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**Presentation on Adaptive Feedforward Linearization
for RF Power Amplifiers - Part 2**

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Adaptive Feedforward Linearization for RF Power Amplifiers

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About the Author



Shawn P. Stapleton

- Professor: Simon Fraser University
- Focus on integrated RF/DSP applications
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- 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 and Topics

Adaptive Feedforward Linearizer

- **Introduction to Adaptive Feedforward Linearization**
- **Technology Overview of Linearization**
- **Key Features, Feedforward Techniques & Concepts**
- **Performance Requirements**
- **Linearization Design Tools**
- **Conclusion**

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

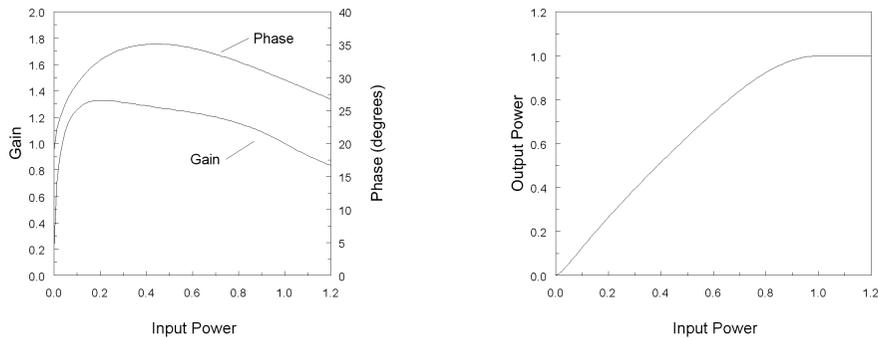
Introduction

- Power Amplifier Linearization Distortion
 - due to fluctuating envelope. (ie. QPSK, 64 QAM, etc.)
- Two methods of achieving linear amplification:
 - Back-off a Class A amplifier, subsequently reducing the power efficiency and increasing the heat dissipation. Expensive solution.
 - Linearize a power-efficient amplifier using external circuitry.
- Adaptation is required to compensate for component tolerances and drift, as well as 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.

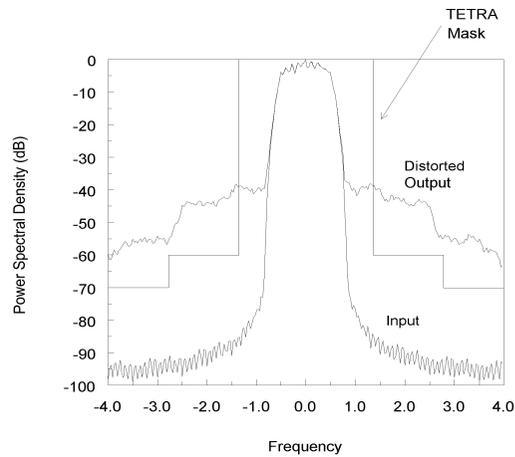
Power Amplifier Characteristics



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



Simulated Power Spectra: Class AB Power Amplifier with Pi/4 DQPSK input signal

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

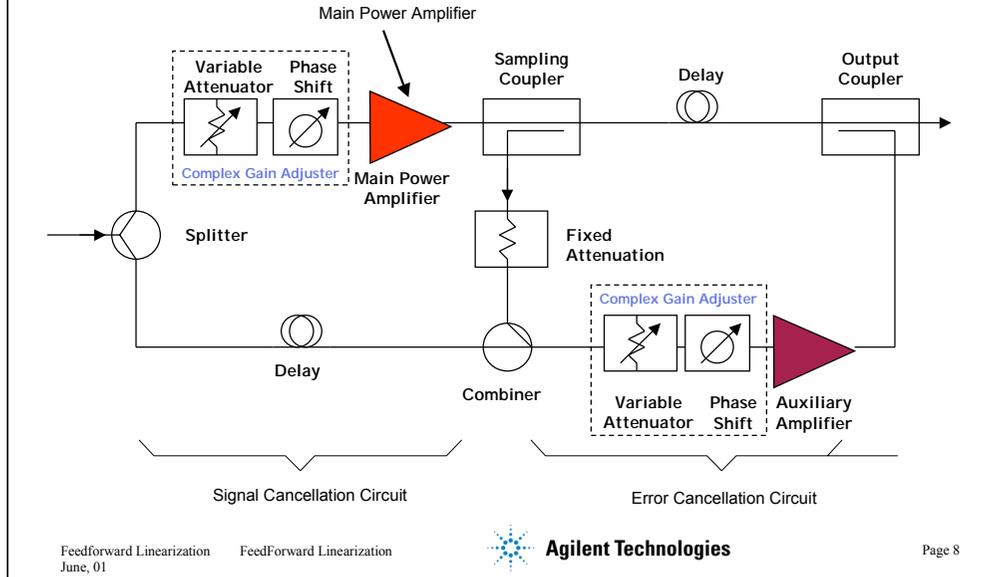
Linearization approaches:

