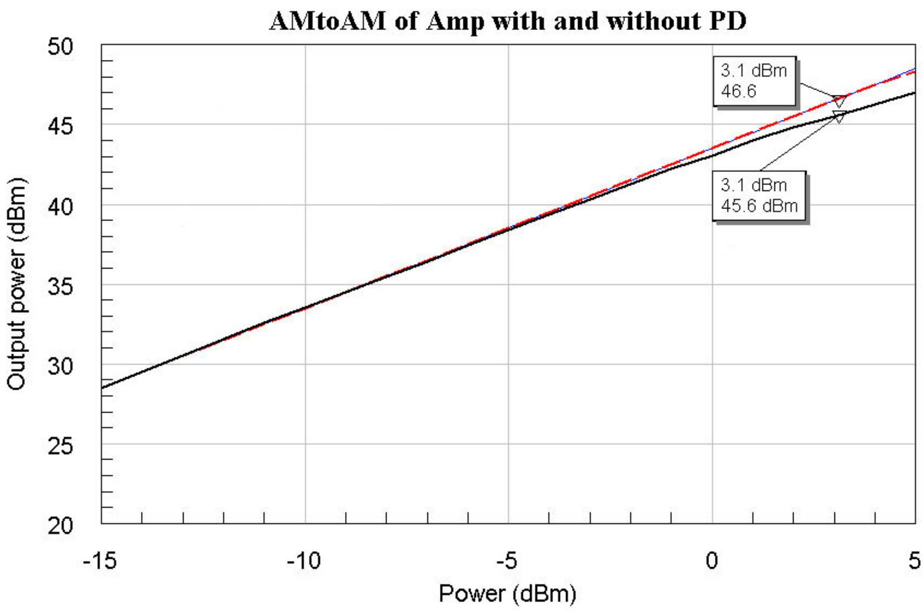

Figure 5.8: AM/AM at center frequency 2400 MHz at 46 ℃ with and without predistorter

in this measurement. The spreadsheets which these graphs are based on, is found in appendix D on page 63. The same results are in addition included digitally.

5.2.1 Predistorter performance

Figure 5.10 on the next page shows the performance of the predistorter for different frequencies and also for different temperatures at 2400 MHz. A 21,35 dB reduction of the third order IM levels stands as the best result. The plot shows that the predistorter reduces third order IM levels at an average of 18,3 dB and IM5 of 9,3 dB.

The mismatched predistorters reduces third order IM levels 16,69 dB at the most. This result is from a predistorter with wrong temperature but correct frequency. The worst match is the predistortion corrections for 1800 MHz trying to correct the a signal at 2690 MHz. This situation caused the predistorter to be slightly destructive, raising the upper fifth order IM levels with 0,36 dB. However, an average reduction of the third order IM levels of 10,3 dB and fifth order IM levels of 4,4 dB is achieved.

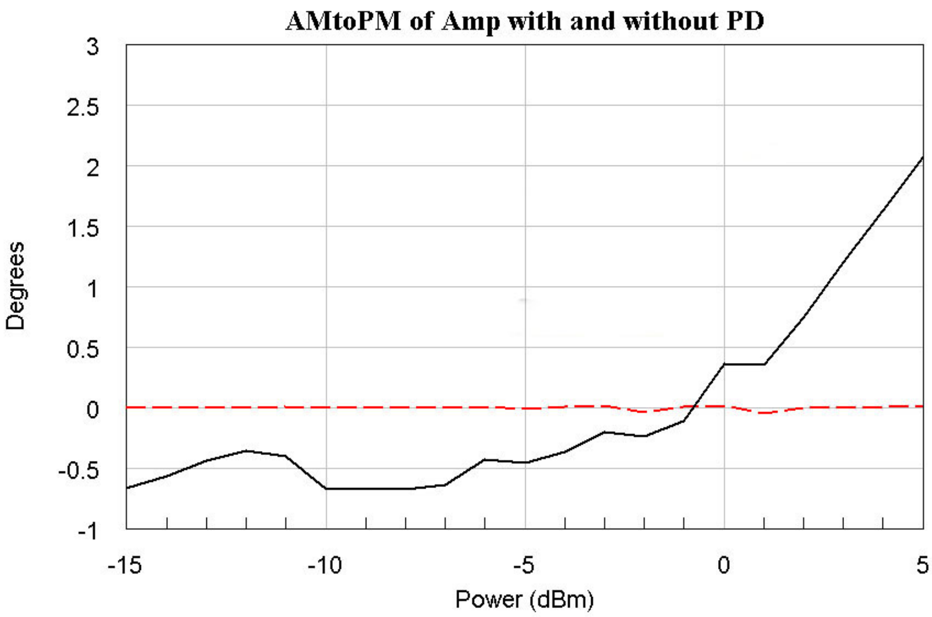

Figure 5.9: AM/PM at center frequency 2400 MHz at 46 ℃ with and without predistorter

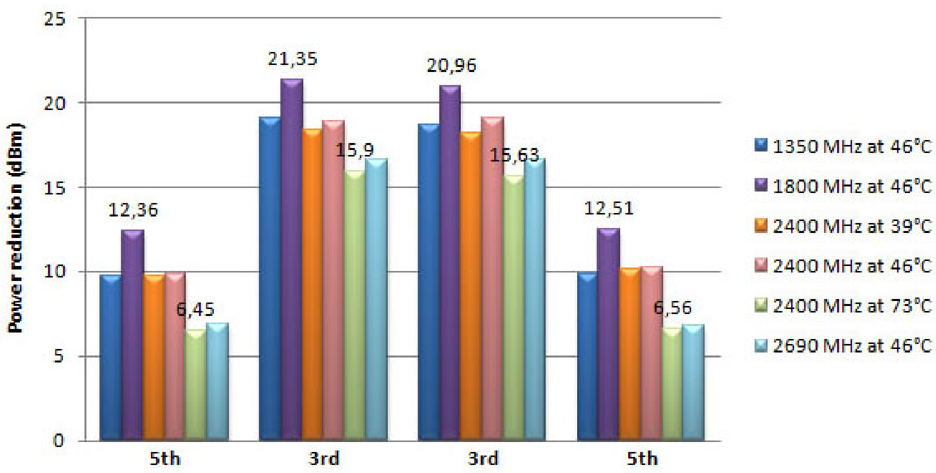

Figure 5.10: Correction with matched predistorter

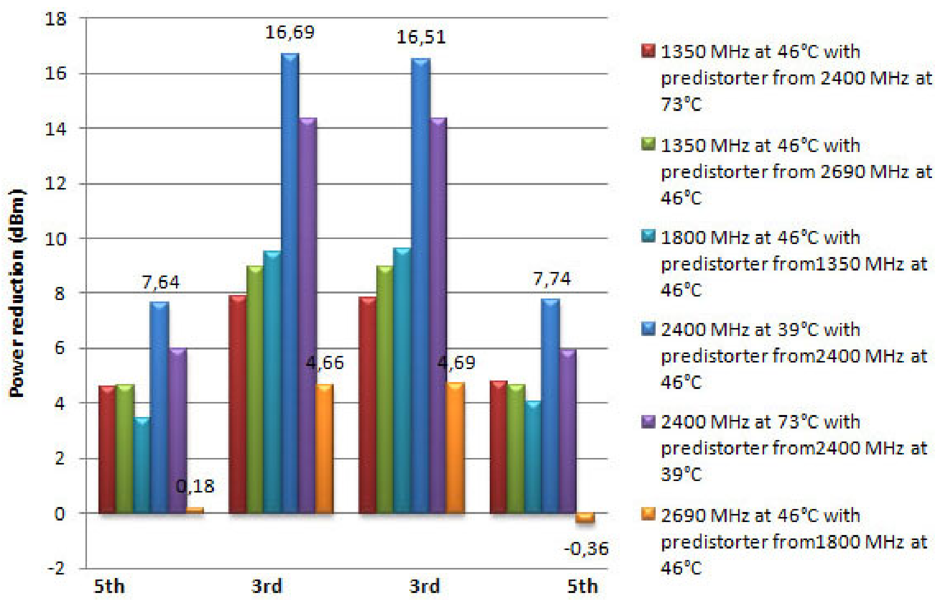

Figure 5.11: Correction with mismatched predistorter

5.2.2 1 dB compression point

Figure 5.12 shows the P1dB for different frequencies and temperatures without predistortion. The new P1dB after predistortion is more than the peak power of the modulated signal.

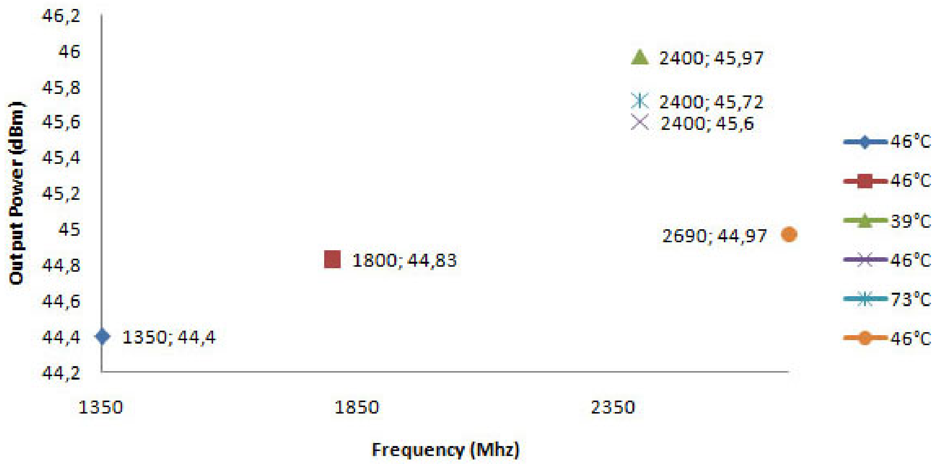

Figure 5.12: The 1 dB compression point for some of the PA's operating points

5.2.3 Relative AM/AM and AM/PM

The relative AM/AM curves and AM/PM curves shown in figure 5.13 on the next page and 5.14 on the facing page are normalized by the VNA. The purple line in 5.13 on the next page shows the most nonlinear operation point: 1350 MHz at 46 °C. The red line in 5.13 on the facing page represents the condition with most linearity: 2400 MHz at 39 degrees.

The red line in 5.14 on the next page is the most linear test point, and the purple line the most nonlinear test point. These are the same operating points drawn in bold in figure 5.13 on the facing page

5.2.4 Temperature differences

The frequency 2400 MHz was also examined at different temperatures because it showed the strongest nonlinearity. The simulations show a improvement for all frequencies, and more than 20 dB reduction of the IM3.

Figure 5.15 on page 32 shows the variation in IM products as the temperature is varied between 39°C, 46°C and 73°C. The operation point at 2400 MHz is

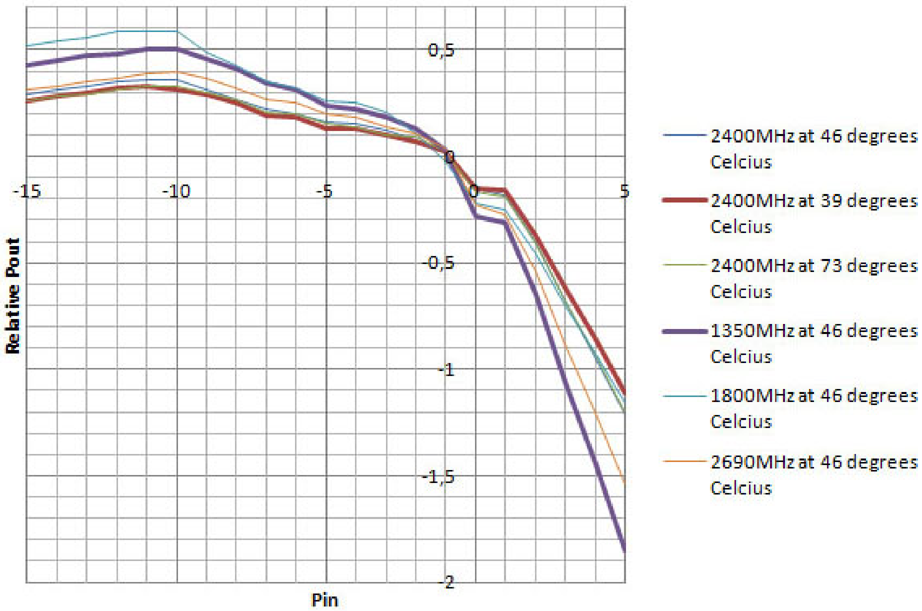

Figure 5.13: Relative AM/AM

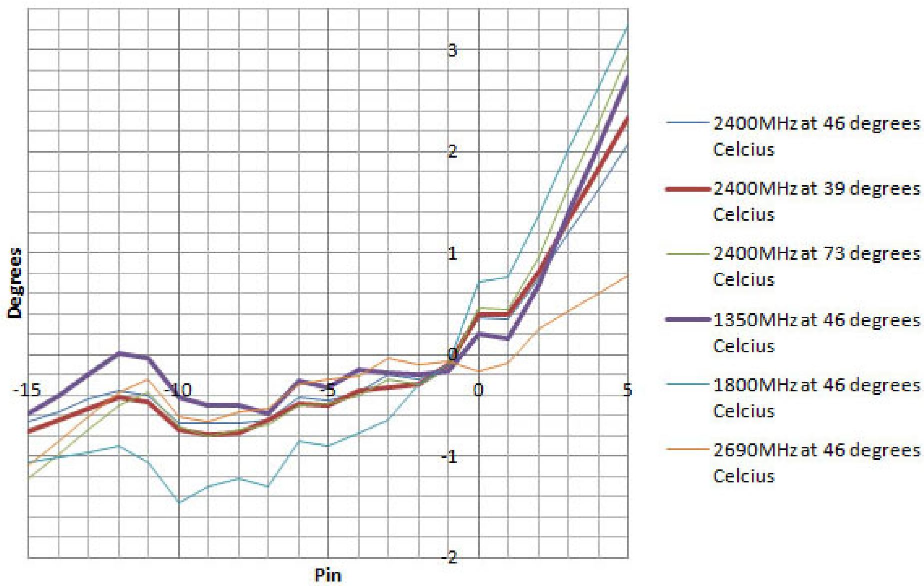

Figure 5.14: AM/PM

chosen because it is the operation point showing most nonlinearities. The IM products deviates up to 0,58 dB for third order IM levels, and up to 0,28 dB for fifth order IM levels. The temperature ranges from 39 ℃ to 73 ℃.

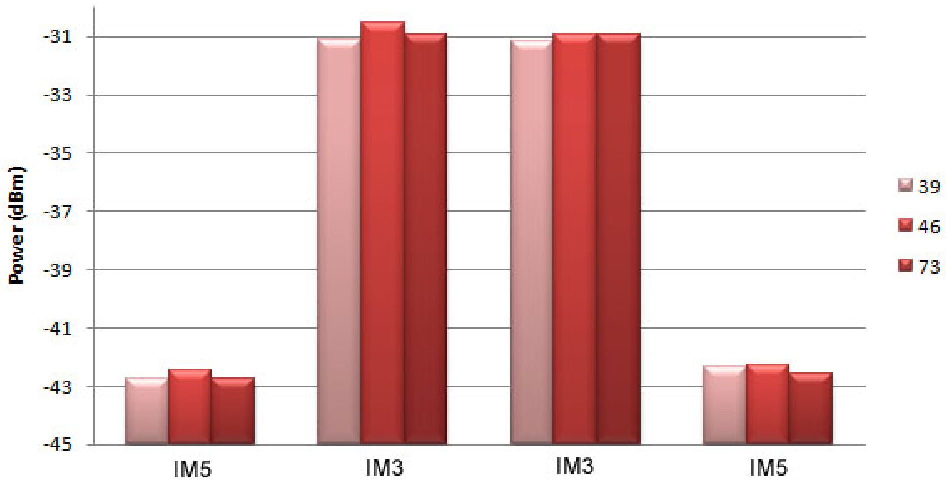

Figure 5.15: IM products at different temperatures

6

Discussion

6.1 The model

This predistorter was bound to the use of an open loop solution, making a memoryless design the only option. The radio will therefore have to rely on other linearization elements to avoid memory effects. The choice of transistors and materials in addition to a careful design of the bias circuitry have a big impact of the amount of memory effects present.

Predistorters which includes memory effects show performances of around 30 dB reduction of the IM products [4] [3]. Memoryless predistorters typically manage less than 10dB.

6.1.1 Behavioral versus physical modeling

Behavioral models are the easiest way of describing a PA. This black box approach makes the model applicable for many designs since the PA designers do not need to reveal their secrets to the people making the predistorter. The empirical measurements have large influence on the final results when this model is used.

Physical models requires extensive knowledge of the PA. The complexity of PAs often make the physical model unreachable.

6.1.2 Polynomials

As the modulation schemes becomes more complex, the PAR increases. This requires higher degrees of freedom for the polynomials trying to model the amplifier. Asymmetry in the IM bands and sharp cutoffs are also difficult for the polynomials. To model an amplifier which sharply goes into saturation is difficult even with a seventh order polynomial [7].

IM3 are the main contributor to compression and saturation effects at low input levels. As the PA is driven towards P1dB however, IM5 and IM7 may even dominate the distortion [4].

A LUT based model is careless about the degree of distortion, and models sharp saturations much easier. The complex mathematics which comes with the polynomial models is avoided to the benefit of the DSP units.

6.2 Two-tone test

The two-tone test gives a good insight in the theory of intermodulation products and is suitable as basis for calculating coefficients in a polynomial model. If digital predistortion based on lookup tables is used, modulated excitation signals are a better choice than two sine waves.

