The Evolution of Linearizers for High Power Amplifiers

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Abstract — **Today, linearization is of enormous importance because of society's need for greater and greater amounts of information, and the economic and practical restrictions on the spectrum available for its transmission. Interest in reducing distortion is not new. It dates back to early years of radio. Information transmission rate is directly related to distortion level. Linearity and amplifier efficiency are also linked, with higher linearity normally yielding lower efficiency. Thus the development of technology to increase an amplifier's linearity as means to increase its efficiency is an important piece in the development of linearization. This paper traces the evolution of power amplifier linearization from its inception to the linearizers produced today. It reviews the different forms of linearization and then discusses the roots of modern linearization, which originated from applications in digital wireless communications, and from the needs of the space industry. The state of current linearizer development and limitations is also presented.**

***Index Terms* — linearizer, linearization, history, predistortion, feedforward, feedback, high power amplifiers.**

I. Introduction

Technology has changed the communication business. Virtually all communications now use bandwidth efficient digitally modulated signals, and often involve the transmission of large quantities of information at high data rates. For such signals amplifier linearity is a major concern. For most HPAs, output power can be traded for linearity. The poorer the linearity of an HPA, the greater is the advantage of linearization. For most HPAs, the closer it is operated to maximum power, the greater its efficiency. As a consequence, better efficiency and reduced power overhead is made possible by linearization. Ultimately HPAs of smaller size, weight, and thermal load result. Interest in linearization is not new and dates back to the 1920s during the expansion of the telecommunications industry and the beginning of radio broadcasting. Two of the three forms of linearization, feedforward, feedback and predistortion, in use today were conceived of in this decade. The seeds planted nearly one hundred years ago are still being applied to linearize new HPA designs that enable even higher efficiencies and performance for the information hungry world of the 21st Century.

II. Feedforward Linearization

Records indicate feedforward (FF) to be the first form of RF linearization conceived. It was invented by Howard Black in 1923 at Bell Telephone Laboratories [1]. He came up with the idea while working on ways to reduce distortion in multiplex telephone systems in which many voice modulated carriers are transmitted over a single telephone cable. For transmission over long distances, many amplifiers must be used. The distortion from these amplifiers is a major problem, as the distortion of each amplifier can add. The FF concept is ingeniously simple, but is rather complex to implement. A block diagram of a basic FF system is shown in Fig. 1.

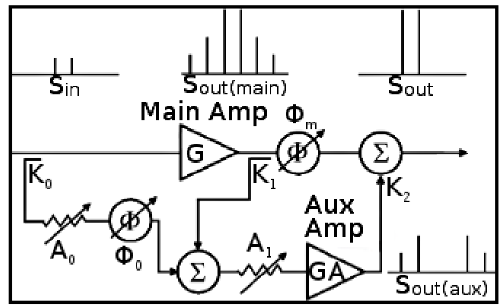

Fig. 1. Feed-forward linearization employs two loops

The system consists of two loops. The first loop subtracts samples of the input signal (S_{in}) from the output signal ($S_{out(main)}$) to produce a sample of the main amplifier's distortion. $S_{out(main)}$ consists of the amplified input signal plus any distortion introduced by the amplifier.

$$S_{out(main)} = GS_{in}\angle\Phi_{amp} + IMD \quad (1)$$

G is the gain and $\angle\Phi_{amp}$ is the phase shift introduced by the main amplifier. The samples of S_{in} (SS_{in}) and $S_{out(main)}$ ($SS_{out(main)}$) are respectively

$$SS_{in} = K_0 S_{in} \text{ and } SS_{out(main)} = K_1 S_{out(main)} \quad (2)$$

K_0 and K_1 are the coupling coefficients of the directional couplers used to sample S_{in} and $S_{out(main)}$ respectively. If SS_{in} is attenuated and delayed in phase then

$$A_0 SS_{in}\angle\Phi_0 = -SS_{out(main)} \text{ or}$$
$$A_0 K_0 S_{in}\angle\Phi_0 = GK_1 S_{in}\angle(\Phi_{amp} + 180°) \quad (3)$$

