

Implementation of Efficiency Enhancement Techniques in the Linear Region of Operations of Power Amplifier

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Abstract - Radio signals typically are subject to very large transmission losses and distortions due to nonlinearities that might be added by the limited dynamic range of power amplifiers [1], [2]. Particularly, the signal gets distorted when the power amplifier is used at its full rated RF power level and/or Maximum efficiency is attained only at one single power level, usually closer to the maximum rated power of the device. Thus, linear RF power amplifiers with high efficiency and, power gain are recommended to compensate such nonlinearities. But achieving high efficiency and high linearity simultaneously in power amplifier design, is the most challenging task. In this paper, implementations of efficiency enhancement techniques in the linear region of operations of power amplifier are discussed as a solution to these distortions. Techniques to improve efficiency, such as Chireix outphasing or Linear amplification using Non linear Component (LINC), Doherty Configuration, Kahn Envelope Elimination, Restoration (EER) and Envelope Tracking (ET) are presented and discussed.

Keywords: Amplifier, Efficiency, Linearity, power, class A, class B, class C, Doherty, Chireix, envelope tracking, outphasing.

I. INTRODUCTION

RF power amplifiers are typically located at the final amplification stage of the transmission chain, and therefore must produce enough output power to overcome the mitigation effects of the channel between the transmitter and the receiver. These systems requirements impose stringent design challenges to efficiently convert DC power to RF output power and to provide acceptable degree of linearity of the power amplifier to prevent spectral spreading and intermodulation.

The power amplifier is critical component in wireless communications; it is typically the most power hungry device. Knowing the possibilities for trading power per unit cost with efficiency and distortion often forms the basis for the entire system architecture design.

II. METHOD OF AMPLIFICATION

Amplifiers are classified according to their circuit configurations and methods of operation into different classes, such of these are A, B, AB, C, and F. These classes range from entirely linear with low efficiency to entirely non-linear with high efficiency.

Class A: This amplifier has the highest linearity relative the other classes especially when operating in backed off mode from full power. It operates in a linear region of its operating mode and is equivalent to a current source. The configurations of class-A, B, and C amplifiers can be either a push-pull or a

single ended tuned version. To achieve high linearity and gain, the amplifier's gate and drain dc voltage should be chosen properly so that the amplifier operates in the linear region. In Class A, the active devices operate over the full 360° of the input signal phase, but the efficiency is less than 50%.

Class B: This amplifier suffer from cross-over distortion and hence less linear than class A. The active devices operate over 180° of the input signal phase and the efficiency is less than 78.5%. Operate as complementary "push-pull" pairs.

Class AB: This amplifier is a compromise between class A and class B in terms of efficiency and linearity. The transistor is biased as close to pinch-off as possible, typically at 10 to 15 percent of I_{dss} . In this case, the transistor will be on for more than half a cycle, but less than a full cycle of the input signal.

Class C: This is a more non-linear device and is applicable in situations where the efficiency is a critical issue other than linearity. The active devices operate less than 180° of the input signal phase and have efficiency which is greater than 78.5%.

Class F: This is one of the highest efficiency amplifiers. It uses harmonic resonators to achieve high efficiency, which results from a low dc voltage current product. In other words, the drain voltage and current are shaped to minimize their overlap region.

It is well known that power amplifiers cannot operate efficiently when used for linear amplification. The classes A, B and AB are considered linear amplifiers and have been used for linear applications such examples are amplitude modulation (AM), single-sideband modulation (SSB), and quadrature amplitude modulation (QAM). In addition, they can be used in linear and wide band applications such as the multi-carrier transmission.

III. CHIREIX OUTPHASING OR LINEAR AMPLIFICATION USING NON LINEAR COMPONENT (LINC)

In 1930s Chireix outphasing power amplifier was invented by Chireix to improve the efficiency and linearity of an AM-broadcast transmitter. It was used up until 1970 in RCA "ampliphase" AM-broadcast transmitters. Still in the 70s of last century, it came into use as microwave frequencies under the name LINC – Linear amplification using Non linear Component [3]. A Chireix outphasing technique (LINC) combines two nonlinear RF power amplifiers into a linear RF power amplifier system. The two power amplifiers are driven with signals of different phases and the phase are controlled so that the addition of the power amplifier outputs produces a system output of the desired amplitude that the addition of the power amplifier outputs produces a system output of the desired amplitude.

