Linear power amplifiers for digital cellular: an introduction

Bill Vassilakis, Principal Engineer, and Eric G Hawthorne, Hihg Power Amplifier Product Line Manager, for M/A-COM's Microelectronics Division in Lowell, Massachusetts, USA outline a number of linear power amplifier design approaches. Each technique features varying degrees of linearity vs power efficiency to match requirements of the end system.

The demand for linear power amplifiers (PAs) has been created by a combination of the introduction of digital cellular systems and the evolution of smaller, microcells demanding frequency agility.

A number of linear amplifiers techniques are available with varying degrees of linearity vs power efficiency including class A, class AB, broad band linearized, narrow band linearized.

The choice of design clearly depends on the end system requirements such as number of carriers, bandwidth of operation and modulation scheme. For example, a system requiring amplification of a single carrier using the North American TDMA modulation scheme ($\pi/4$ DQPSK, 48.6kb/s & $\alpha=0.35$) will require either a good class AB or a narrow band linearized amplifier.

Most narrow band digital cellular transmitter applications can now be met using class AB designs. Improvements in basic transistor technology and developments in class AB bias circuit technology have significantly reduced the benefits of adding the additional cost and complexity of narrow band linearization. Typical achievements are summarized in table 1.

Table 1: Typical performance with alternative linear design approaches

Class A Applications

Pre-amplifiers

IP3 up to 50dBm
Drivers for high power, broad band linearized PAs
Very low power multicarrier transmitters

Power amplifiers

IP3 up 50 to 56dBm
Low to medium power multicarrier transmitters (up to 2W Pavg)

Class AB Applications

Equivalent IP3 up to 60dBm (Pavg=45dBm, IMD=-30dBc)
Single carrier PAs for analogue or digital modulation schemes
Main amplifiers for feed forward linearized systems

Feed-forward linearized class AB

Equivalent IP3 up to 73dBm (Pavg=43dBm, IMD=-60dBc)
Medium to high power multicarrier transmitters (up to 20W Pavg)

Much of our own work has focused on improvements in Class AB amplifier performance for single and multicarrier applications. This paper describes the class AB bias techniques used and the performance enhancement provided by feed-forward linearization.

The feed-forward technology takes advantage of good starting linearity provided by the class AB designs and uses microprocessor control to provide very fast linearization tracking for dynamically varying input signal conditions.

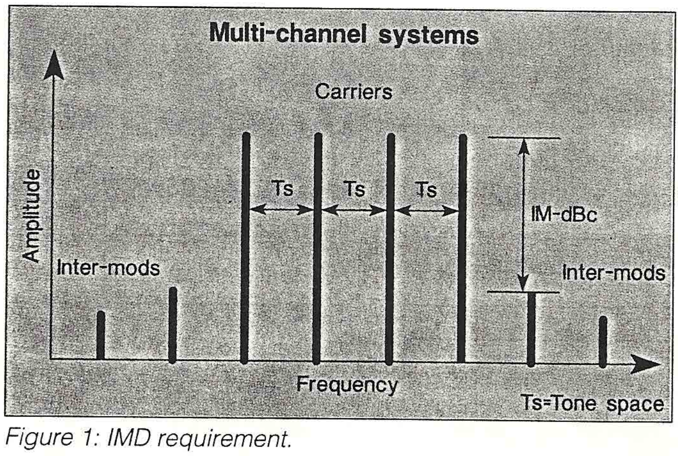

Figure 1: IMD requirement.

Class AB Bias Circuit Design

When an amplitude modulated signal is applied to a Class AB amplifier, a signal whose frequency is equal to the modulating frequency appears at the bias circuits of the amplifier. This occurs because the conduction angle is less than 360° as is the case for Class A amplifiers.

In order to ensure low distortion, the bias supply must present low impedance to the transistor up to and including the highest modulating frequency. In a multi-tone system, as shown on figure 1, this frequency is:

(n-1) * Ts MHz where n is the number of tones and Ts is tone spacing.

In digital cellular systems the frequency of operation is in the 800-1000MHz range over a 20-25MHz bandwidth. Any number of tones may be present up to a total of 32. The required operating power level from the amplifier output transistor is 42dBm average with 32 tones present. The minimum intermodulation distortion (IMD) must be -30dB before any correction is applied with respect to any one carrier. This transistor is then combined in quadrature in order to obtain the total required power output.