S_{in} is canceled and the output of loop 1 is K_1IMD. A_0 and Φ_0 are respectively the attenuation and phase shift introduced in loop 1 for adjustment of the carrier cancellation. The second loop subtracts the amplified sampled distortion of loop 1 from a delayed $S_{out(main)}$ to produce, *ideally*, a distortion free output signal (S_{out}). The loop 1 output signal is amplified by an auxiliary (aux) amplifier of gain GA and phase shift Φ_{aux} to provide a correction signal ($S_{out(aux)}$) of sufficient level to cancel the distortion introduced by the main amplifier. $S_{out(aux)}$ is combined with the main amplifier signal at a final directional coupler of coefficient K_2. When

$$S_{out(aux)} = A_1 GAK_1 K_2 IMD\angle(\Phi_{aux} + \Phi_1) = IMD\angle(\Phi_m + 180°) \quad (4)$$

then the HPA output will be distortion free. A_1 and Φ_1 are respectively the attenuation and phase shift introduced in loop

2 for adjustment of the distortion cancellation. Φ_m is a delay added after the main amplifier to equalize the delay introduced by the aux amplifier.

$$S_{out} = S_{out(main)} \angle \Phi_m + S_{out(aux)} \qquad (5)$$

Black worked for more than 4 years to trying to produce a practical FF amplifier without success. His application required very high level of linearity over a wide percentage bandwidth. His problem was that he could not maintain the cancelation over temperature, aging and frequency with the vacuum tube amplifiers used in his time. It was not until solid-state came into use and the need for highly linear HPAs for cell telephone base stations in the 1980s that FF came into wide use. And even with solid-state in almost all applications adaptive control was needed to maintain the cancelation [2].

From the discussion it may appear that an undistorted output can be obtained from a FF HPA right up to saturation (SAT). However, saturated output power can never be obtained from a FF HPA because of the losses in the phase shifter and couplers, located after the main amplifier. The main signal, Sout1, is reduced in amplitude due to passing through the K_1 coupler. K_1 can be made very small, provided the main amplifier has sufficient gain. The K_2 of the final directional coupler must also be relatively small to minimize loss of output power. Since the two signals, (carriers and distortion), being combined are not at the same, power will be split between the load and the coupler's *dump* port. Furthermore the HPA's *true* SAT power should be considered. A FF HPA combines both the power of the main and the auxiliary (aux) amplifier. The sum of the saturated power of both these amplifiers should be considered when comparing the performance of different forms of linearization. The smaller K_2 is set, the larger in power needed from the aux amplifier. The aux amplifier must also be operated relatively linear so as not to introduce distortion of its own. In practice distortion cancellation can be achieved only to about 6 dB from SAT. Thus FF is not viable for linearization of HPAs to be operated near SAT. In addition, it has a considerable power and complexity overhead that limit HPA efficiency. Thus, cell telephone base station manufactures started seeking other types of linearization that could provide better efficiency. Today other linearization methods provide comparable distortion cancellation with higher efficiency and considerably less complexity.

III. Feedback Linearization

After failing with FF linearization, Black envisioned the concept of a negative feedback (FB) amplifier in 1927. He realized that by feeding the output back to the input, 180°out of phase, the distortion could be greatly reduced at the expense of gain. He initially met with considerable skepticism including rejection of his patent because it was thought to be a a kind of "perpetual motion machine". He eventual won and was able to produce reliable multi-carrier amplifiers that provided more than 60 dB of IMD rejection. His concept became the foundation for the feedback amplifier industry and was widely used in RF HPAs, but has limitations when applied at higher frequencies and bandwidths.

The use of linear networks for feedback, as done by Black, is well documented but has seen little use at microwaves. The reason for this reluctance is due to concerns about HPA stability, Black referred to it as *squealing*, and the difficulty in making networks with non-ideal components function over wide frequency bands. Indirect feedback (IFB) techniques have been more widely applied. In this approach an HPA's input and output signals are detected and lowpass filtered, and the resulting *baseband* signals compared. The error signal (Ve) is used to modify the amplifier's characteristics so as to minimize distortion.

$$V_e = |DS_{out} - DS_{in}| \qquad (6)$$

where DSout and DSin are respectively the detected output and input signals. Ve can be used to control the gain of the HPA by means of a voltage variable attenuator. Superior linearity is obtained by correcting both amplitude and phase as illustrated in Figure 2.

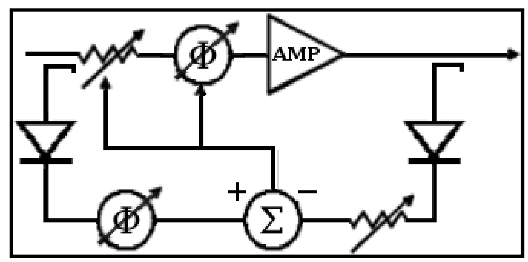

Fig. 2. IFB compares HPA's detected output to input difference.