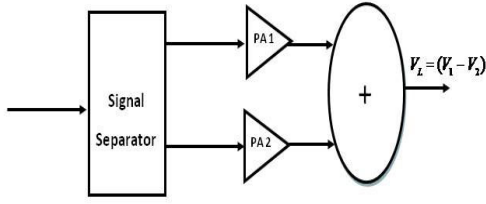


Fig. 1. Outphasing power amplifier.

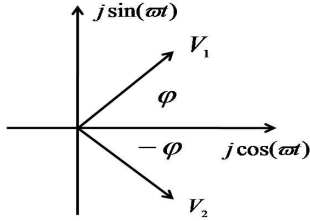


Fig. 2. Phase form of two voltages at the output of two nonlinear power amplifiers.

The basic principle of the simple outphasing technique (transformer coupler) and Chireix outphasing technique (transmission line coupler with shunt reactance) is that, the modulated signal is separated into two outphased signal with constant envelopes. Since the input signals to the two power amplifiers have constant envelope; regardless of the amplitude of the input signal to the signal separator, a nonlinear high efficient power amplifier could be used to amplify the signal after the signal separator, and the amplitude information of the original input signal is then recovered at the output in the summing operation [2], [4], [5] (Fig. 1).

The signal separator circuit generate two sinewave signals with phases of φ and $-\varphi$. These two signals are then amplified by two high efficient and non linear power amplifiers and added together to produce the output signal. The outputs of power amplifiers can be represented as V_1 and V_2 can be written in phasor form using Fig. 2 as following:

$$V_1 = V (\cos \varphi + j \sin \varphi) \quad (1)$$

$$V_2 = V (\cos \varphi - j \sin \varphi). \quad (2)$$

The output voltage across the load is given by:

$$V_L = V_1 - V_2 = 2Vj \sin \varphi. \quad (3)$$

The output voltage is proportional to $\sin \varphi$ after summing. In order to recover the original signal at the load, the signal separator must generate a phase that is inverse sine function of $A(t)$ which is ($\varphi = \arcsine(A(t))$), i.e. the phase deviation φ must be the inverse sine of normalized signal envelope. When the $\varphi = 90^\circ$, the peak output is obtained, which causes the two power amplifiers output to be added in phase. It also be noted when the $\varphi = 0^\circ$, the zero output is obtained, which causes the two power amplifiers output to cancel each other. When the $\varphi =$ Intermediate values, then the intermediate values of the amplitude of the output signal is obtained. The key action of an outphasing amplifier takes place at the output and purely re-

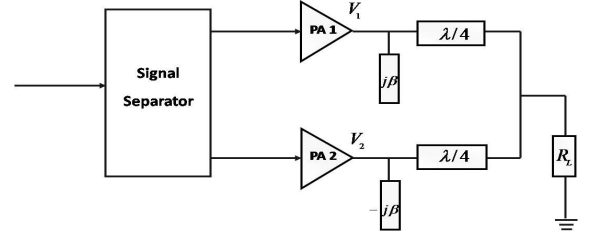


Fig. 3. Chireix-outphasing power amplifier.

lies on the mutual active load pulling of the two devices delivering power into a common load.

The current at the load can be written as:

$$I_L = \frac{V_L}{R_L} = \frac{V_1 - V_2}{R_L}. \quad (4)$$

Therefore, according to equation (1), (2) and (3) the total output power is:

$$P_{out} = \frac{1}{2} \frac{4V_L^2 \sin^2 \varphi}{R_L} = -2 \frac{V^2 \sin^2 \varphi}{R_L} \quad (5)$$

As the φ approaches 0° when the output power is backed off, the reactive component value increases. These will decrease the efficiency of the two power amplifiers at back-off region.

As proposed by Chireix [4], those reactive components can be compensated. The power amplifier 1 with the output voltage V_1 , an inductor can be placed in shunt to resonate out the capacitive reactance. In addition the output of the other power amplifier 2 with output voltage V_2 , a capacitor can be placed in shunt to resonate out the inductive reactance (Fig. 3).

IV. DOHERTY CONFIGURATION

In 1936 W.H Doherty, from Bell Telephone Laboratories Inc, proposed the high efficiency power Amplifier called Doherty Amplifier [6]. The concept of the Doherty power amplifier configuration involves the use of two or more power amplifiers and the quarter wave transmission line coupler or impedance inverting network. The resultant linear power amplifier achieves a higher efficiency at the outputs below peak output power (PEP) than conventional class B linear power amplifier [6], [7]. The simple configuration of the Doherty power amplifier consists of two RF power amplifiers "Carrier (Main)" and "Peak (Auxiliary)" connected in parallel with their outputs joined by a quarter-wave length transmission line, which performs impedance transformation.

