



Agilent EEsof EDA

Presentation on RF Predistortion of Power Amplifiers - Part 2

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Module 1:

RF Predistortion of Power Amplifiers

Active linearization has become an important technology in modern communications systems. The emphasis on higher data rates and spectral efficiency has driven the industry towards linear modulation techniques such as QPSK, 64 QAM, or multicarrier configurations. The result is a signal with a fluctuating envelope which generates intermodulation (IM) distortion from the power amplifiers. Since most of the IM power appears as interference in adjacent channels, it is important to use a highly linear power amplifier. Linearization of a power-efficient amplifier is a desirable alternative to backing-off a Class A amplifier which would result in low power efficiency as well as considerable heat dissipation. An RF predistorter has the distinct advantage of being capable of handling moderate bandwidths while continuously adjusting for component drift and power level changes. This predistortion technique can function independently from the modulation scheme.

Shawn P. Stapleton

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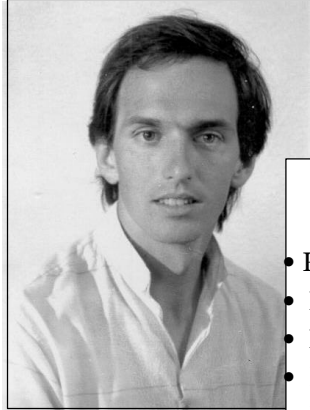
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About the Author



Shawn P. Stapleton

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- Focus on integrated RF/DSP applications
- PhD, 1988, Carleton University, Canada
- RF/Microwave communications systems
- Expert in Adaptive Linearization techniques

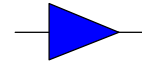


Shawn P. Stapleton is a Professor at Simon Fraser University. He research focuses on integrated RF/DSP applications for Wireless Communications. He received his BEng in 1982, MEng in 1984 and PhD in 1988 from Carleton University, Canada, where his studies were focused on RF/Microwave Communications. Before joining Simon Fraser University, Shawn worked on a wide variety of projects including: multi-rate digital signal processing, RF/Microwave communications systems, and Adaptive Array Antennas. While at Simon Fraser University he developed a number of Adaptive Linearization techniques ranging from Feedforward, Active Biasing, Work Function Predistortion to Digital Baseband Predistorters. He has published numerous technical papers on Linearization and has given many presentations at various companies on the subject. He continues to research the field of utilizing DSP techniques to produce Power Efficient Amplifiers for Mobile Communications applications.

Shawn P. Stapleton is a registered Professional Engineer in the province of British Columbia.



Agenda & Topics



RF Predistortion of Power Amplifiers

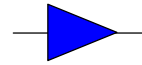
- Introduction to Adaptive RF Predistortion
- Technology Overview of Linearization
- Key Features: RF Predistortion Techniques & Concepts
- Adaptation Techniques
- RF Predistortion Design Tools
- Conclusion



You will receive an introduction and basic overview of the key features, technologies, and performance requirements of Predistortion in this paper. Solutions for solving some of the design challenges will also be presented. An adaptive Work Function Based Predistorter is demonstrated using the ADS. More in depth analysis can be obtained in the references at the end of this technical information session.



Introduction



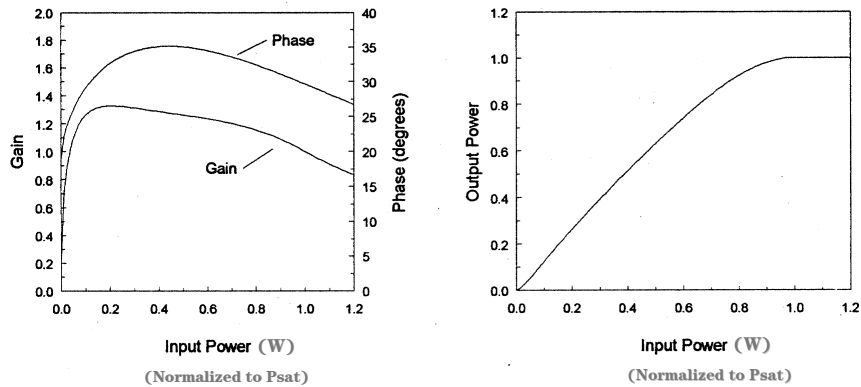
- Power Amplifier Intermodulation distortion
 - due to fluctuating envelope: QPSK, 64 QAM, etc.
- Two methods of achieving linear amplification:
 - Back-off the Class A amplifier - this reduces the power efficiency and increases the heat dissipation.
 - Linearize a power-efficient amplifier using external circuitry.
- Adaptation is required to compensate for component tolerances, drift, and input power level variations.

Increasing demand for spectral efficiency in radio communications makes multilevel linear modulation schemes such as Quadrature Amplitude Modulation more and more attractive. Since their envelopes fluctuate, these schemes are more sensitive to the power amplifier nonlinearities which is the major contributor of nonlinear distortion in a microwave transmitter. An obvious solution is to operate the power amplifier in the linear region where the average output power is much smaller than the amplifier's saturation power (ie. Larger output back-off). But this increases both cost and inefficiency as more stages are required in the amplifier to maintain a given level of power transmitted and hence greater DC power is consumed. Power efficiency is certainly a critical consideration in portable systems where batteries are often used or in small enclosures where heat dissipation is a problem. Another approach to reducing nonlinear distortion is the linearization of the power amplifier.