- **Work Function Predistortion**
 - limited accuracy
- **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
- ➔ • **FeedForward**
 - Based on inherently wideband technology
 - Adaptation is required

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 work function 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 is less bandwidth limited. 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 cost is high complexity. Automatic adaptation is essential to maintain performance.

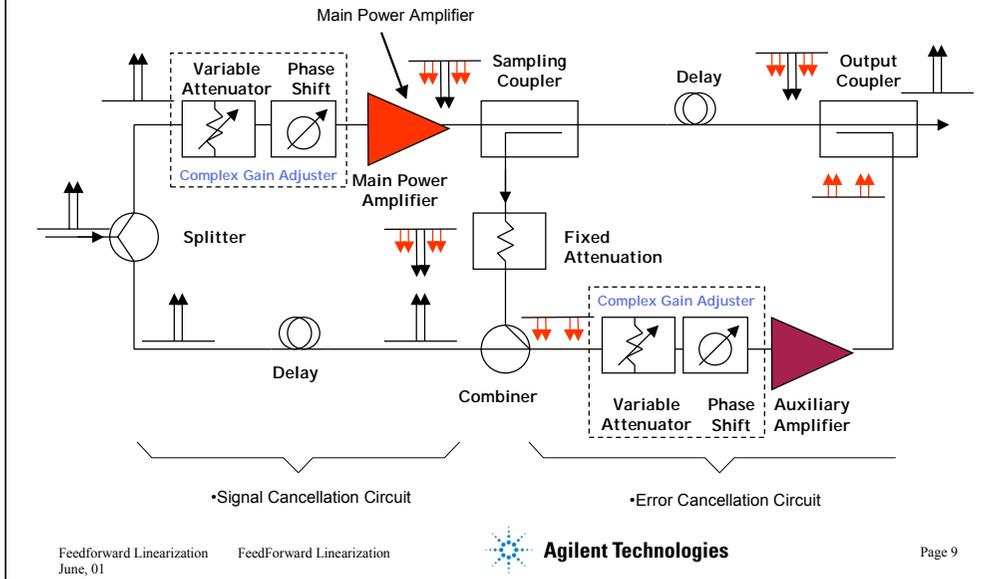
Feedforward Linearization



In 1927, H.S. Black of Bell Telephone Laboratories invented the concept of negative feedback as a method of linearizing amplifiers [1]. His idea for feedforward was simple: reduce the amplifier output to the same level as the input and subtract one from the other to leave only the distortion generated by the amplifier. Amplify the distortion with a separate amplifier and then subtract it from the original amplifier output to leave only a linearly amplified version of the input signal.

The feedforward configuration consists of two circuits, the signal cancellation circuit and the error cancellation circuit. The purpose of the signal cancellation circuit is to suppress the reference signal from the main power amplifier output signal leaving only amplifier distortion, both linear and nonlinear, in the error signal. Linear distortion is due to deviations of the amplifier's frequency response from the flat gain and linear phase [2]. Note distortion from memory effects can be compensated by the feedforward technique, since these effects will be included in the error signal. The values of the sampling coupler and fixed attenuation are chosen to match the gain of the main amplifier. The variable attenuation serves the fine tuning function of precisely matching the level of the PA output to the reference. The variable phase shifter is adjusted to place the PA output in anti-phase with the reference. The delay line in the reference branch, necessary for wide bandwidth operation, compensates for the group delay of the main amplifier by time aligning the PA output and reference signals before combining. The purpose of the error cancellation circuit is to suppress the distortion component of the PA output signal leaving only the linearly amplified component in the linearizer output signal. In order to suppress the error signal, the gain of the error amplifier is chosen to match the sum of the values of the sampling coupler, fixed attenuator, and output coupler so that the error signal is increased to approximately the same level as the distortion component of the PA output signal.