The Doherty amplifier works like the so called "active load pull techniques". To understand how the configuration of Doherty amplifier really works, the active load pull technique should be understood first. This concept is extended to the combination of two different devices with different biasing results in the Doherty configuration. When two power amplifiers are connected in parallel, one can modify the impedance seen by the other through proper biasing.

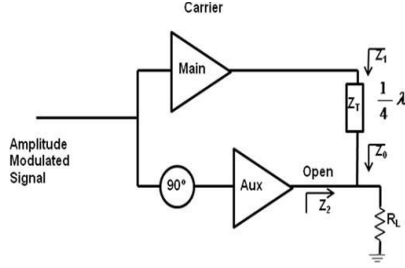


Fig. 4. Doherty power amplifier.

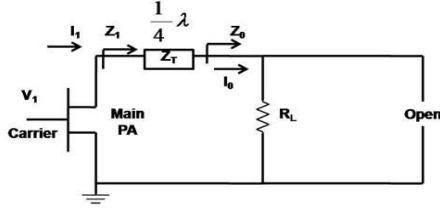


Fig. 5. Low level input signal.

Figure 4 shows the configuration of a Doherty power amplifier where the carrier (main) amplifier and peak (auxiliary) amplifier contribute equal power at peak power. The peak (auxiliary) amplifier is biased with a small conduction angle compared to the carrier (main) amplifier. The working principle of the Doherty power amplifier can be best described by dividing the level output power into low level, medium level and high level power regions [7].

A) Stage I

During the low cycle of the input signal, the instantaneous amplitude of the input signal is not sufficient to turn on the peak (auxiliary) amplifier and appears as an open circuit (Fig. 5). The total low level signal is received by the carrier (main), which acts as a controlled current source. The carrier (main) amplifier sees the load through the quarter-wave length transmission line and operates exactly the same as an ordinary power amplifier. As the peak (auxiliary) amplifier appeared to be an open circuit, these enable the carrier (main) amplifier to see high output impedance which leads to its saturation while the current has reached only half of its maximum value; and the voltage already reached its maximum value. Since the voltage has reached its maximum value, the system works with maximum efficiency though it does not deliver the maximum power.

The quarter wavelength line, enable the carrier (main) amplifier to see high output impedance which leads to its saturation and keeps it maximum voltage at constant condition.

The input, output and characteristic impedance of a quarter wavelength transmission line are related by:

$$Z_1 = \frac{Z_T^2}{R_L} \quad (4)$$

B) Stage II

In the region of medium level power, suitable biasing will enable the peak (auxiliary) amplifier to turn on when the carrier (main) amplifier is saturated. At this point the peak (auxiliary) amplifier will act as a controlled current control so-

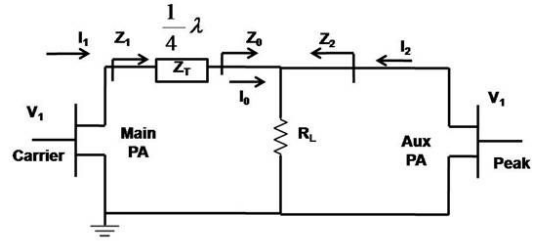


Fig. 6. Medium and high level input signal.

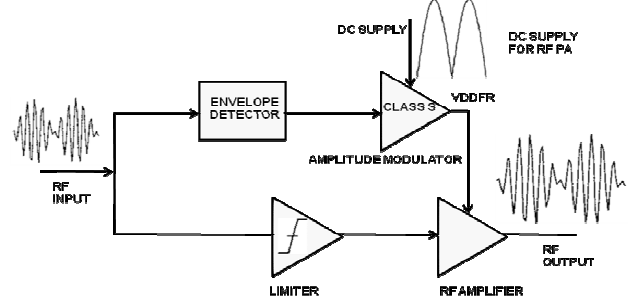


Fig.7. Kahn Envelope elimination and restoration – Technique.

urce while the carrier (main) amplifier acts as a controlled voltage source. Once the peak (auxiliary) amplifier starts to supply current, the current will increase the impedance at Z_0 seen by the quarter wavelength (Fig. 6) (According to the active load pull technique).