The internal radio modem was used to generate the two sine waves instead of two separate signal generators separated with a coupler. As a result, the two sine waves modulates each other. The two amplitudes is not exactly equal which causes asymmetry in the IM products. The spectrum analyzer shows a leak from the local oscillator in the modem which reaches up to approximately -20 dBc.

The ALC in the radio modem, however, showed a deviation of maximum 0,35 dB from the supposed 1,5 dB steps. Also, the resolution bandwidth of the spectrum analyzer is too small for the signal bandwidth, resulting in approximately 7 dB lower power measurements. Because of this, the measurements are not considered accurate enough to measure the loss of cables and the attenuator. These error sources applies however for all the test points. The measurement data is therefore still valuable to see how the PA acts at different parts of the bandwidth. Figure 5.4 on page 24 and 5.5 on page 25 shows how the PA suffers from most IM3 at the lower part of the frequency band.

6.3 The predistorter

The choice of predistorter method depends on the existing design, performance ambitions and the extra cost. If digital predistortion is chosen, it is really the model of the amplifier which makes a difference. The predistortion part of the process consists of the inversion of the PA characteristic, the creation of corrections and adding these to the original signal.

Whether a polynomial model is chosen or not, a DSP solution will include lookup tables. They may store the coefficients of the polynomial, or direct corrections to the signal. A polynomial model needs a larger logical part to solve for the corrections, while retrieving direct corrections demands less processing. The size of the LUT depends on the precision level needed.

The Digital to Analog Converter (DAC) following the DSP unit restricts the number of bits which can be used, again determining the precision level of the PA model. The predistorted signal is lowpass filtered before reaching the DAC. It is therefore very important to consider all the elements succeeding the predistorter to identify bottlenecks further down the chain.

6.4 Modulated excitation signals

Figure 5.7 on page 27 shows the spectrum of the 16QAM modeled signal with and without the predistorter matched to the operation point. The simulation shows no visible shoulders on the predistorted output signal. This represents the best possible outcome of this predistorter. The harmonics and the power spectrum outside the scope of the predistorter will probably be higher than before. This will increase the strain on the filters following the PA.

The AM/AM curve in figure 5.8 on page 27 of the predistorted signal almost overlaps with the linear gain curve. It may seem as if the amplifier no longer have a point separating these two curves with as much as 1 dB. This is of course not the case. Since this predistorter is a passive device, it is not able to restore the missing power when the main PA saturates. This ensures that the P1dB will not move too far from where it is in this figure 5.8 on page 27.

Figure 5.9 on page 28 shows how the AM/PM effects are virtually eliminated. The AM/PM curve of this PA deviates already less than 1 degree for most of the operating region, which indicate that AM/AM distortion is of most importance for this PA.

The 16QAM excitation is similar to the signals the PA will encounter during normal operation. This will give a more realistic model of the PA than what a two-tone test would have done.

The demodulated signal received from the signal generator will suffer from bit errors as long as the receiver is unaware of the exact bit sequence sent from the generator. This is possible to avoid using Matlab [6]. Less noise in the measurement can be obtained by synchronizing the signal generator and the VNA with a separate cable.

Since the PA is operating at the maximum output level, the measurement will be most accurate around this point. This is also the point where the PA suffers from most compression, and hence the point where the predistorter will be most effective. To achieve greater accuracy at lower power levels, the same measurements must be taken at lower operating points. In most cases however, the PA lies well inside the required boundaries at these levels.

An inaccurate model can cause the predistorter to be destructive. A few scenarios where the a mismatched predistorter is therefore set up, to give a picture of the performance as the memory effects kick in. The effect of the predistorter is mostly positive, and only one set showed slightly negative results.

6.5 Reducing distortion

The PA is currently running at an operation point well backed off from the P1dB. An operating point closer to the P1dB means increased efficiency and transmitting range. If the 16QAM modulation should be upgraded to 64QAM the operation point will have to be further backed off, as the PAR increases with the number of constellation points.

The IP3s is not used in this measurement. The inaccuracy of the actual data points close to P1dB makes it difficult to compare PAs using this measure.

Figure 5.10 on page 29 gives a maximum performance for this model. Figure 5.11 on page 29 is probably giving a better picture, as memory effects will make this model mismatched much of the operating time. This diagram shows the results when correction values for wrong operating point distorts the signal. Only one of the tests shows slightly destructive results, and most of the time IM3 are reduced approximately 9 dB and IM5 4 dB.

Figure 5.12 on page 30 shows how the operating point 2400 MHz at 39℃ has the highest P1dB. This is an indication that this operating point is the most linear one, which corresponds well with the relative AM/AM curves in figure 5.13 on page 31. The operation points with the lowest and highest P1dB are drawn in bold. The same reasoning can however not be based on figure 5.14 on page 31.

6.6 Asymmetry

Figure 5.1 on page 22, 5.2 on page 22 and 5.3 on page 23 shows the asymmetry in the IM products. The asymmetry changed with frequency, reaching a maximum of 8,21 dB at 2400 MHz for the IM5.

AM/AM and AM/PM distortion do not happen with perfect synchronization. This creates asymmetry in the IM products [3]. Some of the asymmetry seen in the two-tone test comes from the amplitude levels of the fundamentals being unequal. Unintentional modulation of the bias network is also a common cause of asymmetrical IM products.

6.7 Temperature effects

Temperature effects are defined as the variations in the transconductance g_m of the transistor, and hence the gain of the PA since to the transistor is temperature dependent. Ambient temperatures and running time will decide the large variations, while high and low peaks will represent a faster change of the temperature. Since thermal impedance has a large time constant, narrowband applications with slow-varying envelopes suffers more from these effects than wideband applications. The wideband applications' fast envelope fluctuations keep the dissipated power almost fixed to an average value, and hence the temperature of the device nearly constant [7].

Variation due to temperature changes is only measured at three points. Since no temperature chamber was available, the PA was measured at 39℃ as the radio was turned on after resting. The ambient temperature was around 21℃ and typical operation temperatures around 46℃. It was forced to reach 76℃ by unscrewing the cooling ribs. These three test points are meant to simulate different ambient temperatures.

As seen from figure 5.15 on page 32 the PA quite resistant to these temperature changes at 2400 Mhz. This suggests that not too many different temperature points need to be included in the collection of lookup tables.

6.8 Implementation

As seen in appendix A on page 43, there is a field-programmable gate array (FPGA) in front of the PA. This unit includes among other things the radio modem which generated the sinuses for the two-tone test. The FPGA contains 160 memory blocks of 16kb (2 kilobytes). The predistorter may occupy 6-8 blocks, which limits the size of the look-up tables.

This model is using linear interpolation to map the input to the correct output. An intermodulation scheme may also be used between two neighboring entries in the LUT to decrease the size.

In the current model the entries are filled up with 54 bit numbers. The LUTs in the model includes 21 entries per frequency point. The IM3 products fluctuates about 6 dB along the bandwidth. Because of this, the frequency steps might have to be held small in a complete model. The chosen model contains 8 tables using steps of 200 kHz. In addition, the tables should cover different operating temperatures, in this case cold, medium and warm. And finally the I and Q channel need a table each. This adds up to 48 tables giving a total of 1008 entries.

With 4 digits per entry, each entry needs 14 bits and the whole set of table uses 14,112 kb, which is not more than a single memory block. This leaves reasonable room for extension of the model if more accuracy is needed.

The FPGA however uses 12 bits, limiting the output numbers at I and Q channel to a number between 0-4096. Not all of the dynamic range is used, but the total signal may have to be scaled down. This will cause implications to the rest of the chain following the FPGA. The DAC limits the number of bits, and the vector modulator and filters following must be examined to see if they can handle the scaling.

Before applying any predistortion scheme to system, a commercial manufacturer should check if patents apply. Digital predistortion, both with and without memory, is a heavily patented area, and most of the techniques presented in [3] lies under patent.

7 Conclusion

A memoryless predistorter is created for a power amplifier(PA) used in a high end radio link. The PA is modeled by empirical measurements covering different temperatures and frequencies.

The traditional two-tone test has been discarded, and a modulated signal is used instead. The 16QAM [1] signal is similar to what is normally used by the amplifier.

A behavioral model is made based on lookup tables(LUTs). This allows the PA to be linearized without extensive knowledge of its internals. The intuitive digital predistorter with lookup tables, is a reasonable choice for a memoryless predistorter.

The predistorter consists of an open loop design which uses lookup tables to correct the signal before it is sent to the PA. It corrects the I and Q channel at baseband, and needs therefore one LUT per channel.

The simulations in AWR VSS show an average reduction of third order intermodulation levels of 18,3 dB and fifth order IM levels of 9,3 dB. The largest reduction of third order IM levels is 21,35 dB.

Since a memoryless predistorter is likely to become mismatched due to memory effects, some measurements were taken where the signal is predistorted with corrections from another operating point. This results in an average reduction of 10,3 dB of third order IM levels, and 4,4 dB of fifth order IM levels. These simulation results look very promising for real testing.

The main reason to choose a memoryless predistorter is the low cost and easy implementation. An existing design might also require an open loop predistorter. The choice then remains whether to use a polynomial of some kind or a lookup table to model the PA. Choosing the best polynomial for

[1] quadrature amplitude modulation with 16 points

the PA characteristic and develop the right coefficients is a complex task. The intuitive lookup table, with short design time, is a reasonable choice for memoryless predistorters.

A later upgrade to a closed loop predistorter including memory effects, can reuse the existing predistorter. The increase in performance may this time justify the development of a polynomial model of the PA.

7.1 Further work

The digital predistorter demonstrated is based on simulations. The assumptions of a "memoryless environment" calls for implementation and a real tests to see the true performance of this predistorter.

The characterization process may be optimized for production by controlling every aspect of the measurement setup from Matlab [6]. A stream lined production depends on good methods of characterizing each PA.

Before implementation, more thorough measurements should be done to ensure the quality of the PA model. The model is critical to the end results, and it needs more precision than it has at this point. It needs also to include lower power levels taken at smaller frequency steps. All these test should be taken at several temperatures.

The precision level needed is also interesting, as it will reduce characterization time to a minimum. Since each PA needs separate characterization, this could decrease production time considerably.

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A

Appendix A: System description from KDA

KONGSBERG

Masteroppgave for IET ved NTNU i 2009 fra RF-gruppe i Kongsberg Defence and Aerospace / Defence Communications

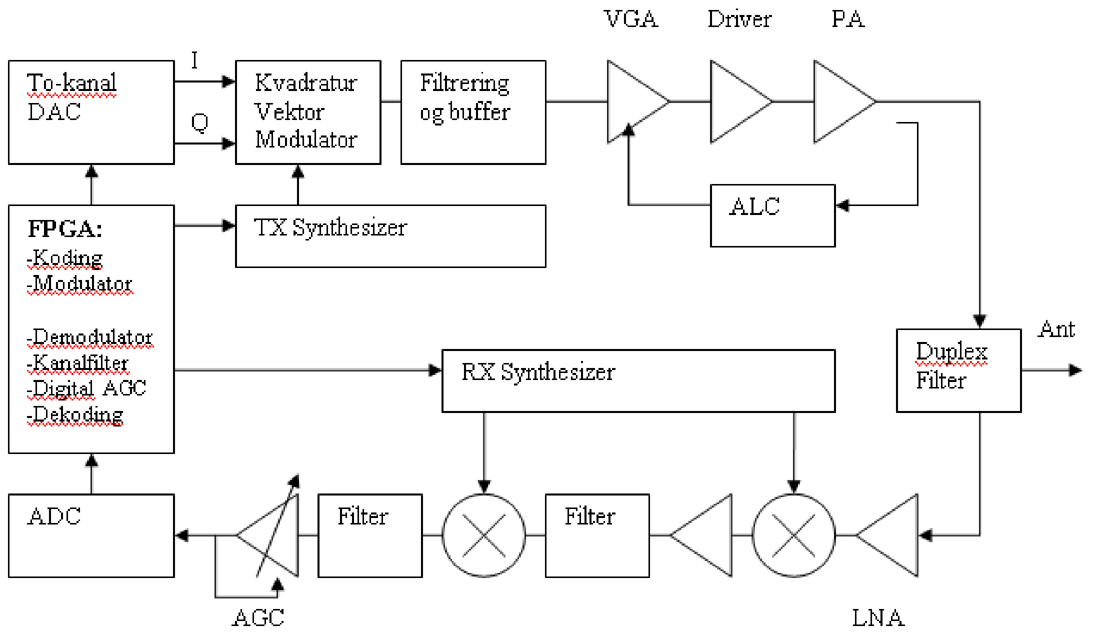
Dokument nummer:
Rev.:
Dato: 2008-11-06
Forfatter: PTEK / GHA

1.INNLEDNING

Kongsberg Defence and Aerospace har en avdeling som utvikler militære kommunikasjonssystemer. Avdelingen heter Defence Communications og holder til på Billingstad i Asker

En radiolinje er en full dupleks punkt-til-punkt radio. Våre radiolinjer opererer med datarater fra 256kbps til 16384kbps og vi bruker frekvensdelt multipleksing. Radioen sender og tar altså i mot samtidig, men ikke på samme frekvens. Avstanden mellom senderfrekvens og mottakerfrekvens kalles dupleksavstand, og er i dette tilfellet på ≥50 MHz. Den aktuelle radioen for denne oppgaven går i frekvensbåndet 1350MHz til 2690MHz (NATO Bånd 3). Uteffekt er omkring 2W (+33dBm) og modulasjon er 16-QAM.

Dagens radiolinjer er tradisjonelt bygget opp, med dobbelt superheterodyn mottaker, sampling på andre mellomfrekvens og direkte konvertering i senderen, se forenklet blokkskjema:



2.MASTER/HOVEDOPPGAVE

2.1 Linearisering/predistorsjon av effektforsterker i NATO Bånd III+

For å ha tilstrekkelig lineær sender, kjører KDA i dag 16-QAM signalene med back-off i forhold til maksimal utgangseffekt tilgjengelig fra effektforsterkeren. Grovt forenklet må man kjøre med en back-off fra 1dB kompresjonspunktet omtrent som Peak-to-Average-Ratio (PAR) i det modulerte signalet, dvs ca 5 dB for 16-QAM (avhengig av roll-off med mer).

Det er ønskelig å kunne kjøre forsterkeren nærmere 1dB-punktet, men da må signalet forvrenges på forhånd (Pre-distortion) slik at det etter å ha blitt kjørt gjennom den ulineære forsterkeren ser ut som om det er kjørt i en lineær forsterker. Altså slik at pre-distortion og ulinearitet kansellerer hverandre. Videre ser vi på å gå opp fra 16-QAM til 64-QAM, noe som stiller enda strengere krav til linearitet.

Det finnes en rekke teknikker for dette, bl.a. feed-back, feed-forward, open loop og polar loop med flere. KDA ønsker at studenten i denne oppgaven ser på et open loop system, eventuelt med en vurdering av hvilke forbedringer som kunne vært oppnådd med kunnskap om effektnivå på utgang av forsterkeren.

Oppgaven bør starte med et litteraturstudie med formål å velge en modell for forsterkeren. En mulighet er å lage en "behavioral" modell av forsterkeren. En slik modell befatter seg ikke med de kretstekniske løsninger, men ser kun på signal inn og ut av enheten. Alternativ kan man modellere forsterkeren i en ulineær modell på kretsnivå i AWR Microwave Office.

Trinn to vil være å lage en modell for KDA sin effektforsterker. Ideelt sett for hele frekvensområdet og aktuelt temperaturområde, men for å begrense omfanget kan man konsentrere seg om en eller tre frekvenser (nederst, øverst og midt i båndet) og romtemperatur. Modellen bør som minimum modellere tredjeordens effekter.

Modellen bør så verifiseres mot målte data i en simulator. Da KDA bruker AWR Microwave Office og Visual System Simulator, ser vi helst at studenten benytter samme verktøy, eventuelt sammen med/koplet til Matlab.

På bakgrunn av litteraturstudiet og modelleringen kan så en metode for å linearisere forsterkeren tas frem. Et mål kan være å senke tredje ordens intermodulasjonsprodukter med 6 dB, noe som grovt regnet vil gi mulighet for å øke uteffekt 2 dB. KDA foreslår å fokusere på 3. ordens effekter i denne oppgaven, da de dominerer. Lineariseringen bør skje gjennom manipulasjon av I og Q-signalene på basebånd.

Da modemet i radioen hvor basebånd I og Q er tilgjengelig er relativt komplisert, regner KDA med at oppgaven avsluttes med simulering av predistorter i Visual System Simulator for å vurdere effekten av lineariseringen.

B

Appendix B: RL532A Specifications

KONGSBERG

RL532A – Tactical Radio Link

A new generation Eurocom and IP radio

The RL532A Radio Link provides reliable and secure communications in a hostile electronic warfare (EW) environment.

Unique ECCM/EPM methods include automatic output power control, adaptive frequency hopping, AFE and PJP techniques.

ECCM/EPM
For data rates 256 to 2048 kbit/s RL532A offers Basic-, Double-Rate,- and Adaptive Frequency hopping. In the unique AFH mode, a jammed frequency will automatically be removed from the hop set.

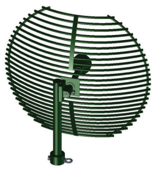
Fixed frequency narrow band radio connections at 2048, 8448 and (opt.)16384 kbit/s are provided to accommodate modern network structures and data transfer needs.