The power amplifier's characteristics tend to drift with time, due to temperature changes, voltage variations, channel changes, aging, etc. Therefore a robust linearizer should incorporate some form of adaptation.



Power Amplifier Characteristics



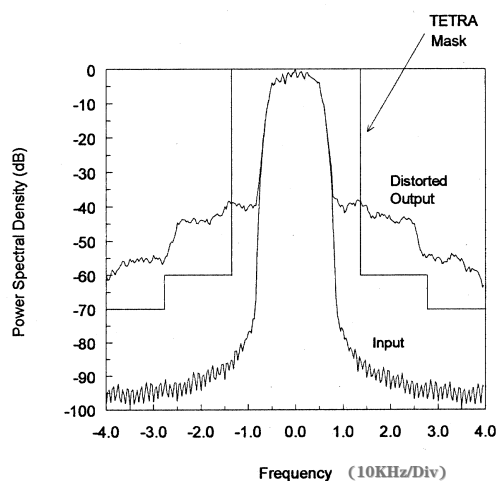
Measured Characteristics of a Typical Class AB Power Amplifier



Nonlinear amplifiers are characterized by measurement of their AM/AM (amplitude dependent gain) and AM/PM (amplitude dependent phase shift) characteristics. Not only are RF amplifiers nonlinear, but they also possess memory: the output signal depends on the current value of the input signal as well as previous values spanning the memory of the amplifier. Class AB power amplifiers (~25% efficient) are more power efficient than Class A amplifiers (~5% efficient). Class AB amplifiers exhibit gain roll-off at low input powers as well as at saturation.



Power Amplifier Spectral Output



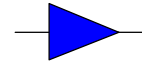
Power Spectra: Class AB Power Amplifier with $\pi/4$ DQPSK modulation



Regulatory bodies specify power spectral density masks which define the maximum allowable adjacent channel interference (ACI) levels. TETRA [3], for example, uses a $\pi/4$ DQPSK modulation format with a symbol rate of 18 KHz; channel spacing is 25 KHz. The Class AB power amplifier is operating at a back-off power of 3dB.

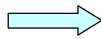


Technology Overview



Linearization approaches:

- FeedForward Linearization
 - Based on inherently wideband technology
- Digital Predistortion
 - Limited Bandwidth (DSP implementation)
- Cartesian Feedback
 - Stability considerations limit bandwidth and accuracy
- LINC
 - Sensitive to component drift and has a high level of complexity
- Dynamic Biasing
 - Limited ACI suppression
- RF Based Predistortion
 - Limited accuracy of function model
 - Implemented at RF with low complexity
 - Adaptation is required



Adaptive RF Predistortion
April 01



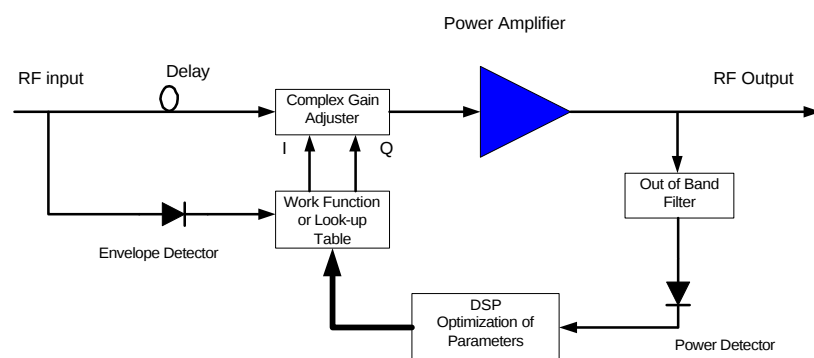
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Several other linearization techniques have been developed. Predistortion is the most commonly used technique, the concept is to insert a nonlinear module between the input signal and the power amplifier. The nonlinear module generates IMD products that are in anti-phase with the IMD products produced by the power amplifier, reducing the out-of-band emissions. The RF based predistorter [9] has two distinct advantages: 1) the correction is applied before the power amplifier where insertion loss is not as critical 2) the correction architecture has a moderate bandwidth. The digital predistortion technique [10] have higher complexity but offer better IMD suppression, however, bandwidths are low due to limited DSP computational rates. Cartesian feedback [1], has relatively low complexity, offers reasonable IMD suppression, but stability considerations limit the bandwidth to a few hundred KHz. The LINC technique converts the input signal into two constant envelope signals that are amplified by Class C amplifiers and then combined before transmission. Consequently, they are very sensitive to component drift. Dynamic biasing is similar to predistortion, however, the work function operates on the Power Amplifiers operating bias. Feedforward linearization is the only strategy that simultaneously offers wide bandwidth and good IMD suppression: the price for this performance is the higher complexity. Automatic adaptation is essential to maintain performance.



