An Overview of Efficiency Enhancements With Application To Linear Handset Power Amplifiers

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Abstract **– A consequence of high spectral efficiency provided by second and third generation cellular systems is the requirement for linear power amplifiers in the transmitter unit of the mobile handset. The battery nature of the mobile phone emphasizes high amplifier efficiency for extending talk time and battery life. This represents an inherent trade-off between amplifier efficiency and linearity. Recent efforts have focused on considering alternative approaches with the goal of improving the efficiency/linearity performance trade-off compared to traditional single-ended Class A/B topologies. Some alternative approaches are examined here.**

I. INTRODUCTION

Advanced cellular systems such as EDGE and W-CDMA achieve higher spectral efficiencies and/or data rates than previous ones. With some exceptions (e.g., GSM), the requirement for a linear power amplifier (PA) in the transmitter of the mobile unit is generally imposed. Traditionally, this amplifier is implemented as a single ended Class A/B configuration and operated with sufficient power back-off to minimize compression of peak envelope excursions thereby achieving linearity, but at inherently lower efficiency. Since system level considerations may require the PA to function for extended time periods at moderate to greatly reduced power levels, amplifier efficiency and linearity become important over a broad range of output power levels. This paper examines several approaches to improving the linearity/efficiency performance trade-off.

II. ENVELOPE FOLLOWING

An envelope following (EF) amplifier relies on modulating the drain (or collector) bias voltage w.r.t. the instantaneous input envelope signal (Fig. 1) such that the RF amplifier is in or near gain compression for all envelope signal levels. The overall amplifier is efficient if both the envelope and RF amplifiers are efficient. The dc power (into the RF PA) is the product of the average drain supply voltage $(\overline{V_{dd}(t)})$ and average supply current $(\overline{I_{dd}(t)})$. Compared to fixed supply operation, this product can be significantly smaller. For linear amplification, both amplitude and phase characteristics must be preserved. Hence,

$$\Phi_{out}(t) = \Phi_{in}(t) + \Phi_{offset} \tag{1}$$

and

$$\frac{E_{out}(t)}{E_{in}(t)} = G \tag{2}$$

Where Φ and E denote phase and envelope voltage. Inclusion of a feedback loop comparing the detected output envelope voltage to the input envelope allows controlling the Class-S modulator to satisfy the requirements of Eq. 2 [1,2]. The RF amplifier must inherently exhibit limited am/pm to meet requirements of Eq. 1.

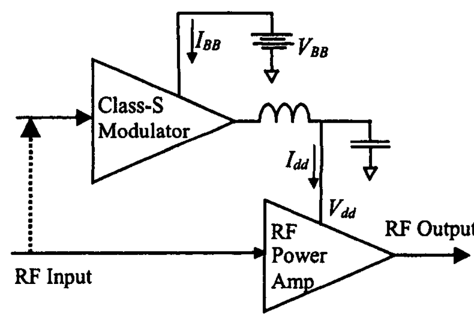

Fig. 1 Simplified diagram of ET linear power amplifier.

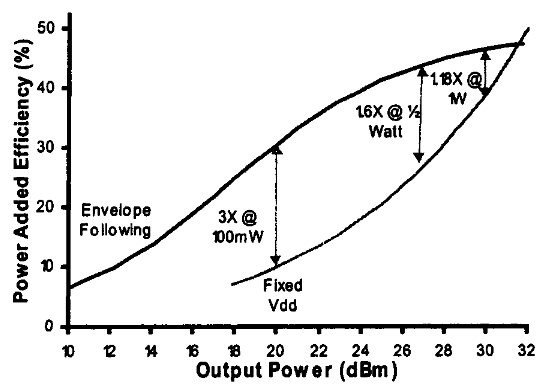

Fig. 2 Measured performance of EF and comparison to fixed supply operation for an IS-136 signal.