Spectrum at Nodes



The spectral components generated from a two tone input signal are depicted at various nodes in the feedforward linearizer. When the spectrum is flipped this implies that the signal is in anti-phase. The main power amplifier generates spurious intermodulation products at its output. Notice the function of the signal cancellation circuit is to eliminate products at its output. Notice the function of the signal cancellation circuit is to eliminate the linear component. The result is an error signal which contains only the distortion component. The function of the error cancellation circuit is to amplify and phase shift the error signal so that the distortion when combined with the main power amplifier's output will be eliminated.

Design Techniques

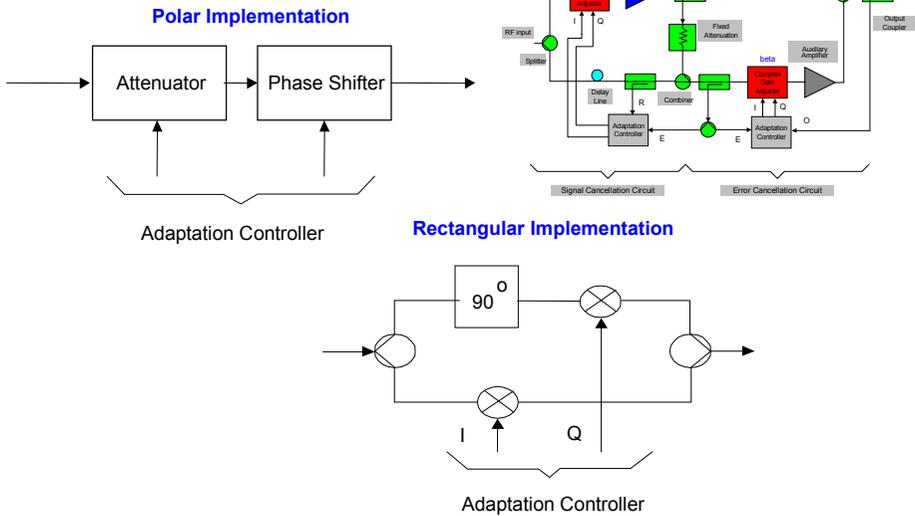
FeedForward Linearization

- Generic adaptation techniques ...
 - Insert pilot signals to guide the adaptation
 - Minimize power at critical nodes
 - Use gradient evaluation to drive the adaptation

Several patents concerned with adaptive feedforward systems appeared in the mid-eighties, and many more appeared in the early nineties. These patents dealt with two general methods of adaptation both with and without the use of pilot tones, namely adaptation based on power minimization[5] and adaptation based on gradient signals [4]. The control scheme for the former attempts to adjust the complex vector modulator in the signal cancellation circuit in such a way to minimize the measured power of the error signal in the frequency band occupied by the reference signal. In the error cancellation circuit the frequency band is chosen to include only that occupied by the distortion. 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 signal cancellation circuit is the power in the error signal, this power is minimized when the reference signal is completely suppressed, leaving only distortion. The surface for the error cancellation circuit is the power in the linearizer output signal, the power is minimized when the distortion is completely suppressed from the Power Amplifier output signal. The gradient is continually being computed and therefore no deliberate misadjustment is required.

Complex Gain Adjuster



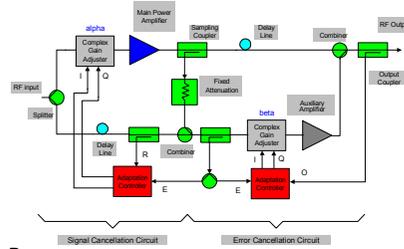
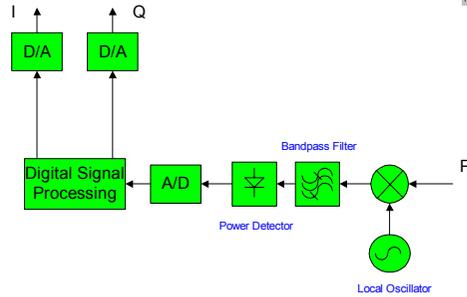
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Typical implementations of the complex gain adjuster is shown for the polar coordinates and rectangular coordinates. The mixers in the rectangular implementation can be replaced by bi-phase voltage controlled attenuators (VCA). The fact that the two 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.