However, increasing in the impedance of Z_0 results in decreasing the impedance of Z_1 , which is the impedance seen by the carrier (main) amplifier. This causes the main amplifier output voltage to remain constant without reaching saturation whilst increasing the output current from the main amplifier. This means, the increase in the output current increases the resultant output power.

The importance of a quarter wavelengths at this stage causes the impedance seen by the carrier (main) amplifier to decrease as the peak (auxiliary) amplifier turns on. This guarantees highly efficient power combining between the two amplifiers. At this point Z_1 becomes:

$$Z_1 = \frac{Z_T^2}{R_L \left(1 + \frac{I_2}{I_0}\right)} \quad (6)$$

And Z_2 is

$$Z_2 = R_L \left(1 + \frac{I_0}{I_2}\right) \quad (7)$$

C) Stage III

Finally, when both amplifiers carrier and peak contribute to the same amount of power to the load, the Doherty amplifier is working at the high power level, i.e. $I_0 = I_2$ (Fig. 6). In this region when $I_0 = I_2$, and by substituting $I_0 = I_2$ in Z_1 and Z_2 equation at the high level input power, these become:

$$Z_1 = \frac{Z_T^2}{2R_L} \quad (8)$$

$$Z_2 = 2R_L \quad (9)$$

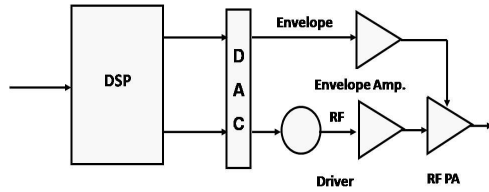


Fig. 8. Envelope tracking – Technique.

V. KAHN ENVELOPE ELIMINATION AND RESTORATION (KAHN EER)

In 1950s Leonard Kahn developed a technique called Envelope Elimination and Restoration (EER) as a means of improving the efficiency of broadcast transmitters [9].

It is combinations of highly efficient, but nonlinear RF power-amplifier with a highly efficient envelope amplifier to build a high efficiency linear RF power amplifier as shown Fig. 7. The limiter removes the envelope from the signal and therefore allows the highly efficient but nonlinear power amplifier to amplify only the constant amplitude phase modulated carrier. Amplitude modulation of the final RF power amplifier restores the envelope to the phase-modulated carrier in which it, creates an amplified replica of the input signal [9], [10].

This technique provides high efficiency over a wide dynamic range, and therefore produces a high average efficiency over a wide dynamic range of signal and power back-off level. Generally this has good linearity, since this does not depend upon the linearity of its RF power transistors.

The most important factors affecting the linearity are the envelope bandwidth and alignment of the envelope and phase modulation. The envelope bandwidth must be at least twice the RF bandwidth and the misalignment must not exceed one-tenth of the inverse of the RF bandwidth

VI. ENVELOPE TRACKING (ET)

It is similar to Kahn techniques. The supply voltage is varied to conserve power and allow the power amplifier to operate linearly. By dynamically biasing the drain voltage, the highest possible power added efficiency (PAE) can be obtained. This strategy improves the efficiency of the power amplifier by superimposing the envelope signal at the drain so that the transistor will consistently operate at the efficient region [11], [12].

The envelope signal is calculated from the baseband signal and amplifying by the envelope amplifier; and at the same time the complex IF signal is up converted and amplified by the power amplifier [13].

The average efficiency of an envelope tracking power amplifier strongly depends on the peak-to-average power ratio (PAPR) and on the probability density function (PDF) of the modulated input signal since the drain bias voltage varies in proportion to the amplitude of input signal.

VII. CONCLUSIONS

This paper has presented the efficiency enhancement techniques which can be used to achieve higher efficiency at a low-level output power. These techniques have become critical in the design of power amplifiers where the main concern is power consumption and spectral efficiency. Chireix

outphasing or Linear Amplification using Non linear Component (LINC), Kahn Envelope Elimination and Restoration (EER) and Envelope Tracking (ET) involve complex architectures design, and required the use of external control circuits and signal processing; except Doherty configuration which does not require any additional components. The self-managing characteristic of the Doherty amplifier has made its implementation more attractive. Applying these techniques represents step forward on the concept of the efficiency enhancement and linearity compensation in RF power amplifier design concepts.

VIII. ACKNOWLEDGEMENT

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