RF Based Predistortion



Adaptive RF Predistortion
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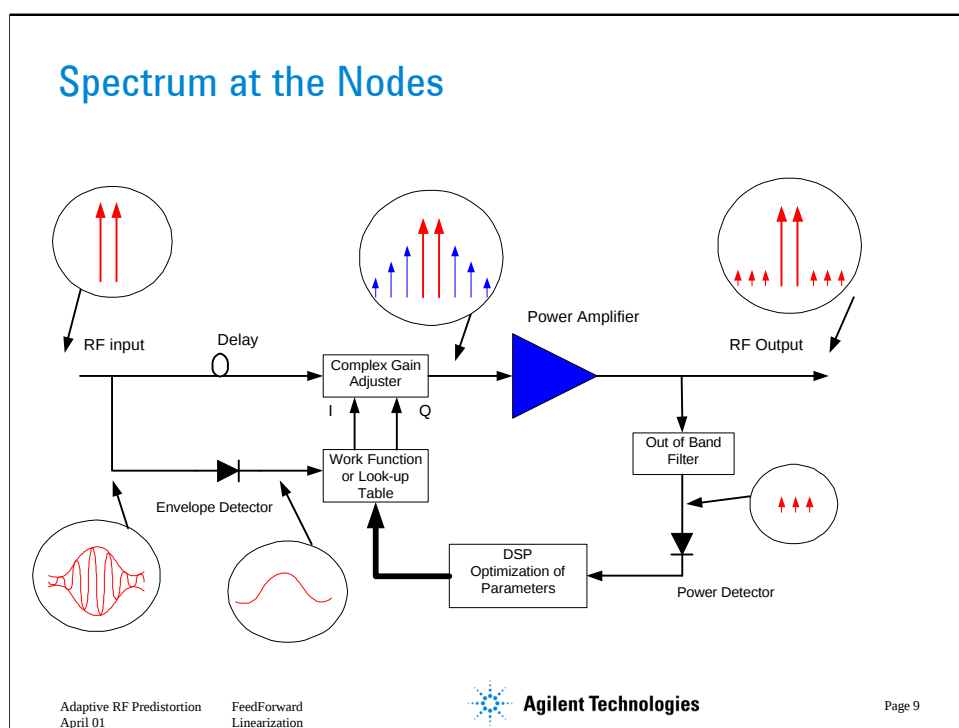
FeedForward
Linearization



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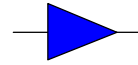
The linearizer creates a predistorted version of the desired modulation. The predistorter consists of a complex gain adjuster which controls the amplitude and phase of the input signal. The amount of predistortion is controlled by two nonlinear work functions that interpolate the AM/AM and AM/PM nonlinearities of the power amplifier. Note that the envelope of the input signal is an input to the work functions. The feedback path samples a portion of the undesired spectrum for which the DSP adjusts the work function parameters so as to minimize the undesired signal. The undesired signal is typically the adjacent channel power.



We can observe the spectral response at various nodes in the RF predistorter given an two tone input signal. The function of the envelope detector is to extract the amplitude modulation of the input RF signal. The delay line in the upper branch compensates for the time delay that occurs as the envelope passes through the work function. The complex gain adjuster, once optimized, will provide the inverse nonlinear characteristics to that of the power amplifier. Thus one can observe at the input mode to the power amplifier, the spectral growth from the predistorter. Ideally the intermodulation products will be of equal amplitude but in anti-phase to those created as the two tones pass through the power amplifier. The out-of-band filter will sample the adjacent power interference (ACPI). The function of the DSP is to slowly adapt the work function parameters so that the ACPI is minimized.



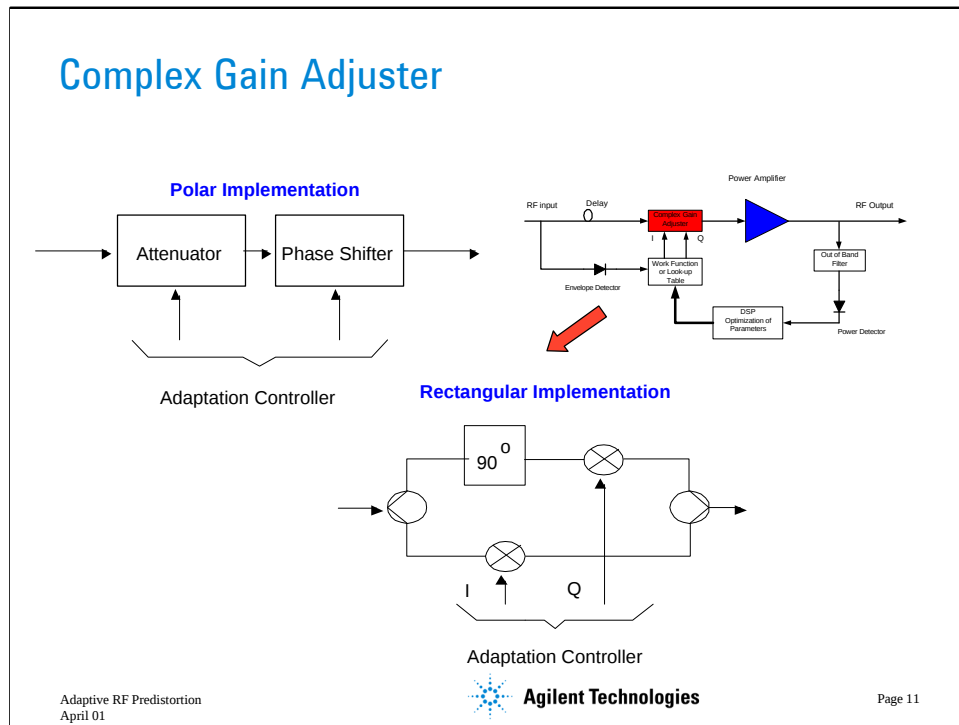
Design Techniques



RF Based Predistortion

- Generic RF predistortion techniques
 - Work function (ie. polynomial, exponential)
 - Look-up table
 - Analog nonlinearity (ie. Diodes)
- Generic adaptation techniques...
 - ACI power minimization
 - Gradient evaluation