An alternate approach known as Cartesian feedback separates the signal into in-phase and quadrature components. This eliminates the need for phase shift components, and still allows the correction of gain and phase by adjusting the amplitudes of two orthogonal components. Fig. 3 shows an example of a Cartesian feedback system. The baseband in-phase and quadrature components are compared and used to control the attenuators in a vector modulator.

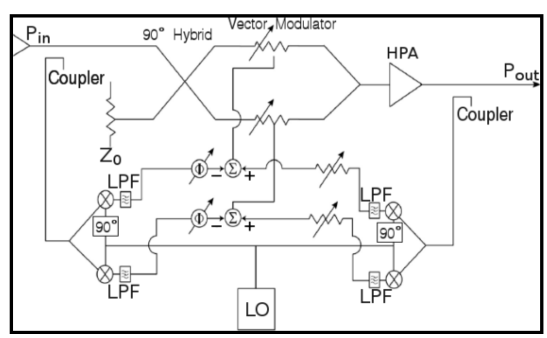

Fig. 3. Cartesian feedback eliminates phase correction components.

High linearity can be achieved by using IFB, which is self-correcting for changes due to environmental and aging effects. IFB's principal limitation is an inability to handle wideband signals. It is "practically" difficult to make a feedback system responds to signal envelope changes much greater than several

MHz, because of the delay (Δt_S) of the amplifier and associated signal processing components. The signal bandwidth must satisfy

$$BW < 1/4\,\Delta\,t_s \quad (7)$$

for significant correction. Thus the total delay must be less than 25 ns for a 10 MHz BW. Microwave HPAs can have delays of 10 to 20 ns. An advantage of Cartesian feedback is that the BWs of the in-phase and quadrature components are approximately equal. While in Polar feedback systems, the BW of the phase component is much greater than the BW of the amplitude component.

IV. Predistortion Linearization

In recent years predistortion linearization (PDL) has become dominant because of its relative simplicity, wide dynamic range, wideband operation and cost effectiveness. The majority of PDLs are implemented digitally primarily for telecom applications because of the size of this market. There are still significant applications for analog PDL particularly for applications requiring large bandwidth, where analog techniques can be more cost effective. PDL generates a non-linear transfer characteristic that can be thought of as the reverse of an HPA's transfer response in both magnitude and phase as seen in Fig. 4.

An alternate way of thinking of PDL is to view the linearizer as a generator of intermodulation distortion (IMD) products. If the IMDs produced (in the HPA) by the PDL are equal in amplitude and 180 degrees out phase with the IMDs generated by the HPA, the IMDs will cancel. As already discussed, this condition occurs when the gain and phase of the linearized HPA remain constant with change in power level. In dB, the gain of the linearizer (GL) must increase by the same amount the HPA's gain (GA) decreases.

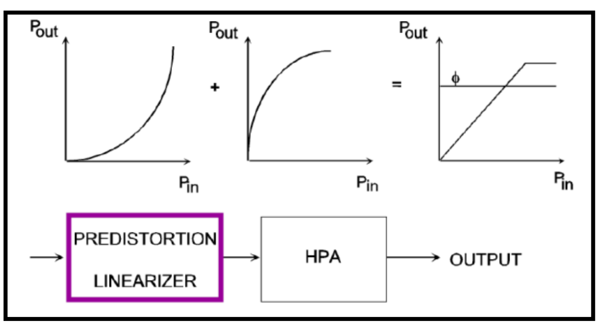

Fig. 4. PDL response is opposite to an HPA's in magnitude & phase.

$$GL(P_{outL}) - GL_{ss} = -[GA(P_{inA}) - GA_{ss}] \text{ where } P_{outL} = P_{inA} \quad (8)$$

where GL_{ss} and GA_{ss} are respectively the small signal gains of the linearizer and the HPA, and $GL(P_{outL})$ and where GL_{ss} and GA_{ss} are respectively the small signal gains of the linearizer and the HPA, and $GL(P_{outL})$ and $GA(P_{inA})$ are respectively these gains as a function of linearizer output and HPA input levels. Likewise, the phase shift introduced by the linearizer must increase by the same amount the HPA's phase decreases, (or vice-versa depending on the phase direction of the HPA).

