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### Presentation on Digital Predistortion of Power Amplifiers

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# Module 1:

## Digital 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. A digital baseband predistorter has the distinct advantage of being capable of handling rapid fluctuations in amplifier characteristics, however it typically operates on low bandwidth signals. This predistortion technique can function independently from the modulation scheme.

Shawn P. Stapleton

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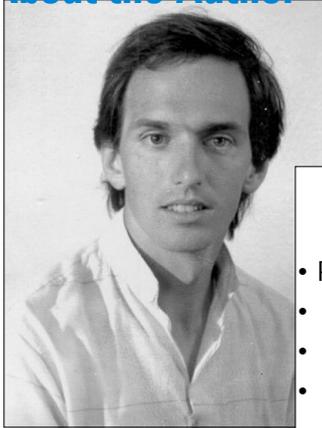
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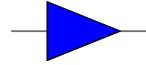
### Shawn P. Stapleton

- Professor: Simon Fraser University
- 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

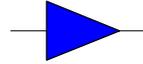


## Digital Predistortion of Power Amplifiers

- **Introduction to Adaptive Digital Predistortion**
- **Technology Overview of Linearization**
- **Key Features: Digital Predistortion Techniques & Concepts**
- **Adaptation Techniques**
- **Digital 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 digital baseband 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

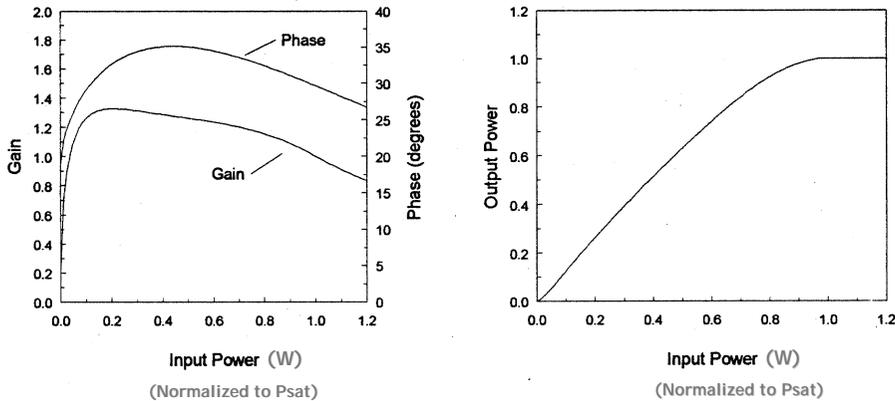


- Power Amplifier Intermodulation distortion
  - due to fluctuating envelope: QPSK, 64 QAM, etc.
- Two methods of achieving linear amplification:
  - Back-off the Class A amplifier - this reduces the power efficiency and increases the heat dissipation.
  - Linearize a power-efficient amplifier using 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.

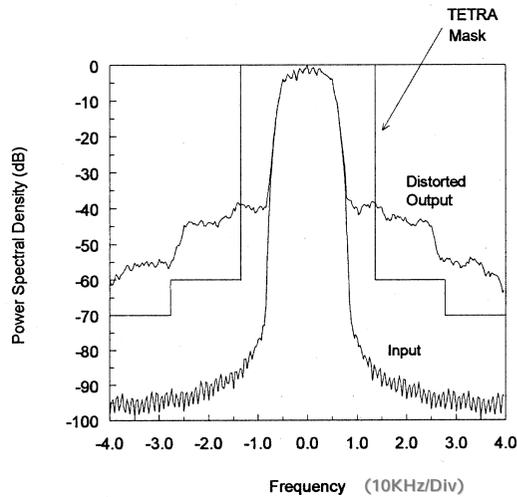
## Power Amplifier Characteristics



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. The loss of gain at low levels is due to the crossover region created by the push/pull transistor configuration.

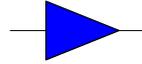
## Power Amplifier Spectral Output



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, 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. In order to meet the regulatory mask, at least a 20 dB improvement in the intermodulation products is required.

# Technology Overview



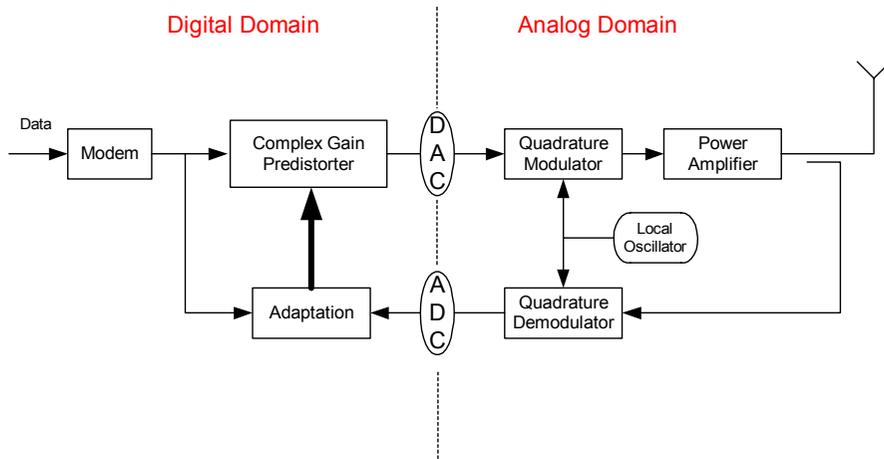
## Linearization approaches:

- **FeedForward Linearization**
  - **Based on inherently wideband technology**
- **RF Predistortion**
  - **Limited accuracy of function model**
  - **Implemented at RF with low complexity**
- **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**
- Digital Predistortion
  - **Limited Bandwidth (DSP implementation)**
  - **Good IMD suppression**



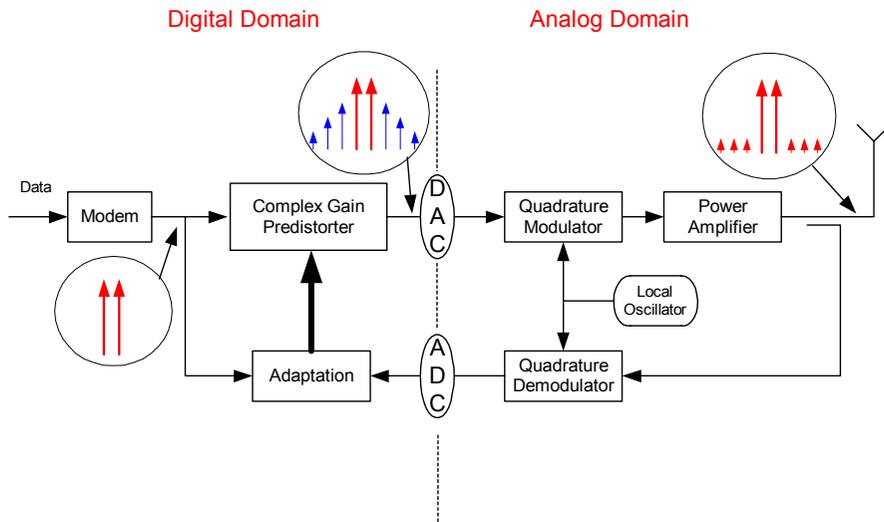
Several linearization techniques have been developed. Predistortion is the most commonly used technique, the concept is to insert a nonlinear module between the input signal and the power amplifier. The nonlinear module generates IMD products that are in anti-phase with the IMD products produced by the power amplifier, reducing the out-of-band emissions. The RF based predistorter 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. Cartesian feedback, 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 Amplifier's operating bias. This technique creates transient spikes from the effects of rapid bias switching. 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. The digital predistortion technique [1-9] has a higher complexity but offers better IMD suppression. However, bandwidths are low due to limited DSP computational rates. Digital predistortion is typically implemented at baseband using either a DSP chip, a Field Programmable Gate Array or an ASIC.

# Digital Predistortion



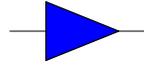
This slide illustrates the software/hardware boundary for the adaptive linearization circuit. In addition to a Power Amplifier, it also requires a coupler, quadrature modulator and demodulator as well as an A/D and D/A converter. Note that the same oscillator is used in the Up and Down conversion for coherence, some methods require a phase shifter for achieving stability. 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 the entries of a Look-up Table 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 Look-up table. The feedback path samples the distorted signal for which the DSP adjusts the Look-up Table entries so as to minimize the level of distortion.

# Spectrum at the Nodes



We can observe the spectral response at various nodes in the digital baseband predistorter given a two tone input signal. The function of the adaptation block is to extract the amplitude modulation of the input RF signal and adjust the Look-up Table entries. The entries of the Look-up Table will be indexed by the level of the input signal envelope. 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 function of the DSP adaptation block is to adjust the Look-up Table entries so as to minimize the difference between the input signal and a scaled version of the output signal from the power amplifier. Thereby minimizing the level of distortion.

# Design Techniques



## Digital Predistortion

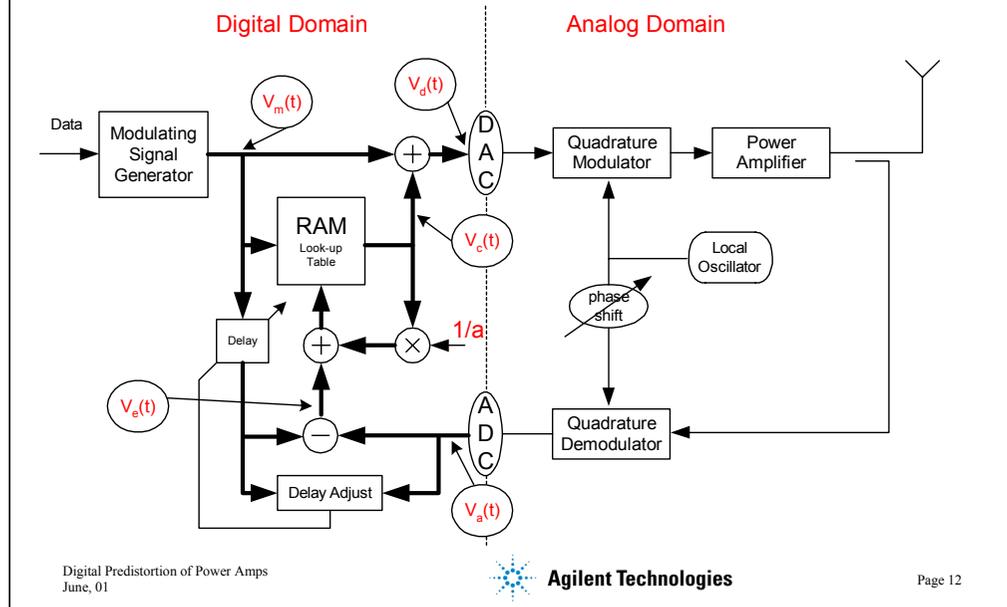
- Generic digital predistortion techniques
  - complex vector mapping look-up table
  - complex gain look-up table
  - cartesian feedback
- Generic adaptation techniques...
  - Secant method
  - linear convergence