The requirement on the bias supply of providing low impedance to high frequencies is not easily met. One standard practice is to use many bypass capacitors in order to cover the entire possible modulation frequency range. One problem with this approach is that parallel resonances occur between the capacitors and circuit instabilities that affect circuit performance are problematic.

A broad band emitter follower circuit may be used instead that exhibits a low impedance characteristic over the entire range of operation. Such a bias circuit for the amplifier is shown in figure 2.

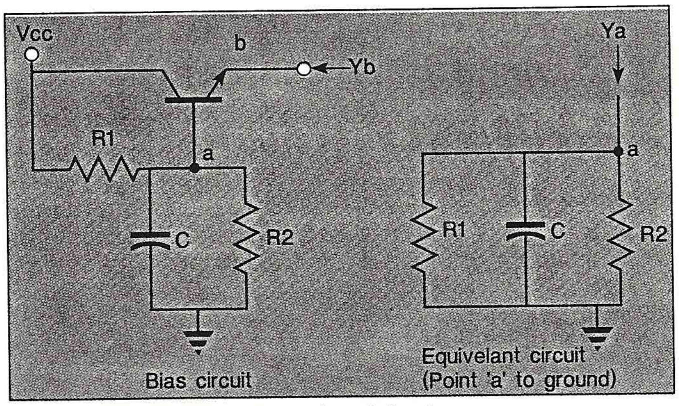

Figure 2: High frequency emitter follower.

Yb is the impedance presented to the base of the bipolar power transistor. The average dc voltage required is in the range of 0.7 Volts for a transistor quiescent current (when no RF is applied) of about 0.3 Amps. The collector supply voltage is 26Vdc.

Referring to figure 2, assuming unity gain voltage output, the emitter output current will be the current into the base scaled by the β of the transistor. Since impedance is inversely related to current, the impedance at the emitter (point "b") will be related to the impedance at the base (point "a") by 1/β. Deriving the admittance for point "a":

$$Ya = \frac{1}{R_1} + \frac{1}{R_2} + j\omega C$$

$$\text{Let } \frac{1}{R} \equiv \frac{1}{R1} + \frac{1}{R2}$$

now

$$Ya = \frac{1}{R} + j\omega C = \frac{1}{R}(1+j\omega RC)$$

Given that the gain is a function of frequency,

$$\beta \equiv \frac{\beta o}{1+j\frac{\omega}{\omega_c}}$$

where βo ≡ dc current gain,

$$Yb = \frac{\beta o}{1+j\frac{\omega}{\omega_c}} * \frac{1}{R}(1+j\omega RC) = \frac{\beta o * (1+j\omega RC)}{R * (1+j\frac{\omega}{\omega_c})}$$

$$\text{if } RC = \frac{1}{\omega_c} \quad \text{then} \quad Yb = \frac{\beta o}{R}$$

$$\text{and} \quad Zb = Zin = \frac{R}{\beta o}$$

Real and independent of frequency!

These equations hold true as long as parasitics due to components and layout are kept to a minimum. Figures 3 and 4 exhibit Class AB bipolar transistor performance with a multitone signal input.

Feed-Forward Linearized Class AB

Using bipolar technology as the main amplifier building block and a microprocessor based control system a feed-forward amplifier has been designed with greater than 60dBc IMDs. The concept of feed-forward in narrow bandwidths is well established. This linearization technique allows for a more efficient operation than class A. Efficiency in class AB operation is superior even when considering that an error amplifier must be used. Figure 5 shows a simplified block diagram of a feed-forward system. A splitter divides the input signal to two equal ports. One signal is sent to the main power amplifier and the other to the cancellation path as the reference. The output of the main amplifier due to its non-linear transfer function includes a distortion component. A portion of this signal is sampled, and combined with a time delayed and phase rotated reference signal with the result being a signal that is representative of the amplifier distortion only. This component is adjusted by a fixed gain, rotated and recombined with the main signal with the result being a signal that is essentially free of distortion. The non-ideal behavior of the two loops are individually characterized by vector error terms and the equations relevant to the system performance can be written as:

i) Carrier cancellation

$$A_1*C_2=-C_1*T_1*k_1*\exp(i*\phi_1)$$

ii) Intermodulation cancellation

$$A_2*C_2*C_3=-T_2*k_2*\exp(i*\phi_2)$$

In these equations, ideal behaviour is achieved when k_1, k_2, ϕ_1 and ϕ_2 are unit magnitude and zero phase.