ECCM/EPM features for fixed frequency services (16QAM) include **APC** - Automatic Power Control: Power output is automatically reduced to the minimum needed - to avoid detection, and automatic step-up at jamming or interference).
AFE - Automatic Frequency Evasion: at interference - automatic switchover to a good frequency pair.
PJP - PulseJammer Protection: Advanced channel coding techniques (FEC and Interleaving) in combination with a pulse-jammer detection algorithm that prevents loss of synchronization.

MMI
The RL532A is self-instructing with a high degree of automatic functions for ease of operation. A radio link can be configured and established in a very short time.

The terrestrial interface-type is selectable by operator for flexible network integration.

An integral Network Data Carrier system provide quick and easy network establishment and elimination of operator errors. The operator has access to all radio parameters and O&M-information using a local PC or (opt.)remotely from the EriTac System CMS computer (Communication Management System).



High gain grid antenna
1350 - 2700 MHz
Typical gain: 26dBi

Features:
- Light weight and small – Easy handling
- Narrow band modulation – 16 QAM available for 2048, 8448 and (opt.)16384 kbit/s
- Quick Deployment – Efficient link establishment and planning
- Field proven equipment – Reliable principles of operation
- Advanced Frequency Hopping algorithms (FSK) from 256 up to 2048 kbit/s.
- Designed for a multi-vendor System Environment (international standards) – Flexible data interface and (option) SNMP based management
- SW defined modulation
- Interfacing of routers in an IP-based network – two separate IEEE 802.3 Ethernet interface are available, one dedicated to data traffic and one for RL management

W O R L D C L A S S - through people, technology and dedication

Specifications

Rack with RL532A, Bulk Encryption Unit CD510 and Multimedia Switch CPX300

General

Frequency Range	1,35 – 2,69 GHz
Duplex Space	Minimum 50 MHz
Channel Spacing	125 kHz (500kHz for 16384 kbit/s)
Transmission Capacity	256, 512, 1024, 2048, 8448, and (opt.)16384 kbit/s, *
Modulation	FSK / 16 QAM *
Order Wire	Digital 16 kbps ADPCM

Transmitter

Output Power	5 W (+37dBm)
Auto mode dynamic range	20 dB
Spurious Attenuation	80 dB
Harmonic Attenuation	60 dBc for 2nd & 3rd harmonics 80 dBc for higher order

Receiver

Spurious Attenuation	80 dB for freq outside f_c ± 3%
Sensitivity	
256 kbit/s	-100 dBm (B-FSK)
512 kbit/s	-97 dBm (B-FSK)
1024 kbit/s	-94 dBm (B-FSK)
2048 kbit/s	-91 dBm (B-FSK)
2048 kbit/s	-92 dBm (16 QAM)
8448 kbit/s	-86 dBm (16 QAM)
16384 kbit/s(opt)	-82 dBm (16 QAM)

Port Interfaces

Router Interface:
IEEE802.3 Ethernet 10/100 baseT
ITU V.11

Eurocom "D/1"

Physical Interface	4 balanced pairs
Level Data	1V p-p (AMI) ± 15%
Level Clock	1V p-p (NRZ) ± 15%
Impedance	130 ohm balanced

ITU V.11

Physical Interface	4 balanced pairs
Level Data	4V p-p (NRZ) ± 15%
Level Clock	4V p-p (NRZ) ± 15%
Impedance	100 ohm balanced

G.703 HDB3

Physical Interface	2 balanced pairs
Level Data	± 2,37 V ± 10%
Impedance	120 ohm balanced

ECCM

In Conventional FH Mode:

256 kbps	13 dB
512 kbps	13 dB
1024 kbps	10 dB
2048 kbps	7 dB

In Adaptive FH Mode:
256, 512, 1024 and 2048 kbps
A fixed partial band jammer, blocking 70% of the spreading BW with jammer channel ≥ 20 dB stronger than wanted signal, shall be excluded within 2 seconds for all data rates.

Dimensions and Weight

Height	177 mm
Width (total)	483 mm
Depth (total)	385 mm
Weight:	<21 kg

*** Options (opt.):** Other modulation methods and 34 Mbit/s data rate

Power Supply

Input Voltage:	19-32 V DC
Power consumption, typical	120W

LZTR 103047 Rev. E1 opt_redused size, 2008.09.19

KONGSBERG

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C

Appendix C: Two-tone test

Measurement of input signal to PA versus output signal from PA.

Input Frequency	Power level	1st harmonic IM							
		7th	5th	3rd	1st	1st	3rd	5th	7th
1350	Const.	-74,71	-72,25	-57,33	-7,22	-7,22	-57,1	-72,06	-75,07
1500		-75,83	-73,36	-56,98	-7,44	-7,43	-57,4	-71,98	-76,77
1650		-76,83	-71,4	-56,01	-7,27	-7,26	-56,54	-70,72	-74,27
1800		-76,71	-70,48	-55,37	-7,31	-7,29	-55,79	-69,54	-74,88
1950		-74,51	-69,31	-54,74	-6,69	-6,69	-54,7	-69,37	-74,94
2100		-76,24	-69,35	-55	-6,83	-6,86	-55,45	-69,25	-75,91
2250		-80	-69,7	-55,21	-6,65	-6,66	-55,75	-69,47	-80
2400		-75,89	-70,2	-56,66	-6,89	-6,9	-57,18	-69,64	-75,27
2550		-76,1	-70,09	-57,99	-6,96	-6,96	-58,57	-71,29	-76,71
2690		-80	-72,33	-59,02	-7,7	-7,71	-59,49	-72,4	-80

Output Frequency	Power level	1st harmonic IM							
		7th	5th	3rd	1st	1st	3rd	5th	7th
1350	16	-21,49	-5,9	12,41	36,46	36,44	12,49	-10,47	-15,98
2700	15	-22,38	-19,18	5,08	35,16	35,13	6	-20,09	-23,38
4050	14	-34,15	-26,77	0,72	33,7	33,67	1,68	-23,49	-38,66
	8	-43,14	-42,22	-18,14	24,67	24,67	-17,97	-41,85	-43,84
1500	16	-32,61	-6,51	12,3	36,01	35,99	12,33	-15,73	-19,83
3000	15	-22,52	-18,95	5,17	34,73	34,75	5,91	-21,8	-25,72
4500	14	-31,49	-29,17	1,04	33,34	33,33	1,9	-23,75	-37,37
	8	-44,48	-41,94	-16,35	24,39	24,39	-16,27	-41,89	-45,87
1650	16	-18,63	-5,62	14,16	35,93	35,91	13,98	-16,29	-23,75
3300	15	-22,39	-19,44	8,1	34,7	34,69	8,14	-29,51	-29,13
4950	14	-30,94	-27,74	3,01	33,3	33,28	3,47	-26,89	-34,8
	8	-43,72	-40,3	-16,03	24,35	24,35	-15,88	-40,5	-43,62
1800	16	-14,2	-9,59	10,86	35,91	35,89	10,3	-7,73	-19,03
3600	15	-27,96	-22,37	6,66	34,6	34,57	6,61	-32,71	-25,26
5400	14	-32,53	-23,88	2,18	33,18	33,17	2,61	-24,66	-34,93
	8	-42,86	-38,52	-16,38	24,13	24,14	-16,3	-38,43	-43,43
1950	16	-16,4	-13,51	9,65	35,87	35,87	9,4	-10,58	-17,48
3900	15	-32,15	-23,36	5,26	34,51	34,51	5,49	-31,89	-31,72
5850	14	-35,34	-26,89	0,86	33,1	33,12	1,41	-27,16	-36,98
	8	-44,66	-38,77	-15,85	24,05	24,09	-15,68	-38,41	-43,91
2100	16	-18,93	-16,76	8,95	35,98	35,96	9,01	-12,96	-20,77
4200	15	-37,05	-26,29	4,56	34,74	34,74	5,14	-33,64	-35,9
6300	14	-36,75	-31,31	0,41	33,29	33,28	1,32	-28,58	-38,06
	8	-43,46	-38,49	-15,35	24,17	24,16	-15,11	-38,27	-45,21
2250	16	-25,64	-35,02	6	35,8	35,79	6,74	-21,48	-35,68
4500	15	-32,93	-30,94	1,93	34,49	34,43	3,37	-26,49	-37,14
6750	14	-39,09	-36,48	-1,35	33,03	33	0,21	-29,16	-40,79
	8	-45,12	-38,32	-14,61	24,36	24,34	-14,5	-38,99	-45,26
2400	16	-16,75	-11,36	8,1	36,53	36,46	8,32	-19,57	-19,23

4800	15	-21,1	-38,46	2,66	35,37	35,32	3,71	-22,82	-23,75
7200	14	-30,76	-24,06	-1,25	33,87	33,84	0,88	-22,06	-35,49
	8	-50	-39,93	-14,27	25,09	25,07	-13,92	-38,75	-50
2550	16	-15,28	-11	5,62	36,11	36,03	6,73	-18,26	-15,77
5100	15	-21,45	-23,35	0,37	34,89	34,78	2,38	-18,37	-24,16
7650	14	-30,97	-22,24	-2,58	33,55	33,44	-0,1	-20,39	-37,9
	8	-43,33	-41,19	-15,04	24,64	24,64	-14,64	-38,47	-43,54
2690	16	-24,21	-5,82	8,54	35,79	35,75	9,84	-10,78	-18,62
5380	15	-18,44	-14,5	2,25	34,43	34,37	3,93	-17,42	-20,47
8070	14	-29,22	-22,98	-2,52	32,99	32,95	-0,67	-20,16	-35,78
	8	-45,75	-41,31	-17,07	23,83	23,82	-16,66	-41,1	-46,31

1st harmonic LO leak			2nd harmonic IM							2 nd harmonic LO leak		
3rd	1st	3rd	7th	5th	3rd	2nd	3rd	5th	7th	3rd	3rd	5th
-65,92	-55,5	-65,96	-80	-80	-64,04	-56,6	-64,52	-80	-80	-65,34	-65,92	-80
-60,12	-58,97	-60,32	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80
-63,39	-54,27	64,05	-80	-80	-76,37	-72,6	-77,39	-80	-80	-75,55	-77,08	-80
-68,02	-59,4	-66,06	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80
-57,6	-59,88	-58,45	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80
-59,89	-53,47	-59,5	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80
-59,52	-63,62	-59,93	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80
-66,85	-66,72	-66,17	-80	-80	-80	-67,5	-80	-80	-80	-80	-80	-80
-63,12	-61,82	-61,86	-80	-80	-80	-72,6	-80	-80	-80	-80	-80	-80
-61,65	-64,06	-64,67	-80	-80	-80	-80	-80	-80	-80	-80	-80	-80

1st harmonic LO leak			2nd harmonic IM							2 nd harmonic LO leak		
3rd	1st	3rd	7th	5th	3rd	2nd	3rd	5th	7th	3rd	3rd	5th
-24,93	-12,14	-25,2	-13,59	-1,84	8,63	16,15	8,38	-1,96	-15,13	-27,86	-27,54	-13,28
-25,04	-13,84	-25,07	-26,5	-15,77	7,97	14,16	7,7	-15,69	-29,22	-28,95	-28,22	-17,97
26,88	-14,76	-26,2	-50	-25,34	5,3	11,33	5,11	-24,39	-42,95	-30,67	-30,06	-25,72
-34,63	-24,09	-35,38	-50	-45,57	-10,98	-5,32	-10,95	-44,63	-46,22	-40,71	-41,07	-50
-15,88	14,09	16,2	-19,42	-11,27	2,62	9,76	2,31	-11,2	-22,06	-50	-45,13	-15,34
-17,58	-16,34	-17,88	-32,99	-29,97	1,27	7,25	0,99	-28,38	-36,53	-50	-50	-19,81
-19,29	-17,37	-19,34	-45,18	-32,98	-1,9	4,13	-2,14	-36,38	-44,73	-50	-50	-27,24
-28,22	-26,55	-28,7	-50	-50	-19,17	-13,1	-19,26	-50	-50	-50	-50	-50
-18,5	-13,11	-18,84	-23,97	-16,45	-10,9	-1,29	-10,83	-16,68	-24,49	-50	-50	-22,12
-21,1	-13,57	-21,14	-31,92	-19,73	-9,7	-2,13	-9,86	-19,7	-33,76	-50	-50	-24,77
-22,3	-14,54	-23,53	-40,52	-25,21	-10,69	-3,92	-10,85	-25,44	-40,23	-50	-50	-32,87
-33,42	-22,5	-33,05	-50	-50	-26,13	-20,3	-26,37	-50	-50	-50	-50	-50
-23,35	-15,54	-23,27	-23,3	-23,1	-8,67	-5,59	-8,29	-22,1	-23,38	-50	-50	-20,54
-24,93	-17,7	-24,55	-44,95	-20,48	-14,83	-13,6	-14,6	-20,41	-41,2	-50	-50	-24,39
-27,57	-18,85	-25,48	-40,81	-27,68	-28,52	-25,4	-27,67	-28,2	41,45	-50	-50	-32,48
-36,19	-27,24	-34,16	-50	-50	-41,91	-34,9	-40,24	-50	-50	-50	-50	-50
-15,16	-16,76	-15,15	-22,5	-22,77	-3,87	0,83	-3,7	-20,81	-22,32	-43,24	-46,36	-22,77
-16,96	-18,6	16,93	-37,39	-21,47	-8,44	-4,44	-8,33	-21,33	-36,42	-45,48	<-50	-26,75
-17,93	-19,97	-18,37	-39,54	-27,06	-15,11	-10,6	-15,16	-27,64	-39,83	-50	-50	-33,8
-26,29	-29,07	-27,37	-50	-50	-37,2	-32,8	-37,55	-50	-50	-50	-50	-50
-16,26	-8,51	-15,66	-32,32	-30,59	-11,54	-6,57	-11,24	-28,56	-31,15	-50	-50	-27,78
-17,72	-10,22	-17,56	-50	-30,77	-16,23	-11,5	-16,13	-30,62	-50	-50	-50	-33,69
-19,58	-12,05	-19,09	-50	-39,21	-21,84	-16,3	-21,6	-39,28	-50	-50	-50	-50
-28,38	-21,34	-28,54	-50	-50	-41,01	-35,1	-40,7	-50	-50	-50	-50	-50
-16,7	-18,69	-17,36	-50	-32,63	-17,75	-12,7	-17,35	-33,05	-45,37	-50	-50	-28,04
-18,23	-20,81	-18,49	-50	-38,25	-22,13	-16,4	-22,03	-39,37	-50	-50	-50	-33,12
-19,76	-22,18	-19,89	-50	-50	-26,03	-20,2	-26,2	-50	-50	-50	-50	-38,58
-27,98	-31,1	-38,64	-50	-50	-41,52	-36,9	-40,43	-50	-50	-50	-50	-50
-25,09	-21,89	-21,51	-40,56	-29,83	-12,56	-7,43	-12,32	-29,53	-40,82	-50	-50	-12,93

-25,39	-22,61	-23,4	-43,47	-33,45	-16,99	-11,8	-16,94	-34,03	-43,32	-50	-50	-18,41
-26,92	-24,25	-24,76	-50	-44,91	-21,61	-15,9	-21,53	-45,58	-50	-50	-50	-26,08
-34,99	-32,79	-34,54	-50	-50	-38,91	-33,2	-39,72	-50	-50	-50	-50	-50
-18,6	-18,9	-20,02	-50	-42,6	-26,7	-22	-26,97	-41,55	-50	-50	-50	-18,01
-20,66	-20	-20,28	-50	-50	-31,11	-26,1	-30,98	-45,11	-50	-50	-50	-23,33
-22,45	-20,66	-22,65	-50	-50	-35,32	-29,9	-35,3	-50	-50	-50	-50	-30,12
-31,04	-29,46	-31,39	-50	-50	-50	-50	-50	-50	-50	-50	-50	-50
-18,19	-21,62	-20,52	-44,42	-39,09	-21,24	-16,9	-21,81	-39,73	-50	-50	-50	-23,49
-19,64	-22,95	-22,19	-50	-41,55	-25,91	-21,3	-26,26	-42,02	-50	-50	-50	-28,12
-20,56	-23,73	-23,08	-50	-43,05	-30,87	-26	-30,88	-50	-50	-50	-50	-33,36
-29,52	-33,44	-32,3	-50	-50	-50	-43,2	-50	-50	-50	-50	-50	-50

3rd harmonic IM			Temp		Currents			
3rd	3rd	5th	HPA	LPA	LPA 1	LPA2	HPA 1	HPA 2
-73,46	-73,85	-80						
-72,7	-72,23	-80						
-74,9	-75,24	-80						
-80	-80	-80						
-80	-80	-80						
-80	-80	-80						
-80	-80	-80						
-80	-80	-80						
-71,52	-71,26	-80						
-72,37	-72,24	-80						

3rd harmonic IM			Temp		Currents			
3rd	3rd	5th	HPA	LPA	LPA 1	LPA2	HPA 1	HPA 2
-4,69	-4,77	-13,48	37	31	564	558	548	526
-10,5	-10,66	-18,42	38	31	534	527	519	503
-17,3	-17,4	-26,14	40	33	509	504	497	487
-43,72	-42,7	-50	47	40	457	454	461	456
-6,49	-6,53	-15,54	44	37	579	571	562	528
-12,2	-12,28	-19,93	42	35	542	536	530	504
-17,48	-17,73	-24,94	40	34	515	513	508	489
-45,87	-46,9	-50	38	32	456	457	467	462
-12,4	-12,41	-22,34	39	33	607	578	581	548
-17,48	-17,73	-24,94	39	33	559	543	539	518
-25,27	-25,34	-32,95	39	33	527	516	512	496
-50	-50	-50	40	33	460	457	465	462
-11,88	-11,86	-21,04	40	34	559	570	563	555
-17,31	-17,4	-24,95	40	34	528	536	527	519
-24,71	-24,45	-32,03	38	31	504	512	499	496
-50	-50	-50	39	33	457	460	461	460
-13,81	-13,84	-23,03	40	33	536	555	540	558
-19,2	-19,29	-27,24	43	36	509	527	511	522
-25,83	-25,81	-33,02	41	35	492	504	495	500
-50	-50	-50	41	35	457	460	465	462
-19,9	-20,01	-29,07	38	31	513	570	544	543
-25,43	-25,56	-32,83	37	31	516	536	520	516
-31,79	-31,77	-39,17	37	31	497	513	500	462
-50	-50	-50	38	32	458	460	465	462
-20,77	-21,13	-27,35	40	33	562	567	543	519
-25,84	-25,55	-33,04	38	33	534	542	516	501
-31,89	-31,64	-39,75	38	33	509	518	500	488
-50	-50	-50	39	33	461	461	467	462
-5,44	-5,48	-13,13	40	33	624	614	539	539