$$\Phi L(P_{outL}) - \Phi L_{ss} = -[\Phi A(P_{inA}) - \Phi A_{ss}] \text{ where } P_{outL} = P_{inA} \quad (9)$$

It seems likely that predistortion would have been conceived in the early days of radio, but there is little literature showing the application of PDLs in HPAs before the 1970s. Some of the earliest applications were for the linearization of the traveling wave tube amplifiers (TWTAs) used on satellites. Higher linearity was needed for satellite communications, where HPA efficiency is of paramount importance. Both of these metrics are greatly improved by PDL. The first satellite linearizers were not flown until the early 1980s and used analog PDL. RCA's Astro Space Division was among the first to fly linearized TWTAs and was the first to fly a MMIC linearizer. Today virtually all satellite HPAs are linearized. Because of their success in space, PDLs migrated to the ground segment and by 1995 were integrated into many uplink HPAs. About the same as PDL was being developed for satellites, the need for higher data rate wireless digital communications was building. Bandwidth efficient digital modulations as 16 and 64QAM were introduced to meet this need. These modulations required higher linearity HPAs to keep bit error rates (BER) at an acceptable level. Because the modulation was already digital, the next step was to digitally predistort the modulation to correct the distortion. This work marked the beginning of digital PDL. By the 1990s cell telephones were moving from analog to digital modulation. Digital linearization followed this move and enable higher efficiency HPAs that replace ones using FF linearization. After the millennium, the telecom industry moved to signals with higher and higher peak-to-average ratios. To maintain efficiency, HPAs with special architectures were needed. Today Doherty and envelop tracking/polar HPAs dominate telecom. These HPAs require linearization even more than their predecessors and almost universally employ digital PDL to maintain satisfactory linearity.

V. Memory Effects

The importance of memory effects started to be recognized in HPA/linearizer papers in the late 1980s. Memory effects are the dependence of the non-linear behavior of an HPA not only on the *present* amplitude of the signal, but also on its past values.

$$V_o = f(V_{in}, time) \quad (10)$$

Memory effects can be caused by a variety of problems. Some of the most important are a) frequency memory effects due to change in an HPA's nonlinearity with frequency; b) bias memory effects due to change in a device's bias (at both the drain and gate of FETs) caused by changes in the signal envelope; and c) temperature memory effects. Great care should be taken in the design of an HPA to minimize these effects, if the maximum benefit of PDL is to be achieved. With digital PDL, often the solution to memory effects is the application of complex signal processing and multi-dimensional lookup tables that weight both the present and recent past events. With analog predistortion, the linearizer's nonlinear characteristics can be tailored to match the HPA's nonlinearity over frequency. TWTAs, for example, generally need a greater phase change at the high end of their operating band. The biggest contributor to the nonlinearity of memory effects is often modulation of drain and gate bias voltages due to a signal's changing envelope. As the envelop increases, more drain current is drawn, and the resulting voltage drop across the impedance of the inductor (decoupling circuitry use to isolate the RF path from the dc supply) causes the drain voltage to decrease. This ripple effectively *amplitude modulates* (AM/AM) the signal to produce sidebands at the same frequencies as the IMD. A worst case scenario will occur for high power, low drain voltage HPAs, operating at low frequencies with very wide signal bandwidth (high envelope frequency). Variations in the envelope of a signal can also produce rapid changes in a power device's temperature.

VI. Modern Linearization

There are needs for linearizers to operate over wider bandwidths and at higher frequency. For wideband applications a PDL's gain and phase transfer characteristics must change over frequency as well as with input level to match the changes of the HPA's nonlinearity at different frequencies. In addition, small signal (linear) gain and phase (time delay) must be maintained over the frequency range of interest. If an HPA's small signal gain changes with frequency, the gain correction required from the PDL will be shifted and if not matched, the improvement in linearity degraded. Consequently HPA gain ripple is a major problem. Over narrow bandwidths, phase delay is not a problem, but with wideband linearization systems care must be taken to insure that distortion correction products are not significantly shifted in phase relative to the carriers that generated them. Over time the linearizer bandwidth have increased from kHz range to where production analog PDLs operate over multi-GHz bandwidths. Fig. 5 shows the response of a PDL he increasing gain and decreasing phase typically needed to correct a GaN HPA over a 2 to 20 GHz frequency range. The lower curve in the top graph and the upper curve in the bottom graph are respectively the small signal gain and phase frequency responses. As the PDL is driven with greater input power, these responses move apart to produce the increasing gain change and the deceasing phase change needed to correct the HPA's distortion.

