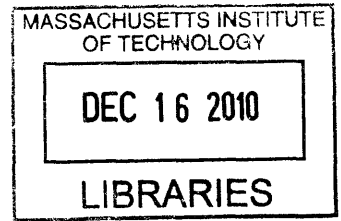


**RF Power Amplifier Linearity Compensation for
MRI Systems**

by
Gabriel Torres Chico



Submitted to the Department of Electrical Engineering and Computer
Science

in partial fulfillment of the requirements for the degree of **ARCHIVES**

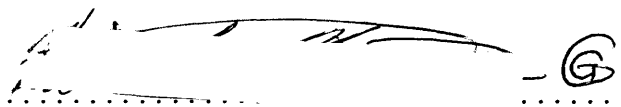
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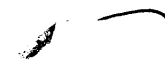
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September 2010

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Abstract

In this thesis, a polar-feedback linearization system for use with MRI RF power amplifiers was designed and simulated. The design here presented is intended to replace Analogic's (located in Peabody, Massachusetts) feed-forward, digital linearization scheme. This involved the selection and testing of components meeting the stringent specifications required for a high enough level of fidelity, as well as a simulation of the amplitude loop of the linearization system designed using the data acquired from one of Analogic's RF power amplifiers and the components selected. The intention of the simulation is to show that a polar-feedback solution is an effective method for linearizing the response of the RF power amplifier. A prototype system to test the feasibility of the design in real conditions was also constructed.

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Chapter 1

Introduction

Radio frequency power amplifiers are a crucial component of MRI systems. A magnetic pulse, powered by an RF power amplifier, is necessary to generate a signal that can be picked up by the receiver coil to produce an image.

The RF power amplifiers for MR applications are analogous to the RF amplifiers used in FM and TV broadcast systems, but have key differences. For the FM radio broadcast industries, the RF ranges from 87.9 to 108 MHz, and each FM channel is 0.2 MHz wide. The power of an FM broadcast transmitter is comparable to that of an MRI system RF power amplifier, reaching a few tens of kW. However, since all of the baseband information is contained as phase variations (or frequency deviation) of the RF carrier, FM broadcast RF amplifiers are mostly Class-C RF amplifiers to get the maximum efficiency and operate at a constant RF output power. On the other hand, TV broadcast industries uses low level amplitude modulation for the video information and then amplified to multi kW by linear RF amplifiers similar to that of MR RF power amplifiers. The frequencies in MR are defined by the strength of the static magnetic field and the type of atoms being excited. In biological specimens, ^1H is the most abundant MR-relevant nucleus. The frequency relation for ^1H is 42.58MHz/Tesla, therefore a 3T system would operate at 127.71 MHz. The RF power amplifier in an MR amplifier can usually output a few tens of kW of power, but this is generally pulsed, while most broadcast system amplifiers are operated in continuous-wave. The power consumption of amplifiers used for MRI is not as critical

as those in communications systems, such as cell phones, but fidelity and linearity are critical for slice selection and high image quality. Even though TV broadcast RF amplifiers require both gain and phase linearity in the order of less than 3% over the dynamic range, the typical dynamic range for TV industries for video AM is less than 20 dB, whereas MRI RF amplifiers require similar amplitude and phase linearity but operate over a 60 dB dynamic range of modulation signal level, which is many orders of magnitude higher than that of TV broadcast industry requirements. The typical modulation signal bandwidth for MR RF envelope is between 200 - 400 kHz. Therefore, appropriate linearity compensation techniques are of particular importance for the application. There is much interest in effective linearization for said RF power amplifiers.

Chapter two describes the power amplifier linearization system being proposed, as well as the compensation scheme previously in place in Analogic's (located in Pabody, MA) RF amplifiers for MRI, and provides the background on linearization techniques relevant to those systems.

Chapter three describes the testing procedures for the components selected for the new linearization system and the results of the simulation of said system.

Chapter four summarizes the conclusions drawn from the project, and discusses possibilities for future expansions.

1.1 Motivation for the project

The motivation of the project is to improve on the linearization system currently in place in Analogic's (located in Peabody, MA) power amplifiers. This correction scheme is described in detail in Chapter 2.

Chapter 2

Design for amplitude correction

The task is the following: design an appropriate scheme for the envelope retrieval of the amplifiers RF input and RF output, and also a scheme for compensation of both amplitude and phase gain. The closed-loop circuit must be very fast with a typical response time between 0.5 and 1 μ s and the envelope-retrieval elements must have around 80 dB of dynamic range in order to meet the minimum 60 dB dynamic range that is required for the MR RF envelope. Even though RF envelopes in MR can be a slow-varying sinc pulse, with 200-400 kHz bandwidth, some MR system manufacturers employ a square RF pulse for calibration that goes from no power to full power within a few hundred nanoseconds. Hence the linearity compensation scheme must account for the fast transition of a rectangular RF envelope without causing any overshoots in the rectangular RF envelope. It must also have sufficient resolution to cover the 60 dB dynamic range.

The design proposed in this thesis uses polar feedback to perform the compensation. It incorporates two separate loops, one for amplitude correction and one for phase correction. The correction may be done digitally, or with an analog system, but the current design and prototype employ an analog system for the correction.

Determining the feasibility of the design requires a number of steps, following the review of related literature. The selection of appropriate components is crucial for both generating a simulation and the construction of a prototype.

Once the appropriate components have been selected, they must be characterized

both to check for conformance with the specifications stated in each components data sheet, as well as to generate meaningful data points to generate an accurate mathematical model for use in the simulation. Using data from a sample PA yields an accurate amplifier characteristic to be used in the simulation.

Using the data collected, a Matlab simulation of the proposed design in ideal conditions can be performed. This provides insight into the stability of the system. This step is a deciding factor on whether or not the system is feasible and the design is sound.

2.1 Motivations for amplifier linearity compensation

The correction system currently in place in Analogic's RF amplifiers uses a digital signal processor with a lookup table to perform the correction. In this correction scheme, the amplifier gain and phase nonlinearities are characterized over the amplifiers dynamic range without any compensation. Knowing the non-linear nature of the amplifier, and the characteristics of gain and phase correction elements, a specific compensation voltage is calculated outside of the system. The compensation signal is introduced at the small-signal end of the RF amplifier. A compensation signal that represents the error or deviation from the ideal linear transfer characteristic is added at the small-signal end of the RF amplifier, altering the input to correct for the known non-linearities.

The current system couples the RF output of the power amplifier to an envelope detector. The envelope information is digitized, and then the envelope is altered appropriately. The distorted envelope signal then goes through a digital-to-analog converter, and is then fed to a gain control element. This alters the envelope of the RF input signal, compensating for the nonlinearities in the power amplifier. A block diagram of the system is shown in Figure 2-1.

Though it works for most cases, this correction scheme cannot account for changes

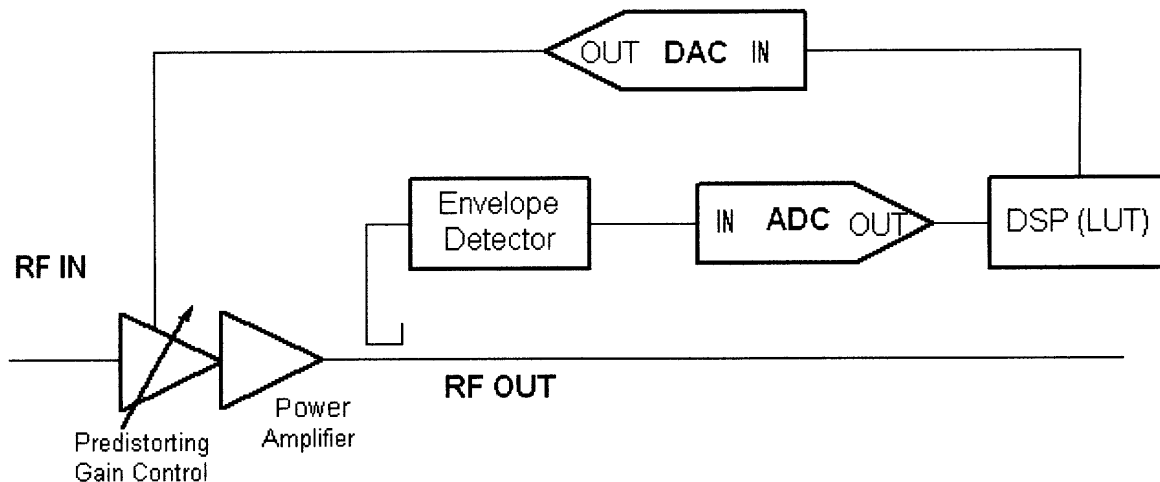


Figure 2-1: Feed-forward digital correction

in temperature and load mismatch. The desired closed-loop correction system must be able to account for these changes, over all possible operating conditions.