Several patents concerned with adaptive predistortion systems appeared in the mid-eighties, and many more appeared in the early nineties. These patents dealt with two general methods of adaptation, namely adaptation based on power minimization[5] and adaptation based on gradient signals [1]. The control scheme for the former attempts to adjust the complex gain adjuster in such a way so as to minimize the measured power of the error signal in the out-of-band frequency. Once the optimum parameters have been achieved, deliberate perturbations are required to continuously update the coefficients. These perturbations reduce the IMD suppression. Adaptation using gradient signals is based on continually computing estimates of the gradient of a 3 dimensional power surface. The surface for the RF predistorter circuit is the difference between the input signal and the scaled output signal, this power is minimized when the error signal is completely suppressed. The gradient is continually being computed and therefore no deliberate misadjustment is required. There are three distinct RF predistortion techniques. The work function based approach utilizes a low order polynomial to fit the AM/AM and AM/PM characteristics of the power amplifier. The look-up table technique has more accuracy in fitting to the power amplifier's characteristics. However, it requires a more sophisticated adaptation technique. The analog nonlinearity technique consists of using diodes to generate IMD's. These IMD's will be phased and attenuated so as to be in anti-phase with those created by the PA.



Typical implementations of the complex gain adjuster is shown for the polar coordinates and rectangular coordinates. The mixers in the rectangular implementation can be replaced by bi-phase voltage controlled attenuators (VCA). The fact that the two branches of the vector modulator (VM) are in phase quadrature and that the VCA's are capable of bi-phase operation, ensures that the VM can achieve phase shifts anywhere in the range $[0, 360]$. The attenuation is set to a nominal value where the gradient with respect to voltage is largest, conditions for fast adaptation. Care must be taken to ensure that no additional nonlinearities are introduced.



The polar work function implementation requires the use of a complex gain adjuster which has attenuation and phase shifting capability. The work function consists of a simple 2nd order polynomial in terms of the squared envelope. When this function is multiplied by the input signal in the complex gain adjuster this will produce a 5th order polynomial in terms of the signal envelope. There are 4 parameters which are slowly adapted by the DSP or microprocessor with the ultimate goal of minimizing the adjacent channel power interference.



The rectangular work function implementation requires the use of a complex gain adjuster which has in-phase and quadrature controls. The work function consists of a simple 2nd order polynomial in terms of the squared envelope. When this function is multiplied by the input signal in the complex gain adjuster this will produce a 5th order polynomial in terms of the signal envelope. There are 4 parameters which are slowly adapted by the DSP or microprocessor with the ultimate goal of minimizing the adjacent channel power interference.



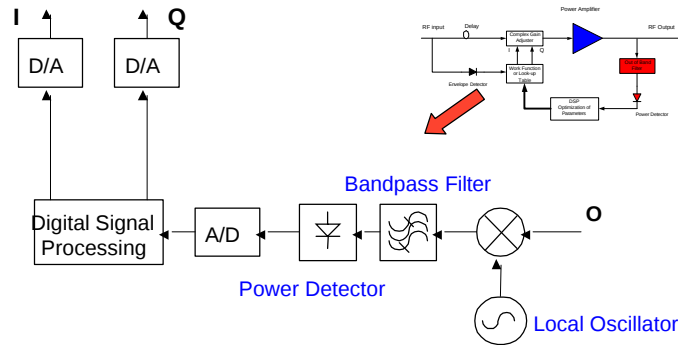
The look-up table technique requires an analog to digital converter to index the two tables. The tables can be order as in-phase and quadrature components or as amplitude and phase shift components. Because of the large number of table entires that need to be optimized, adaptation is typically performed at baseband. Where the error signal, resulting from the difference between the output and input signal, is used as an update parameter for the look-up table entries. This method requires a sample by sample comparison between the input and output. Increasing the complexity but improving the overall suppression. Otherwise the table entries could be optimized based on adjusting the table entires to conform to a higher order function. Reducing the complexity but with a degraded suppression performance.



The analog nonlinearity predistorter has been used for many years. The basic concept is the generation of intermodulation products through the use of diodes. The generated IMD components will be phase shifted and amplitude controlled and then combined with the fundamental component . The predistorter's IMD component will ultimately be positioned in anti-phase with those created by the power amplifier. This technique has a limited suppression capability.



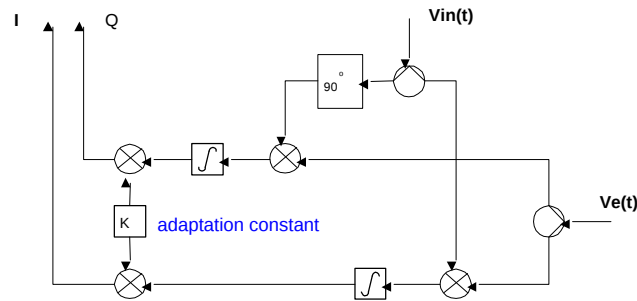
ACI Power Minimization



This adaptation controller is representative of the “minimum power” principle applied to RF predistortion. The control voltages “I” and “Q” are adjusted so as to minimize the power in port “O”. Port “O” is a sample of the interference created in the adjacent channel. Some of the drawbacks of this method are its slow convergence to the minimum and its sensitivity to measurement noise, especially near the minimum. Power measurements are inherently noisy and therefore long dwell times are required at each step in order to reduce the variance of the measurement. Two methods have been devised to mitigate this problem. A tuneable receiver is used to select a frequency band that includes only distortion and the controller works to minimize this quantity. Another approach is to subtract a phase and gain adjusted replica of the input from the output. Ideally leaving only the distortion, which is fed into port “O” and used in the minimization algorithm.