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Previous efforts [1] have shown the feasibility of realizing a high speed Si CMOS based Class-S modulator implemented using a 5 MHz dc-dc buck converter with an efficiency of ~90% at 1A of current with a 3.5 volt supply. The performance of an EF amplifier using this Class-S modulator and where the RF amplifier is implemented as a two-stage GaAs HEMT IC is illustrated in Fig. 2. Efficiency performance for both EF and fixed bias operation is illustrated in Fig. 2 with the amplifier driven by an IS-136 signal. Excellent efficiency is maintained with increasing levels of back-off and a marked improvement compared to fixed bias is noted. At 10 dB power back-off (20 dBm output power) for example, more than a 3X improvement in efficiency is obtained compared to fixed drain bias. Distortion components are well within system level specifications for output power levels of 30 dBm and lower (Fig. 3). Rejection provided by the two-pole L/C filter attenuates spurious products (of 5 MHz) by more than 70 dBc [1].

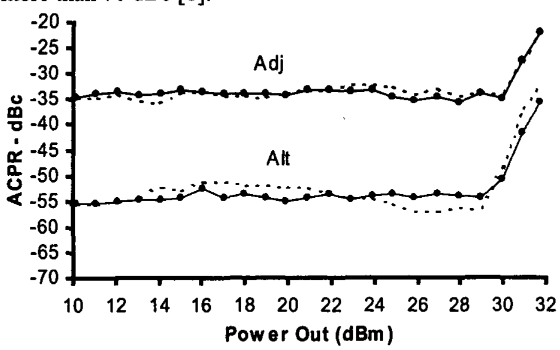

Fig. 3 Measured EF amplifier distortion performance - - IS-136 signal format.

III. ENVELOPE TRACKING

The requirement in an EF amplifier for the Class-S modulator to produce a supply voltage with high current drive that can "follow" the envelope of the input signal becomes problematic for wider bandwidth signals. A wider bandwidth necessitates an increase in switching speed that ultimately results in higher dynamic losses in the N- and P-MOS devices which then lowers the efficiency of the Class-S modulator and EF amplifier. Hence, this approach becomes unattractive in IS-95 CDMA and W-CDMA systems.

Of particular interest in CDMA systems is variation in mobile unit transmitted power due to system level power control. In this case, average output power is defined over relatively long time intervals (long term relative to modulation rate). Variations in the average level occur on a much longer time interval than the modulation rate to account for distance and environmental effects. This relationship is shown in Fig. 4 as a probability distribution function (PDF) of amplifier output power (measured in a reverse link CDMA urban environment). Similar distribution functions have been shown by other authors [2,3]. It is note worthy to observe that amplifier operation near maximum output power is quite limited; highest probability is close to 20 dB power back-off.

Envelope Tracking (ET) is a supply modulation technique that can be very effective in situations where the power amplifier functions primarily in deep back-off for extended time periods. In contrast to EF systems where the supply voltage is modulated w.r.t. the modulated envelope signal, the ET technique varies supply bias w.r.t. the RMS magnitude of the input modulated envelope signal. This occurs on a time scale that is considerably slower than the modulation rate. Under power back-off, bias voltage V_{dd} is lowered to a value less than battery V_{BB} by a switching dc-dc converter (Fig. 1). Efficiency is improved since the power consumed by the amplifier (product of average current $I_{dd}(t)$ and voltage V_{dd}) is significantly less than would be the case if operated at higher voltage supply voltage V_{BB}. Amplifier efficiency can be high over the full output power PDF region assuming losses within the modulator are small. Linearity considerations (Eq.2) require voltage V_{dd} to be set just large enough to prevent excessive compression of peak envelope excursions. Further, the RF amplifier must exhibit limited am-pm distortion as a function of supply voltage (Eq. 1) if acceptable spectral regrowth and EVM is to be achieved.

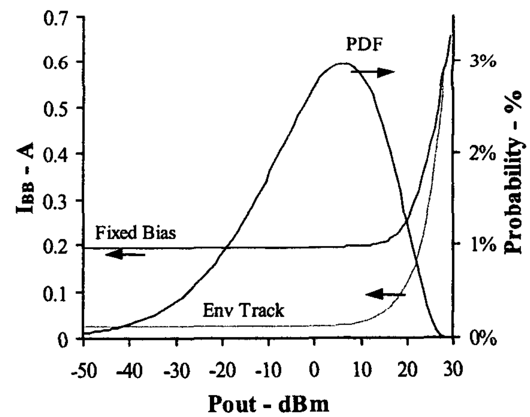

Fig. 4 Measured performance of ET and comparison to fixed supply operation for an IS-95 CDMA signal.