2.2 Background on linearization techniques

A number of linearization techniques have already been explored, and can be found in the literature, as in [1],[2],[3] and [4]. A brief discussion of some with marked similarities with the system currently being used in the amplifier being studied, and similarities with the proposed new design will serve to frame the problem more clearly. In this projects particular application, there is no access to the baseband information, thus posing an additional challenge. A brief overview of RF power amplifier linearization techniques can be found in [1].

Something else to note is that much of the research in RF power amplifiers is geared towards communications, where the efficiency of the power amplifier and the bandwidth are more significant, and some fidelity can be sacrificed to decrease power consumption. In MRI applications, it is the fidelity that is critical, and power consumption not as much of a concern. Though the bulk of PA research is geared towards communiations, especially cellular phones, there is research being performed on MR hardware, such as that being performed by Greig Scott and others at the Stanford

MRI groups, as presented in [8], [9], [10].

2.2.1 Adaptive Predistortion

Adaptive predistortion is similar to the current linearization system present in the RF power amplifiers studied. The linearization system currently in place in the amplifiers being studied uses a digital signal processor to implement the correction, by predistorting the RF inputs envelope. Though generally effective, predistortion solutions are unable to account for changes in the nonlinearity of the amplifier. Adaptive predistortion attempts to remedy that by dynamically updating the amplifier's model to account for changes such as those caused by aging and load mismatch. Adaptive predistortion (like simple predistortion) carries the difficulty of needing to carefully model the power amplifier. Though not conceptually difficult to understand, it is not simple to execute. A more complete treatment of adaptive predistortion can be found in [6].

2.2.2 Envelope elimination and restoration

First proposed by Kahn in [6] and also discussed in [2], EER is performed by first eliminating the envelope by way of a limiter to have a constant amplitude phase signal, and using an envelope detector to get the amplitude information. The magnitude and phase information are then amplified separately and combined to produce the desired RF output. Fig. 2-1 shows the block diagram of the EER linearization scheme as first proposed by Kahn in [5].

EER shares some similarities with the design proposed, but the design proposed depends on polar feedback, with separate amplitude and phase correction loops. EER may also be performed in a closed-loop system, as described in [2].

2.2.3 Logarithmic amplifiers

Logarithmic amplifiers are a significant part of the design being proposed to perform the correction. A brief overview is given, and a more complete treatment is given in

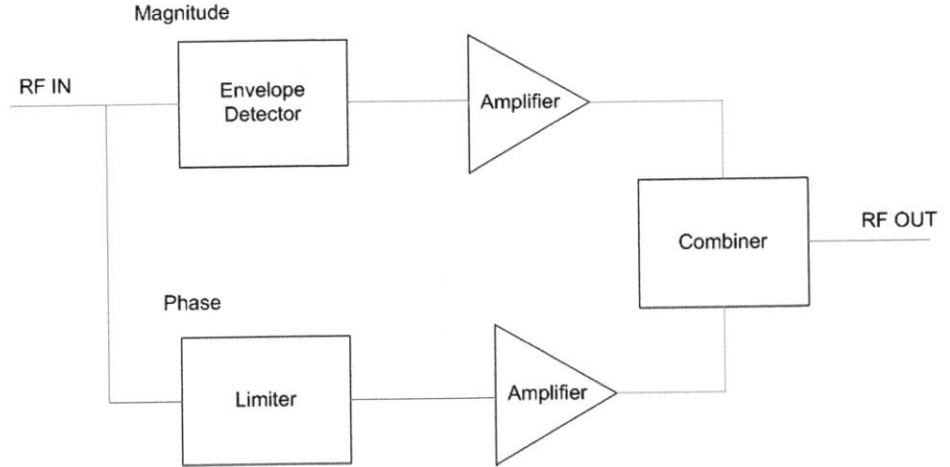


Figure 2-2: EER Basic Diagram

[7]. A logarithmic amplifier must have a transfer function of the form:

$$V_{out} = V_y \log(V_{in}/V_x)$$

The logarithm is most often base 10, as this relates best to decibels. V_x is some intercept voltage, such that when $V_x = V_{in}$, we get an output of 0. V_y determines the slope of the line, and thus is known as the "slope voltage". The fact that a logarithmic amplifier is linear in dB makes it particularly useful to our application, since what would be a logarithmic function in linear scale becomes a linear function in logarithmic scale, we can perform linear operations for the analysis and the simulations, simplifying the mathematics of the operations performed to linearize the signal.

A more complete discussion of logarithmic amplifiers can be found in [7].

2.3 New correction system

The main objective of the project is to prepare a new linearity compensation system for the amplifier. Figure 2-3 is an illustration of the first iteration of the design of the linearity compensation system.

This design performs the correction using a digital system. A digital correction

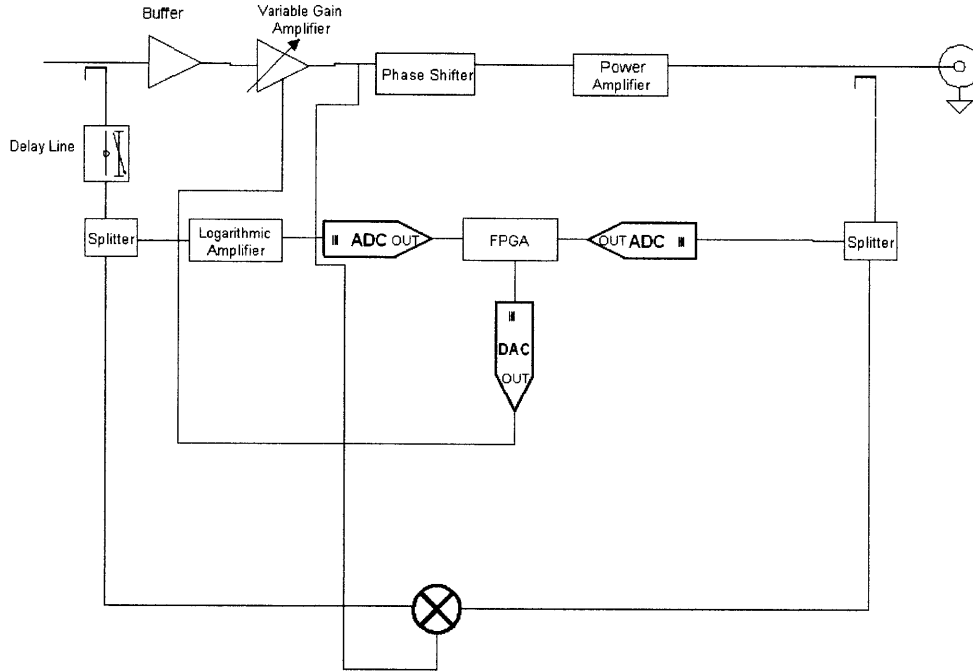


Figure 2-3: First iteration of the linearity compensation system

system for the linearization is very versatile. If it is necessary to implement filters, or make other corrections, the alterations require re-programming, as opposed to having to construct a new analog circuit for the correction. Some of the recent work in MRI systems, such as that presented in [10] have nearly all-digital RF transmission and reception.

The reasoning behind using polar feedback is the following: as the amplitude and phase are orthogonal functions, they can be corrected separately. The phase loop is, in fact, very similar to the amplitude loop, but would employ phase detectors where the amplitude loop employs envelope detectors, and would perform the correction by way of a phase shifter as opposed to a VGA. Due to time constraints, the focus of the project is the amplitude correction loop of the linearization system.

2.3.1 Amplitude correction loop

The block diagram for the amplitude correction system is shown in Figure 2-4. In the system, the RF input is coupled and sent into a logarithmic amplifier, which functions

as the envelope detector. The correction is performed by sending the error signal, as output by the comparator, into the VGA and using that to alter the RF input signal to account for the nonlinearities in the amplifier. In principle, this system should function to account for the amplifier nonlinearities and preserve fidelity of the RF output waveform to that of the input. Figure 2-4 shows a simplified block diagram digital version of the system, while Figure 2-5 presents the block diagram in analog, similar to the one modeled in the simulation.