There are three generic digital predistorters. The cartesian feedback linearizer is the most simplistic of the techniques and is based on the classical feedback control system. The power amplifier's input is proportional to the error that results from the subtraction of the undistorted input signal from that of the power amplifier output. The drawbacks to this technique are the linearity and bandwidth dependence on the feedback time delay as well as the potential instability. Another technique is the complex vector mapping look-up table (LUT) approach, in which the output vector of the LUT is a predistorted version of the input vector. The drawback to this technique is the stability requirement for an accurate adjustment of the phase shifter in the feedback path. The complex gain LUT technique eliminates the need for a phase shifter. This approach uses the envelope of the input signal as the index to the LUT entries. The input signal is then multiplied by the table LUT values which are the predistorter's complex gains.

There are various adaptation techniques available, two of the most common approaches are the secant method and the linear convergence method. The secant method requires the formulation of the adaptation into a root finding problem. The root is the error resulting from the difference between the input and a scaled version of the output. The root is a function of the table entries which are adjusted using the classical secant method [4]. The linear convergence method is a slower method but is simpler to implement. This approach uses a scaled version of the resulting error signal to adjust the LUT entries iteratively. The scaling parameter controls the rate of convergence.

The cartesian feedback technique [1] has the virtue of simplicity; the amplifier input complex envelope is proportional to the difference between the desired and measured amplifier output. This negative feedback technique is constrained in the amount of reduction in distortion achievable. Both the linearity as well as the bandwidth are critically dependent on the feedback loop delay. The negative feedback gain adjusts the level of nonlinear distortion. Another issue is that of stability, where precise adjustment is required of the RF phase shifter.

## Complex Vector Mapping LUT

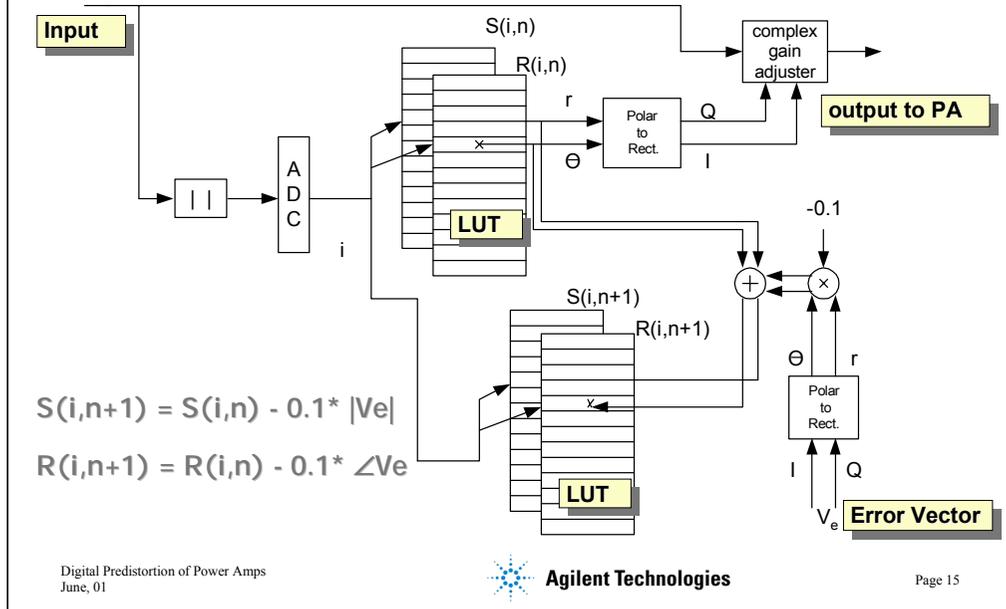


The complex vector mapping LUT [6] approach compares the measured signal  $V_a(t)$  with the reference signal  $V_m(t)$ , the resultant error signal is used to update the RAM Look-Up Table. There exists some delay in the feedback path that needs to be compensated for by delaying the reference signal before a comparison is made. The delay adjusting circuit can use the modulation characteristics to continuously track the delay. Typically the delay is controlled to within  $1/64$  th of a symbol duration this will keep sufficient linearization. This technique also requires a phase shifter in the feedback path for stability in the adaptation update and tends to slow the convergence time. This particular configuration uses the linear convergence approach where “a” is the updating gain parameter. The compensating vectors  $V_c(t)$  are stored in the RAM look-up table and indexed by the instantaneous input vectors. Thus the requirement for a large random access memory for storing all the possible input vector states. Typically a 10 bit A/D and D/A is sufficient for achieving -60 dBc intermodulation levels.