Complex Correlator Gradient Method



$$\alpha = K_{\alpha} \int ve(t) \bullet vin(t)^* dt$$

$$ve(t) = vo(t) - vin(t) \text{ (contains only distortion)}$$

The gradient method is an alternative to the minimum power principle for adaptation. The RF predistorter circuit can use either a complex baseband correlator or a bandpass correlator. The simplest iterative procedure is the method of steepest decent. In the context of quadratic surfaces, one begins by choosing an arbitrary initial value of α which defines some point on the error surface. The gradient of the error surface at that point is then calculated and α is adjusted accordingly. Well known in estimation theory is that for quadratic error surfaces, the correlation between the basis $vr(t)$ and the estimation error $ve(t)$ is identical to the gradient of the error surface and thus can be used to drive the adaptation algorithm. The method of steepest descent coupled with the stochastic gradient signal $(ve(t) \bullet vm(t)^*)$ suggests the above algorithm for the adjustment of α .

The gradient will be zero when $vr(t)$ and $ve(t)$ are decorrelated, which implies that the error signal contains only distortion. The gradient method is faster than the minimum power methods and does not require continuous misadjustments in order to determine the direction of change. However, it is sensitive to DC offsets at the output of the mixers.



Agilent ADS RF Predistortion Simulation

Simulation Parameters:

- 1) Two Tone Modulation ($F_c=850$ MHz, $\Delta=1$ MHz)
- 2) 5th order polynomial work function
- 3) Adjacent channel power minimization
- 4) Dwell Time of 450 μ sec per iteration
- 5) Iterative LMS adaptation between α_3 and α_5
- 6) Motorola Power Amplifier
- 7) Ideal passive components assumed

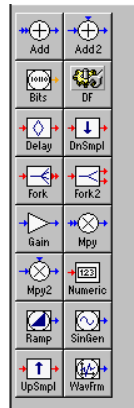


The Agilent ADS RF predistorter simulation example is based on the rectangular work function technique. Where we utilize the secant method to adapt the work function coefficients so as to minimize the ACPI. The 4 coefficients are iteratively adjusted with 450 microseconds of power averaging. A motorola power amplifier is used in the co-simulation. We have assumed the passive components, such as the power splitters and combiners are ideal.

For demonstration purposes we have used a two tone input centered on 850 MHz.



ADS Simulation Setup



*Data Flow Controller and Variables
that will be used in the Simulation:*

DF

```
DF
DF1
DefaultStart=0.0
DefaultStop=5000.0
DefaultTimeUnit=usec
DefaultSeed=1234567
SchedulerType=ClusterLoop
DeadlockManager=ReportDeadlock
TimeStamp=NoMultirateDelay
```

```
Var  VAR
Eqn  VAR1
Average=450
TimeStep=1/25
FreqCenter=.850
FundUpper=FreqCenter+Delta
FundLower=FreqCenter-Delta
Delta=.5e-3
DroopRate=3e+4
```

Adaptive RF Predistortion
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FeedForward
Linearization



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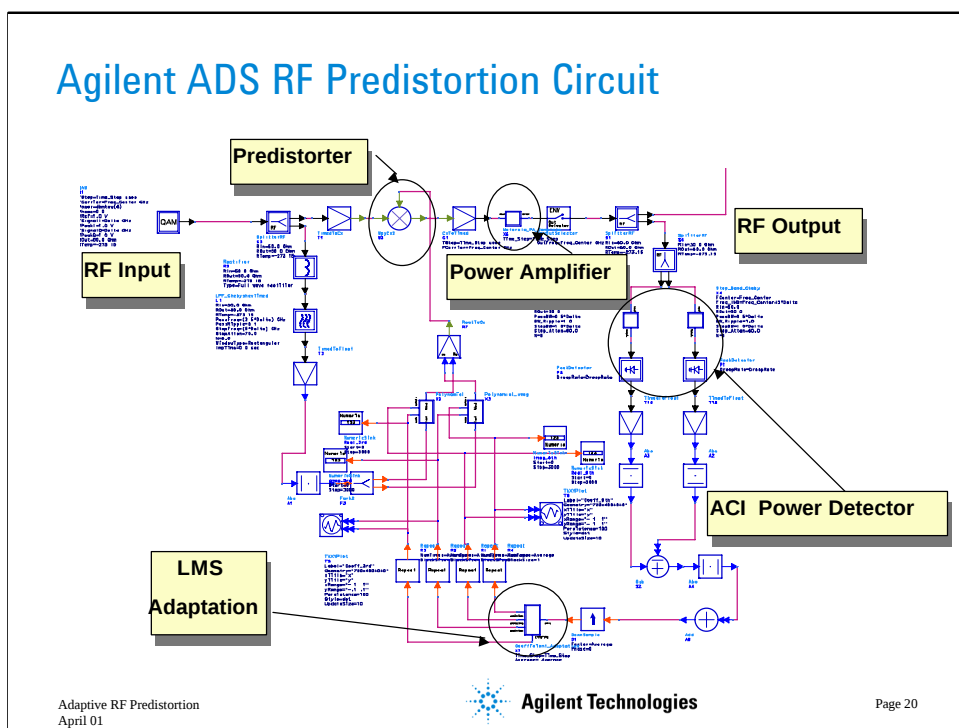
Agilent Ptolemy simulation controller and the variable equation block for defining the RF Predistorter parameters.

