Current Techniques for Enhancing the Efficiency of Ultra Linear Power Amplifiers

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Abstract

Modern, spectrally efficient high data rate wireless communications systems require linear Power Amplifiers in order to faithfully reproduce their complex modulation waveforms while maintaining minimum occupied bandwidth. For example, the popular 64QAM Orthogonal Frequency Division Multiplex (OFDM) modulation used in 54 Mbps 802.11a and g “Wi-Fi” WLANs requires an Error Vector Magnitude (EVM) no greater than -25 dB (i.e. <5.6%) in order to meet consortium specifications. Practical tests on WLANs have verified that deterioration of EVM much beyond this point does indeed cause higher Bit Error Rate (BER) and therefore significantly reduced system throughput.

To further complicate matters, these PA’s must often be capable of driving non-ideal (i.e. high VSWR) variable antenna load impedances such as commonly found in personal portable equipment such as Notebook Computers. This requires even more PA power back-off than in the ideal case and therefore further reduces the PA’s efficiency.

Many of these wireless appliances are battery operated, placing severe constraints on operating current. PA efficiency is therefore high on the list of desired attributes.

This paper begins by establishing a performance baseline for the relatively inefficient Class A Power Amplifier most commonly used today in linear applications and then discusses possible performance enhancements derived from more sophisticated techniques, such as:

- Class B Amplifiers
- Dougherty PA’s
- Feed Forward Amplifiers
- Digital Baseband Pre-distortion
- LINC (Linear Amplification using Nonlinear Components)
- Envelope Elimination and Restoration (EER)
- Practical combinations of the above techniques

We live in a world of ever increasing technological complexity. There are recent marketing trends requiring more wideband PA performance, approaching one octave operation, while maintaining the high DC conversion efficiency. Unfortunately, several classical approaches to obtaining more efficient PA’s do not scale well to this requirement. This paper will therefore emphasize designs providing requisite broadband performance.

In each case, tradeoffs of potential power savings, relative complexity, size and cost are presented. Of note: In spite of the proliferation of PA applications in the modern wireless world, we do not yet have a neat, simple solution to the problem of achieving broadband linear high power amplification while coupling to a somewhat variable load as is typically the case in personal portable equipment. So, the research continues and this paper is therefore a “work in progress”.

The Classical Class A Amplifier

The Class A amplifier is a good baseline for our discussion and is well documented in the literature\(^1\). It is characterized by the continuous flow of current in the PA. The bias and Load Line are adjusted so as to bias the amplifier well into its linear region. It is therefore capable of low distortion. However the DC
conversion efficiency is relatively poor and will not practically exceed 15-20% when used with complex digital modulation such as 64QAM. In the case of 64QAM, the Class A PA must typically be backed off as much as 5-6 dB from its 1 dB compression point in order to achieve required linearity – perhaps even further when finite VSWR is factored in. On a positive note, it is relatively low cost, simple to design with predictable performance and capable of relatively broadband performance.

**Class “AB” and “B” PA’s**

This class of PA’s, as stand-alone devices, are capable of incrementally improved performance, particularly when using fairly simple digital modulation, say up to and including the QPSK format. A practical PA would really be biased for Class AB operation rather than Class B, since the latter implies current only flowing ½ the time which would not yield adequate linearity. Efficiencies typically run 25-30% and they are capable of relatively broadband performance. This is however a fairly low cost extension of Class “A” PA technology. However, it is often desirable, in the case of battery powered equipment, to achieve higher efficiencies than this PA class can yield. I’ll therefore limit the discussion of this class to the brief overview presented above.

**Doherty PA’s**

Of historical note, this technology was originally developed back in the mid 1930’s where it was used in high power AM Broadcast Vacuum Tube PA’s. As a compromise, it did not require the high power audio generation of a Plate Modulated AM PA design, i.e. 50% of the Carrier PA DC input, but achieved a significantly higher efficiency than a Class AB Linear Amplifier producing the same output power. The recent interest in complex digital modulation has caused a substantial rebirth of this technology.
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\[ R_{Ax} = \left( \frac{Z_2}{Z_1} \right)^2 \times R_L = 102\Omega. \]

The \( \frac{\pi}{4} \) transmission line at the input of the Aux PA ensures in-phase summing of the RF collector currents of the two PA’s. Since the saturated Main PA output is now four times less than under peak power conditions, the collector efficiency is twice that of a conventional Class B PA and can theoretically achieve approximately 78% even though it is backed off in power. We conclude therefore that the collector efficiency is reasonably high at both peak power output and its transition point.