The complex gain Look-up Table technique [4] adapts the table entries to achieve the inverse AM/AM and AM/PM characteristics from that of the power amplifier. The LUT is indexed by the instantaneous amplitude of the input signal. If the power amplifier nonlinearity is well behaved at lower power levels then the LUT can be indexed by the square of the input amplitude. In this case as little as 64 table entries have been demonstrated to provide sufficient spectral control. A particular advantage of this approach is that the complex gain function can adapt very quickly to channel changes because of the reduced number of LUT entries that need to be adjusted.

The complex gain function  $F\{x\}$  is indexed by the instantaneous input amplitude. The LUT entry for the corresponding input vector's amplitude is then multiplied by the input signal vector. The updates to the predistorter LUT are continually adjusted by comparing the reference complex envelope  $V_m(t)$  with the sampled feedback modulation  $V_a(t)$ . The resultant loop error vector is then separated into a scaling and rotation error component. For all inputs to the amplifier of identical instantaneous signal amplitude, the scaling and rotation errors will be identical.

# Linear Convergence



S and R represent the scaling and rotation errors which are stored in the LUT [5] and are indexed by the instantaneous input amplitude. Using linear convergence with an update gain parameter equal to -0.1, the new LUT entry will replace the previous value according to the scaling and rotational error. This approach requires the use of both a polar to rectangular transformation as well as a rectangular to polar transformation.

## ADS RF Predistortion Simulation

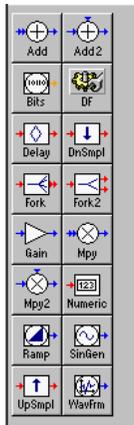
### Simulation Parameters:

- 1) Multi-tone Modulation ( $F_c=800$  MHz,  $BW=25$  MHz)
- 2) 64 entry look-up table
- 3) Complex gain look-up table technique
- 4) linear convergence parameter is -0.1
- 5) Behavioral model for Power Amplifier
- 6) Ideal passive components assumed

The ADS digital baseband predistorter simulation example is based on the complex gain look-up table technique. Where we utilize the linear convergence method to adapt the LUT entries so as to minimize the level of undesired distortion. The LUT consists of only 64 entries which are indexed by a 6 bit A/D converter. The power amplifier used in this example has a behavioural model. We have assumed the passive components, such as the power splitters and combiners are ideal.

For demonstration purposes we have used a multi-tone input centered on 800 MHz. The bandwidth has been exaggerated to demonstrate the adaptation requirements for wide bandwidths.

## ADS Simulation Setup



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

DF

```
Var Eqn VAR  
VAR1  
Time_Step=0.01  
Freq_Center=800  
Delta=5
```

```
DF  
DF2  
DefaultStart=0.0  
DefaultStop=100.0  
DefaultTimeUnit=usec  
DefaultSeed=1234567  
SchedulerType=ClusterLoop  
DeadlockManager=ResolveDeadlock  
TimeStamp=NoMultirateDelay
```

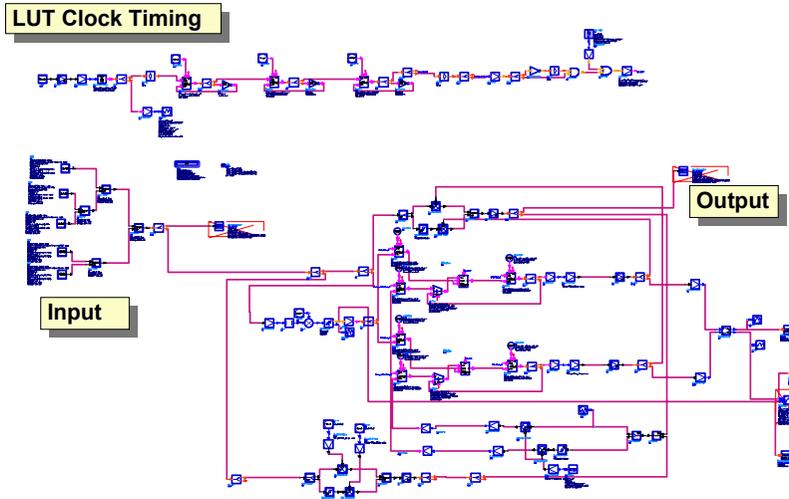
Agilent Ptolemy simulation controller and the variable equation block for defining the Digital Baseband Predistorter parameters.

Time\_Step is the simulation step time in microseconds.

Freq\_Center is the center frequency in MHz .

Delta is one half the frequency separation between tones.

# ADS Digital Predistortion Circuit



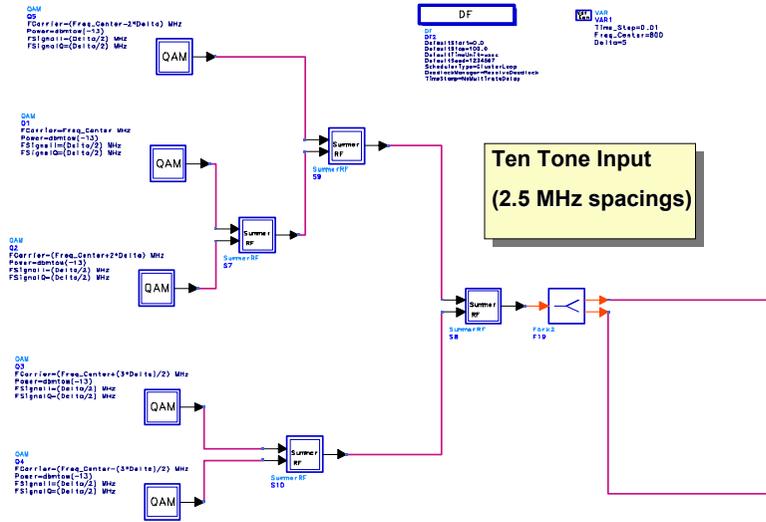
Digital Predistortion of Power Amps  
June, 01