Average is the dwell time in microseconds.

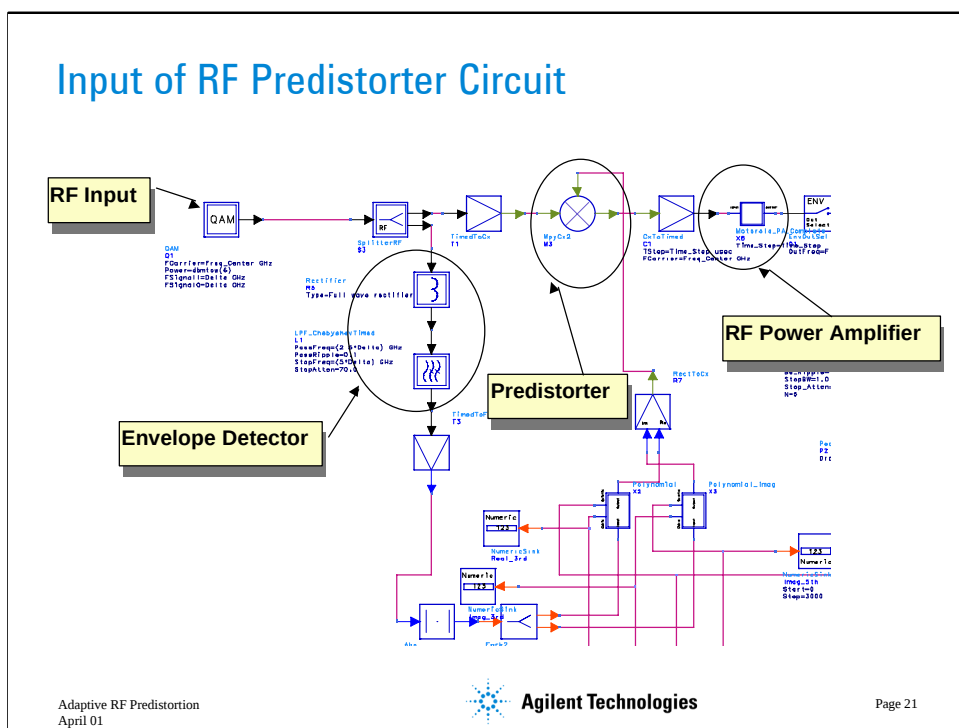
Freq_Center is the center frequency .

Delta is one half the frequency separation between tones.

DroopRate is the decay time for the peak detector in Volts/second.



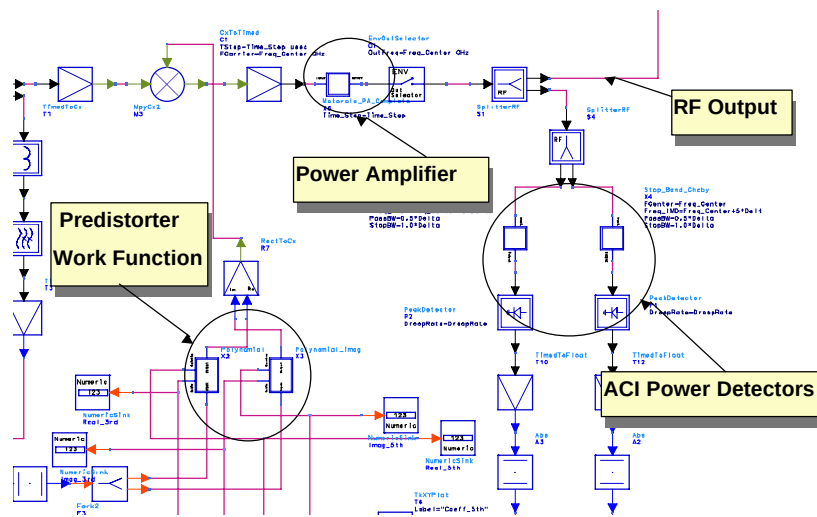
The Agilent ADS circuit schematic for RF predistorter . The adaptation technique is based on the power minimization method. The rectangular implementation is used for the complex gain adjuster. The input consists of a two tone modulation. The adaptation technique is a least mean squared approach.



Focusing on the input. The predistorter consists of a complex multiplication based on the in-phase and quadrature inputs. A full wave rectifier followed by a low pass filter is used for the envelope detector.