A useful method in evaluating amplifier performance should consider efficiency over the full PDF. Hannington, *et al* [2], define an average power-usage efficiency is given by:

$$\eta_{ave} = \overline{P_{out}} \Big/ \overline{P_{in}} \qquad (3)$$

Where $\overline{P_{out}}$ *and* $\overline{P_{out}}$ represent the average RF output power and average dc power supplied to the RF amplifier, respectively. Both are functions of the PDF.

Measured results for an ET amplifier using the previously mentioned CMOS based Class-S modulator switching at 5 MHz is shown in Fig. 4 and Table 1 [4]. From a battery voltage of 3.5 V, amplifier bias voltage V_{dd} to amplifier is stepped-down such that it varies with the RMS value of the input signal and is large enough to meet spectral linearity of –46 dB and –56 dB adjacent and alternate channel power ratios (ACPR), respectively. ACPR is measured as the ratio of power in a 30 KHz bandwidth offset from the carrier by 885 KHz or 1.98 MHz for the alternate channel to the power in the main CDMA channel. In deep power back-off, V_{dd} can be lowered to below 0.3 V and still meet linearity requirements. Near full output power, losses within the Class-S modulator limit the maximum voltage to about 3.3 V, a 0.2 drop from the battery supply, and thus some reduction in maximum output power occurs, compared to fixed bias. Measured results show dramatically lower mean battery current in the ET amplifier (~ 1/5) compared to fixed bias.

Table 1
Comparison of Fixed Supply Bias to Envelope Tracking

	Fixed Bias	ET
$\overline{I_{BB}}$	199 mA	39 mA
η_{ave}	2.2 %	11.4 %

IV Digital Pre-Distortion

Digital pre-distortion is a promising technique of improving the efficiency/linearity trade-off in power amplifiers. Although many variations exist, the concept fundamentally relies on pre-conditioning the modulated signal prior to amplification in a manner, which often approximates the inverse complex gain characteristics of the power amplifier. Hence, the pre-distorted signal becomes linearized after amplification.

Although considerable work in this area has been reported for multi-channel and multi-carrier base-station type signals, little work has been reported for signals associated with mobile unit amplifiers. The intent of this work is to illustrate the application of algorithmic-based digital pre-distortion in W-CDMA [5] handset amplifier and note potential improvements in efficiency and linearity.

In this work, the pre-distorted signal is generated algorithmically using a polynomial expansion of the form:

$$S_{pd}(t) = S(t)\left\{1 + C_3|S(t)|^2 + C_5|S(t)|^4 + \ldots\right\} \qquad (4)$$

where *S(t)* denotes the complex input base-band signal and $S_{pd}(t)$ denotes the pre-distorted signal to be applied to the input of the power amplifier. Terms C_3, C_5, and so on, are complex pre-distortion coefficients whose values are dependent on the amplifier non-linearity. This simple form is particularly advantageous to digital implementation. While the use of more coefficients generally improves distortion performance, this work considers two cases, a) one coefficient (C_3) and b) two terms (C_3 and C_5).

Measured gain and am/pm characteristics for a GaAs PHEMT based amplifier operating from a 3.5 V supply is illustrated in Fig. 5. The amplifier exhibits very flat gain for power levels up to 31 dBm; after which gain compresses. The am/pm distortion is quite low with less than 4° exhibited up to 2 dB gain compression.

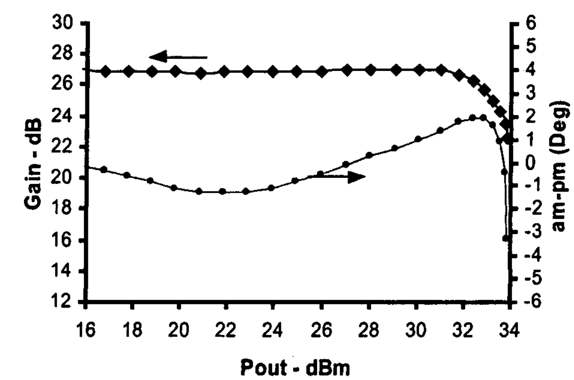

Fig. 5 Measured amplifier gain and am/pm performance.