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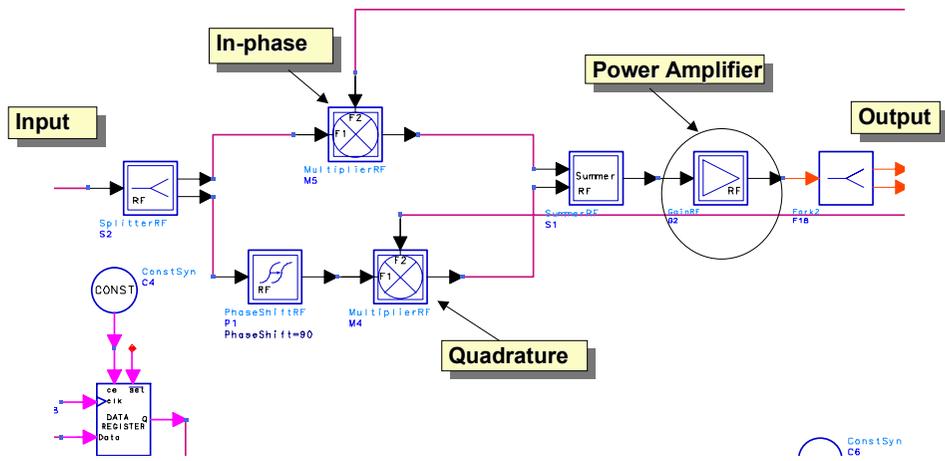
The ADS circuit schematic for the digital baseband predistorter. The adaptation technique is based on the linear convergence method. The rectangular implementation is used for the complex gain adjuster. The input consists of a multi-tone modulation. The timing clocks used for the DSP control is located up top. A behavioural model is used for the power amplifier.

# Input of Digital Predistorter Circuit



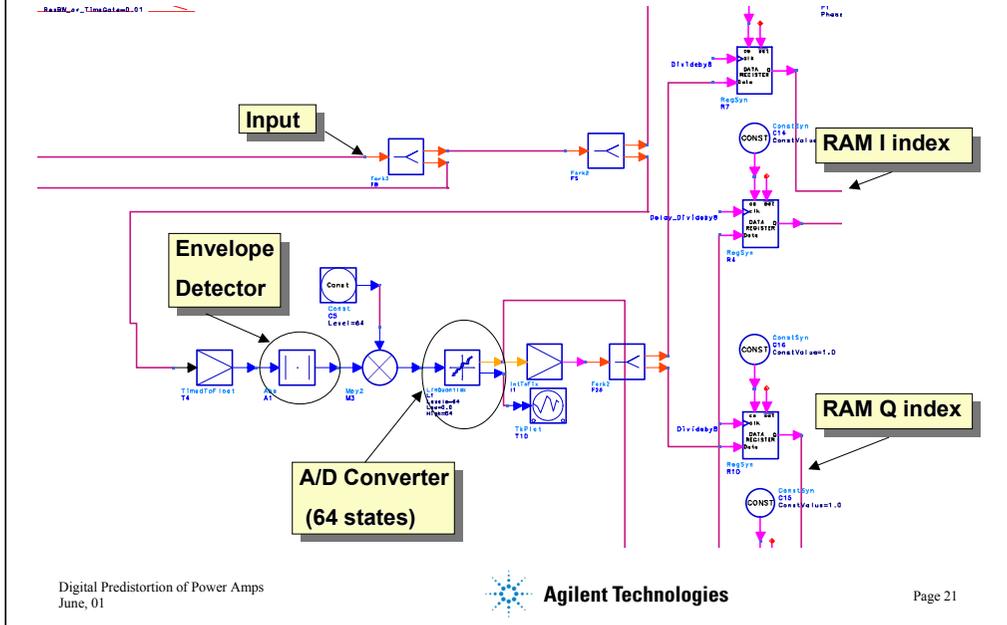
Focusing on the input. A ten tone input signal with frequency spacing of 2.5 MHz is used. The signal sources are 5 equal power quadrature modulators that independently generate two tones.

# Complex Gain Adjuster of Predistorter



The complex gain adjuster consists of two real multipliers, a 90 degree phase shifter, a power splitter and a power combiner. Because we are using a behavioural model for the power amplifier we can avoid the frequency translations.