Power Minimization Controller

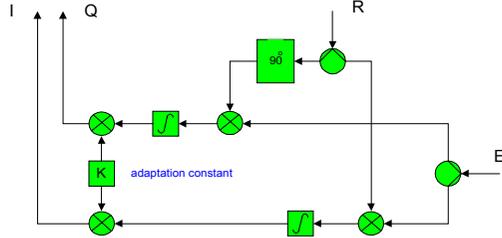


- **Signal Cancellation Circuit : BPF includes linear and IMD products {P is E input}**
- **Error Cancellation Circuit : BPF includes only IMD products {P is O input}**

This adaptation controller is representative of the “minimum power” principle applied to feedforward linearization. The control voltages “I” and “Q” are adjusted so as to minimize the power in port “P”. Port “P” is a sample of the error signal in the signal cancellation circuit. 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.

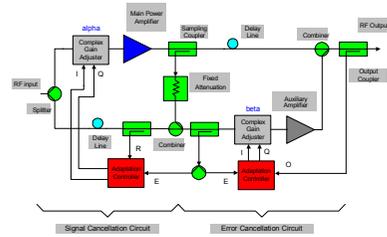
The power minimization principle can also be applied to the error cancellation circuit. However, the output signal at port “P” will carry the amplified signal as well as the residual distortion. Since the residual distortion is several orders of magnitude smaller than the amplified signal, the minimization algorithm will require an excessively long dwell time at each step. 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 “P” and used in the minimization algorithm.

Complex Correlator Gradient Method



$$\alpha = K_{\alpha} ve(t) \cdot vr(t)^* dt$$

$$\beta = K_{\beta} vo(t) \cdot ve(t)^* dt$$



The gradient method is an alternative to the minimum power principle for adaptation. The signal or error cancellation circuits can use either a complex baseband correlator or a bandpass correlator. The simplest iterative procedure is the method of steepest descent. 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 $(ve(t) \cdot vm(t)^*)$ suggests the above algorithm for the adjustment of α and β .

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. Long convergence times can result in the error cancellation circuit for similar reasons as with the minimum power method, this can be mitigated by suppressing the linear portion of the output signal before correlating.

FeedForward Design Issues

Accuracy requirements in the Error Cancellation Circuit

$$\text{IMD}_{\text{output}} = |\epsilon_{\beta}|^2 \cdot \text{IMD}_{\text{amplifier}}$$

(1% accuracy in β ($\epsilon_{\beta} \cong 0.01$) to lower IMD power by 40 dB). Other distortions must maintain the same limits of accuracy: linear ripple, auxiliary amplifier nonlinearities, etc.

Accuracy requirements in the Signal Cancellation Circuit

$$|\epsilon_{\alpha}| \cong \sqrt{(\text{IMD}_{\text{output}} \cdot \text{IMD}_{\text{amplifier}})}$$

(if $\text{IMD}_{\text{amplifier}}$ were -20 dB and the target value of $\text{IMD}_{\text{output}}$ were -60 dB, then α would have to be adjusted to an accuracy of 0.0001). The same would be required for all components in the lower branch.

The signal cancellation loop relies on subtraction of nearly equal quantities and is therefore sensitive to any coefficient misadjustment. The error cancellation circuit's adaptation coefficient β depends on the desired reduction of intermodulation power, rather than the target for absolute intermodulation levels. The accuracy of the adaptation coefficients also applies to any inadvertent linear filtering in either branch of the error cancellation circuit. Ripple over the band of interest must fall within the same limits of accuracy as for β . Similarly, any nonlinear effects in the auxiliary amplifier or the complex gain adjusters must be held to the same levels.

The convergence of α and β are coupled, hence, we can express the required accuracy of α in terms of the observed power amplifier intermodulation and the desired intermodulation at the output of the feedforward linearizer.

FeedForward Design Issues

Delay Mismatch and Bandwidth

If the delay mismatch is denoted by τ , then the complex baseband frequency response of the cancellation circuit is proportional to

$$H(f) = 1 - e^{j2\pi f\tau} \cong -j2\pi f\tau$$

which holds for small $f\tau$.

In the signal cancellation circuit, for 40 dB suppression at the band edge ($f = \text{Bandwidth}/2$), corresponding accuracy of 0.01 is required. This implies that τ must be held to 0.3% of the reciprocal bandwidth.