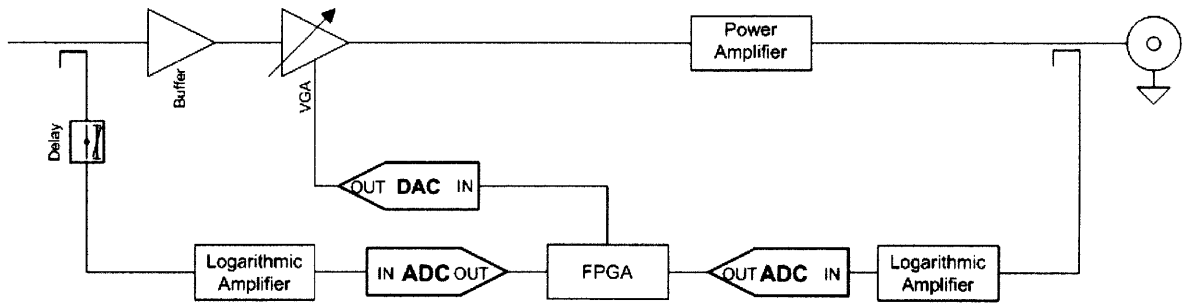


Figure 2-4: Closed-loop amplitude correction, with digital circuit elements

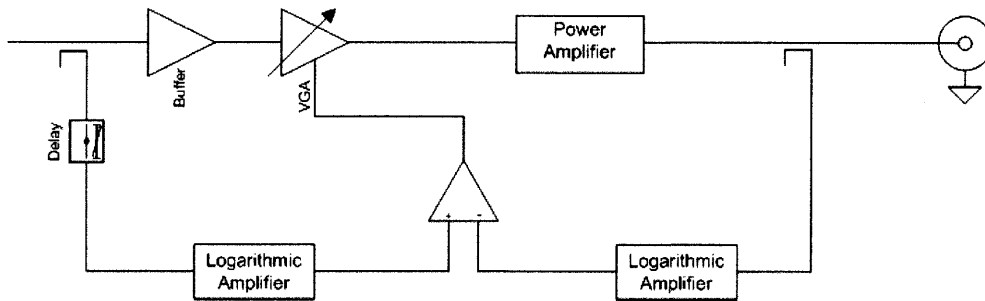


Figure 2-5: Analog closed-loop amplitude correction

Chapter 3

Testing Procedures and Simulation

The characterization of the selected components is crucial to the generation of the simulation. This section describes the testing procedures used to generate the functions that describe the behavior of the components selected for the construction of the prototype.

In Chapter 2, a detailed list of the system's requirements are provided.

3.1 RF Power amplifier

The RF PA is the heart of the problem. Though it is desired that the output of the PA be faithful to the input, the result is certainly not so. To appropriately model the PA, we use real testing data from a sample PA to construct a function for the amplifier characteristic. We would like the error to be less than 0.3 dB. Using a 40-dB ramp (figure 3-1) and the amplifier's gain characteristic (in response to the input shown in figure 3-1), we can determine the amplifier output, and thus, the amplifier's transfer function.

Figure 3-2 shows the amplifier's gain function. With a bandwidth of 4.7 dB, it is evident that we are far from the constant gain that we would like the amplifier to have. In figure 3-3, we can see a graph of the amplifier characteristic. In figure 3-4, we can see how a linear fit matches the data, and figure ?? shows the difference between the actual amplifier characteristic and the linear fit.