# LUT Index for Digital Predistorter



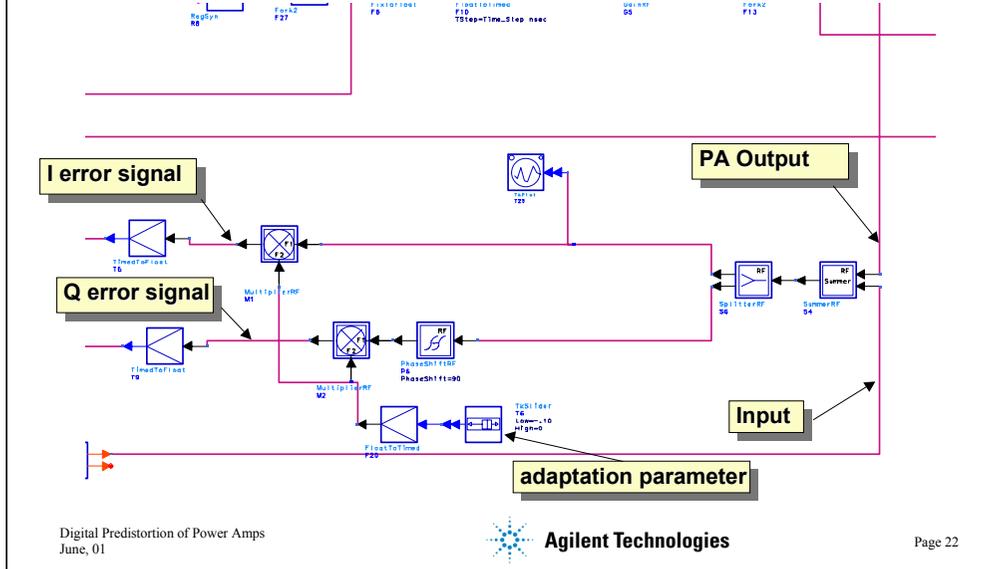
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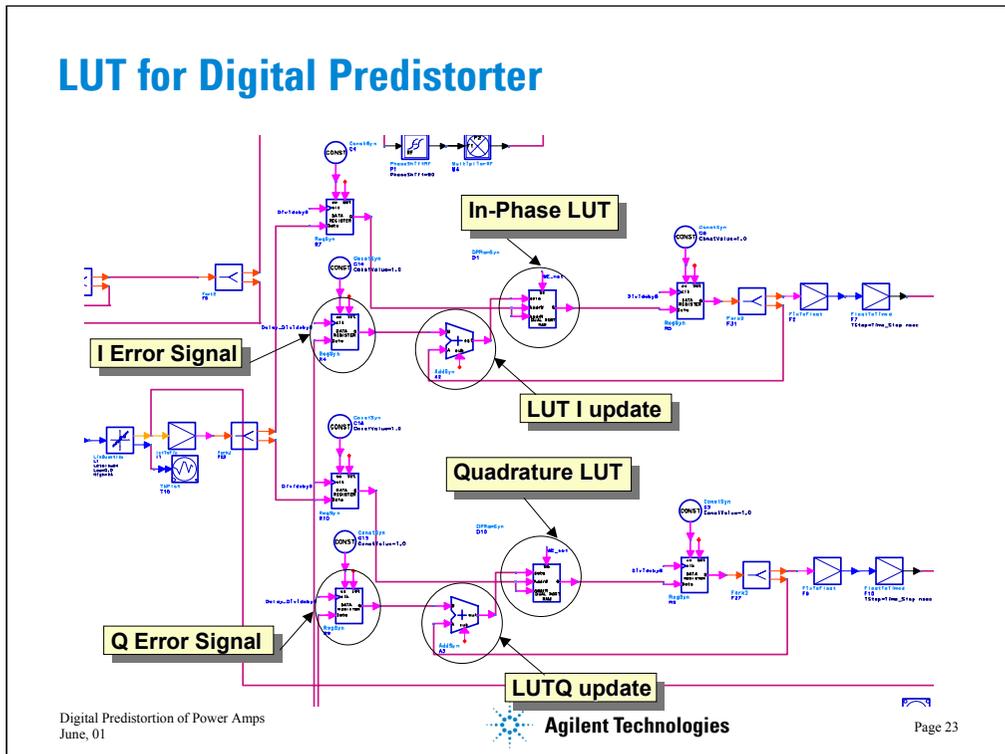
The input signal is split into two paths; the upper path is directed towards the complex gain adjuster, the lower path is used for envelope detection. In this particular example we are index using the magnitude of the input signal as well as using only a 6 bit A/D converter. The A/D converter will index the In-phase and Quadrature entries stored in the RAM Look-up tables. If we were to index using the square of the input amplitude then the achievable intermodulation reduction can be improved. Similar performance improvement can be obtained by using a higher # of bit analog to digital converter.

# Feedback Error Signal for Predistorter



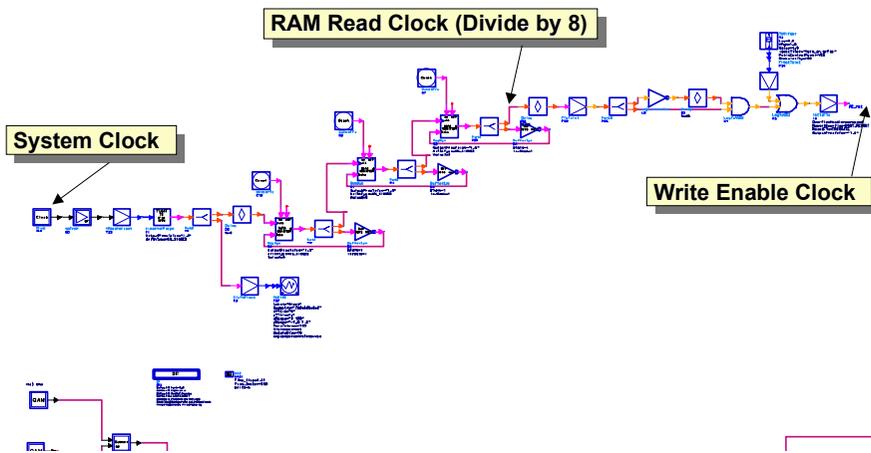
The complex gain function's table entries are continuously updated by monitoring the error vector. The input signal is inverted before being summed with the measured power amplifier output signal. In this particular example, because we are using a behavioural model for the power amplifier the feedback delay is constant and has been taken into account. We have used the linear convergence adaptation technique, where the adaptation parameter has been set to -0.1. The resultant I and Q error signals are used to update the respective RAM Look-up tables.