In the error cancellation circuit the IM spectral distribution is broader. A reasonable specification might be 30 dB suppression over 3x Bandwidth, which leads to a delay mismatch product of 0.3%.

(Note: For 1 MHz bandwidth, τ cannot exceed 3 ns, and for 10 MHz it cannot exceed 0.3 ns.)

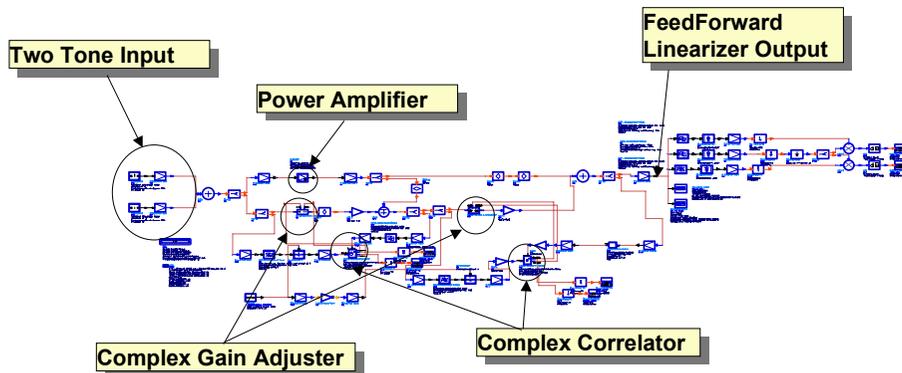
Assuming that the coefficients are perfectly optimized and no inadvertent linear distortion exists from the passive components. A delay difference between the upper and lower branches of a cancellation circuit will reduce the amount of intermodulation suppression at frequencies near the band edges. The result is a feedforward linearizer with a reduced effective bandwidth.

ADS FeedForward Simulation

Simulation Parameters:

- 1) Two Tone Modulation
- 2) $\alpha = -0.1$ adaptation coefficient
- 3) $\beta = -0.01$ adaptation coefficient
- 4) Iterative LMS adaptation between α and β
- 5) Rectangular Vector Modulator
- 6) 5dB Back-off
- 7) Ideal passive components assumed

ADS FeedForward Circuit



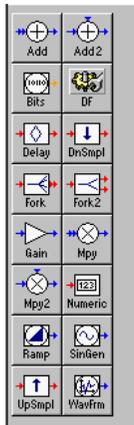
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The ADS circuit schematic for a double loop feedforward linearizer. The adaptation technique is based on the gradient method. The rectangular implementation is used for the complex gain adjuster. The input consists of a two tone modulation.