In order to derive the overall carrier to intermodulation performance improvement, one may assume values for carrier (C) and intermodulation (I) at the output of the main amplifier and using the above equations obtain the

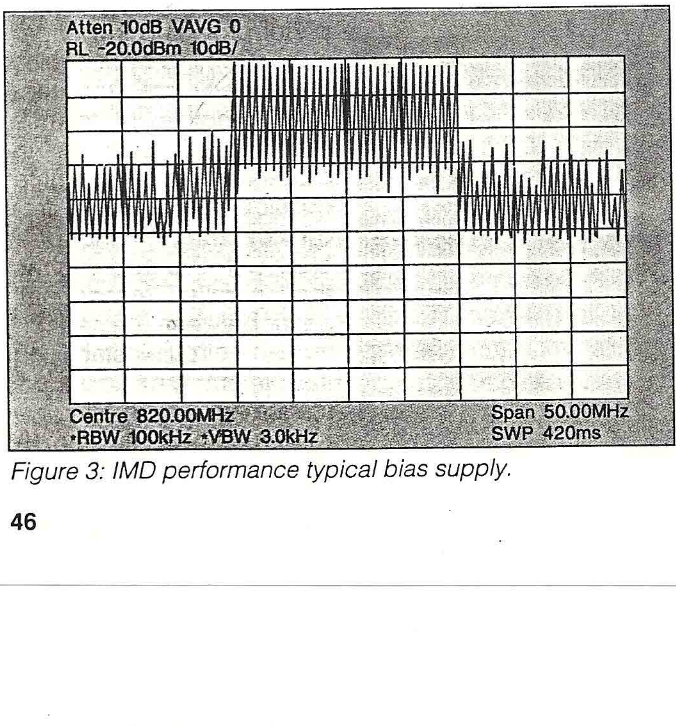

Figure 3: IMD performance typical bias supply.

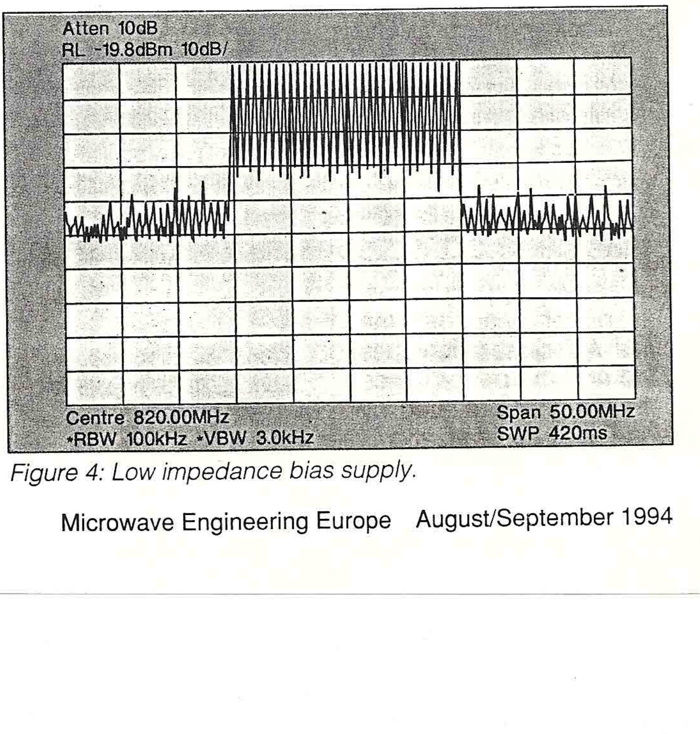

Figure 4: Low impedance bias supply.

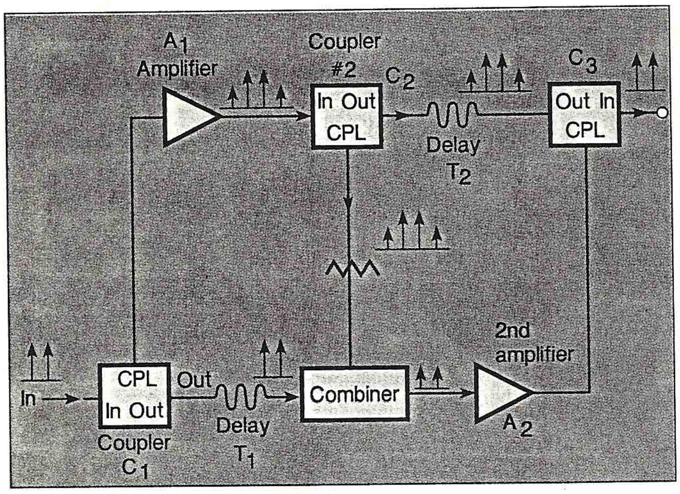

Figure 5: Typical feed-forward system.