# LUT for Digital Predistorter



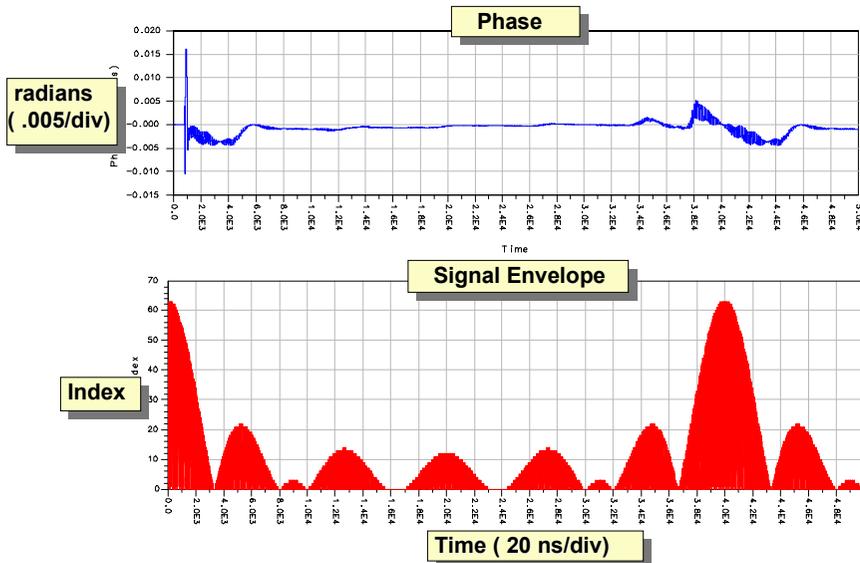
The I and Q error signals are stored in data registers. The previous RAM entries for the In-Phase and Quadrature complex gain function are also clocked to a data register. The RAM table entry which is indexed by the 6 bit A/D converter is then updated by summing the previous values with their respective scaled error signals. The clock timing is important to insure that the data registers have the correct information.

## Clock Timing for Predistorter



The clock timing is essential to insuring that the data is presented to the data registers at the proper time before either being read or written to the RAM Look-up tables. The write enable and read enable clocks are derived for the system clock.

# Optimized LUT Phase for Predistorter



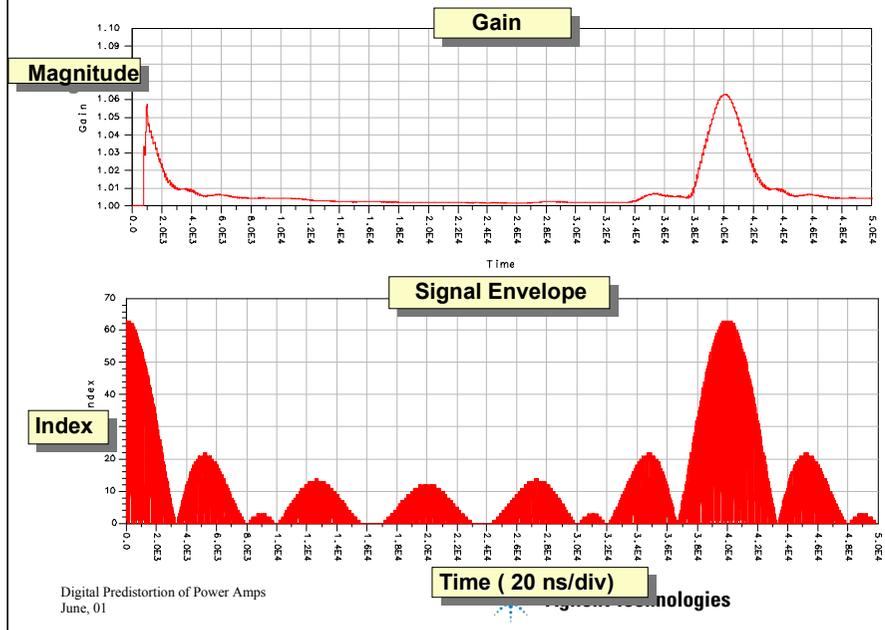
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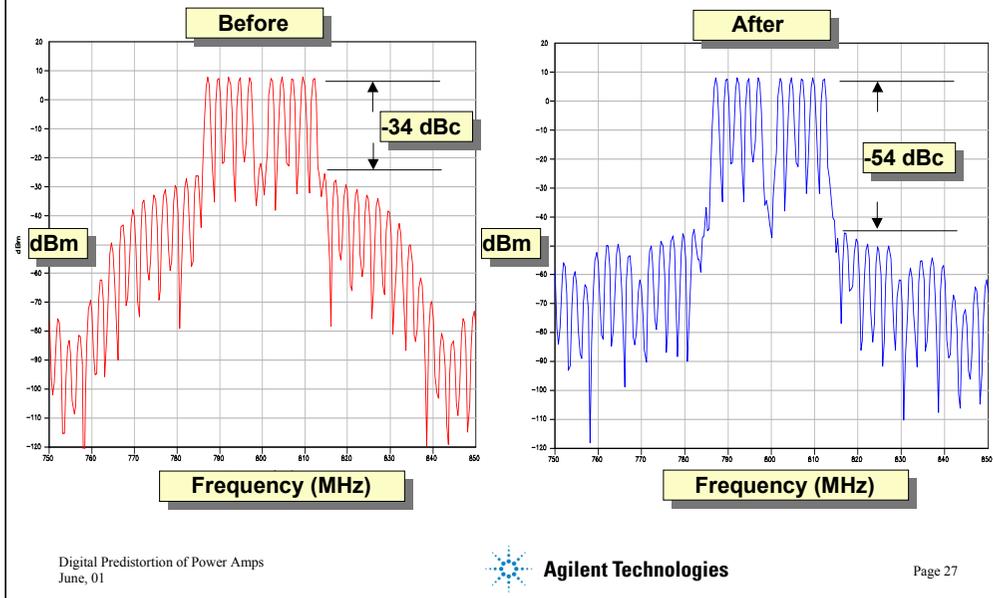
The lower trace demonstrates the fluctuation in the signal envelope for a ten tone input. We can observe that the large envelope peaks occur for only a small fraction of the time but that these will dominate the intermodulation distortion if not compensated. Adaptation using the digital predistorter is very rapid. The upper trace shows the relationship between the amplitude modulation and the phase modulation that is required. Because we are using a behavioural power amplifier model this is essentially amplitude dependent system noise. However, if we were to replace the behavioural model with a transistor level power amplifier then we would see significant AM/PM distortion.