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 Eqn VAR
VAR1
Average=450
TimeStep=1/25
Freq_Center=.850
Fund_Upper=Freq_Center+Delta
Fund_Lower=Freq_Center-Delta
Delta=.5e-3
DroopRate=3e+4
```

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

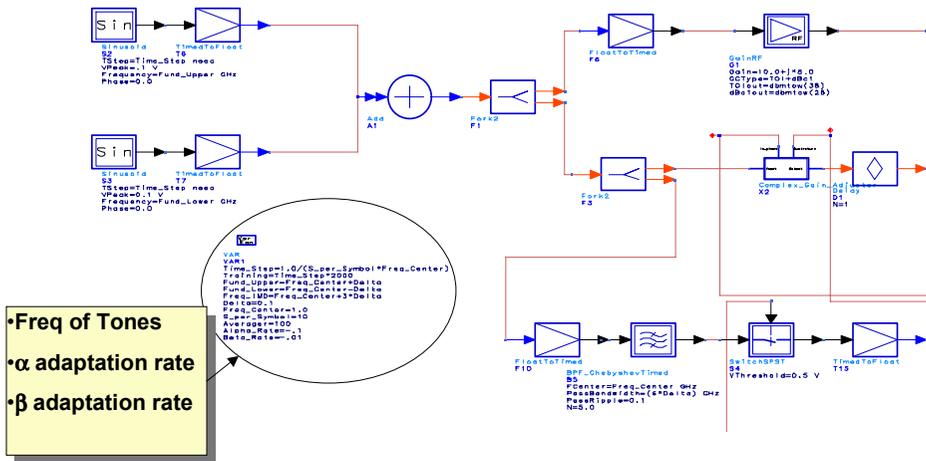
Average is the dwell time in microseconds.

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.

Parameters of FeedForward Linearizer



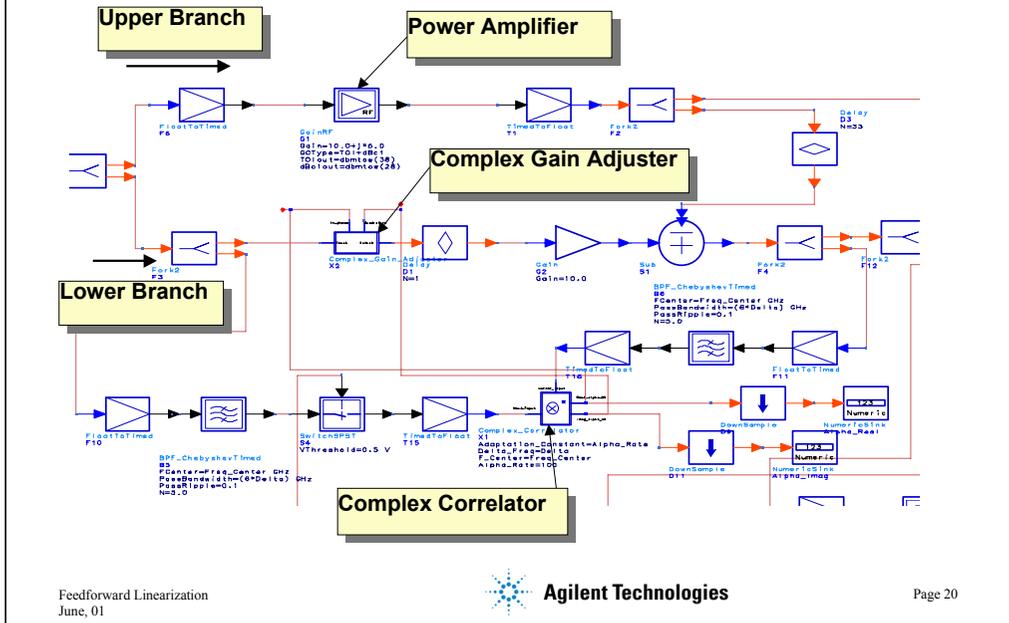
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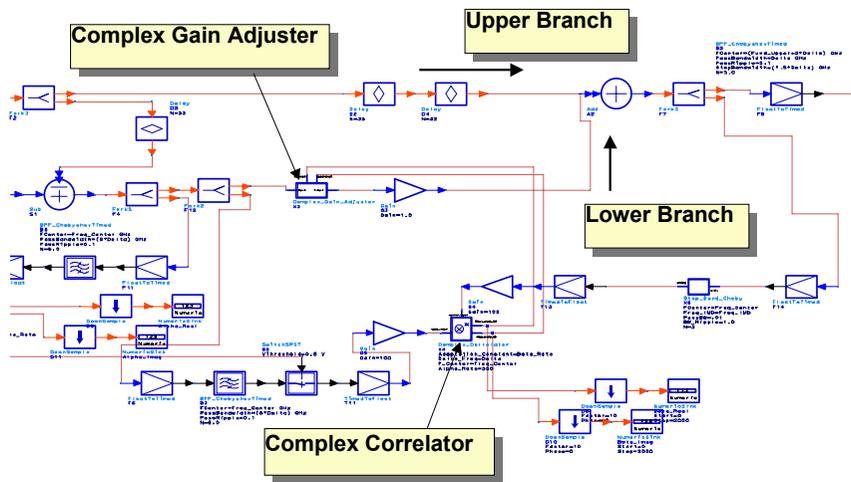
Care must be taken in the choice of adaptation parameters. The best approach is to insure that the signal cancellation loop (α adaptation coefficient) has converged to within a small variance before the error cancellation loop (β adaptation coefficient) begins its convergence.

FeedForward Signal Cancellation Loop



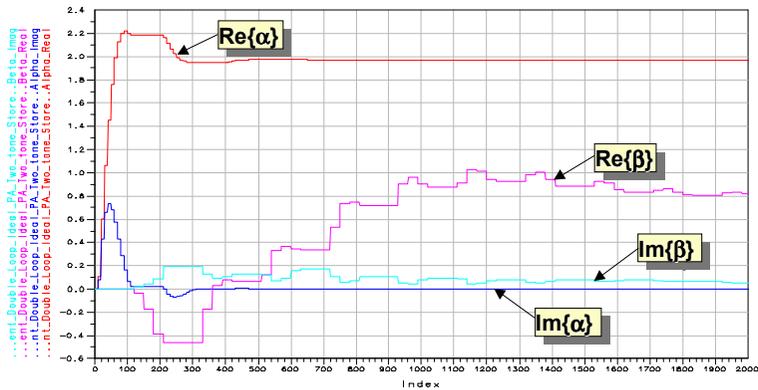
The power amplifier has been set with a gain of $10.0+j5.0$ and a 1dB compression point of 28 dBm. Care must be taken to insure that the time delay is matched between the upper and lower branches. Typically, an attenuator is inserted between the upper branch and lower branch so that the complex gain adjuster is operating at its optimum point.

FeedForward Error Cancellation Loop