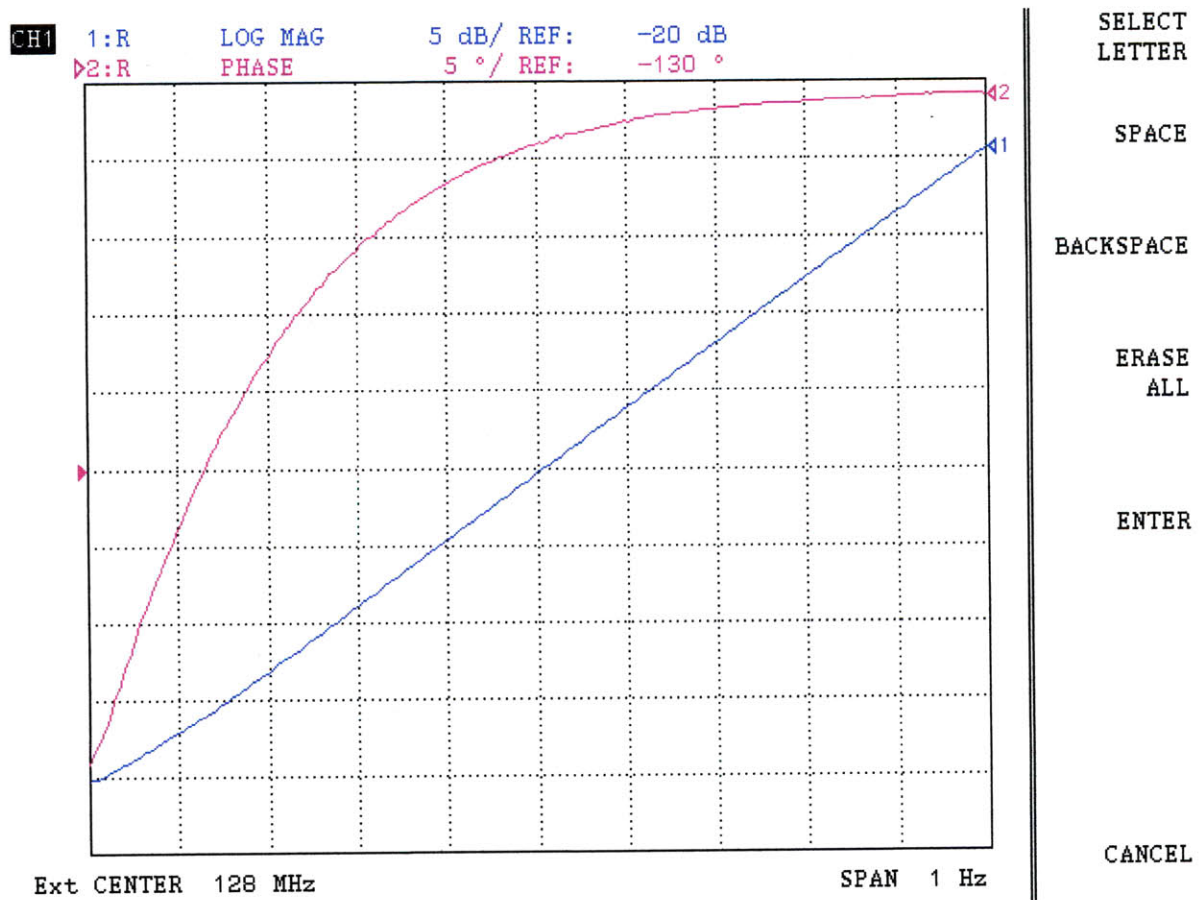


Figure 3-1: Input to the RF PA for testing, a forward 40 dB Ramp

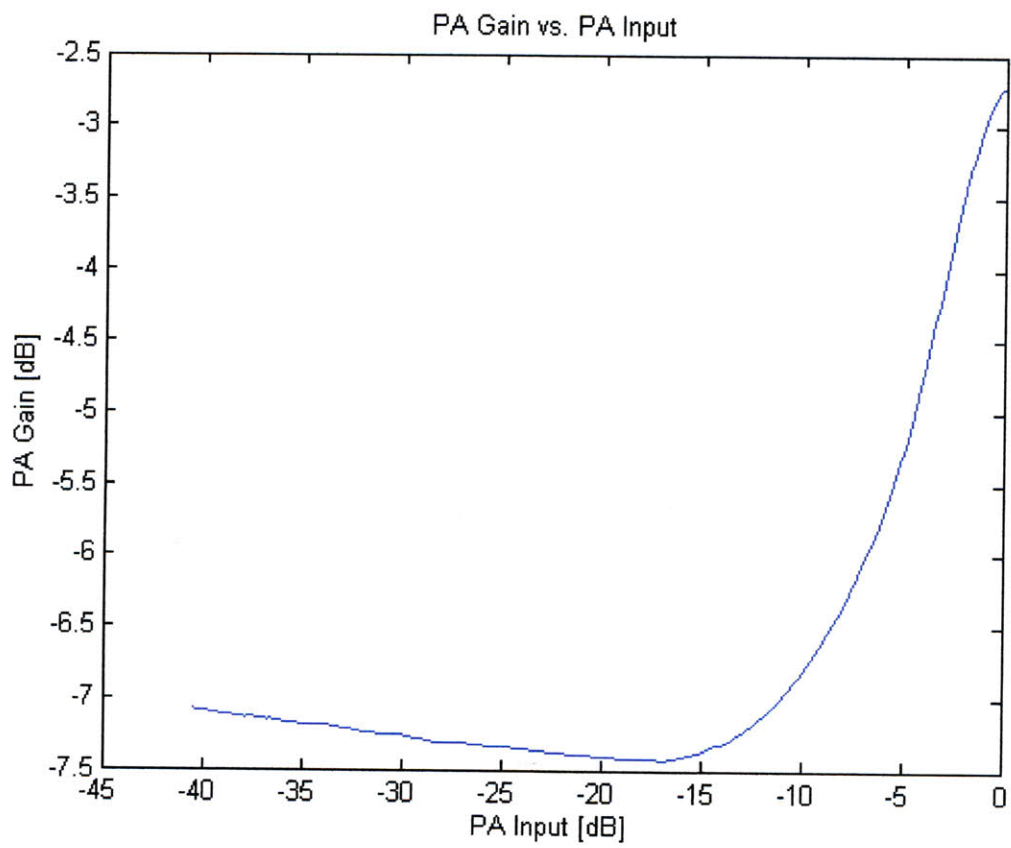


Figure 3-2: PA Gain vs. PA Input in dB

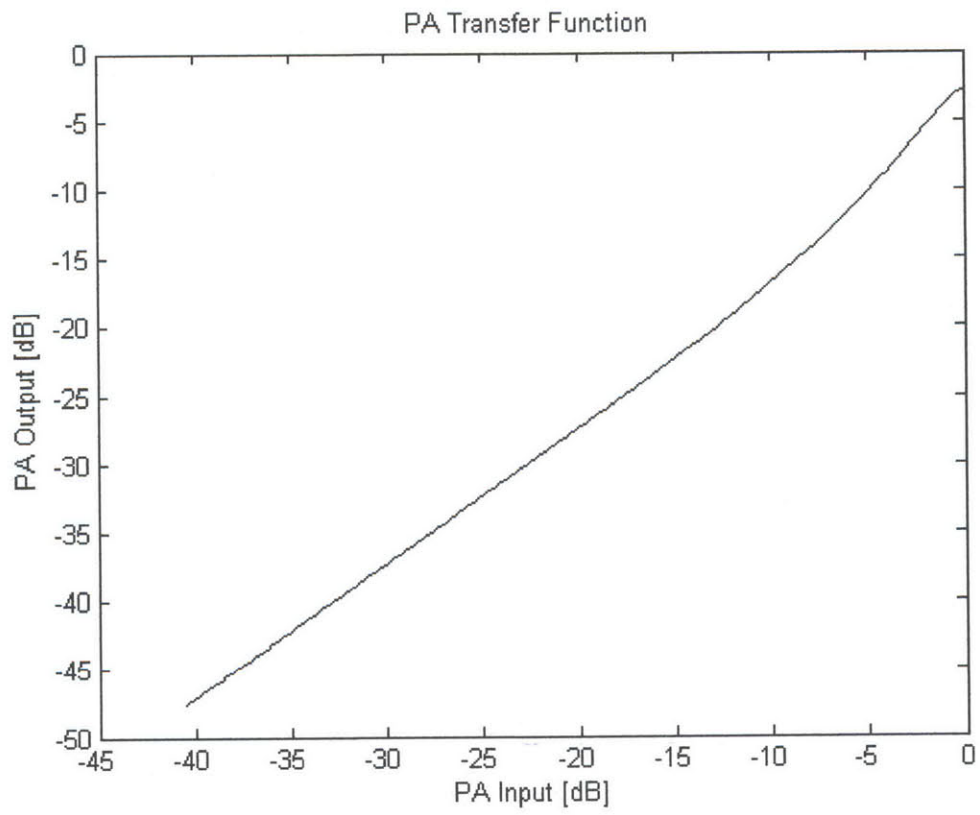


Figure 3-3: PA Transfer Function

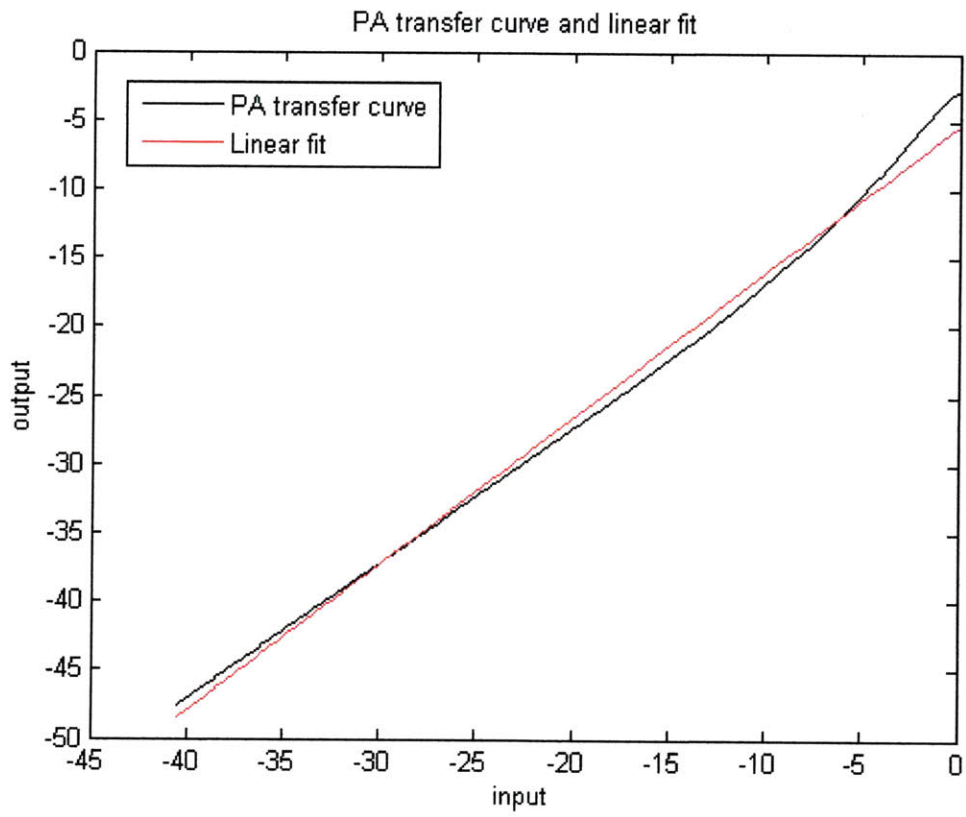


Figure 3-4: PA transfer curve and linear fit

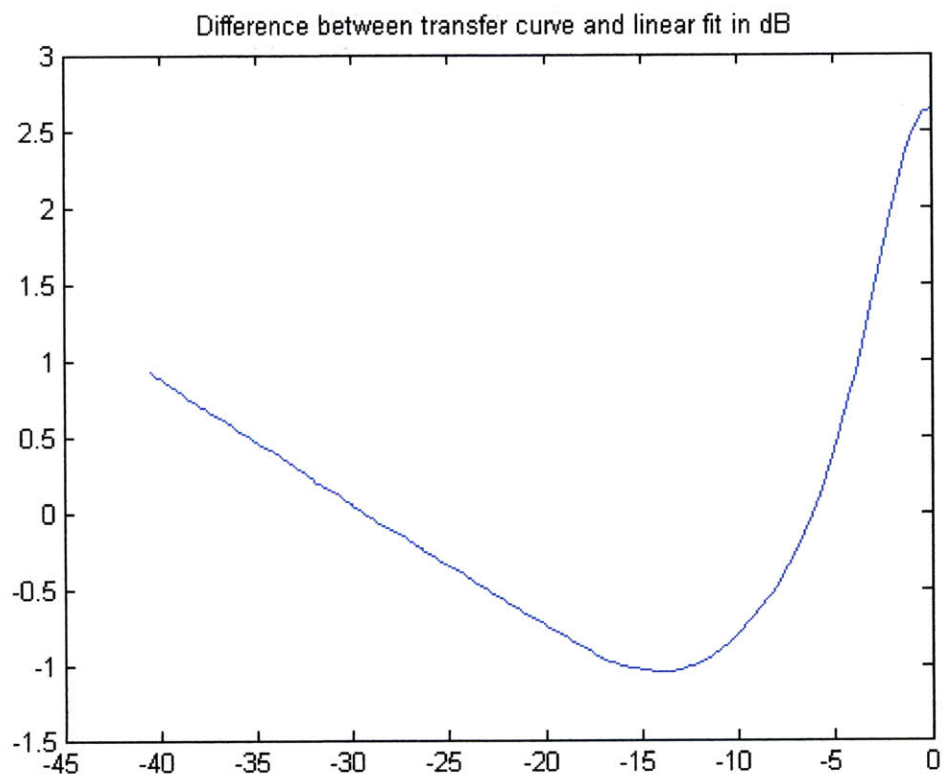


Figure 3-5: Difference between transfer curve and linear fit in dB

With a maximum difference of 2.642 dB between the actual amplifier characteristic and the best-fit line, it is clear that the amplifier is far from being linear, and that this fit would be unsuitable as a model for the behavior of the amplifier. We would like to find the lowest order polynomial fit that would reduce the maximum difference between the transfer function and the fit to less than 0.5 dB. Through experimentation, it is found that the following third-order polynomial describes the behavior of the PA with a maximum difference of 0.2879 dB, within our desired 0.5 dB limit on the deviation. For this PA, the polynomial describing its behavior is:

$$0.5299x^3 + 0.8211x^2 + 11.7020x - 28.4249$$

It is this polynomial function that is used in the Matlab simulation of the amplitude correction system to model the amplifier. Figure 3-6 shows how the third-order polynomial fit matches the data, and figure ?? shows the difference between the two functions.