-11,02	-10,98	-18,62	40	33	581	578	515	515
-17,76	-17,8	-26,02	40	33	546	544	499	496
-44,12	-44,25	-50	40	34	467	465	465	462
-10,11	-10,15	-18,29	40	33	634	613	524	531
-15,56	-15,55	-23,65	40	34	591	575	507	512
-21,45	-21,43	-29,9	44	38	551	542	493	497
-45,35	-46,02	-50	43	36	469	464	465	464
-15,34	-15,49	-24,51	42	34	644	629	530	505
-20,17	-20,2	-28,14	42	35	603	583	511	495
-26	-26,02	-34,44	42	35	566	546	497	484
-50	-50	-50	42	35	469	467	465	461

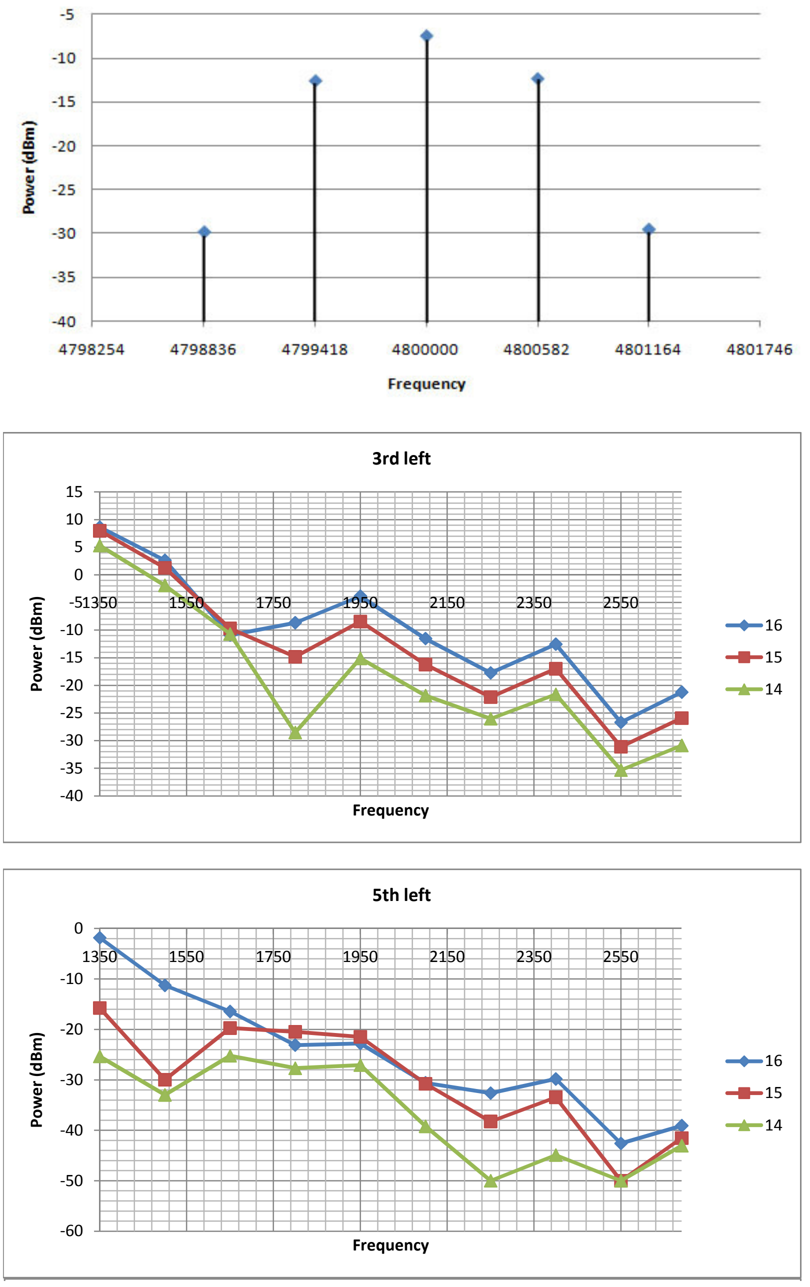

Figure C.1: Second harmonic power spectrum with third and fifth order lower IM products

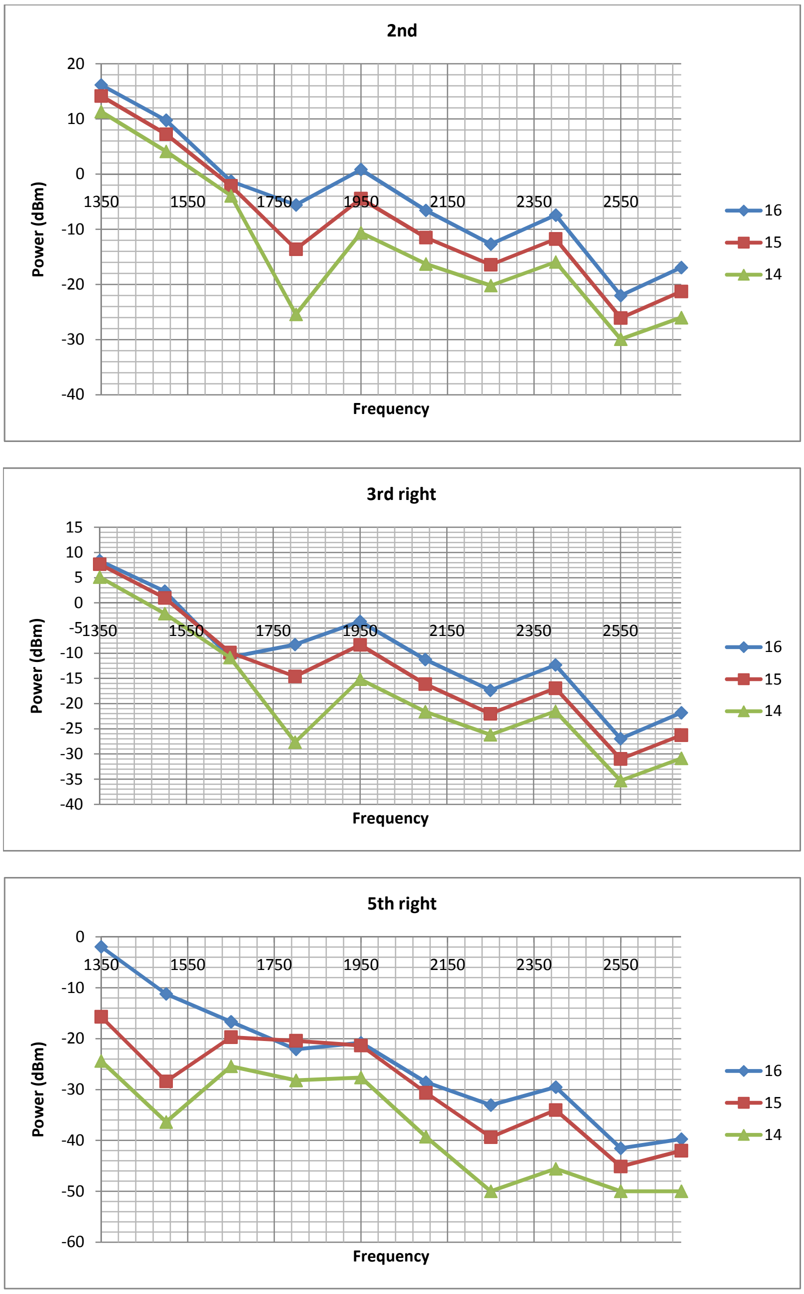

Figure C.2: Second harmonic, third and fifth order upper IM products

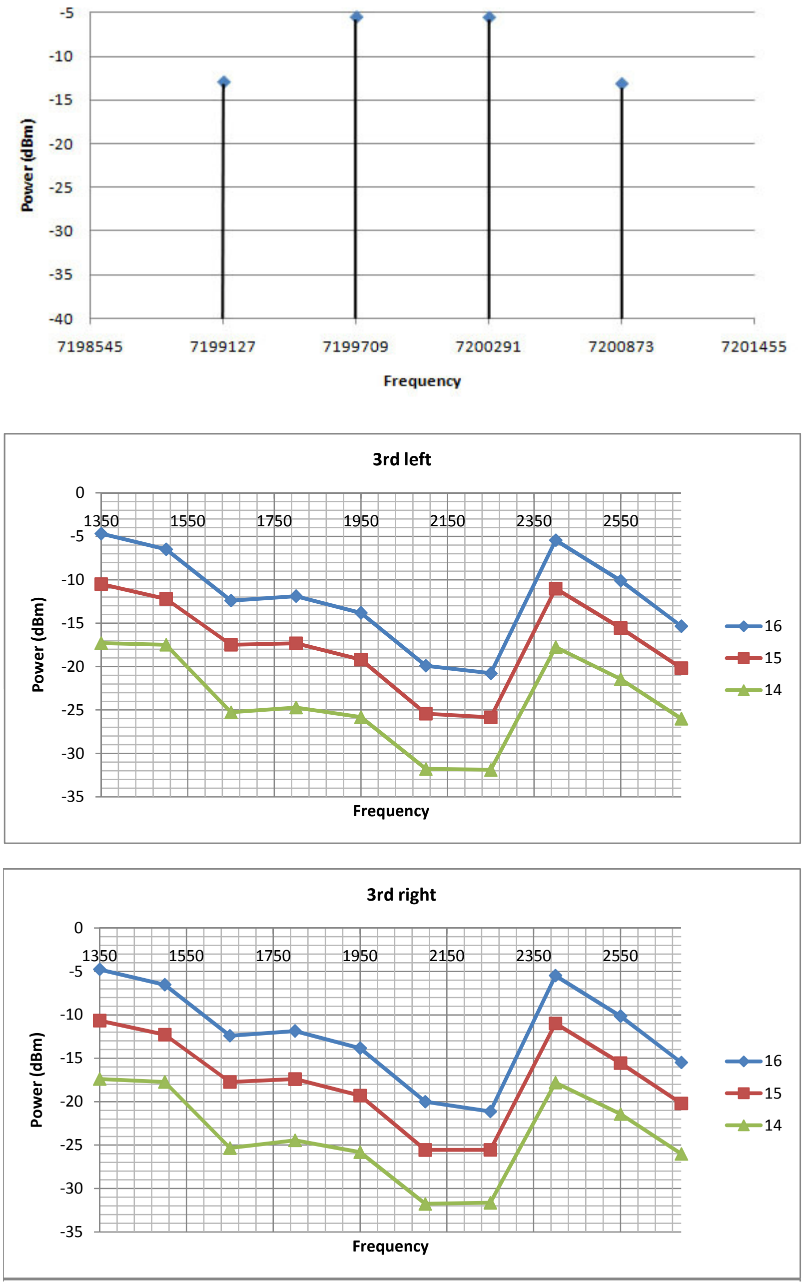

Figure C.3: Third harmonic power spectrum and third order IM products

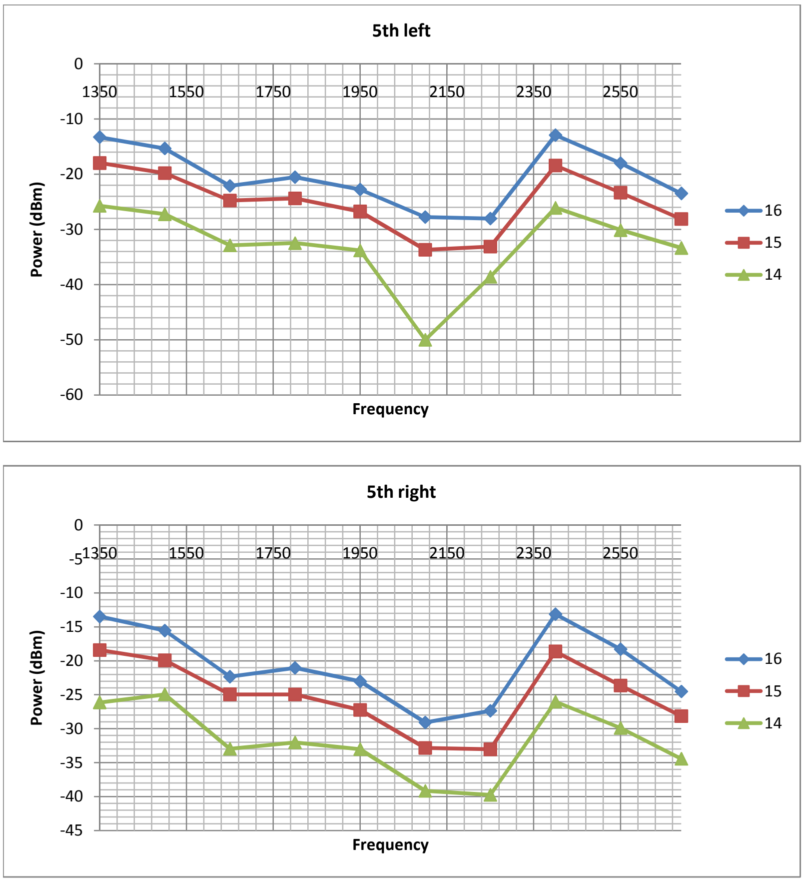

Figure C.4: Fifth order IM products to the third harmonic signal

D

Appendix D: 16QAM modulated signal

Pin	2400MHz at 46 degrees Celcius			2400MHz at 39 degrees Celcius		
	Rel Pout	Pout	Phase out	Rel Pout	Pout	Phase out
dBm	dBm	dBm	degrees	dBm	dBm	degrees
-15	0,29	28,5	-0,67	0,26	28,47	-0,76
-14	0,31	29,52	-0,57	0,28	29,49	-0,65
-13	0,33	30,54	-0,44	0,3	30,51	-0,53
-12	0,35	31,56	-0,36	0,32	31,53	-0,42
-11	0,36	32,57	-0,4	0,33	32,54	-0,47
-10	0,36	33,57	-0,68	0,31	33,52	-0,75
-9	0,31	34,52	-0,68	0,29	34,5	-0,79
-8	0,27	35,48	-0,68	0,25	35,46	-0,77
-7	0,22	36,43	-0,64	0,19	36,4	-0,65
-6	0,2	37,41	-0,43	0,18	37,39	-0,48
-5	0,16	38,37	-0,46	0,13	38,34	-0,5
-4	0,15	39,36	-0,37	0,13	39,34	-0,36
-3	0,12	40,33	-0,2	0,1	40,31	-0,33
-2	0,08	41,29	-0,24	0,07	41,28	-0,29
-1	0,02	42,23	-0,11	0,02	42,23	-0,11
0	-0,15	43,06	0,36	-0,15	43,06	0,4
1	-0,18	44,03	0,35	-0,16	44,05	0,4
2	-0,4	44,81	0,74	-0,37	44,84	0,81
3	-0,68	45,53	1,2	-0,62	45,59	1,33
4	-0,95	46,26	1,63	-0,86	46,35	1,83
5	-1,21	47	2,07	-1,11	47,1	2,33
Avg Pin		-6,02			-4,96	
Avg Pout		37,19			38,81	
Linear gain		43,21			43,77	

Including real losses

From generator	-7
FSQ offset	31

The offset used in the measurements are switched with correct numbers from table under.

