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Adaptive FeedForward Linearization for RF Power Amplifiers- Part 1

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Seminar: Gain Without Pain November 2000

Adaptive FeedForward Linearization for RF Power Amplifiers

Shawn Stapleton Agilent Technologies 1400 Fountaingrove Parkway Santa Rosa, CA 95403



Abstract

Amplifier 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 adaptive feedforward linearizer has the distinct advantage of being able to handle wide bandwidths while continuously adjusting for component drift and power level changes.

Biography

Dr. Shawn P. Stapleton has 17 years of experience in the design of RF and microwave circuits and systems. He is presently professor of electrical engineering at Simon Fraser University as well as a consultant for Agilent EEsof. He has developed GaAs MMIC components, including mixers, amplifiers, frequency dividers and oscillators. His most recent work includes digital signal processing, mobile communications and RF/microwave systems.





This section of the workshop provides an introduction to feedforward linearization. We will cover key features, technologies, and performance issues. Approaches to solving some of the design challenges will also be presented. An adaptive feedforward linearizer is demonstrated using the Agilent Advanced Design System. Additional reference information is also available.





The 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 power amplifier nonlinearity—the major contributor to nonlinear distortion in microwave transmitters. 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—that is, the output power is reduced or backed off. Unfortunately, this approach increases cost, reduces efficiency, and consumes more power since more stages are required in the amplifier to maintain a given transmitted power level. With power efficiency a critical consideration for systems that are battery operated or require small enclosures where heat dissipation is a problem. Linearization of a power-efficient Class AB amplifier is a much more desirable alternative to reducing nonlinear distortion than backing-off.

Unfortunately, power amplifiers exhibit both linear and nonlinear behavior, and these characteristics have a tendency to change over time due to repeated exposure to temperature changes, voltage variations, channel changes, and aging. Therefore, any robust linearization approach must incorporate the capacity for adaptability.





Power amplifier nonlinearities are typically characterized by amplitude dependent gain (AM/AM) and amplitude dependent phase shift (AM/PM). But in addition to nonlinearities, RF amplifiers also possess memory—that is, the output signal depends on the current value of the input signal, as well as previous input values spanning the memory of the amplifier.

Class AB power amplifiers provide about 25 percent efficiency and are more power efficient than Class A amplifiers, which only attain about five percent efficiency. Class AB amplifiers also exhibit gain roll-off at low input powers and at saturation.





Many design constraints are the result of regulatory bodies, which specify power spectral density masks defining the maximum allowable adjacent channel interference (ACI) levels. For example the European Tetra radio standard uses a $\pi/4$ DQPSK modulation format with a symbol rate of 18 KHz; and channel spacing of 25 KHz. This plot shows the input and output characteristics for a Class AB power amplifier operating at a back-off power of 3dB overlaid on the Tetra standard mask.





The notion of using negative feedback to linearize amplifiers is not new by any means. First described in 1927 by H.S. Black of Bell Telephone Laboratories, the concept for feedforward is simple. With the amplifier output reduced to the same level as the input, the difference between them is only the distortion generated by the amplifier. Further, if this resulting distortion is then amplified with a different amplifier and then subtracted from the original output, theoretically, we are left with only the linear amplified portion of the input signal.

Feedforward linearization utilizes two circuits—an input signal cancellation circuit and a distortion- or error-cancellation circuit. The signal-cancellation circuit suppresses the input reference from the output of the main power amplifier, leaving only its linear and nonlinear distortion components in an "error" signal.

Linear distortion is due to deviations of the amplifier's frequency response from the flat gain and linear phase. Note that distortion from memory effects can also be compensated using the feedforward technique, since these effects are included in the error signal. The sampling coupler and fixed attenuation are chosen to match the gain of the main amplifier. Variable attenuation is included in the circuit to enable the output level to be precisely adjusted to match the input reference, while the variable phase shifter adjusts the power amplifier output in an anti-phase arrangement with the input reference. The delay line in the error-cancellation branch is necessary for wide-bandwidth operation, and compensates for the group delay of the primary amplifier by time-aligning the power amplifier output and reference signals before they are combined.