We have now a reasonably complete model of the PA for the simulation. Now we must model the other components of the amplitude correction system and show that it serves to linearize the response of the amplifier.

3.2 Component selection and characterization

A significant part of implementing a design is the selection of appropriate components: assuming ideal components would be ineffective in the construction of a product working in real (and stringent) conditions. This section describes how the components were chosen, what the key parameters are, how the devices were tested for conformance to the stated specifications and how the model of each component was generated for the simulation.

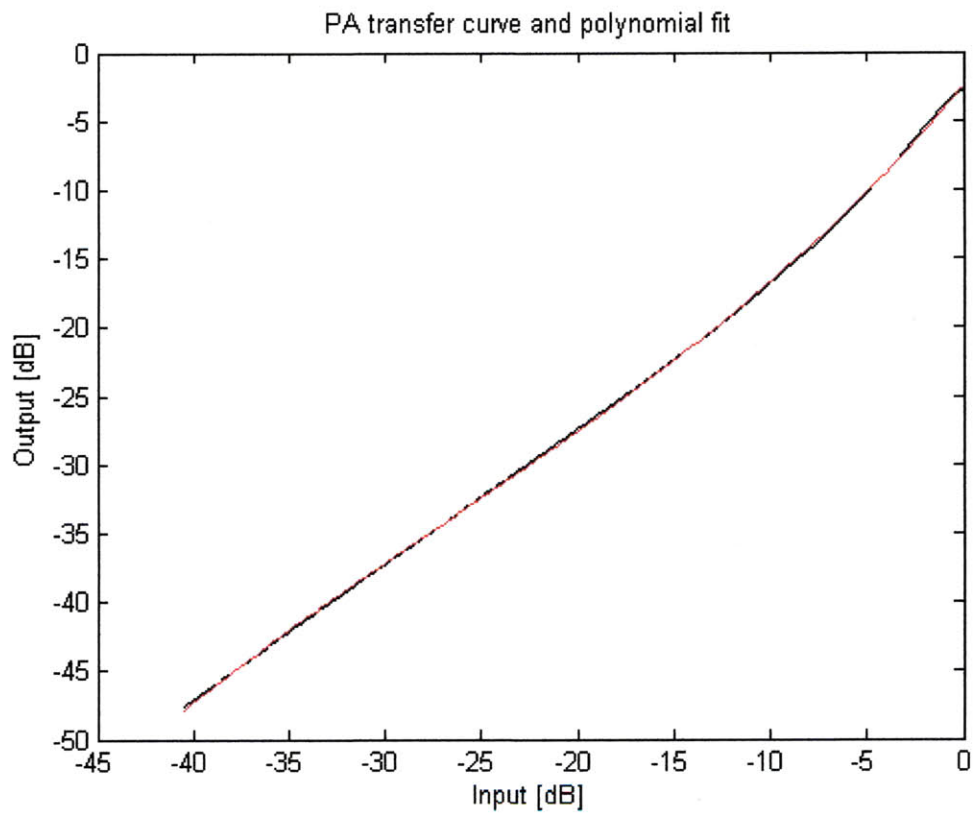


Figure 3-6: PA transfer curve and third-order polynomial fit

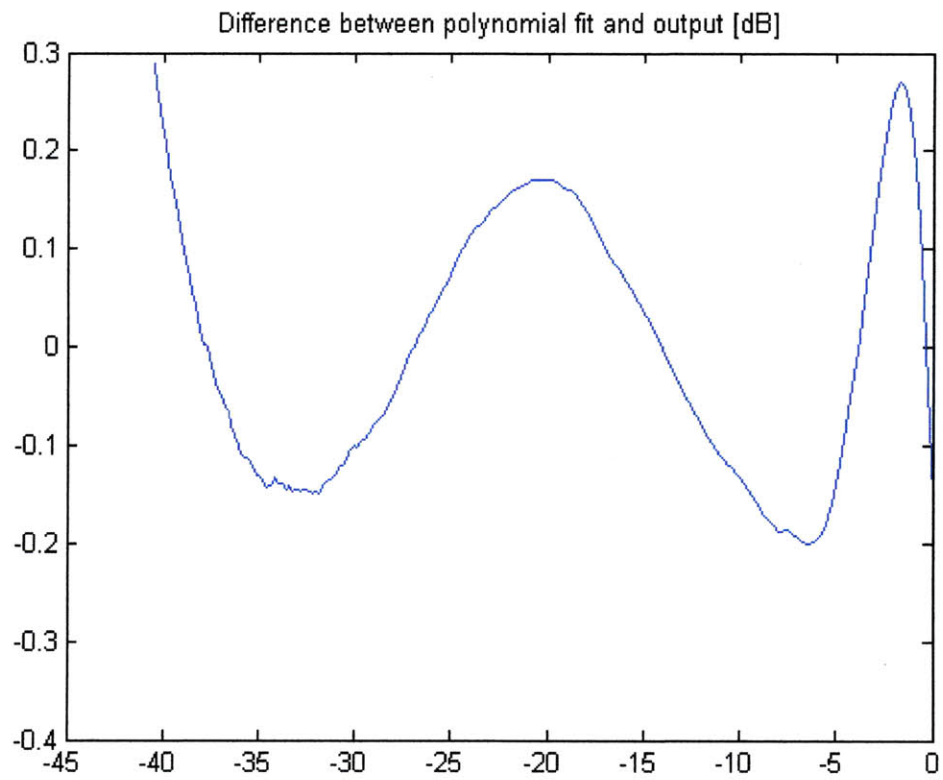


Figure 3-7: Difference between transfer curve and third-order polynomial fit in dB

3.2.1 Logarithmic amplifiers

The logarithmic amplifier selected for the envelope detection is the AD8310. We require that the system have a dynamic range of at least 80 dB, and we want the entire system to have a latency of $0.5 \mu\text{s}$. The device (AD8310 logarithmic amplifier) fits our requirements, as it has a voltage rise time of less than 15 ns, a dynamic range of 95dB, and a frequency range from DC to 440 Mhz . The complete specifications can be found in [11].

The linearity of the device was tested by applying 100 Mhz sine wave inputs from 0.2V to 0.2mV. This translates to a range from 0 to 80 dBm. The value of the output was recorded for each one dBm change in the input voltage, providing 81 data points, sufficient to define the device's transfer function. Figure 3-1 graphs the device's output in volts versus its input in dBm, along with a linear fit of the data, the units of the slope being V/dB. The device has a slope voltage of 23.9 mV/dBm, less than 1% different from the slope voltage of 24mV/dBm stated in [11].

3.2.2 Variable gain amplifier

The VGA required for the correction must have a fast response, as we desire that the entire system have a latency of less than $0.5 \mu\text{s}$. It must also have a high enough gain to truly compensate for the nonlinearities in the PA. The AD8368 amplifier characteristic was extracted by introducing gain control voltages from 0V to 1V, in increments of 0.05V. The data was collected with the VGA in increasing gain mode, such that the slope should be 37.5dB/mV. The measurements were noisier towards the lowest and highest values of gain control voltages, and the nonlinearity can be seen in figure 3-8. Because of these variations, and the linear fit's slope is of 36.6 dB/V. If we remove the data points close to the end values, the slope becomes 37.5dB/V.