# Optimized LUT Gain for Predistorter



We can observe the predistorter's complex gain functions amplitude expansion required to offset the power amplifier gain compression as we near the saturation region. For small envelope fluctuations the gain is approximately unity within a small error.

## Multi-Tone Simulation of Predistorter



The first figure shows that driving the power amplifier at 5dB back-off generates high levels of intermodulation power. The second figure shows the resultant output from the digital baseband predistorter once the LUT entries 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

### Digital Predistortion

- Adaptive Digital Predistorters have moved from the Research to the Development phase.

### Design Solutions

- The ADS Digital 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.

## Exercises

- 1) Modify the Power Amplifier behavioral model to include AM/PM distortion and observe the changes in the Optimized LUT Gain and Phase plots.
- 2) Modify the example project so that the envelope detector takes the square of the magnitude. Adjustments will need to be made on the LUT indexing. This configuration should require less LUT entries . Try to explain under what power amplifier characteristics this will not hold.
- 3) Increase the frequency spacing (ie. Modulation bandwidth) and try to explain the reasons for the degradation in performance.
- 4) Modify the Power Amplifier behavioral model to demonstrate more compression and observe the changes in the Optimized LUT Gain and Phase plots as well as the frequency plot. Try to explain the limitations of the LUT predistorter.

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## Resources & References

- [1] Y. Akawa and Y. Nagata, "Highly efficient digital mobile communications with a linear modulation method", *IEEE J. Select. Areas Communications*, vol. SAC-5, pp. 890-895, June 1987.
- [2] H. Girard and K. Feher, "A new baseband linearizer for more efficient utilization of earth station amplifiers used for QPSK transmission," *IEEE J. Select Areas Communications*, vol. SAC-1, pp. 46-56, Jan. 1983.
- [3] A.A.M. Saleh and J. Salz, "Adaptive linearization of power amplifiers in digital radio systems", *Bell System Tech. J.* vol. 62, no. 4, pp. 1019-1033, April 1983.
- [4] J.K. Cavers, "Amplifier linearization using a digital predistorter with fast adaptation and low memory requirements", *IEEE Trans. Vehicular Tech.*, vol. 39, no.4, pp 374-382, Nov. 1990.
- [5] A.S. Wright and W.G. Durtler, "Experimental performance of an adaptive digital linearized power amplifier", *IEEE Trans. On Vehicular Tech.* , vol. 41, pp. 395-400, nov. 1992.

## Resources & References

- [6] Y. Nagata, "Linear amplification technique for digital mobile communications," Proc. IEEE Vehicular Tech. Conf., San Francisco, CA. 1989, pp. 159-164.
- [7] M. Nannicini, P. Magna and F. Oggioni, "Temperature controlled predistortion circuits for 64 QAM microwave power amplifiers", IEEE Microwave Theory Tech. Digest 1985, pp. 99-102.
- [8] J. Namiki, "An automatically controlled predistorter for multilevel quadrature amplitude modulation," IEEE Trans. Communications, vol. COM-31, pp. 707-712, May 1983.
- [9] A. Bateman, D.M. Haines, and R.J. Wilkinson, "Linear transceiver architectures", Proc. 38th IEEE Vehicular Tech. Conf., Philadelphia, PA. June 1988, pp. 478-484.

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