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High-Efficiency Power Amplifier Using Dynamic Power-Supply Voltage for CDMA Applications

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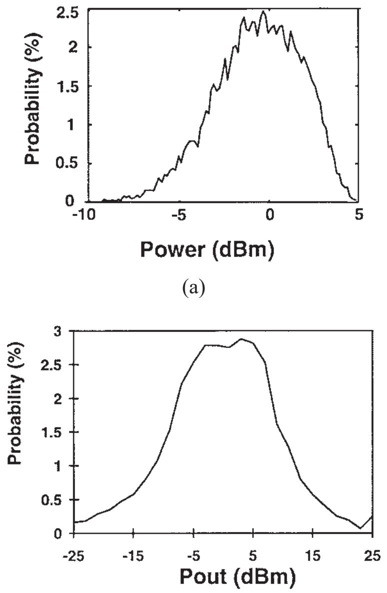
***Abstract*— Efficiency and linearity of the microwave power amplifier are critical elements for mobile communication systems. This paper discusses improvements in system efficiency that are obtainable when a dc–dc converter is used to convert available battery voltage to an optimal supply voltage for the output RF amplifier. A boost dc–dc converter with an operating frequency of 10 MHz is demonstrated using GaAs heterojunction bipolar transistors. Advantages of 10-MHz switching frequency and associated loss mechanisms are described. For modulation formats with time-varying envelope, such as CDMA, the probability of power usage is described. Gains in power efficiency and battery lifetime are calculated. An envelope detector circuit with a fast feedback loop regulator is discussed. Effects of varying supply voltage with respect to distortion are examined along with methods to increase system linearity.**

***Index Terms*—Dynamic supply RF amplifier, envelope restoration amplifier, 10-MHz dc–dc converter.**

I. INTRODUCTION

RF POWER amplifiers used for wireless communications with spectrally efficient modulation formats require high linearity to preserve modulation accuracy and limit spectral regrowth. To minimize distortion, they are typically operated in Class-A or Class-AB mode. Unfortunately, the operation of Class-A or Class-AB RF amplifiers at less than their maximum output power leads to reduced power efficiency. For example, the power efficiency of a Class-A amplifier decreases with output power P_{out} (relative to its peak value $P_{\text{out max}}$) in proportion to $P_{\text{out}}/P_{\text{out max}}$. Similarly, for a Class-B amplifier, the efficiency varies as $(P_{\text{out}}/P_{\text{out max}})^{1/2}$. Class-AB amplifiers have output power variations intermediate between these values. Thus, there is customarily an inherent tradeoff between linearity and efficiency in the amplifier design.



(a)

(b)

Fig. 1. Power output probability distribution for CDMA modulation under: (a) short time variations and (b) long time variations.

The dual requirements of high linearity and high efficiency have been under intense investigation recently for two reasons. First, the current trend is to operate portable wireless phones at only 3.5 V (corresponding to one Li-ion cell, whose voltage drops to 3.2 V near end of life). Under these circumstances, nonlinearities associated with RF device saturation effects become prominent and efficiency drops. Second, to allow for the required variation of RF signal envelopes with modulation schemes such as QPSK or multicarrier signaling, amplifiers have to operate with large peak-to-average power outputs, usually of 5 dB or greater. Specifications such as IS-95 dictate finite distortion levels, limiting the adjacent channel power ratio (ACPR) measured in a 30-kHz bandwidth at 885 kHz from the center of the CDMA spectrum to be no more than −26 dB relative to the average in-band power measured in the same bandwidth. Fig. 1(a) shows the probability distribution of the RF envelope power for a CDMA reverse link waveform (OQPSK modulation) on a time scale corresponding to the inverse of the modulation bandwidth (of order microseconds).

Variations in output power also occur over a slower time scale for CDMA transmission (as well as for all most other cellular protocols) in order to accommodate variable distance between mobile and base, as well as multipath and shadow fading. In many wireless systems, an active feedback control is used to adjust the RF output from the portable transmitter to limit interference effects and save battery lifetime. Fig. 1(b) shows this slower probability distribution (or power usage

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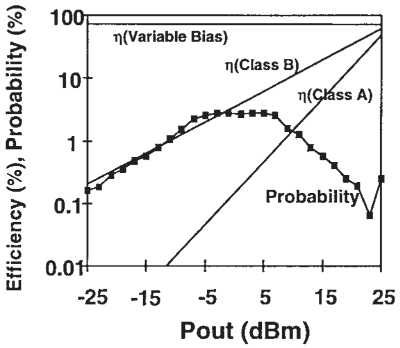

Fig. 2. Variation of efficiency with output power for various amplifier configurations. Also shown is the output power probability distribution for CDMA signals.