In the error cancellation loop, a delay must be inserted in the upper branch to insure proper cancellation when the gradient based adaptation method is used. IF possible a bandstop filter could be incorporated after the output coupler to reduce the linear portion of the output signal. This will effectively speed up the adaptation process. If the power minimization method is used then a bandpass filter will be used to sample the output intermodulation distortion and adapt so as to minimize this quantity.

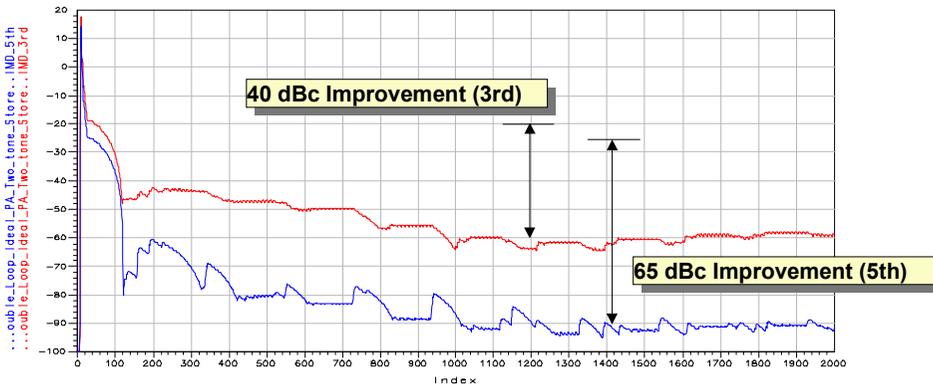
ADS FeedForward Simulation



Double Loop Adaptive Feedforward Linearizer Using Complex Correlators

Notice that in this adaptation procedure the signal cancellation loop has been allowed to converge before the error cancellation loop is turned on. Instability can occur if proper attention is not paid to the adaptation procedure. The error cancellation loop takes longer to optimize because of the order of magnitude difference between the two adaptation rates.

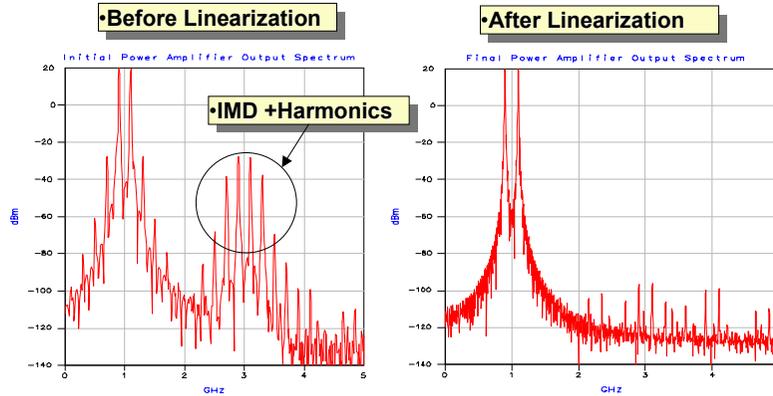
ADS FeedForward Simulation



Double Loop Adaptive Feedforward Linearizer Using Complex Correlators

This curve demonstrates that amount of improvement in both the 3rd order and 5th order intermodulation levels at the output of the feedforward linearizer.

ADS FeedForward Simulation



Double Loop Adaptive Feedforward Linearizer Using Complex Correlators

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 feedforward linearizer once the coefficients have adapted.

Summary

FeedForward Linearization

- Adaptive Feedforward linearizers are moving from the Research to Development phase.

Design Solutions

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

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