A major drawback of the Doherty design is its narrowband nature. Unfortunately, the operation of the Doherty design depends on \( \frac{\pi}{4} \) tuned transmission lines. As such, it is inherently a relatively narrow band amplifier and difficult in practice to broadband with constant efficiency. As a narrowband design, however, it yields greater than twice the collector efficiency of a traditional Class “A” design.

Feed Forward Amplifiers

The Feed Forward amplifier has long been the mainstay of Base Station Power Amplifier design and is well documented in the literature 3. It is a purely analog method of canceling distortion products and consists of a Main Amplifier, three Couplers, two Phase Shifters, and an Auxiliary error Amplifier. It is capable of significantly reducing distortion at moderate power output levels and can yield a useful power output approximately 2 dB higher than the same PA without its added linearizing circuitry.

Its drawbacks are that it is relatively narrowband, costly to produce and bulky in size. Recently, other digital techniques such as Baseband Pre-Distortion are beginning to supplant this approach due to the low cost of Digital Signal Processing (DSP). This technique will therefore not be discussed further in this paper.

LINC (Linear Amplification using Nonlinear Components) Amplifiers

Note: This technique also is known as Outphasing Amplification

Historically, this technique also goes back to the mid 1930’s where it was used in high power AM Broadcast transmitters. Theoretically it is possible, by combining two saturated PA’s with a known RF phase relationship relative to each other, to generate any RF output voltage from zero up to twice the individual PA’s output. With reference to Figure 2 and assuming equal PA output voltages, if the two outputs are combined in phase, twice the individual output voltage would be generated. In the other extreme, if they are combined 180° out of phase, than zero volts would result. At phase angles in between these two points, any intermediate output voltage may be generated.
This technique has had a recent rebirth in popularity due to the availability of an ASIC chip which performs the task of generating the two phase signal at baseband. Baseband pre-distortion is often implemented to further enhance the performance of LINC designs. In the 5 GHz WLAN band, authors of a recent paper describing an application of this ASIC report achievement of a DC Collector efficiency of 65% using 64QAM modulation while maintaining an EVM of -25 dB, an impressive result. To verify reproducibility of the design in a production environment, the authors built a fairly large run of assemblies and achieved consistent results.

The challenge in a LINC design is to combine the signals from the two PA’s with low loss. A practical design using a Chireix Power Combining circuit is shown in Figure 3.
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Due to the use of tuned transmission lines, this design is limited to only a moderate operating bandwidth. However, using classical filter theory, it is possible, to somewhat extend the operating bandwidth by replacing the single ¼ wave transmission lines with cascaded sections of lines. Three sections is a practical limit. It is also possible to build a lower frequency version of the Outphasing Amplifier using lumped elements such as PI sections.

Envelope Elimination and Restoration PA’s

This technique was patented in 1952 by Leonard Kahn, primarily for HF SSB applications, however it is particularly well suited to amplification of digital modulation signals. The EER PA relies on the principle that any complex time varying waveform may be broken down into a phase component and an amplitude component. Kahn, in his original implementation, used a hard limiter to strip the amplitude variations from the signal, leaving only the phase component. Furthermore, he used a Peak Detector circuit to derive the amplitude component. With reference to Figure 4, in a contemporary design transmitting digital modulation and using low cost DSP components, we can generate these signals right at baseband. A Mixer, then translates the Phase component to the final operating frequency to drive the PA.

![Diagram of Envelope Elimination and Restoration PA](image-url)
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degrade the EVM. Fortunately this phenomenon is fairly predictable and can be compensated for in the DSP processing.

2. It is important that the time delay in the PWM modulator be low compared to the chip rate, since time coincidence of the Phase and Amplitude signals is necessary for low distortion. Alternately, time delay equalization may be easily implemented in DSP.

Classical Digital Pre-Distortion techniques may also be used to dynamically correct these two problems. A portion of the output signal is sampled, translated to baseband and compared with the desired signal. A DSP correction matrix may then be generated to cancel the above effects.

Conclusions

This paper has presented some contemporary methods of yielding high efficiency Power Amplifiers suitable for amplification of digitally modulated signals. The “jury is not in” and there is still significant research needed to produce an ideal high efficiency ultralinear PA-to-Antenna interface. Contemporary systems demand low distortion, wideband operation and the ability to preserve these characteristics under conditions of varying PA load impedance – a daunting challenge.

3 Grebennikov, Andrei, op.cit. pp 389-392