Using Amplifiers with Poor Linearity to Linearize Amplifiers with Good Linearity

Thomas P. Weldon and Konrad Miehle

University of North Carolina at Charlotte, Charlotte, NC, 28223, USA

***Abstract* — A new linearization method is presented where a device with poor linearity is combined with a second device having good linearity. The resulting composite device has much better linearity than the two original devices. The new method is applicable to both receivers and transmitters, and is implemented as an integrated circuit without external components. Third order intermodulation distortion is canceled by appropriate design of the gains and intercept points of two amplifiers. Finally, hardware test data is presented both for an integrated circuit prototype and for a prototype using off-the-shelf amplifiers.**

I. INTRODUCTION

The presence of nonlinearities in amplifiers and other devices continues to limit the performance of radio transmitters and receivers. In radio receivers, nonlinearities lead to undesired signals that block the reception of weak signals. In radio transmitters, nonlinearities lead to undesired out-of-band radiation that can interfere with adjacent frequency bands.

The foregoing consequences of nonlinearity have motivated the development of a variety of approaches to linearize devices[1]-[3]. Although these earlier approaches provide varying levels of improvement, they suffer a variety of limitations in performance, complexity, or the need for delay lines. Among these prior approaches are feedforward[1][6], Envelope Elimination and Restoration (EER)[1], Linear Amplification Using Nonlinear Components (LINC)[5], Digital Predistortion[7], and others [8]-[10]. In the digital pre-distortion method, the input signal to a power amplifier is pre-distorted such that the output of the amplifier is the desired linear signal. In EER, the envelope is stripped from the signal and a nonlinear amplifier in conjunction with envelope-based control is used to re-create the original signal at higher power levels. In LINC, two constant-envelope waveforms driving two non-linear amplifiers are combined to form the final signal. Typically, these earlier techniques can suffer from a variety of disadvantages including cost, complexity, signal processing overhead, component phase or time delay matching, and the like. Furthermore, the preceding methods are best suited to power amplifiers in transmitters, and are not generally applicable to receivers.

To address these issues, a new linearization method is presented that employs a simple architecture offering the potential to improve linearity in both transmitters *and* receivers. In addition, the new method can be implemented as an integrated circuit without external components. Finally, the method is sufficiently general to be applied to devices other than amplifiers.

The new linearization method is illustrated in a simple architecture comprised of two amplifiers, with an input circuit to split the input power between the two amplifiers, and with an output circuit to subtract the amplifier outputs[7]. In this, a less linear amplifier is combined with a more linear amplifier, where the resulting linearity of the overall circuit exceeds the performance of the individual amplifiers. Cancellation is then effected by proper design of the gains and third order output intercept points of the two amplifiers. The unanticipated result is that an amplifier with poor linearity can be used to improve the linearity of a second amplifier having better linearity. Although the present paper focuses on the particular problem of third order nonlinearity, the concepts underlying the new method may be applied to other nonlinearities.

The new linearization method is first described in Section II. Then, Section III introduces the conditions necessary for linearization. Experimental results are given in Section IV.

II. NEW LINEARIZATION METHOD

Before proceeding with detailed description of the new method, the underlying principle is first outlined. In this, consider the output spectra of two amplifiers with equal input signals and differing levels of distortion as illustrated in Fig. 1. If the more linear amplifier has higher gain and better linearity, its frequency spectrum may appear as Spectrum 1 on the left of Fig. 1 when two sinusoidal tones are applied as inputs. In Spectrum 1, the input sinusoidal frequencies correspond to the two innermost spectral lines, and the two outermost spectral lines correspond to third order nonlinear distortion. If the second amplifier has lower gain and worse linearity than the first amplifier, it may have an output spectrum as illustrated in Spectrum 2.

If the output signals of the two amplifiers in Fig. 1 are subtracted, then the third order distortion will be canceled

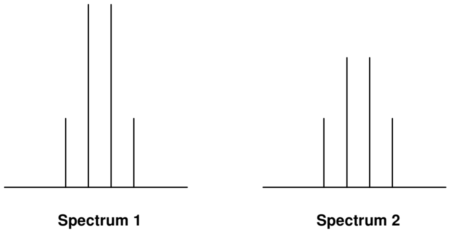


Fig. 1. Illustration of frequency spectra at the output of two amplifiers where two outermost spectral lines in each spectrum represent third order distortion products.

and eliminated since the outermost spectral lines of Spectrum 1 and Spectrum 2 have the same amplitude (assuming the amplifiers are designed for equal phase). Also, the desired linear signal will not be canceled since the innermost spectral lines of Spectrum 1 and Spectrum 2 are of different amplitude. Thus, the final output after subtracting the two amplifier outputs should be devoid of third order distortion.