Feedback Loop of RF Predistorter

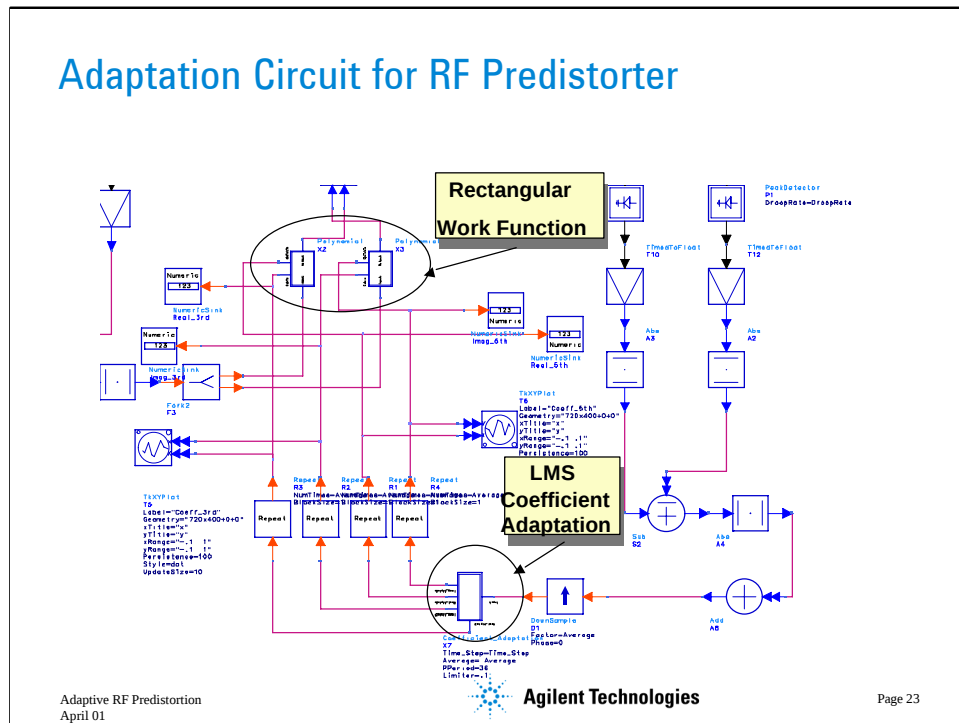


Adaptive RF Predistortion
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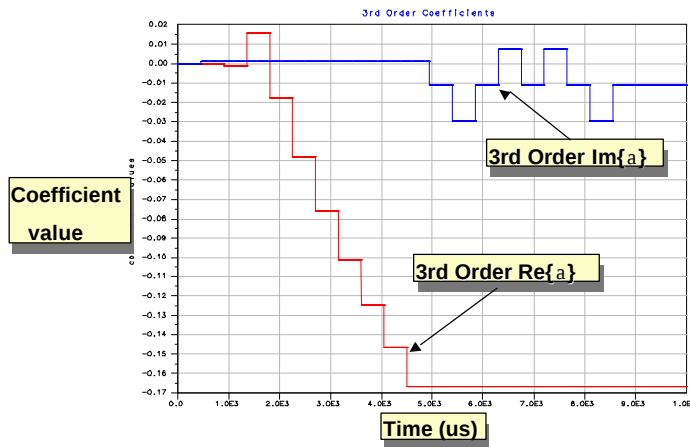
The predistorter work function consists of two second order polynomials in terms of the squared envelope. The adjacent channel power detector used in this simulation consists of two bandpass filters centered on the 3rd and 5th order intermodulation products, followed by peak detectors.



The coefficients in the work functions are optimized using a least mean squared approach. The 4 coefficients are adapted via iteration, starting with the 3rd order coefficients and then switching to the 5th order coefficients.



Coefficient values for RF Predistorter

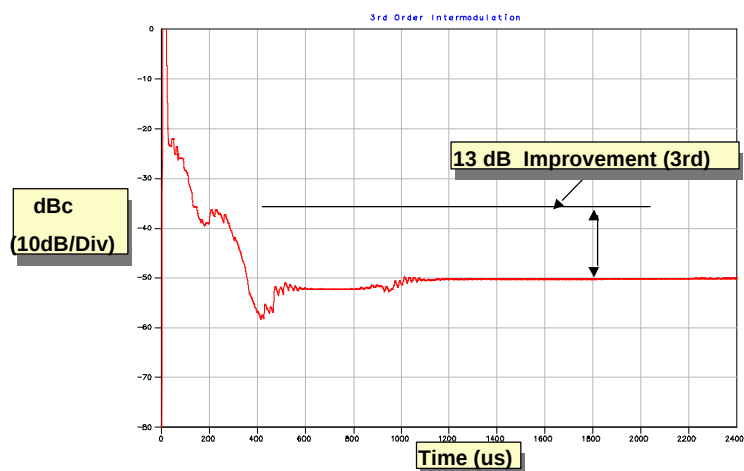


Adaptive RF Predistorter Using Rectangular Coordinate Work Function

Notice that in this adaptation procedure the real 3rd order coefficient is adapted first, followed by the imaginary 3rd order coefficient. The coefficients adapt slowly, a dwell time of 450 microseconds is used for obtaining a stable output power measurement. Instability can occur if proper attention is not paid to the adaptation procedure. The 5th order coefficients are similarly adapted.



IMD3rd Performance of RF Predistorter

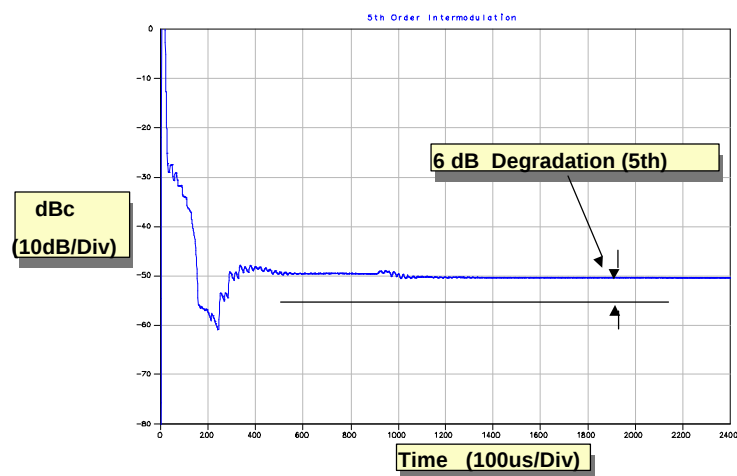


Adaptive RF Predistorter Using Rectangular Coordinate Work Function

This curve demonstrates that amount of improvement in the 3rd order intermodulation levels at the output of the RF predistorter.