Losses in cables and connections

Frekvens	Inn-kabel uten skjøt	Inn-kabel med skjøt	Utkabel og dempeledd
1350	-0,68	-1,43	-30,62
1800	-0,81	-1,69	-30,74
2400	-0,98	-2,04	-30,89
2690	-1,09	-2,19	-30,97

2400MHz at 73 degrees Celcius			1350MHz at 46 degrees Celcius		
Rel Pout dBm	Pout dBm	Phase out degrees	Rel Pout dBm	Pout dBm	Phase out degrees
0,26	28,47	-1,23	0,43	28,64	-0,59
0,28	29,49	-0,99	0,45	29,66	-0,4
0,29	30,5	-0,75	0,47	30,68	-0,2
0,31	31,52	-0,5	0,48	31,69	0,01
0,33	32,54	-0,38	0,5	32,71	-0,04
0,33	33,54	-0,71	0,5	33,71	-0,42
0,3	34,51	-0,81	0,46	34,67	-0,51
0,27	35,48	-0,74	0,41	35,62	-0,51
0,21	36,42	-0,7	0,34	36,55	-0,58
0,2	37,41	-0,5	0,31	37,52	-0,27
0,15	38,36	-0,49	0,24	38,45	-0,32
0,14	39,35	-0,4	0,22	39,43	-0,15
0,1	40,31	-0,24	0,18	40,39	-0,19
0,09	41,3	-0,3	0,13	41,34	-0,2
0,02	42,23	-0,15	0,03	42,24	-0,17
-0,17	43,04	0,46	-0,28	42,93	0,2
-0,19	44,02	0,44	-0,31	43,9	0,15
-0,41	44,8	0,96	-0,65	44,56	0,69
-0,68	45,53	1,64	-1,06	45,15	1,38
-0,94	46,27	2,29	-1,45	45,76	2,06
-1,2	47,01	2,95	-1,85	46,36	2,73
	-4,96			-5,57	
	38,68			38,72	
	43,64			44,29	

1800MHz at 46 degrees Celcius			2690MHz at 46 degrees Celcius		
Rel Pout dBm	Pout dBm	Phase out degrees	Rel Pout dBm	Pout dBm	Phase out degrees
0,52	28,73	-1,06	0,31	28,52	-1,1
0,54	29,75	-1,01	0,33	29,54	-0,86
0,56	30,77	-0,96	0,35	30,56	-0,62
0,59	31,8	-0,91	0,37	31,58	-0,37
0,59	32,8	-1,06	0,39	32,6	-0,25
0,59	33,8	-1,47	0,4	33,61	-0,61
0,49	34,7	-1,31	0,37	34,58	-0,66
0,43	35,64	-1,22	0,32	35,53	-0,57
0,35	36,56	-1,31	0,27	36,48	-0,53
0,32	37,53	-0,86	0,25	37,46	-0,3
0,26	38,47	-0,91	0,2	38,41	-0,25
0,25	39,46	-0,77	0,18	39,39	-0,22
0,21	40,42	-0,65	0,14	40,35	-0,04
0,11	41,32	-0,3	0,11	41,32	-0,11
-0,02	42,19	-0,1	0,04	42,25	-0,07
-0,22	42,99	0,71	-0,23	42,98	-0,17
-0,25	43,96	0,77	-0,27	43,94	-0,09
-0,46	44,75	1,37	-0,54	44,67	0,25
-0,7	45,51	2,01	-0,88	45,33	0,43
-0,93	46,28	2,63	-1,21	46	0,6
-1,16	47,05	3,25	-1,54	46,67	0,78
	-5,31			-4,81	
	38,18			38,84	
	43,49			43,65	

E
Appendix E: Measurements

E.1 1350 MHz at 46 ℃

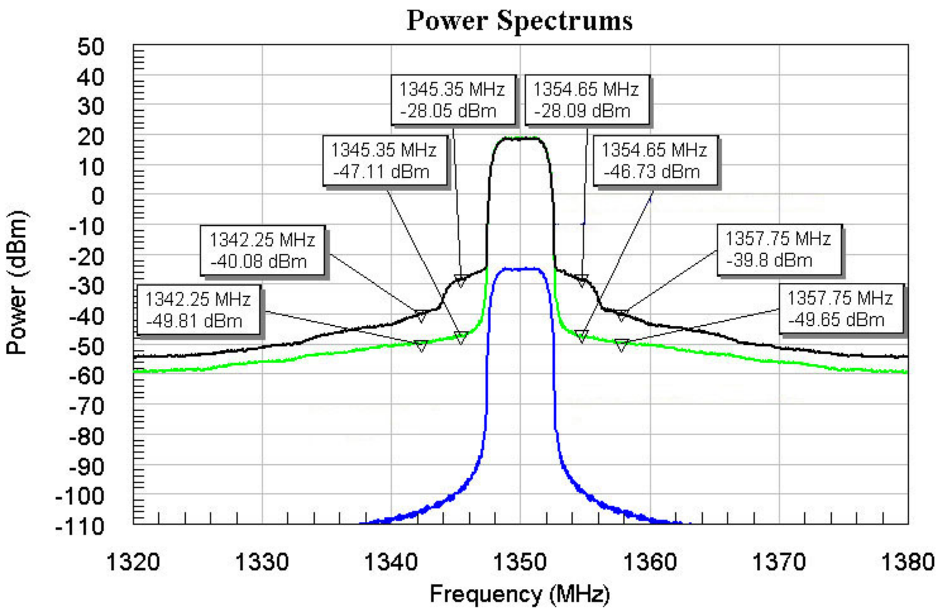

Figure E.1: Power spectrum at center frequency 1350 MHz at 46 ℃

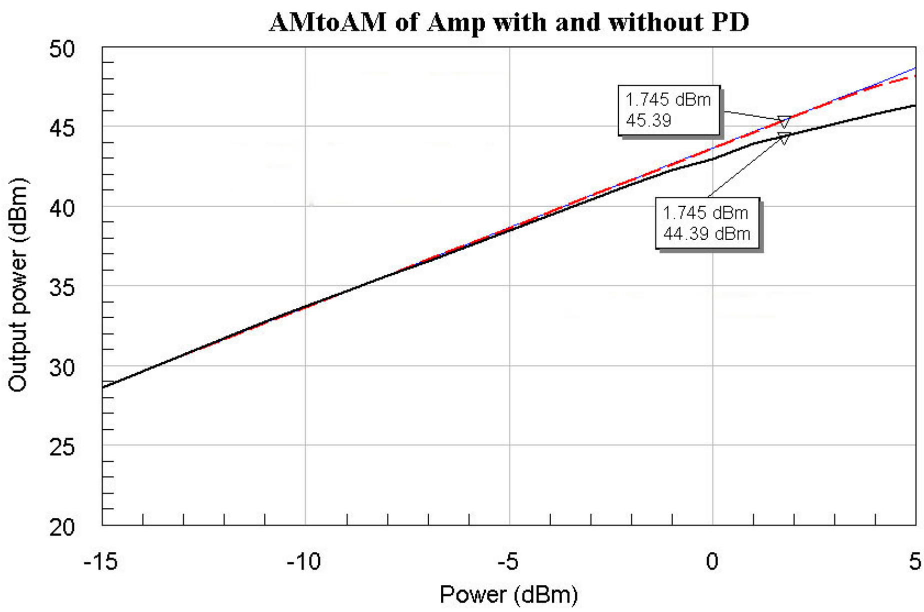

Figure E.2: AM/AM at center frequency 1350 MHz at 46 ℃

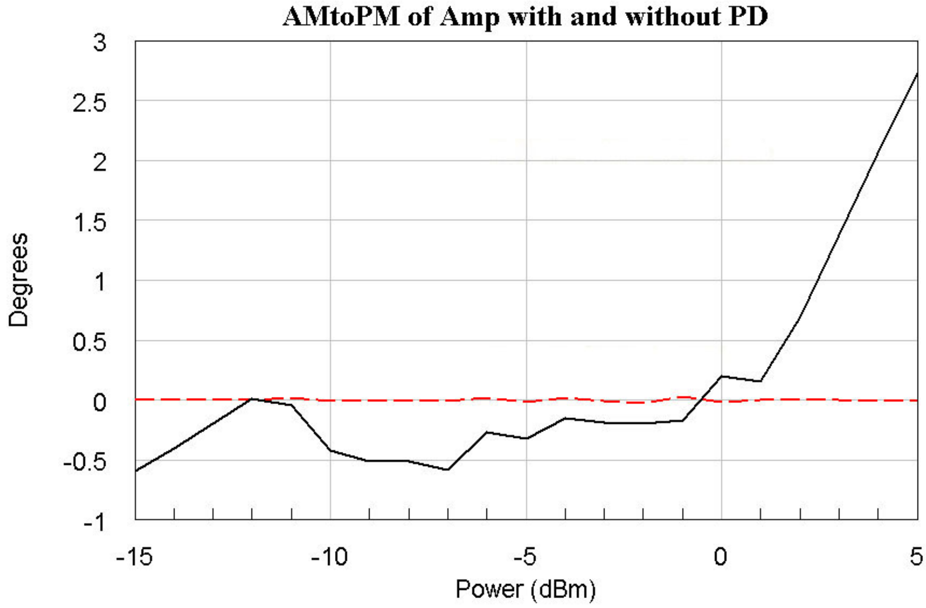

Figure E.3: AM/PM at center frequency 1350 MHz at 46 ℃

E.2 1350 MHz at 46 ℃ with predistorter from 2400 MHz at 73 ℃

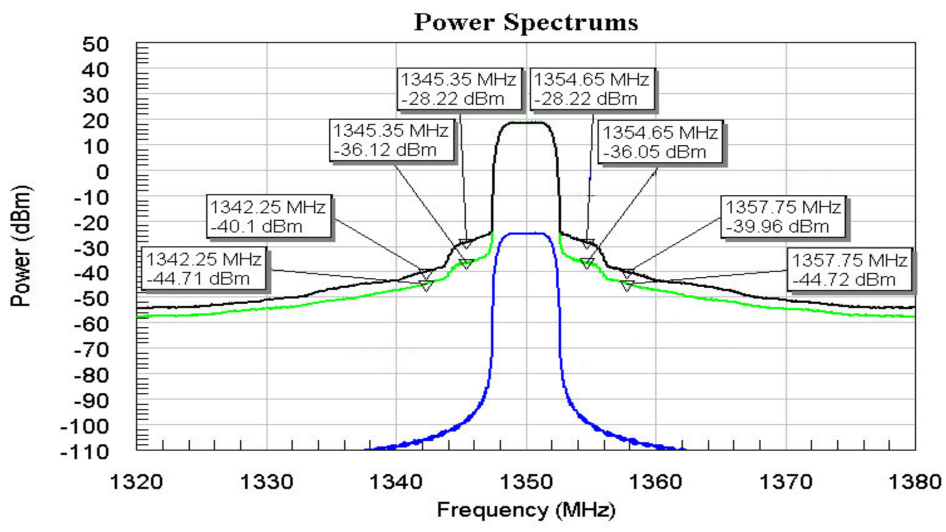

Figure E.4: Power spectrum at center frequency 1350 MHz at 46 ℃ with predistorter from 2400 MHz at 73 ℃

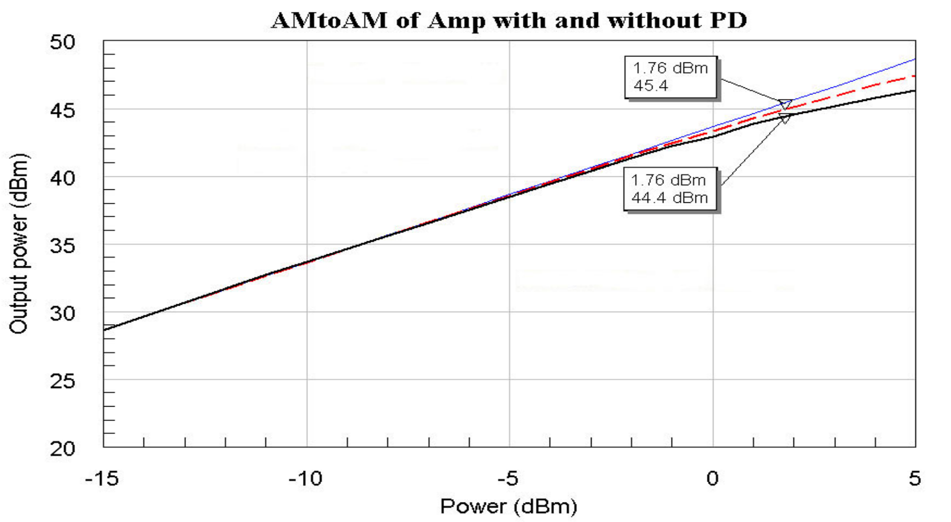

Figure E.5: AM/AM at center frequency 1350 MHz at 46 ℃ with predistorter from 2400 MHz at 73 ℃

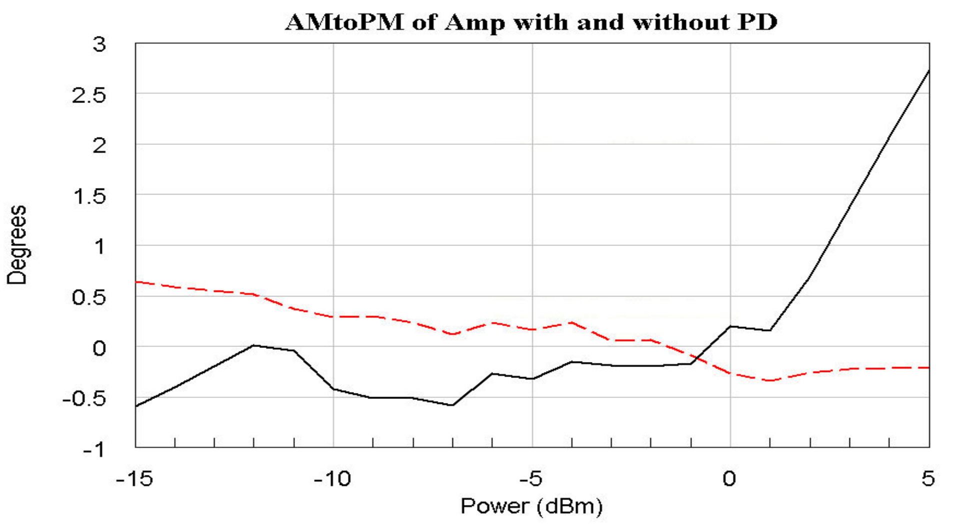

Figure E.6: AM/PM at center frequency 1350 MHz at 46 ℃ with predistorter from 2400 MHz at 73 ℃

E.3 1350 MHz at 46 ℃ with predistorter from 2690 MHz at 46 ℃

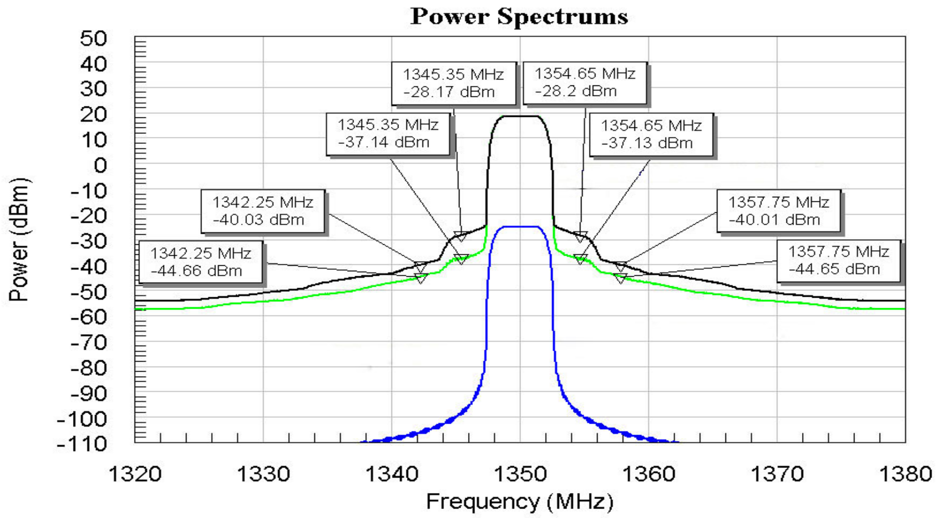

Figure E.7: Power spectrum at center frequency 1350 MHz at 46 ℃ with predistorter from 2690 MHz at 46 ℃

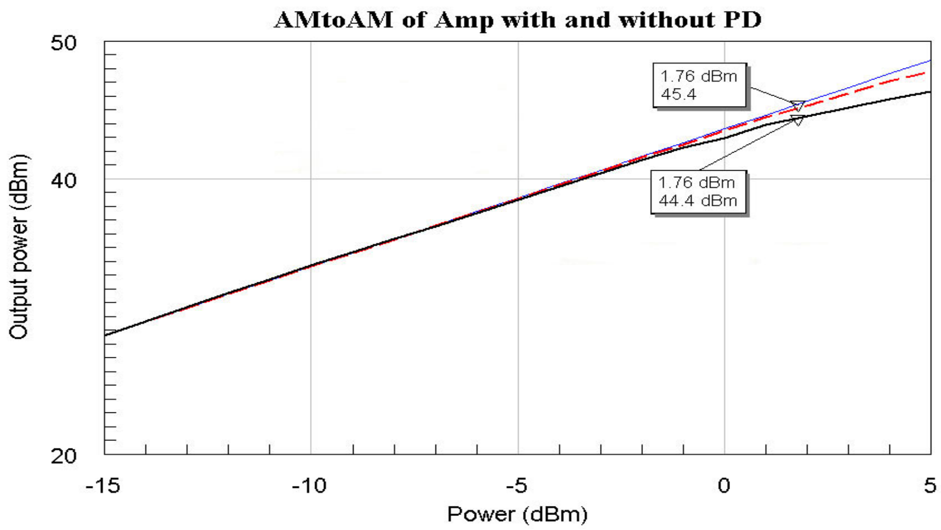

Figure E.8: AM/AM at center frequency 1350 MHz at 46 ℃ with predistorter from 2690 MHz at 46 ℃

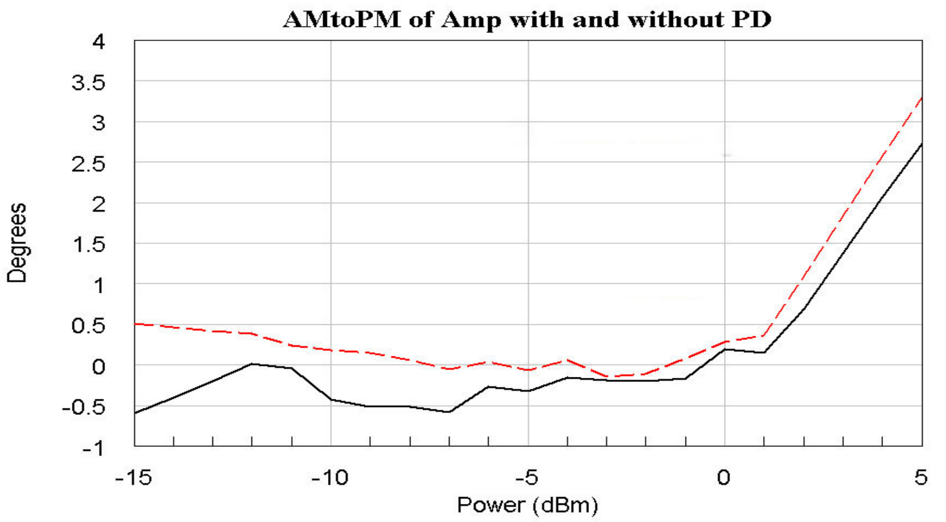

Figure E.9: AM/PM at center frequency 1350 MHz at 46 ℃ with predistorter from 2690 MHz at 46 ℃