In the foregoing discussion, the two amplifiers must be designed to have appropriate gains and third order output intercept points (OIP3) to effect cancellation of distortion. In addition, equal power division is not required at the input or output combiners as long as distortion cancels at the output while preserving the desired signal. Given the fundamental notion illustrated in Fig. 1, many alternative realizations are apparent.

III. CONDITIONS FOR LINEARIZATION

A simple embodiment of the new method is illustrated in Fig. 2. The embodiment of Fig. 2 was chosen to illustrate the method because of the simplicity of the architecture and because of straightforward implementation as a hardware prototype. Other realizations can be readily envisioned. For example, the two 180-degree hybrids shown in Fig. 2 may be implemented in a variety of ways for splitting and subtracting signals in an integrated circuit implementation. Nevertheless, the configuration of Fig. 2 suffices for discussing the principles of the new linearization method.

In Fig. 2, the input signal is first split into two equal-amplitude in-phase signals by the 180-degree hybrid on the left. The outputs of the left 180-degree hybrid in Fig. 2 are applied to two amplifiers U1 and U2. As outlined previously, U1 and U2 have different gains and output intercept points. The second 180-degree hybrid of Fig. 2 recombines the two amplifier outputs with 180-degree phase, effectively subtracting the outputs.

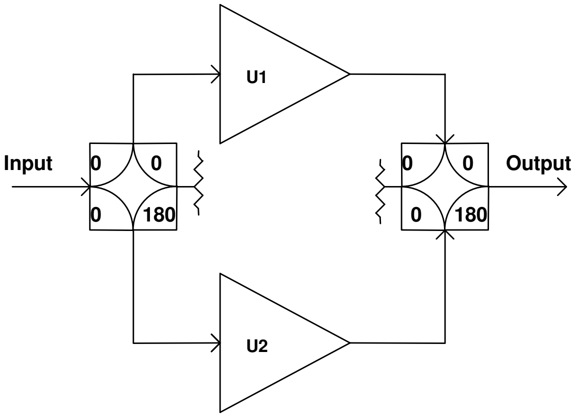


Fig. 2. Block diagram of new linearization method with input signal split in-phase by first 180-degree hybrid and amplifier output signals subtracted in hybrid on the right.

For the circuit of Fig. 2, third order distortion at the output is canceled when:

$$2(OIP3_1 - OIP3_2) = 3(G_1 - G_2)\,, \qquad (1)$$

where the gain of amplifier U1 is G_1 (dB) and the third order output intercept point of amplifier U1 is $OIP3_1$ (dBm). In similar fashion, G_2 (dB) and $OIP3_2$ (dBm) are the gain and third order output intercept point of amplifier U2.

To illustrate the cancellation, consider the particular case of G_1=15 dB and $OIP3_1$=20 dBm, and G_2=5 dB and $OIP3_2$=5 dBm. The third-order two-tone intermodulation distortion for each amplifier output may be calculated as:

$$P_3 = OIP3 - 3(\,OIP3 - Pout\,)\,, \qquad (2)$$

where P_{out} is the linear output power level in dBm, and P_3 is the output power level of the third order distortion in dBm. The condition in (1) causes P_3 in (2) to be the same at the outputs of both amplifiers of Fig. 2, thereby resulting in cancellation of third order distortion.

In the foregoing example, let the input signals to both amplifiers be -10 dBm, in-phase. Then, using (2) the third order distortion level at the output of the first amplifier is P_3 = 20 - 3(20 - (-10 + 15)) = -25 dBm. Similarly, the third order distortion level at the output of the second amplifier is P_3 = 5 - 3(5 - (-10 + 5)) = -25 dBm. Since the distortion is the same level at the output of both amplifiers in this example, the distortion will be canceled when added 180-degrees out of phase in the hybrid on the right of Fig. 2. In addition, with -10 dBm input, the linear signal outputs of the two amplifiers will be 5 dBm for U1 and -5 dBm for U2. And, since the linear components of the signal are of unequal amplitude, they will not be canceled when added 180-degrees out of phase in the hybrid on the right of Fig. 2. Furthermore, cancellation is not affected by input signal level since the third order distortion level of both amplifiers changes 3 dB for each dB change in the linear input signal.

IV. PROTOTYPE AND RESULTS

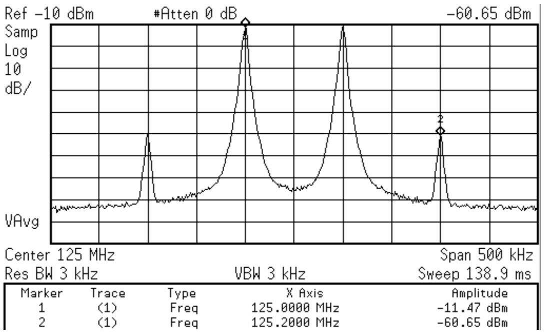
For the purposes of demonstrating the new method, a first prototype was built using off-the-shelf components. Also, a second prototype was implemented as an integrated circuit.