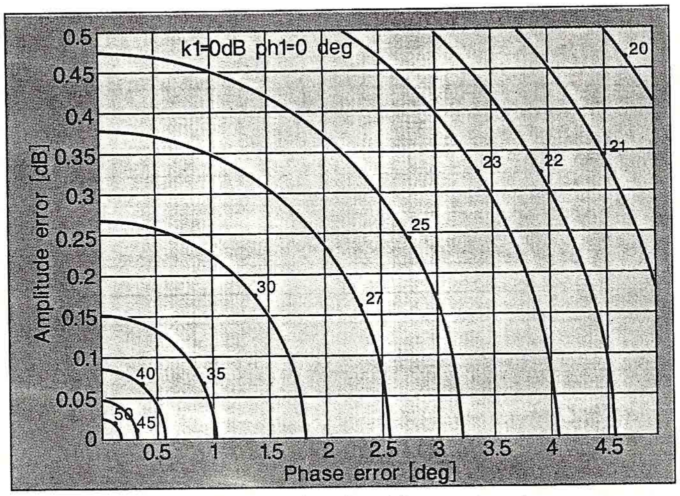

Figure 6: C/I improvement in a feed-forward system.

overall system carrier to intermodulation ratio:
iii) Carrier-to-intermodulation

$$C\_I_{ff}=20\log\left[\frac{1-k_2{*}\exp(i{*}\phi_2){*}(1-k_1{*}\exp(i{*}\phi_1))}{1-k_2{*}\exp(i{*}\phi_2)}\right]$$

If one assumes good cancellation in the first loop then k_1 = 0dB and ϕ_1 = 0° the C/I improvement in the system will be as shown on figure 6 for various phase and amplitude imbalances in the second loop. In this particular design, the amount of cancellation required is in the range of 30dB so the required balance in the output loop is less than 0.25dB amplitude imbalance and less than 1.7° phase imbalance.

A major problem that must be overcome when using class AB based feed-forward systems is deterioration of IMD performance over a large dynamic range. Unlike class A amplifiers where IMDs improve with decreased drive level, the opposite is true when using class AB bipolar transistors. As well, there is a large variation in gain, as much as 5dB over a 20dB drive level change. To improve the performance, a scheme has been invented that adaptively controls the bias level on the power transistors as a function of input power level. Figure 7 is a plot of the main amplifier performance in the feed-forward system with and without adaptive bias control. It is obvious that without this control the amount of cancellation required at low power levels would be not readily achievable.

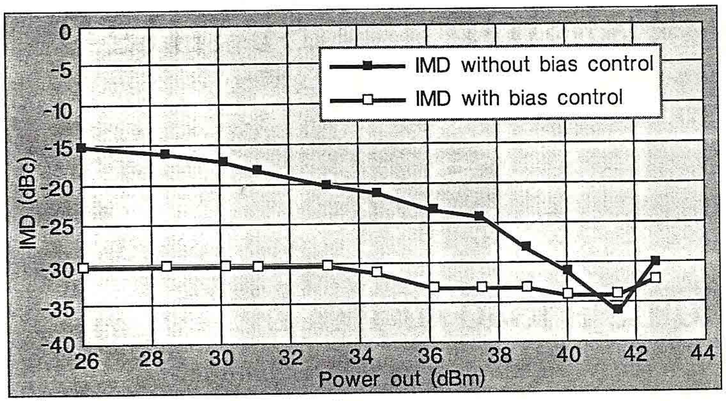

Figure 7: IMD bias control performance.

Table 2

Model number	Frequency	Putput power (Average)	Linearity
CPA-130-WBA	300-500MHz in 2 MHz bands	6W Min Composite	IM3, -60dBc 12 tones
CPA-133-CBS	810-830MHz	18W Min Composite	IM3, -60dBc 32 tones
CPA-132-PBA	1805-1880MHz	0.5W Min Composite	IM3, -60dBc 2 tones

Several other important factors that must be considered carefully when designing a system for manufacturing are:

- Amplitude and delay flatness of main amplifier over the frequency band.
- Amplitude and delay flatness of the auxiliary amplifier over a bandwidth at least 2.5 times that of the main amplifier.
- Temperature stability of all components.