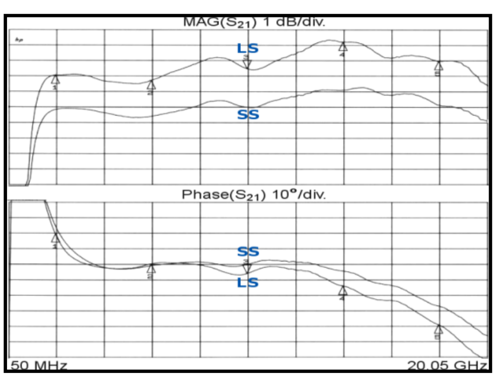

Fig. 5. Wideband PDL with useful 2 to 20 GHz frequency response.

For HPAs operating at > an octave bandwidth, both even and odd order, and IMD and harmonic distortion must be corrected. To date linearized HPAs have been produced with more than 10 GHz of bandwidth and that operate over 2.5 octaves of bandwidth. When PLD were first produced for satellites, the upper limit was at 13 GHz. Work is taking place to extend this limit to > 200 GHz. In this regard, it should be noted that PDL can be performed at a lower frequency including digitally at the modulator and mixed up to virtually any frequency. There are practical limitations on such systems. Generally, the reason for moving to a higher frequency is bandwidth. The lower in frequency PDL is generated, the more difficult it is to achieve the desired performance. A PDL has been produced and tested with a TWTA at 96 GHz – see Fig. 6. For a C/I of 25 dB, the linearization increased its available output power by > 5 dB.

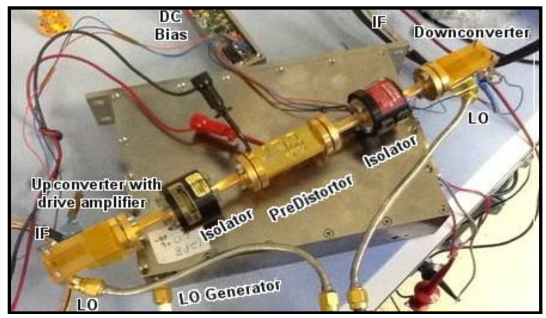

Fig. 6. W-band (92 – 96 GHz) linearizer in test.

VII. Summary

This paper reviews the history and concepts behind the linearizers in use today. PDL is by far the most widely used form of linearization and is commonly generated digitally for use in telecom and limited bandwidth applications. For wider bandwidths, analog PDL is often used. The progress being made to produce linearizers of very wide bandwidth and to extend their capabilities to the upper millimeter-wave bands was covered. Multi-octave PDLs with > 10 GHz of bandwidth and that operate to 100 GHz have been produced.

References

[1] Black, H.S., "Inventing the negative feedback amplifier," *Spectrum, IEEE*, vol.14, no.12, pp.55,60, Dec. 1977.

[2] Smith, A.M.; Cavers, J.K., "A wideband architecture for adaptive feedforward linearization," *Vehicular Technology Conference*, 1998. VTC 98. 48th IEEE, vol.3, no., pp.2488,2492 vol.3, 18-21 May 1998.

[3] Black, H.S., "Stabilized feed-back amplifiers," *Electrical Engineering*, vol.53, no.4, pp.590,590, April 1934.

[4] Kaye, A.; George, D.; Eric, M., "Analysis and Compensation of Bandpass Nonlinearities for Communications," *Communications, IEEE Transactions on*, vol.20, no.5, pp.965,972, Oct 1972.

[5] Katz, A.; Dorval, R., "Evaluation and correction of time dependent amplifier non-linearity," *Microwave Symposium Digest, 1996., IEEE MTT-S International* , vol.2, no., pp.839,842 vol.2, 17-21 June 1996.

[6] Katz, A.; Gray, R.; Dorval, R., "Truly wideband linearization," *Microwave Magazine, IEEE* , vol.10, no.7, pp.20,27, Dec. 2009.

[7] Katz, A.; Chiappetta, M.; Dorval, R., "Predistortion linearization to 100 GHz," *Power Amplifiers for Wireless and Radio Applications (PAWR), 2013 IEEE Topical Conference on*, vol., no., pp.34,36, 20-20 Jan. 2013.