The measured performance of the amplifier under a 3GPP W-CDMA [5] excitation with the signal exhibiting a 3.3 dB peak-to-average ratio is illustrated in Fig. 6. Given distortion goals of –42 dBc and –52 dBc adjacent channel leakage ratios (ACLR) at offset frequencies of +/- 5MHz and +/- 10 MHz, respectively, output power performance is limited to 30 dBm with a maximum efficiency of 38%.

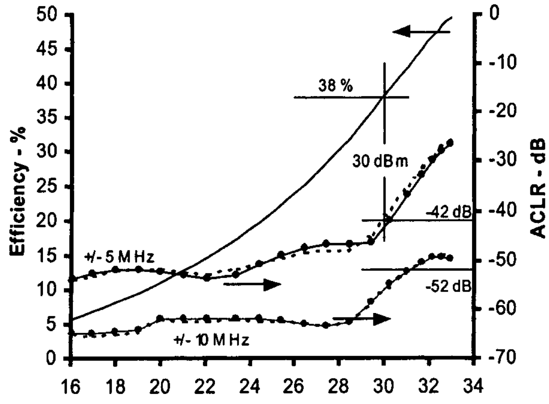

Fig. 6 Measured amplifier performance under a 3GPP W-CDMA excitation.

Measured amplifier performance where the W-CDMA signal is pre-distorted prior to amplification per Eq. 4 is illustrated in Table 2 for output power levels of +30 dBm and +31 dBm. The results indicate that pre-distortion based on using a single coefficient C_3 provides only modest ACLR improvement. This is expected since the single term allows at best a crude representation of amplifier's inverse complex gain characteristics. The improvement resulting from using two coefficients is much greater with one dB additional output power and 4.3 percentage points greater efficiency achieved while still meeting the desired ACLR goals. Since the amplifier exhibits minimal am/pm distortion (Fig. 5), any pre-distortion primarily corrects for gain compression occurring during peak envelope excursions. Measured results showing variation in coefficient C_3 (Pout= 31 dBm) confirm that for optimal correction, the Im(C_3) is near zero (Fig. 7).

V Summary

Many techniques have been proposed to improve the linearity/efficiency trade-off in linear amplifiers found in 2nd and 3rd generation mobiles. Potential improvements offered by supply modulation techniques, including both EF and ET have been illustrated. Due to the need for the Class-S modulator to produce a supply voltage with high current drive, the former is difficult to implement for wide bandwidth signals. The latter, only improves performance when the amplifier is operated in back-off for extended periods of time. Pre-distortion, however, can be useful to improve linearity and/or increase linear output power. Even relatively simple polynomial based pre-distortion using singe and two coefficients show significant improvements.

Table 2

Comparison of Fixed Supply Bias To Pre-Distortion

	Pout dBm	ACLR +/- 5 MHz dB	ACLR +/- 10 MHz dB	PAE %
No PD	30	-42	-55	38
C_3	30	-44	-56	38
No PD	31	-36	-52	42.3
C_3	31	-40	-52	42.3
C_3, C_5	31	-43	-54	42.3

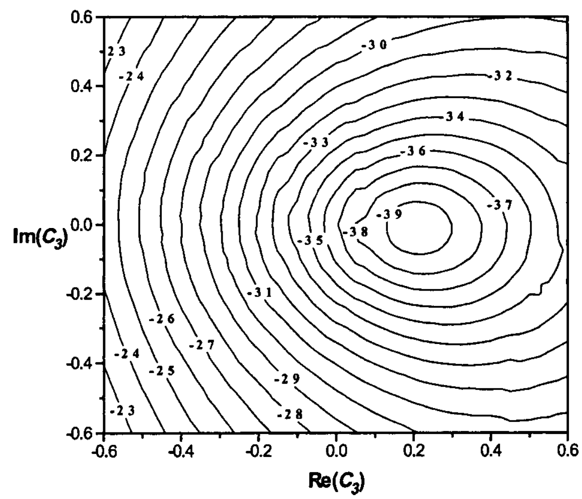

Fig. 7 Measured amplifier ACLR performance (+/- 5 MHz) at 31 dBm output power as a function of PD coefficient C_3.

References:

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