E.4 1800 MHz at 46 ℃

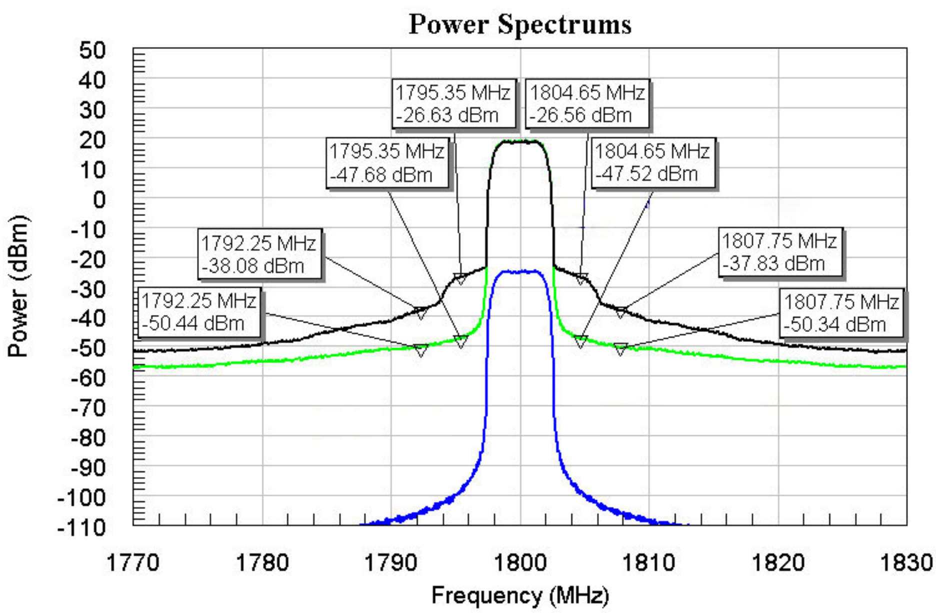

Figure E.10: Power spectrum at center frequency 1800 MHz at 46 ℃

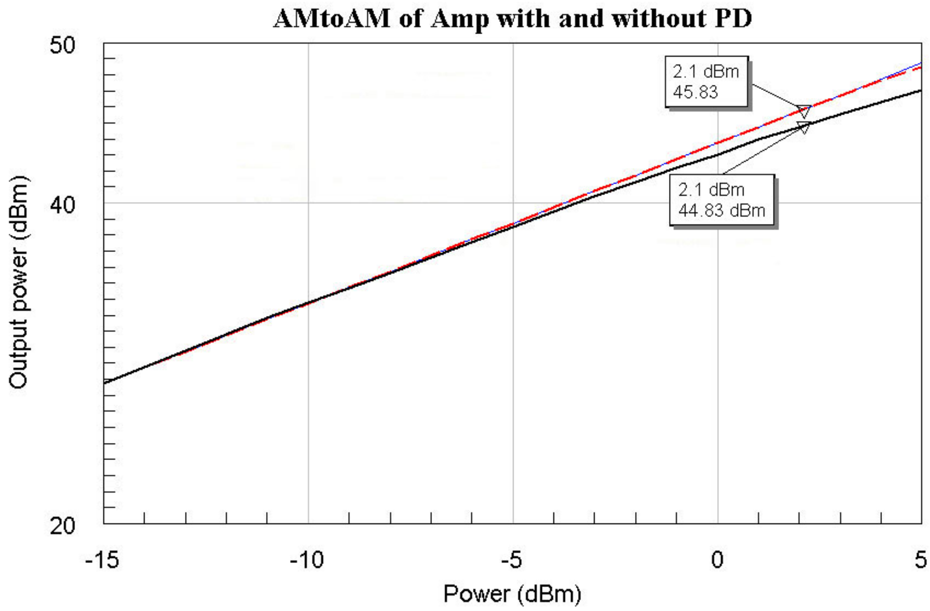

Figure E.11: AM/AM at center frequency 1800 MHz at 46 ℃

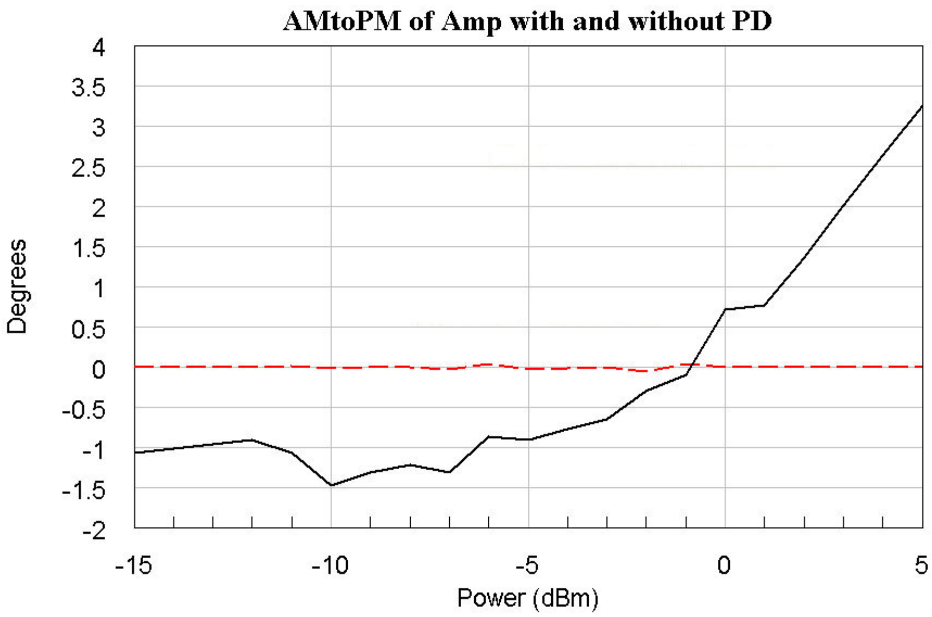

Figure E.12: AM/PM at center frequency 1800 MHz at 46 ℃

E.5 1800 MHz at 46 ℃ with predistorter from 1350 MHz at 46 ℃

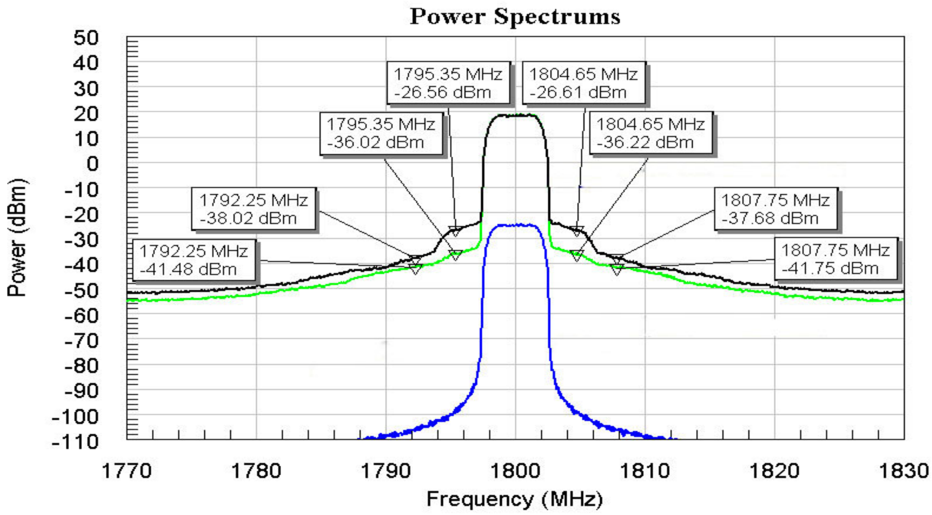

Figure E.13: Power spectrum at center frequency 1800 MHz at 46 ℃ with predistorter from 1350 MHz at 46 ℃

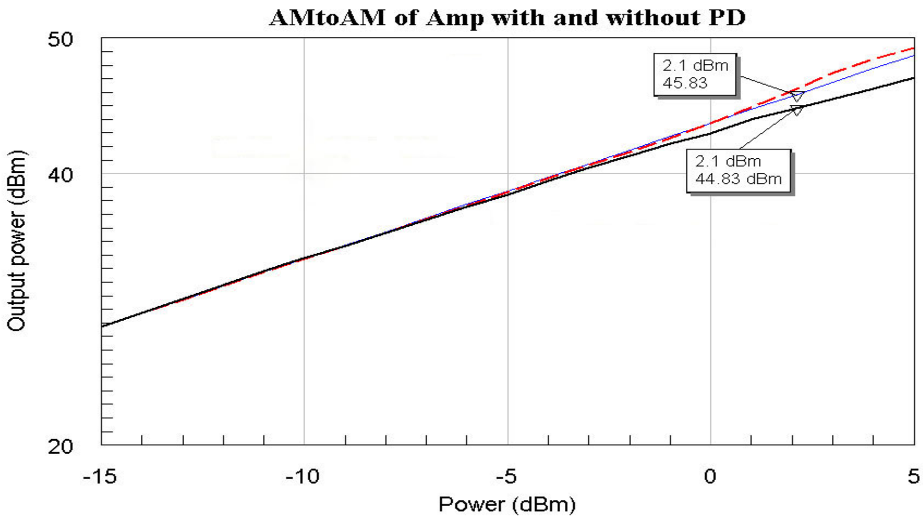

Figure E.14: AM/AM at center frequency 1800 MHz at 46 ℃ with predistorter from 1350 MHz at 46 ℃

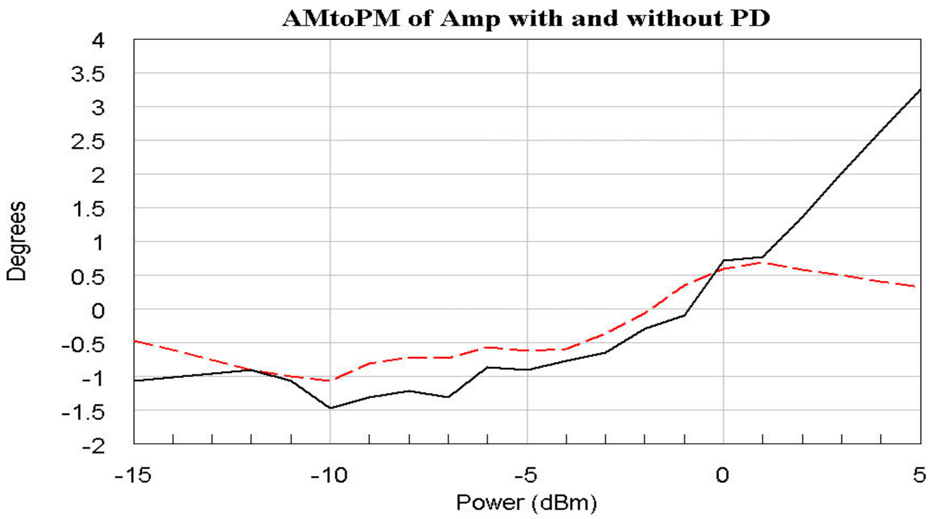

Figure E.15: AM/PM at center frequency 1800 MHz at 46 ℃ with predistorter from 1350 MHz at 46 ℃

E.6 2400 MHz at 39 ℃

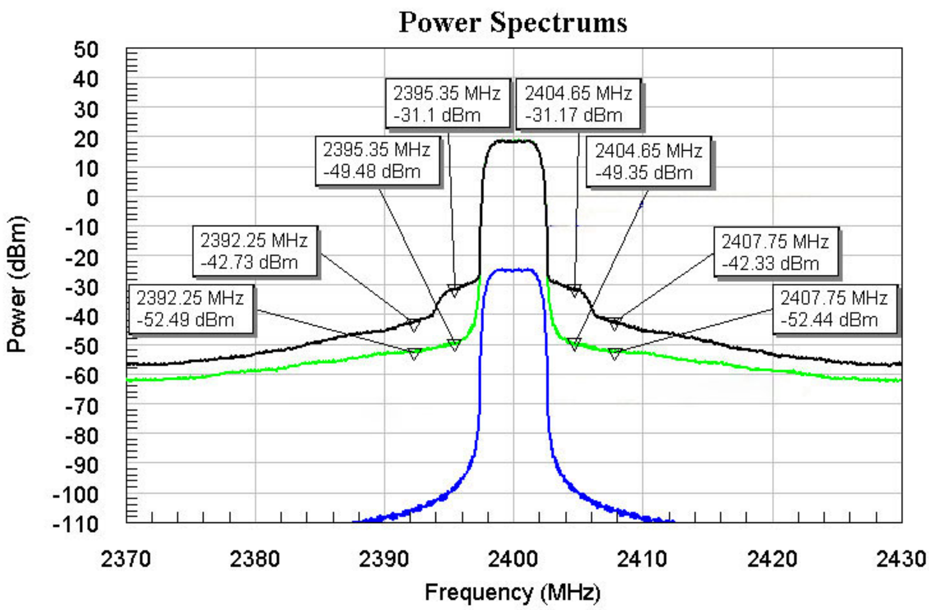

Figure E.16: Power spectrum at center frequency 2400 MHz at 39 ℃

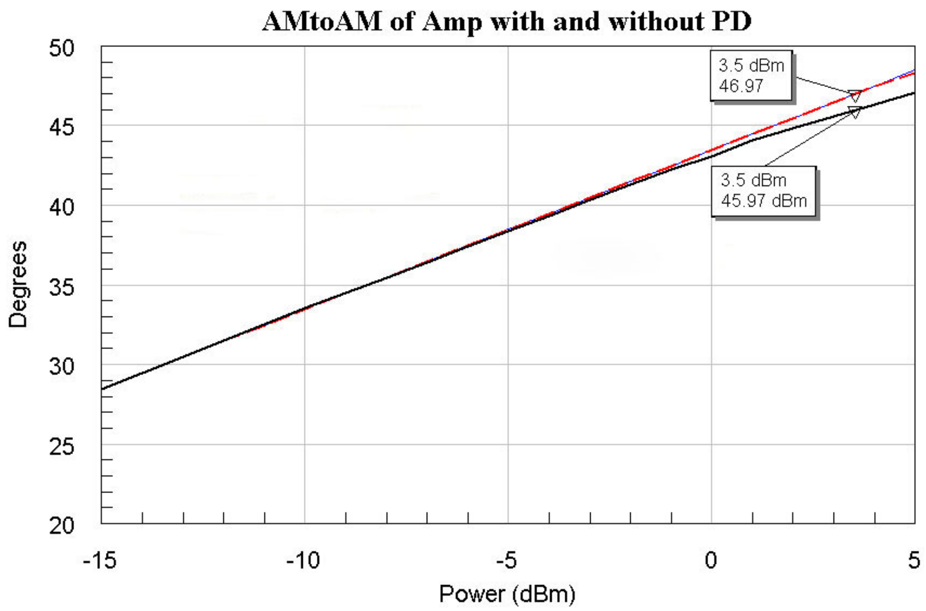

Figure E.17: AM/AM at center frequency 2400 MHz at 39 ℃

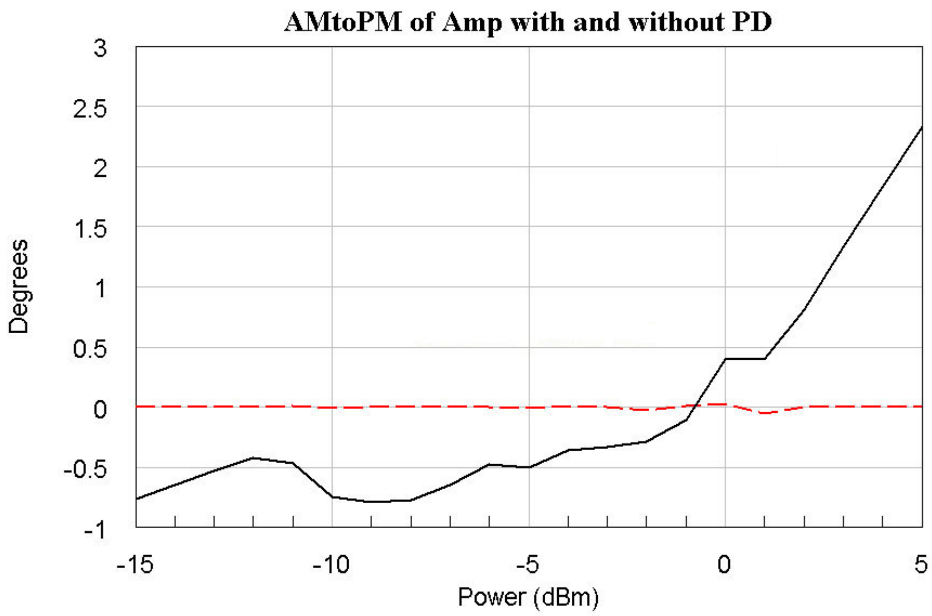

Figure E.18: AM/PM at center frequency 2400 MHz at 39 ℃

E.7 2400 MHz at 39 ℃ with predistorter from 2400 MHz at 46 ℃

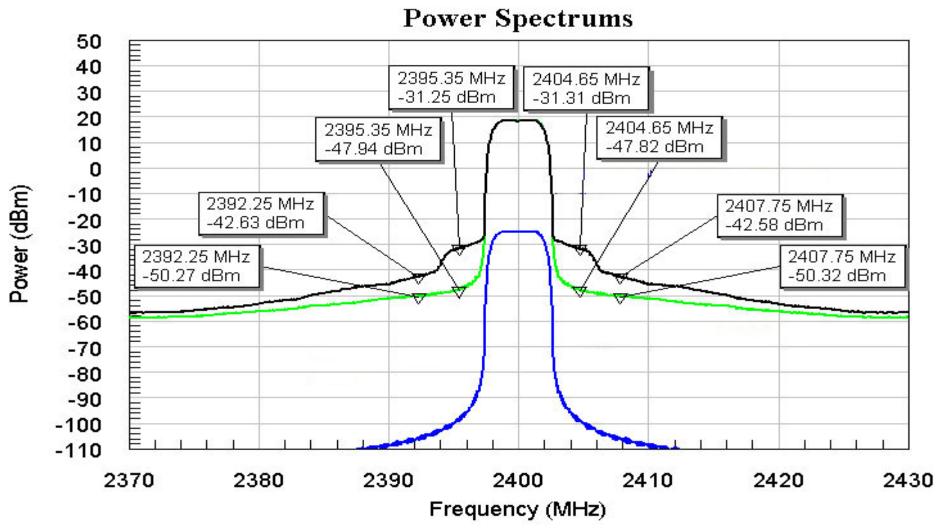

Figure E.19: Power spectrum at center frequency 2400 MHz at 39 ℃ with predistorter from 2400 MHz at 46 ℃

