RF Power Amplifiers are usually used in communication systems to amplify signals to be transmitted by the antenna. Two things that plague the design of RF Power Amplifiers are low efficiency and low linearity inherently existing in Power Amplifiers. This research is to provide a summary of different techniques to boost the efficiency of RF Power Amplifiers while decreasing the nonlinearity of the Amplifiers.

Summary of Conventional Power Amplifiers

Class A Power Amplifier uses the Power Transistor as controlled current sources. With a conduction angle of 360 degree and a subsequent LC tank to select a narrow band of signals, the Class A power amplifier can provide high linearity with low harmonic distortion and low intermodulation distortion. But the efficiency of Class A amplifier is rather low, below 50%.

Class B amplifier uses the same topology with Class A but with the circuit biased at a conduction angle of 180 degree and hence the power efficiency of class B amplifier can be as high as $\pi/4$. With two complementary transistors to provide positive and negative conduction angles, the overall conduction angle can still be virtually 360
degree.

Class C Amplifier biases the transistor at a conduction angle less than 180 degree with an efficiency less than 78.5% depending on the conduction angle. The less the angle the higher the efficiency but the lower linearity.

Efficiency and Linearity Boost Techniques

Some techniques are developed to boost the efficiency of linear power amplifiers. Among them is the Envelope elimination and restoration. This technique apply the input signal to both an envelope detector and a limiter. The limited constant amplitude signal gets amplified by a Class C amplifier whose supply is modulated by the extracted envelope. An envelope feedback is used to make the envelope
To boost the linearity of the amplifier, predistortion can be used which provides the inverse of the amplifier distortion by a DSP to cancel amplifier distortion so that the overall distortion of the system is zero.

Recently, nonlinear Power amplifiers are used which has an inherent efficiency of nearly 100%. The nonlinear Power Amplifiers uses the power transistor as a switch that operates between open and closed conditions. Techniques must be used to get rid of the highly nonlinear feature while utilizing its high power efficiency.

The class D power amplifier is used quite often in communication systems. The topology of the Class D amplifier is a power transistor switch followed by a LC tuning tank and the load resistor. Since the drain current and voltage has no time of overlapping, no power is wasted on the transistor. The maximum efficiency is 100%.
Outphasing Modulation Scheme

It turns out that in order to utilize the highly nonlinear amplifier, what we need is just a constant amplitude signal as it suffers no AM to PM conversion after being applied to the nonlinear amplifier. The following equations shows the principles of AM to PM conversion.

\[ V_{in} = A_m(t) \cdot \cos(\omega_o \cdot t + \beta \cdot \cos(\omega_m \cdot t)) \]

\[ V_{out} = a_1 \cdot V_{in} + a_2 \cdot V_{in}^2 + a_3 \cdot V_{in}^3 \]

\[ DC = \frac{a_2 \cdot A_m(t)^2}{2} \]

\[ FH = (a_1 A_m(t) + \frac{3a_3}{4} A_m(t)^3) \cos(\omega_o \cdot t + \beta \cdot \cos(\omega_m \cdot t)) \]

Higher order harmonics are filtered out.

If \( A(t) \) is independent of time, then the output signal is just a replica of the input signal as higher order harmonics are filtered out. However, to increase the data rate, amplitude modulation must be used as well as phase modulation to provide an additional dimension of modulation and hence twice more data rate. Mechanism of transforming amplitude modulated signal to constant amplitude signal must be provided to make the utilization of nonlinear amplifiers possible.

One technique called outphasing is used to separate one amplitude modulated signal
to two constant amplitude signals that are out of phase by an AM related modulating phase. The mathematics is shown below:

The original signal is

\[ s(t) = [s_i(t) + js_q(t)]e^{j\omega_c t} = r(t) \cdot e^{j[\omega_c t + \phi(t)]} \]

where \( r(t) = \sqrt{s_i(t)^2 + s_q(t)^2} \) and \( \phi(t) = \tan^{-1}\left(\frac{s_q(t)}{s_i(t)}\right) \)

\( s(t) \) can be separated as two constant amplitude signals as \( s(t) = s_1(t) + s_2(t) \), where

\[ s_1(t) = \frac{1}{2} r_{max} e^{j[\omega_c t + \phi(t) + \theta(t)]} \]

\[ s_2(t) = \frac{1}{2} r_{max} e^{j[\omega_c t + \phi(t) - \theta(t)]} \]

\[ \theta(t) = \cos^{-1}\left[\frac{r(t)}{r_{max}}\right] \]

The difficulty for this modulation scheme is that the inverse cosine function is quite difficult to implement by analog circuits. Solutions do exist for analog implementation but the cost, power consumption and complexity is high. Often DSP has to be used in order to use this technique.

Different outphasing Power Amplifier systems have been implemented with very similar architectures. Basically, within every architecture, there is one signal component separator which extracts two constant amplitude signals from the AM and PM modulated signal. This is usually done in digital domain, one two modulators that modulates the outphasing parts of the two constant amplitude signals, two Power Amplifiers that amplifies both signals, and finally one power combiner that combines the signal after the power amplifier.

For best performance, suitable power combiner and amplifiers should be chosen. The conventional transformer based power combiner can provide linear operation but with low efficiency. The new Chireix power combiner can improve the efficiency up to a factor of 2 using two \( \frac{\lambda}{4} \) transmission lines after two amplifiers.
The power amplifier used must perform best as a voltage source to supply fast changing current that will interfere with each other. For this reason voltage mode Class D is best suited for this purpose.

**Case Study**

Among all the realizations of the outphasing power amplification systems, one specific example from Intel is studied in detail. This system uses digitally generated phase information of the two outphasing signal components. This information is then used by a DS modulator to modulate different phases into two carriers from a LO by using two outphase modulator and two inphase modulator. The signals are then combined by a power combiner and got transmitted by an antenna.

![Diagram of outphasing transmitter architecture and DFE details.](image)

The outphase modulator uses VCDL to filter out noise components from the LO. The LO signal is then fed to a delay line whose outputs are given to two muxes. The DS modulator controls the mux to give the LO correct outphase modulation.

![Diagram showing the outphase modulator](image)

The inphase modulator uses DCDL by using banks of capacitors which are controlled by digital logic. The control information is provided by the DS modulator and one LUT that is calibrated according to the environment.

![Diagram showing the inphase modulator](image)
A simplified version of the system is built according to this paper. A delay line and two muxes are used to provide outphase modulation whose outputs are then added and filtered by a bandpass filter.

A sine modulating signal is implemented and the result from the system is satisfactory.
This Power Amplification system is then used in a multi-radio integration SoC chip to provide an efficiency up to 40%. The analog/RF conversion being the last stage of the system, benefit from the superior digital transistor performance is utilized to its maximum for the system.

References


Marian Verhelst, “Multi-radio integration into scaled CMOS SoCs”, Ph.D. Research in Microelectronics and Electronics (PRIME), 2011 7th Conference, 3-7 July 2011, pp1-4