The error-cancellation circuit is used to suppress the distortion component of the power amplifier output, leaving only the linear-amplified component of its output signal. In order to suppress the distortion component of the signal, the gain of the power amplifier used in the error-cancellation circuit must be carefully chosen to match the sum of the effects of the sampling coupler, the fixed attenuator, and the output coupler. Thus, the error signal is amplified to approximately the same level as the distortion component in the power amplifier output signal.



FeedForward Linearization Techniques

Generic adaptation techniques

- Insert pilot signals to guide adaptation
- •power minimization at critical nodes
- •gradient evaluation to drive adaptation



In the mid-'80s and early '90s, many patents were filed covering adaptive feedforward systems. These patents encompass two general methods of adaptation, both with and without the use of pilot tones. The first is adaptation based on power minimization, while the second is adaptation based on gradient signals.

The control scheme for power minimization adaptation is based on trying to adjust the complex-vector modulator in the signal-cancellation circuit. Theoretically, this minimizes the measured power of the error signal in the frequency band occupied by the reference signal. The frequency range chosen for the error-cancellation circuit includes only the bands occupied by the distortion. Once the optimum parameters have been achieved, deliberate perturbations are required to continuously update the coefficients, which reduces the effects of IM distortion suppression.

Adaptation based on the use of gradient signals requires a continuous computation to estimate the gradient of a three-dimensional power surface. The surface for the signal-cancellation circuit consists of 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, and the power is minimized when the distortion is completely suppressed from the primary power amplifier's output signal. Since the gradient is continually computed, no deliberate misadjustment is required.





Since feedforward linearization is based on subtracting nearly equal quantities in the signalcancellation loop, its major parameters must adapt to changes in the operating environment.

The incoming signal is split into two paths comprising the signal-cancellation circuit. The upper path contains a complex gain adjuster and the main power amplifier, which outputs the amplified signal plus distortion.

The second path, or error-cancellation circuit, carries a replica of the primary output with the amplified signal plus distortion, but with latency added to match the delay in the upper path. The complex gain adjuster provides a means of altering the amplitude and phase so that the signal component is cancelled in the lower path, leaving only the distortion. This distortion is fed to the lower path of the error signal cancellation circuit, where it is amplitude and phase adjusted by a complex gain adjuster and then combined with a delayed version of the power amplifier's output. Thus, the distortion is eliminated from the power amplifier's output.



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ADS FeedForward Simulation

Simulation Parameters:

- 1) Two-tone modulation
- 2) K α = -0.1 adaptation rate
- 3) K β = -.01 adaptation rate
- 4) Rectangular vector modulator
- 5) 5dB back-off from 1dB compression point
- 6) Ideal passive components assumed







Here is a circuit schematic for a double loop feedforward linearizer created in the Advanced Design System. 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.





Care must be taken when choosing adaptation parameters. The best approach is to ensure that the signal-cancellation loop (α adaptation coefficient) has converged to within a small variance before the error-cancellation loop (β adaptation coefficient) begins to converge.





When gradient-based adaptation is used, delay must be added to the upper branch of the error-cancellation loop to ensure proper cancellation. If feasible, a bandstop filter may be incorporated after the output coupler to reduce the linear portion of the output signal. This effectively speeds up the adaptation process. If the power minimization method is employed, then a bandpass filter is used to sample the output IM distortion.



In our example, the signal-cancellation loop is allowed to converge before the errorcancellation loop is turned on to avoid instability. This can occur if close attention is not paid to the adaptation procedure. The error-cancellation loop takes more time to optimize than the signal-cancellation loop because of the order of magnitude difference between the two adaptation rates.





This plot illustrates the improvement in both the third- and fifth-order intermodulation levels at the output of the feedforward linearizer.



Taking the example a step further, if we drive the power amplifier using 5dB of back-off, as seen in the plot on the left, high levels of IM power and harmonics are generated. The plot on the right shows the resulting output once the coefficients have adapted.





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Revised: March 27, 2008		

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