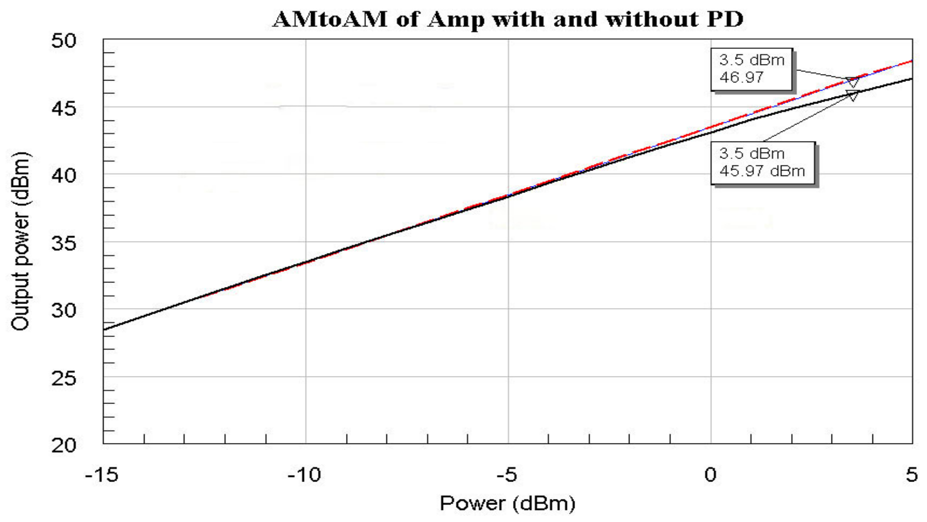

Figure E.20: AM/AM at center frequency 2400 MHz at 39 ℃ with predistorter from 2400 MHz at 46 ℃

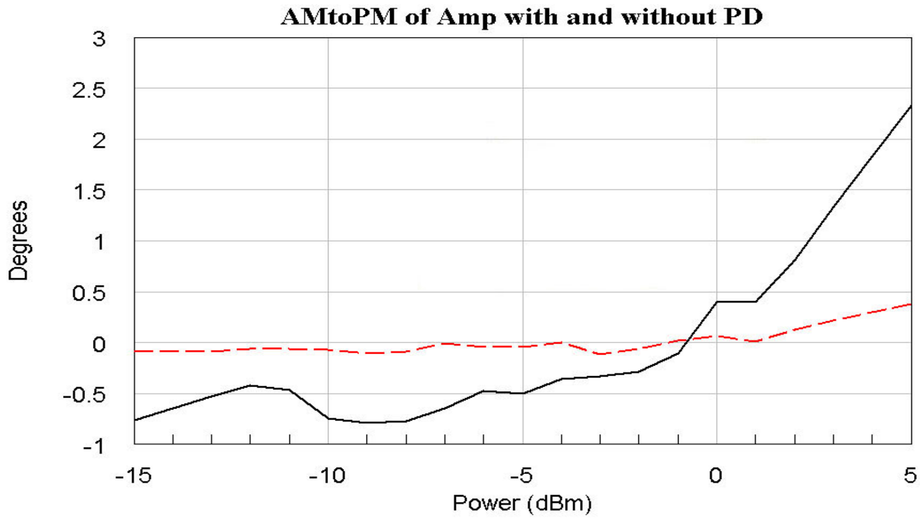

Figure E.21: AM/PM at center frequency 2400 MHz at 39 ℃ with predistorter from 2400 MHz at 46 ℃

E.8 2400 MHz at 46 ℃

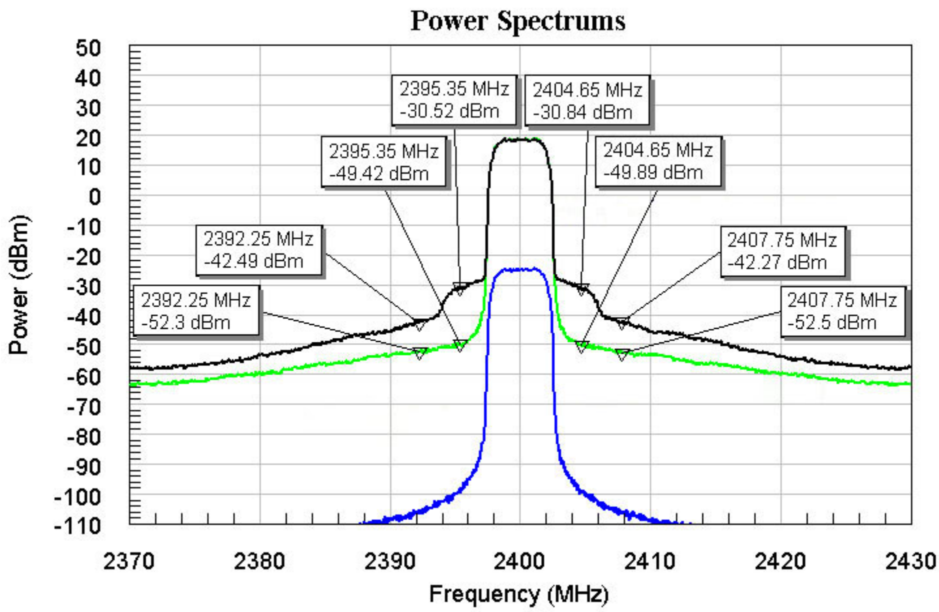

Figure E.22: Power spectrum at center frequency 2400 MHz at 46 ℃

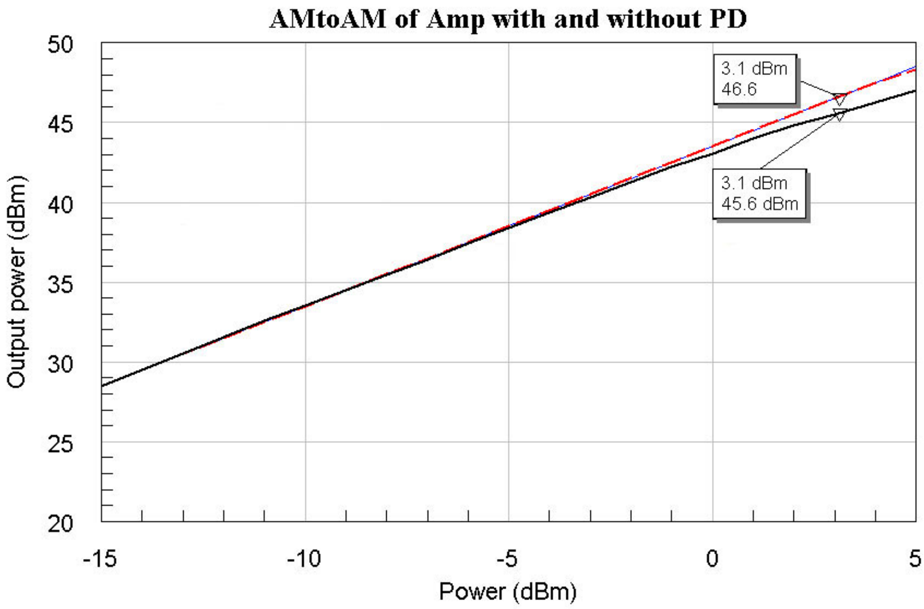

Figure E.23: AM/AM at center frequency 2400 MHz at 46 ℃

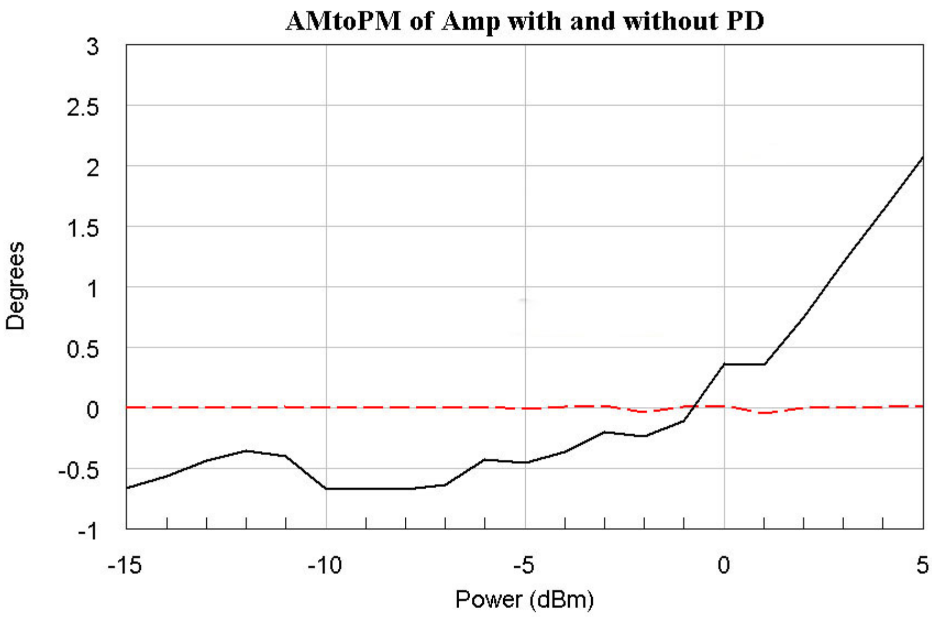

Figure E.24: AM/PM at center frequency 2400 MHz at 46 ℃

E.9 2400 MHz at 73 ℃

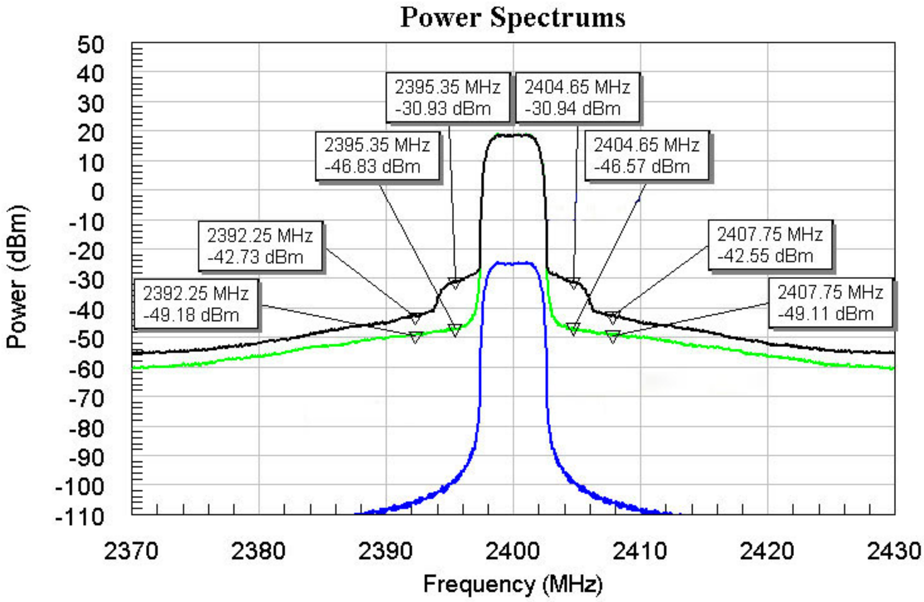

Figure E.25: Power spectrum at center frequency 2400 MHz at 73 ℃

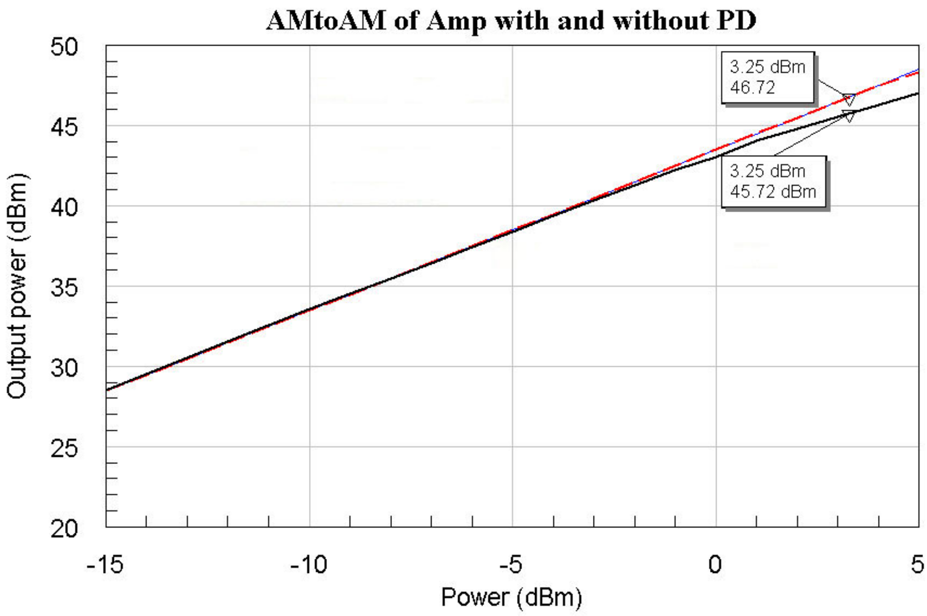

Figure E.26: AM/AM at center frequency 2400 MHz at 73 ℃

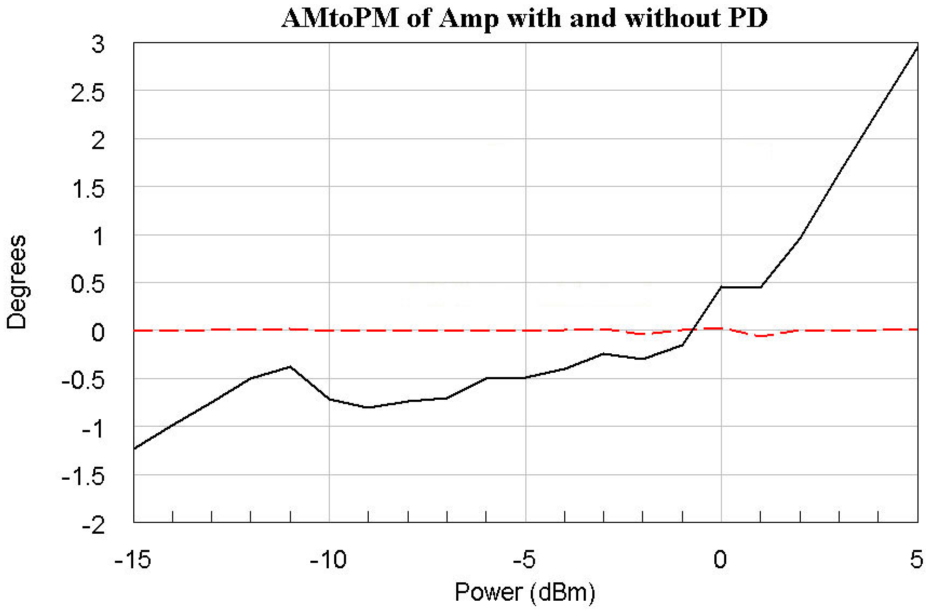

Figure E.27: AM/PM at center frequency 2400 MHz at 73 ℃

E.10 2400 MHz at 73 ℃ with predistorter from 2400 MHz at 39 ℃

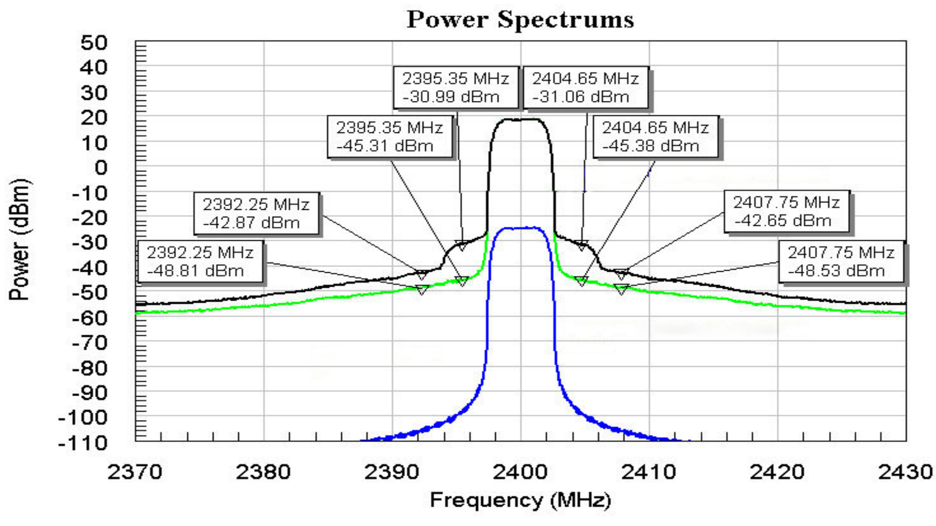

Figure E.28: Power spectrum at center frequency 2400 MHz at 73 ℃ with predistorter from 2400 MHz at 39 ℃