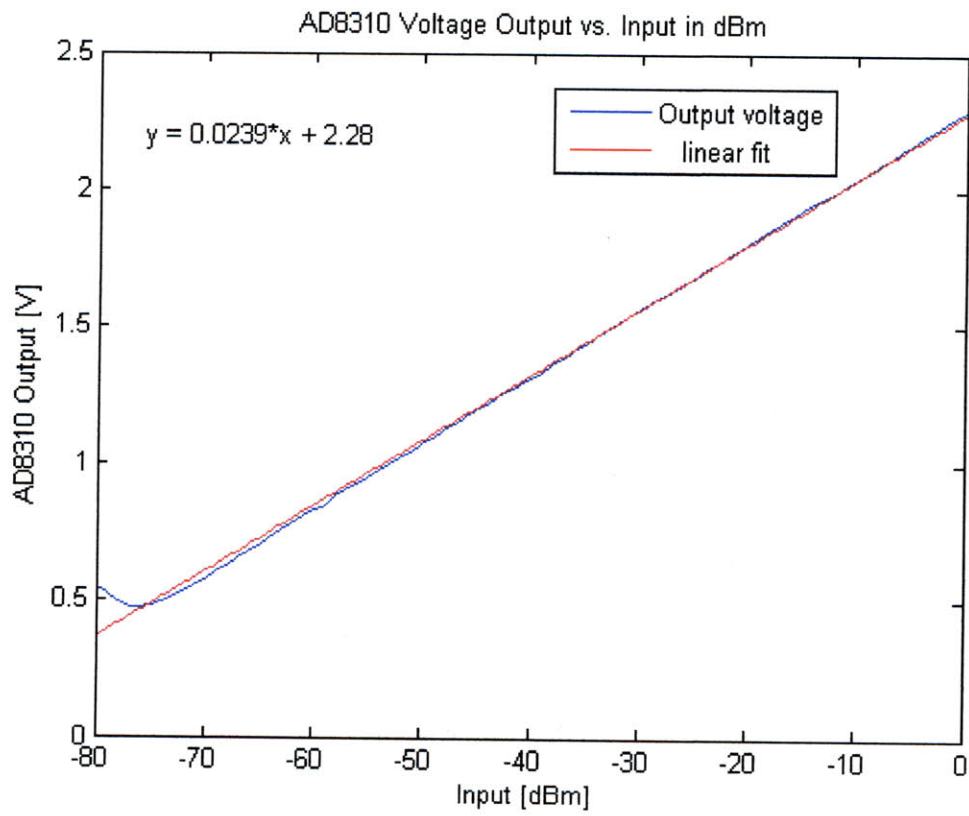


Figure 3-8: AD8310 Output Voltage vs. input voltage in dBm with linear fit

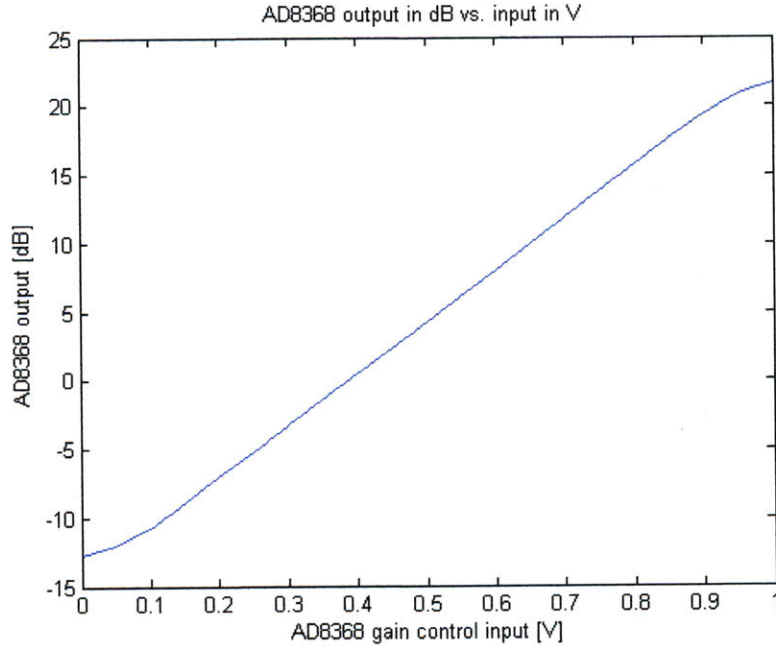


Figure 3-9: AD8368 output in dB vs. input in V

3.3 Simulation

Using the transfer functions derived from the experimental data, a complete model of the amplitude correction system is prepared for simulation. Taking a 40-dB ramp (shown in figure 3-7), the same input function from the amplifier test sequence, we test the ability of the feedback system to eliminate the error and linearize the amplifier response. First, we acquire the response of the logarithmic amplifier (as described by the model derived as explained in section 3.3) to the input signal.. Afterwards we take the response of the PA on the output side, and process that output with the model of the log amp. The comparator then takes the difference between the two logarithmic amplifiers, producing an error voltage. This error voltage serves as the gain control voltage for the VGA, and distorts the input to account for the nonlinearities in the power amplifier. A constant voltage of 0.3418 V is added to the error voltage, so that all variations in gain come from the error voltage (a constant voltage of 0.3418V sets the VGA gain to 0dB). As shown in Figure 3-10, the output of the comparator as it would be without any correction performed is considerable.

In Figure 3-11 we can see the error reduced by four orders of magnitude. This

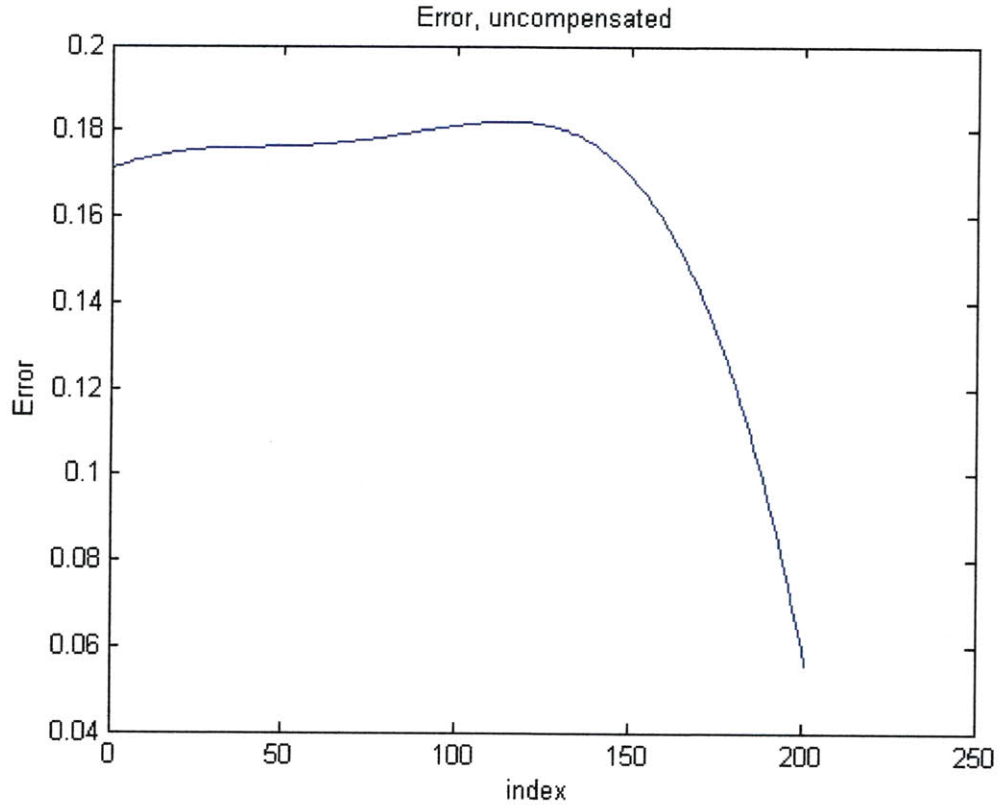


Figure 3-10: Error output from comparator

would indicate that the scheme is functioning as expected, as the error is converging to zero.

The simulation has some simplifying assumptions. It assumes that there is effectively no delay, and the input and output functions match exactly, such that the error in the signal would be solely from the PA. If the delay can be measured accurately in a real application, and the delay element in the line coupling into the logarithmic amplifier detecting the envelope on the input is chosen accordingly, this is not a far-fetched assumption. As to the speed of the system, the response time of the AD8310 is 15ns (from [11]), and the response time on the gain control of the AD8368 is 100ns (from [12]) we are well within the more stringent of the response time specifications stated in chapter 1, a system response faster than $0.5\mu\text{s}$.