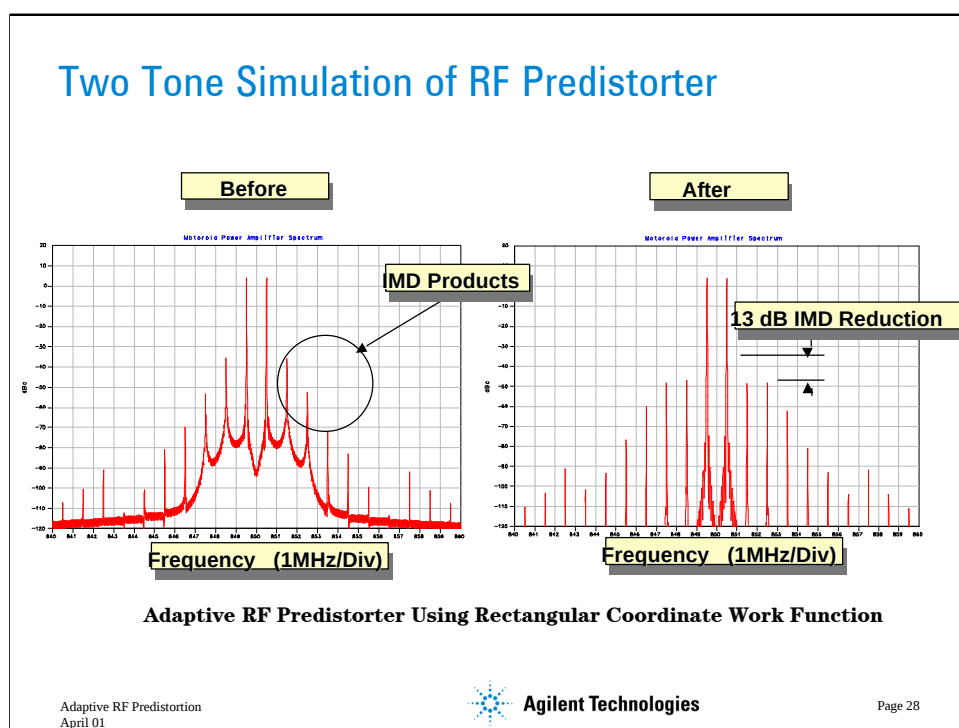


IMD5th Performance of RF Predistorter



Adaptive RF Predistorter Using Rectangular Coordinate Work Function

This curve demonstrates that amount of degradation in the 5th order intermodulation levels at the output of the Rf predistorter.



The first figure shows that driving the power amplifier at 5dB back-off generates high levels of intermodulation power as well as high levels of harmonics. The second figure shows the resultant output from the RF predistorter once the coefficients have adapted. We can observe the spectral growth that occurs using a predistorter. The adjacent channel power is spread over a wider bandwidth but the mask requirements can be met.



Summary

RF Based Predistortion

- Adaptive RF Predistorters are moving from the Research to Development phase.

Design Solutions

- The Agilent ADS RF Predistorter Design example demonstrates the performance achievable with linearization.
- System level simulation provides a solid starting point for building an implementation quickly.
- Designed components can be integrated into a system to witness the impact on overall performance.





Resources & References

- [1] J. Namiki, "An automatically controlled predistorter for multilevel quadrature amplitude modulation", IEEE Transactions on Communications, vol. COM-31, no.5, May 1983.
- [2] T. Nojima and T. Konno, "Cuber predistortion linearizer for relay equipment in the 800 MHz band land mobile telephone system", IEEE Transactions on Vehicular Technology, vol. VT-34, pp. 169-177, Nov. 1985.
- [3] C.G. Rey and E. Clark, "Linearization Performance for a Polar Work Function" Proceedings of IEEE Vehicular Technology Conference, 1998.
- [4] A.N. D'Andrea, V. Lottici and R. Reggiannini, "RF power amplifier linearization through amplitude and phase predistortion", IEEE Transactions on Communications, vol-44, Nov. 1996, pp. 1477-1484.
- [5] S.P. Stapleton and F.C. Costescu, " An adaptive predistorter for a power amplifier based on adjacent channel emissions", IEEE Transactions on Vehicular Technology, vol-41, no.1, Feb. 1992, pp. 49-56.





Resources & References

- [7] M. Nannicini, P. Magni and F. Oggioni, "Temperature controlled predistortion circuits for 64 QAM microwave power amplifiers", IEEE Microwave Theory and Techniques Digest, 1985, pp. 99- 102.
- [8] J.F. Wilson, "The TETRA system and its requirements for linear amplification", IEE Colloquium on Linear RF Amplifiers and Transmitters, Digest no. 1994/089, 1994, pp.4/1-7.
- [9] S.P. Stapleton, G.S. Kandola and J.K. Cavers, "Simulation and Analysis of an Adaptive Predistorter Utilizing a Complex Spectral Convolution", IEEE Transactions on Vehicular Technology, vol. 41, no.4, pp.1-8, November 1992.



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