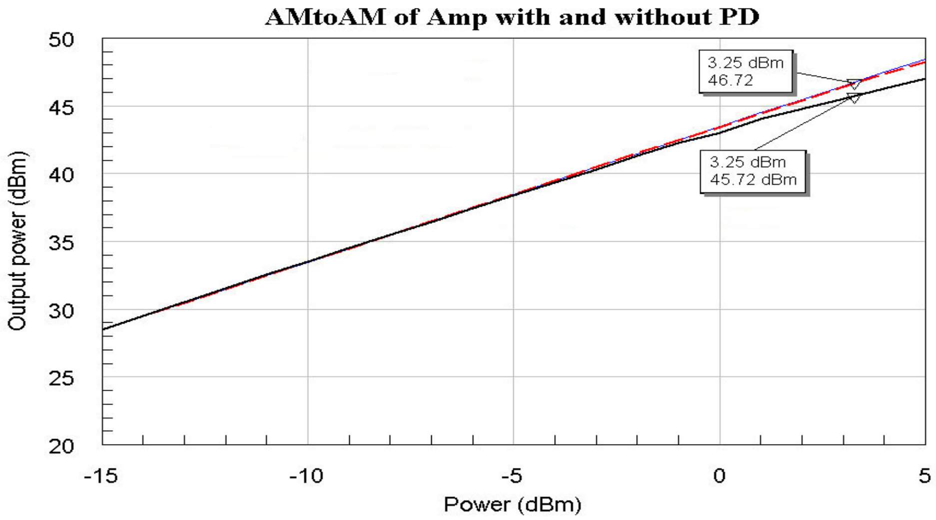

Figure E.29: AM/AM at center frequency 2400 MHz at 73 ℃ with predistorter from 2400 MHz at 39 ℃

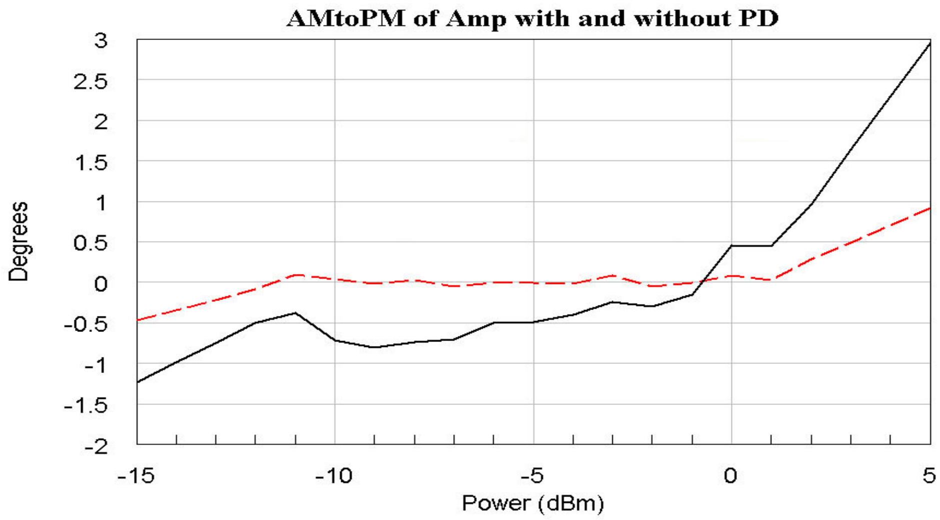

Figure E.30: AM/PM at center frequency 2400 MHz at 73 ℃ with predistorter from 2400 MHz at 39 ℃

E.11 2690 MHz at 46 ℃

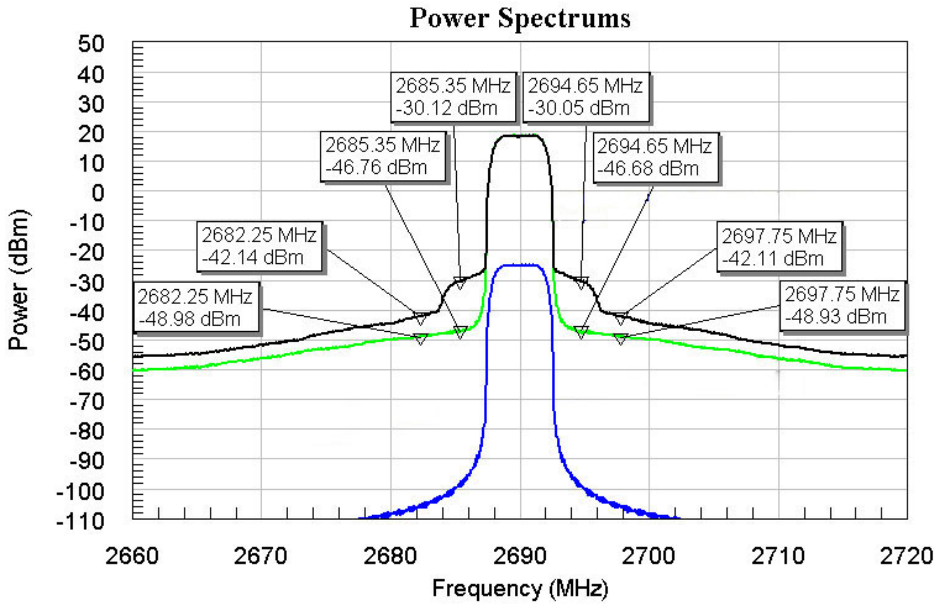

Figure E.31: Power spectrum at center frequency 2690 MHz at 46 ℃

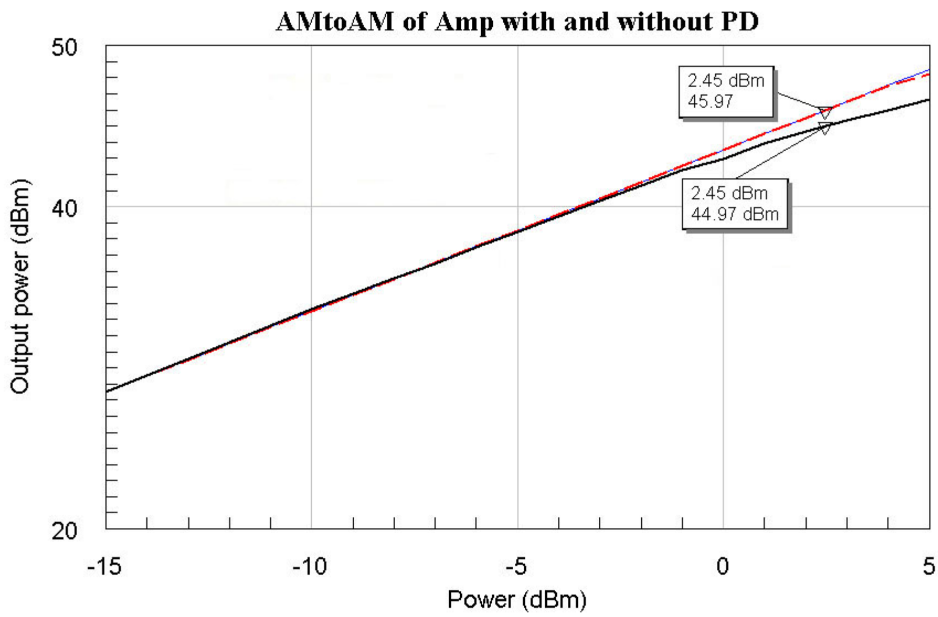

Figure E.32: AM/AM at center frequency 2690 MHz at 46 ℃

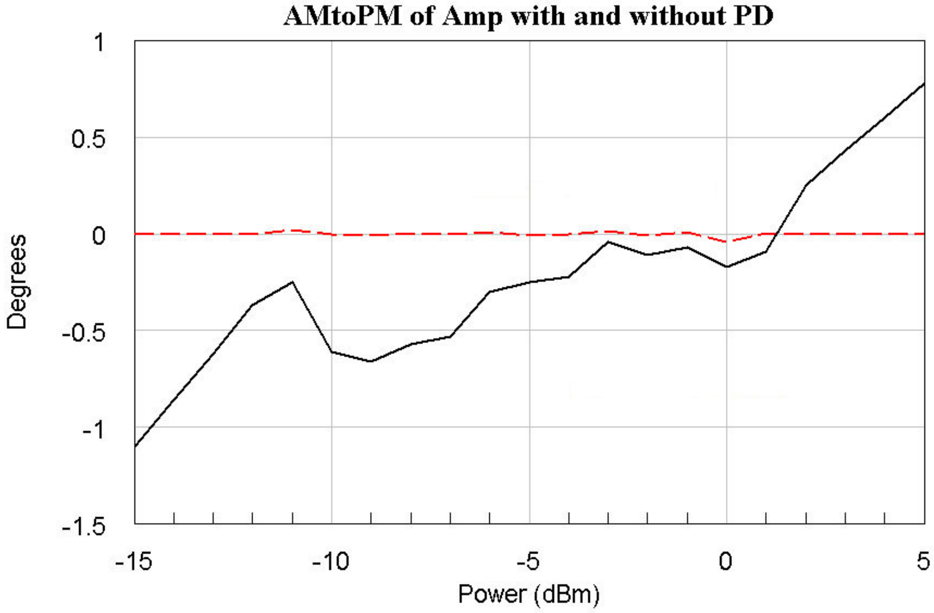

Figure E.33: AM/PM at center frequency 2690 MHz at 46 ℃

E.12 2690 MHz at 46 ℃ with predistorter from 1800 MHz at 46 ℃

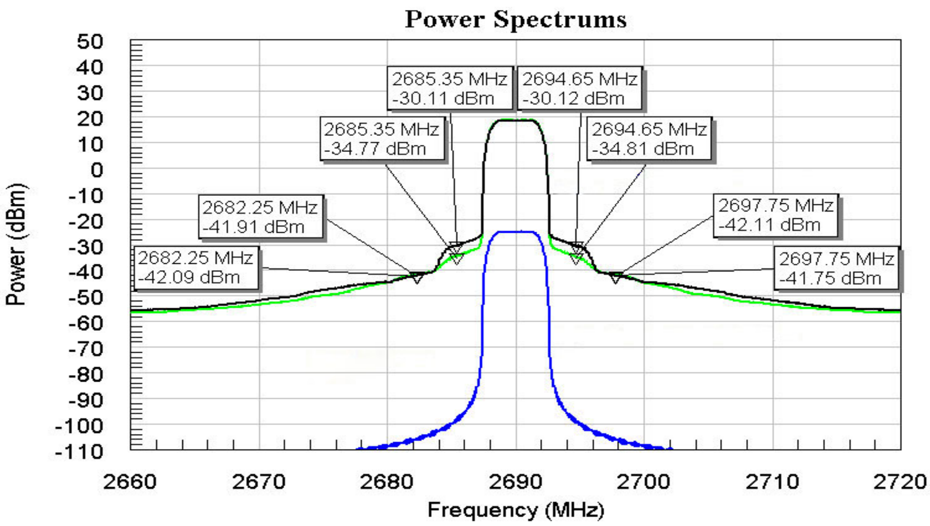

Figure E.34: Power spectrum at center frequency 2690 MHz at 46 ℃ with predistorter from 1800 MHz at 46 ℃

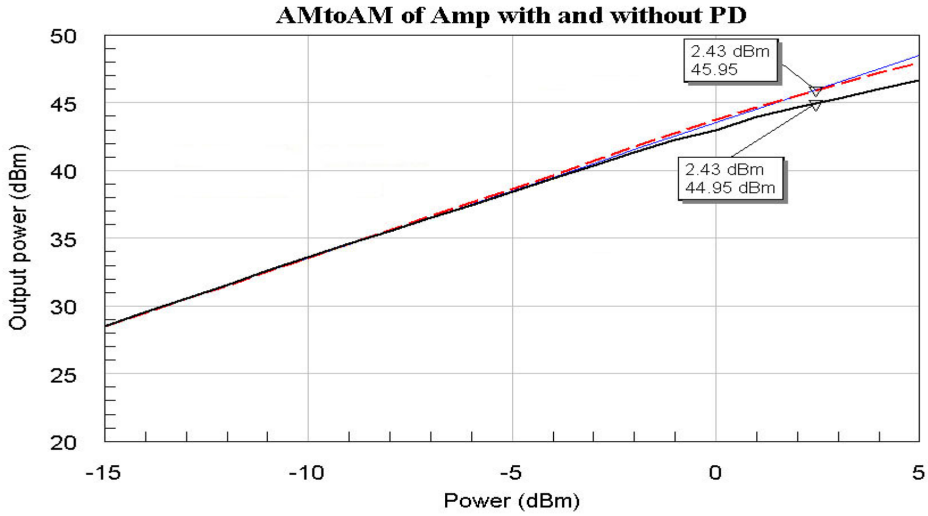

Figure E.35: AM/AM at center frequency 2690 MHz at 46 ℃ with predistorter from 1800 MHz at 46 ℃

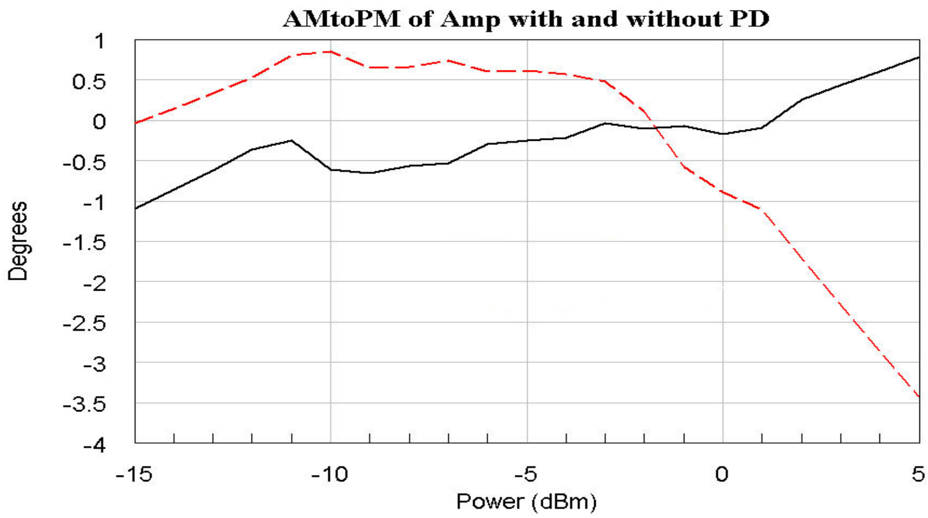

Figure E.36: AM/PM at center frequency 2690 MHz at 46 ℃ with predistorter from 1800 MHz at 46 ℃

F

Appendix F: User guide

F.1 Predistortion using VSS: Overview

Take the following measurements of the amplifier: Pin, Pout and Phase. Put the values from the VNA into the "PA AMPM 1111" table. The other data files need to have the same dimension as "PA AMPM 1111", which means 15 lines of arbitrary numbers. Disable the "Inverse AM_AM and AM_PM", "LUT I" and "LUT Q" tables. Run the simulator for 15-20 sek. Enable the three tables you just disabled and push "analyze". The new data files "newInverseAMPM", "newLUTinphase" and "newLUTquad" will have to be copied to the original data files. All commas must be replaced with periods (use the Edit-menu). Run the simulator again, and you should have the same results as in this report.

F.2 System diagrams

The amplifier diagram reads in the characteristics of the PA, in this model using the look up table "PA_AMPM_1111". From this diagram the "AMtoAM and AMtoPM of Amp" chart is extracted. The VNA Characterization diagram is behind the other two AMtoAM and AMtoPM charts. The component VNA_LS is used in both diagrams and runs the power sweep determining the Input power column in the data files. The values in the data files have to correspond to the values inserted to the VNA_LS instances.

The LUT Pre_Distorter calculates the instantaneous power level of the signal before inserting it into the look up tables for I and Q channel. The resulting output from the LUTs are complex multiplied with the original signal giving out the corrected input for the PA. The Complex Multiplier diagram shows that the multiplication is done after the formula $(a + jb)(c + jd)$.

F.3 Output equations

This window shows all other calculations done in the model not shown in system diagrams. Pin must again correspond to the values in the VNA_LS components as well as the data files. The following lines converts Pout from dBW to dBm and Phi from radians to degrees. Further, Go is defined as the linear gain by taking the difference between Pout and Pin at the first recorded data point. For this reason the model should start well into the linear region of the PA but at the same time reach high enough to push the amplifier into saturation.

Then new values for the "InverseAMPM" data file are found by linear interpolation. The I and Q values for the look up tables are also calculated by converting the dBs into magnitudes. These values are plotted in the "Inverse Am_AM and AM_PM" chart and the "LUT I" and "LUT Q" tables correspondingly. At last these results are written to new data files.