In the first prototype, amplifier U1 of Fig. 2 was implemented with an ERA5SM at 30 mA, amplifier U2 an MAR1SM at 20 mA, and two AMT-2 180 degree hybrids[11]. The currents of the amplifiers were set to the foregoing values and a 13 dB attenuator was added to the output of the MAR1SM, such that the cancellation conditions given in (1) were met.

The output spectrum of the more linear amplifier (ERA5SM) is shown in Fig. 3, taken at the final output of Fig. 2 with the second amplifier turned off. Similarly, the output spectrum of the less linear amplifier (MAR1SM) is shown in Fig. 4. In both cases, the linear signal frequencies are at 125 and 125.1 MHz. Comparing Figs. 3 and 4 to Fig. 1, it can be seen that the third order nonlinear distortion frequencies at 124.9 and 125.2 MHz have approximately equal amplitudes at the outputs of the two amplifiers, and should therefore cancel at the output.

Fig. 5 shows the final output when both amplifiers are turned on, and shows that third order distortion is reduced by approximately 23 dB, from -62 dBm to -85 dBm at 125.2 MHz. Because the linear signal components (-11.47 dBm and –20.44 dBm) were within 9 dB of each other, the prototype shows approximately 3dB reduction in the linear signal components due to the output. Nevertheless, the prototype serves to illustrate the basic principles of the new method.

More recently, a second prototype was implemented as an integrated circuit in a 0.5 micron CMOS process. In this, the circuit of Fig. 2 was implemented as the schematic of Fig. 6 where inputs are applied in-phase to two differential pairs and outputs are subtracted by cross-coupling the differential outputs[12,13]. As before, the output of spectra of the two differential amplifiers are in Figs. 7 and 8. Fig. 9 shows the final output when both amplifiers are turned on, and shows that third order distortion is reduced by approximately 22 dB, from -76 dBm to -98 dBm at 110.2 MHz.



Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	125.0000 MHz	-11.47 dBm
2	(1)	Freq	125.2000 MHz	-60.65 dBm

Fig. 3. Measured frequency spectrum of more linear amplifier (ERA5SM) in prototype.

REFERENCES

[1] Allen Katz, "Linearization: Reducing Distortion in Power Amplifiers," *IEEE Microwave Magazine*, 2:4, pp. 37-49, Dec. 2001.

[2] P. B. Kenington, "Methods Linearize RF Transmitters And Power Amps, Part 1," *Microwaves & RF*, vol. 37, no.13, pp. 102-116, December 1998.

[3] P. B. Kenington, "Methods Linearize RF Transmitters And Power Amps, Part 2," *Microwaves & RF*, vol. 38, no.1, pp. 79-89, January 1999.

[4] B. Razavi, "Challenges in Portable RF Transceiver Design," *IEEE Circuits and Devices Magazine*, vol. 12, pp. 12-25, Sept. 1996.

[5] D. C. Cox, “Linear amplification with nonlinear components,” *IEEE Trans. On Communications,* vol. COM-22, pp. 1942-1945, December 1974.

[6] E. Eid, F. M. Ghannouchi, F. Beauregard, “Optimal Feedforward Linearization System Design,” *Microwave Journal,* pp 78-86, November 1995.

[7] F. Zavosh, D. Runton, C. Thron, “Digital Predistortion Linearizes RF PAs,” *Microwaves & RF,* pp. 96-106, August 2000.

[8] Johansson, M. and Mattson, T., Transmitter linearization using Cartesian feedback for linear TDMA modulation," *Proc. 41st IEEE Vehicular Technology Conference*, pp. 439-444, May 1991.

[9] T. P. Weldon, “Method and Apparatus for Cancellation of Third Order Intermodulation Distortion and Other Nonlinearities”, *US Patent Application 10/101,005,* March 2002.

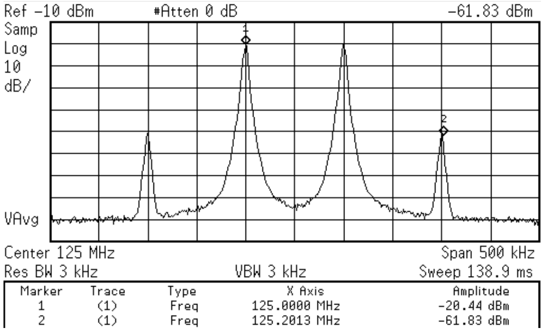
[10] T. H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits,* Cambridge University Press, 1998.

[11] MiniCircuits, P.O. Box 350166, Brooklyn, NY 11235 U.S.A, http://www.minicircuits.com/.