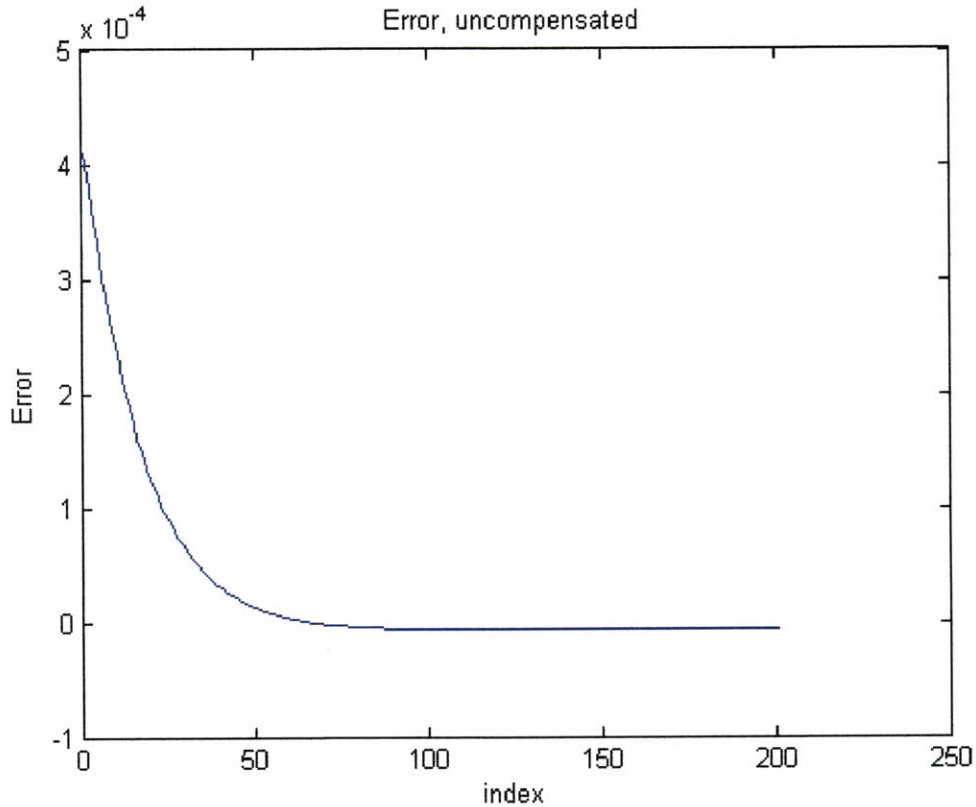


Figure 3-11: Reduced error output from the system

3.4 Prototype

After simulating the amplitude correction system and getting results that indicate that the design is feasible and reasonable, the next step is to build a prototype system for the amplitude correction. This allows us to both test for real system performance, and to account for particular intricacies of the system that may go unnoticed or may not be included in the simulation. The loss from the RF couplers was not accounted for either, but as the attenuation is the same on the input and output sides (a constant -1.2 dB), it would not be significant when taking the difference of the outputs of each logarithmic amplifier.

An explanation each section of the prototype test system is beneficial to understanding how the testing is carried out, and should clarify how the simulation corresponds to physical components.

The procedure to generate the input to the PA is as follows: the Tektronix

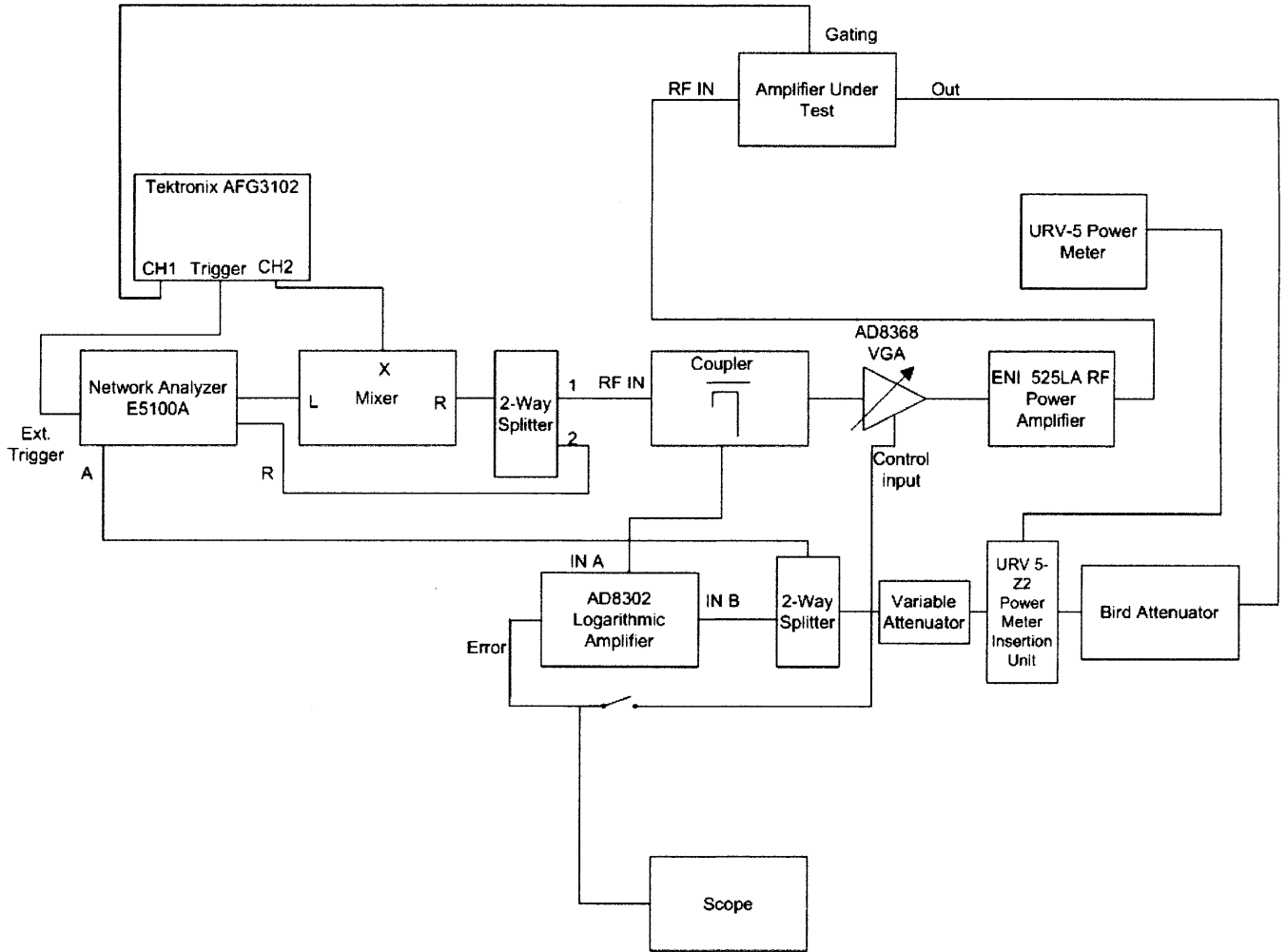


Figure 3-12: Test setup for the system prototype

AFG3102, an arbitrary waveform generator, outputs a 40dB exponential ramp from channel 2. The network analyzer E5100A produces the RF input to the mixer at 128 MHz. The output of the mixer (R in figure 3-12) is the multiplied output of the waveform generator and the network analyzer which is the ramp pictured in figure 3-1. The 2-way splitter produces the reference for the network analyzer to make the comparison. The RF input signal goes through the VGA, the gain of which we can set with a control voltage. Setting the gain to 0 dB would keep the signal as it is, before being sent into the ENI 525LA power amplifier. This would define the RF input being fed into the amplifier under test, the response of which we want to linearize. It should be mentioned that the ENI power amplifier is Class A for an output of up to

25 W, for frequencies between 1 MHz and 500 MHz (we are working at 128 MHz), but should still be characterized and accounted for when considering the RF input to the amplifier under test.

The amplifier under test is the amplifier with the non-linear characteristic and that we are attempting to linearize. A picture of the amplifier under test can be found in Appendix A. The data included in Chapter 3 is the actual non-linear characteristic of the PA.

The URV 5 power meter precisely measures the actual power output from the amplifier by entering a calibration factor for the Bird attenuator. The Bird attenuator has an attenuation factor of -30 dB, and is necessary for the power measurement, as the output of the amplifier under test reached up to 600W, and the insertion unit cannot handle that level of power. Through the variable attenuator we can control the power of the output signal of the amplifier under test to match the power of the input signal. This is the signal fed into IN B of the logarithmic amplifier to produce the error signal. The function of the scope is, as would be expected, to measure the error signal.