In addition to designing RF building blocks with excellent performance, M/A-COM has successfully developed a microprocessor based adaptive control system. This is used to balance both loops and takes into account dynamically varying input signal, environmental and long term aging factors. The most significant design challenge is to produce a control system that can respond quickly enough to adapt to varying input signal conditions without causing degradation in output linearity. By using innovative detector interface circuits and controller algorithms, M/A-COM has designed a control system that meets this challenge and provides reliable system performance over a wide dynamic range.

In addition to Si bipolar based feed-forward amplifiers, Si MOSFETs have been used for lower frequency designs (300-500MHz), and GaAs FET for designs at PCS and DCS1800 frequencies. Table 2 is a product matrix of the various amplifiers that cover UHF, cellular, and PCS bands. System outputs showing linearized performance are presented on figures 8, 9 and 10 for those amplifiers respectively.

M/A-COM has produced a family of standard class A and class

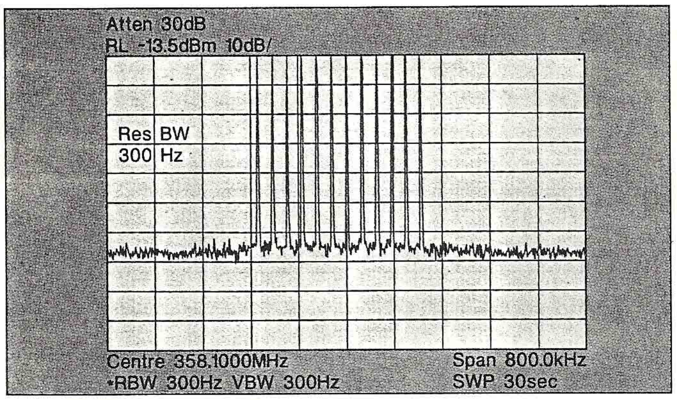

Figure 8: CPA-130-WBA 12 tone output.

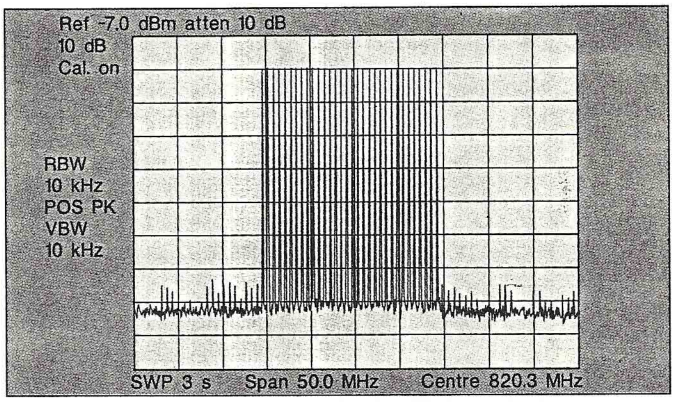

Figure 9: CPA-133-CBS 32 tone output.

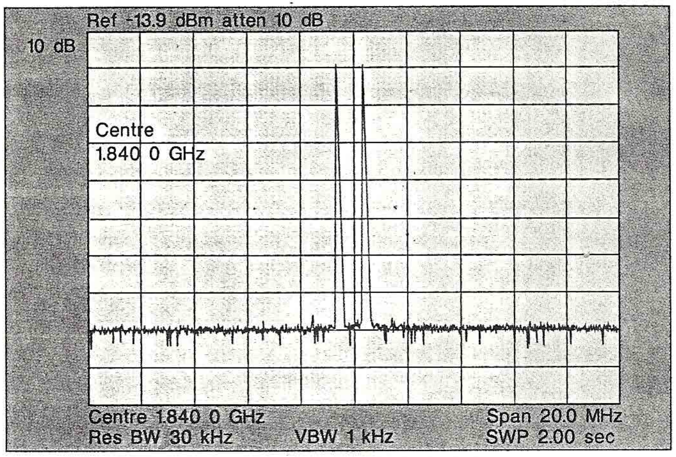

Figure 10: CPA-132-PBA 2 tone output.

AB amplifier designs. The units are intended to demonstrate product capability and can be customized for particular moderate to high volume applications. Changes in output power, packaging, control and alarm circuits are frequently implemented based on customer requirements.

References

[1] F N Sechi, "Linearized Class-B Transistor Amplifiers", IEEE Journal of Solid State Circuits, Vol SC-11, No 2, Apr '71.

[2] N Dye, H Granberg, "Radio Frequency Transistors", pp 59-70, Butterworth-Heinemann ISBN 0-7506-9059-3.

[3] W Bosch, R Pantoja, Inter-Departmental M/A-COM Memorandum.