Errata:

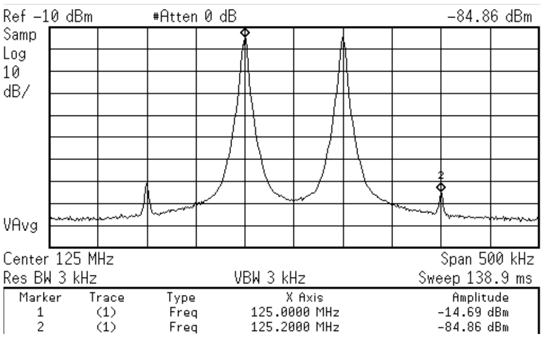
[12] H Khorramabadi and P.R.Gray. "High-Frequency CMOS Continuous-Time Filters," IEEE J. Solid State Circuits, vol. SC-17, no 6, pp. 939-948, Dec. 1984.

[13] C. Toumazou, F. J. Lidgey, and D.G. Haigh, Editors, "Analogue IC Design: the current mode approach," Peter Peregrinus Ltd., United Kingdom.



Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	125.0000 MHz	-20.44 dBm
2	(1)	Freq	125.2013 MHz	-61.83 dBm

Fig. 4. Measured frequency spectrum of less linear amplifier (MAR1SM) in prototype.



Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	125.0000 MHz	-14.69 dBm
2	(1)	Freq	125.2000 MHz	-84.86 dBm

Fig. 5. Measured output spectrum of prototype showing cancellation of third order distortion products.

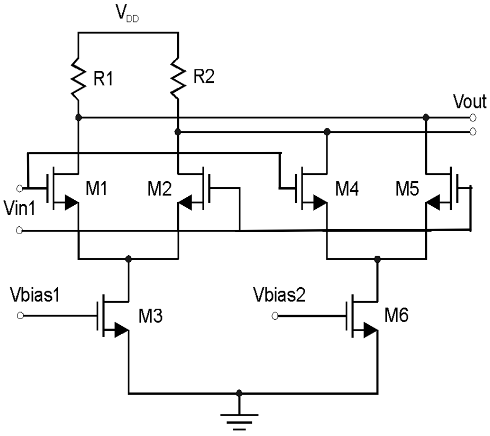
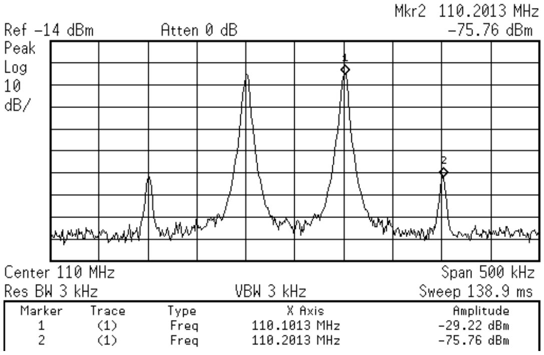
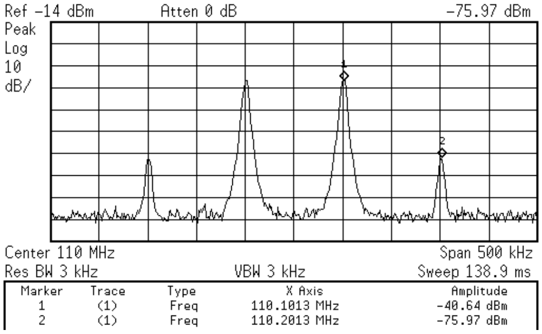


Fig. 6. Schematic of integrated circuit prototype.



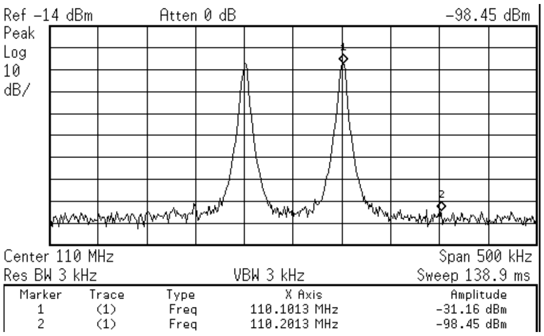
Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	110.1013 MHz	-29.22 dBm
2	(1)	Freq	110.2013 MHz	-75.76 dBm

Fig. 7. Measured frequency spectrum of more linear amplifier in integrated circuit prototype.



Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	110.1013 MHz	-40.64 dBm
2	(1)	Freq	110.2013 MHz	-75.97 dBm

Fig. 8. Measured frequency spectrum of less linear amplifier in integrated circuit prototype.



Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	110.1013 MHz	-31.16 dBm
2	(1)	Freq	110.2013 MHz	-98.45 dBm

Fig. 9. Measured output spectrum of integrated circuit prototype showing cancellation of third order distortion products.