It is worth noting that this prototype system employs an AD8302 to perform the envelope detection and correction. The reasons for this are practical: the AD8302 has dual inputs and can perform the comparison of the signals from the input and output of the logarithmic amplifiers, and using one single device that performs both the envelope detection and the input and output envelope comparison simplifies the test setup. Though this device does not have the desired dynamic range (only 60 dB versus the needed 80dB), the objective of the prototype is to test whether or not the error signal converges to zero, as predicted by the results of the simulation, so trading two separate logarithmic amplifiers and a comparator for the simpler setup of using a single integrated device is valid.

Chapter 4

Testing Procedures and Simulation

4.1 Summary

From the results of the simulations and the behavior of the basic prototype constructed it can be concluded that the use of a polar-feedback linearization system can be an effective method for the correction of nonlinearities in the RF amplifier studied. For a forward input ramp of 40dB, the amplifier showed a gain variation of 4.7 dB. The simulation showed that the system is capable of compensating for the nonlinearities in the system and reducing the error from an initial peak of 0.18 V to a peak error of .04 mV, effectively zero. Despite the simplifying assumptions made in the simulation, these results should hold for a real system.

4.2 Future work

The prototype for the amplitude loop, though completed, has not produced sufficient results to allow for a definitive conclusion on the behavior of the system. It is expected that the behavior of the prototype will confirm the results of the simulation.

Looking at recent work in MR amplifiers, such as that presented in [10], and the original proposed linearization solution, migrating from an analog system to a digital one should also be considered, as it allows for more flexibility.

Phase correction loop: the initial design proposes a phase correction loop as well

as the amplitude correction loop that has been simulated and of which a prototype exists. The phase-shifter for that loop has been selected and tested, but a phase correction loop has not been implemented in simulation or in prototype. A phase correction loop is a significant portion of a complete polar feedback system, and thus, to complete the system, this loop would have to be constructed. The performance of the system as a whole cannot be fully assessed until this loop is completed, and thus is considered a logical next step after the completion of a fully functional amplitude correction loop for the linearization system.

Appendix A

Amplifier under test

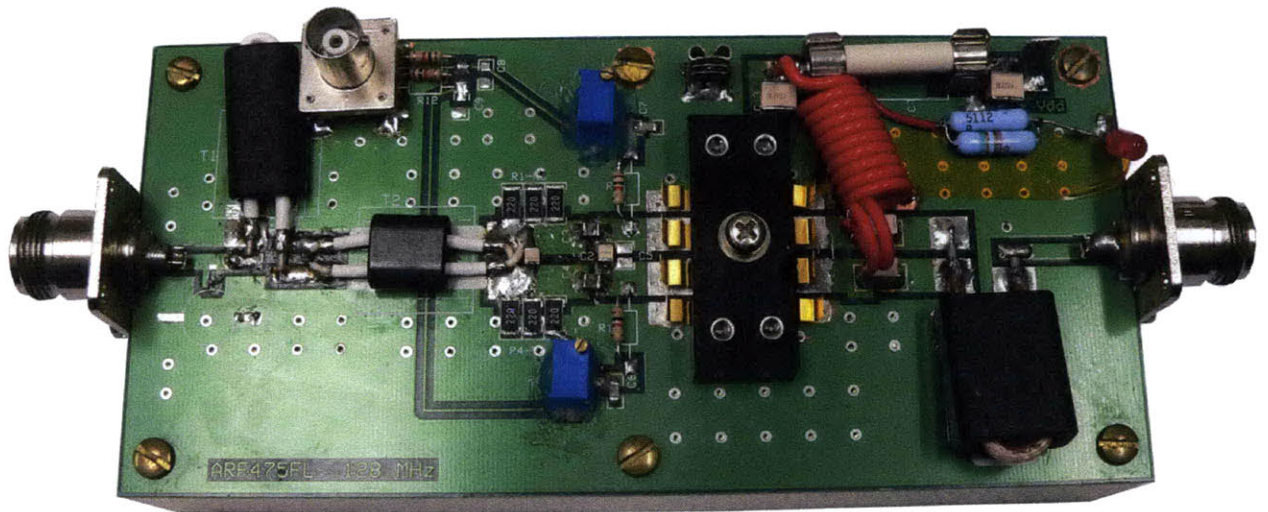


Figure A-1: Amplifier under test

Appendix B

Matlab codes

logAmpResp.m

```
%%Log Amplifier response to input waveform for AD8310
%The a and b values were extracted from a linear fit of the log amp's
%behavior. This calculates the response of the amplifier in volts, not dBm.
function [response] = logAmpResp(input,a, b)

    if isempty(input)==1;
        error('Empty input vector');end
    if nargin < 3, b = 2.2801;end
    if nargin < 2, a = 0.0239;end

    response = (a.*(input))+ b;

%    figure;
%    plot(input,response)
%    title('Logarithmic Amplifier AD8310 Response')
%    xlabel('Input [V]')
%    ylabel('Response[V]')
```

. vgaRespdB.m

```
%Gain control input is in volts, output is in dB.
%When the input voltage is .418 V, gain
%is 0 dB.

function [vgaRespdB] = vgaRespdB(input,gain,offset)
```

```
    if isempty(input)==1;
        error('Empty input vector');end
    if nargin < 3, offset = -12.7;end
    if nargin < 2, gain = 37.5;end

    vgaRespdB = (gain.*input) + offset;
```



```

figure;
plot(vgaRespdB)
title('Variable Gain Amplifier AD8368 Response')
xlabel('Index')
ylabel('Response [dB]')

```

. PATransfer.m

```
function [coeffs,outputfit,r11,r12] = PATransfer(input,output,n)
```

```
close all;
```

```
[coeffs,r11,r12] = polyfit(input, output, n);
```

```
%Polyval draws the function
```

```
outputfit = polyval(coeffs,input,r11,r12);
```

```
figure;
```

```
plot(input,output,'k');
```

```
hold on;
```

```
plot(input,outputfit,'r');
```

```
title('PA transfer curve and polynomial fit')
```

```
xlabel('input')
```

```
ylabel('output')
```

```
figure;
```

```
plot(input, output-outputfit);
```

```
title('Difference between transfer curve and fit')
```

```
xlabel('input [dB]')
```

```
ylabel('difference [dB]')
```

. Amploop.m

```
% Input
```

```
% -> PA->Output
```

```
% -> LogAmp
```

```

%         ->VGA
%
% Output
%         ->LogAmp
%         ->VGA->PA InputPath
.

function[coeffs,cerror,ninp,nout,vgag2]=Amploop(input,output,n,gain,newin)

close all;

PAtransfer(input,output,n);

logrespin = logAmpResp(input);
% figure;
%     plot(input, cthulhu)
%     title('Log Amp Response input Side')
%     xlabel('Input [dB]')
%     ylabel('input Log Amp Response')

[coeffs,r11,r12] = polyfit(input, output, n);
%Polyval draws the function
outputfit = polyval(coeffs,input,r11,r12);

% figure;
%     plot(input,output,'k');
%     hold on;
%     plot(input,outputfit,'r');
%     title('PA transfer curve and polynomial fit')
%     xlabel('input')
%     ylabel('output')
%
% figure;
%     plot(input,output-outputfit);
%     title('difference between fit and output')

```

```

logrespout = logAmpResp(output);

% figure;
%   plot(input, logrespout)
%   title('Log Amp Response output Side')
%   xlabel('Input [dB]')
%   ylabel('PA output Log Amp Response')

error = logrespin-logrespout;
figure;
plot(error)
title('Error, uncompensated')
xlabel('input')
ylabel('Error in V')

cerror = gain.*error;
%   figure;
%   plot(comperror)
%   title('Error amplified')
%   xlabel('Index')
%   ylabel('Error')

%When the VGA's input voltage is 0.3418, the VGA has a gain of 0 dB
vgagain = (vgaRespdB(comperror + 0.34));
figure;
plot(vgagain)
title('vga gain')

ninp = newin + vgagain;
figure;
plot(ninp)
title('input + vga gain')

nout = ninp + (output - input);
figure;
plot(nout);

```

```
lognewout = logAmpResp(nout);  
newerror = cthulhu - lognewout;  
vgag2 = (vgaRespdB(newerror + 0.34));  
figure;  
plot(input, vgag2);  
title('new gain')  
figure;  
plot(input, (input+vgag2));  
figure;  
plot(input, newerror)
```

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