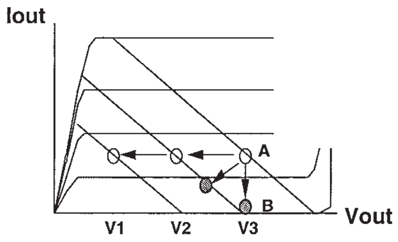

Fig. 3. RF power amplifier transistor current versus voltage characteristics, illustrating representative RF load line and various dc-bias strategies. Point A is the quiescent bias point for Class-A amplifiers and point B for Class-B amplifier. Moving from $V1$ to $V3$ by varying supply voltage yields higher efficiency.

profile) compiled from field tests on CDMA wireless transmission.[1] In Fig. 2, the power usage profile is plotted together with the efficiency versus output power for various amplifier configurations. It is seen that even though the maximum output power capability of the amplifier is approximately 0.5 W, operation at this level occurs only a small fraction of the time. The most probable output power is only 1 mW. At this point, where most of the transmission takes place, a Class-A amplifier has only 0.1% efficiency, while a Class-AB amplifier is typically only 2% efficient.

The variation of efficiency with output power for the amplifiers can be understood by considering the transistor biasing within the power amplifiers. Fig. 3 shows representative output current versus output voltage characteristics for the output transistor. In Class-A amplifiers, the dc current and voltage are kept constant as the output power varies. Consequently, the input dc power is constant, and the efficiency is proportional to RF output power. In the Class-B amplifier, the dc-current bias varies in proportion to the output RF current and, thus, changes according to the square root of output power. The corresponding voltage is kept constant. Another option is to vary the supply voltage in accordance with the output signal level. If both dc voltage and current are varied optimally, then the efficiency of the amplifier can, in principle, be kept high even as the output power decreases (as shown in Fig. 2 for the "variable bias" case). Amplifiers designed to accomplish have been called "envelope tracking" amplifiers.

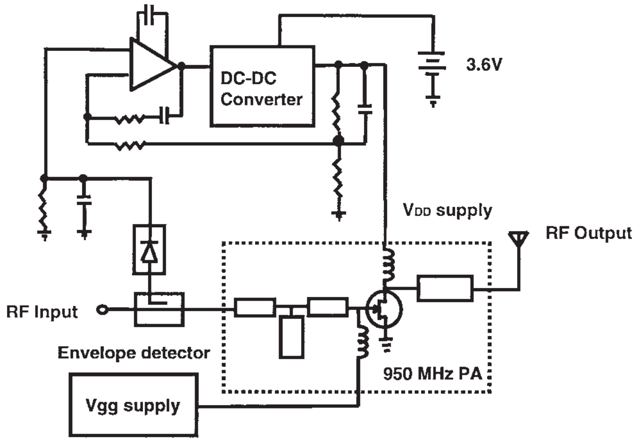

Fig. 4. Schematic diagram of RF amplifier system.

To implement variable voltage bias, Buoli [1] developed a linear regulator power drive, whereby the $V_{\rm DD}$ supplied to a final MESFET amplifier varied with the RF envelope. To save power, this voltage was obtained from a dual source; a minimum voltage of +7 V was fed to the amplifier, which could be overridden by a linearly controlled voltage between 7–12 V, which followed the signal envelope. Although the higher voltage was provided by virtue of a relatively inefficient fast video-type amplifier controlling a linear-pass transistor, the savings in overall system power was up to 45%. Power was saved since, for small signals, the energy source was the 7-V supply (and not the 12-V supply). The dynamic 7–12-V source was used to take care of the peaks required by the modulation format. A related technique for raising the efficiency, due to Raab [2], comprises a Class-S high-level amplitude-modulation scheme, where the modulator takes the form of a step-down buck regulator operating at 200 kHz. The signal input to the RF stage is hard-limited to preserve only the phase information. The envelope of the output signal is controlled by the varying dc supply voltage of the RF stage. This dc voltage is regulated by pulsewidth modulation of the buck regulator. In this system, the maximum frequency of modulation depends strongly on the switching frequency of the buck regulator. Sampling theory requires that this switching frequency be at least twice that of the highest modulation frequency required. In practice, it is usually seen that a factor of ten is required to minimize the effects of filter ripple components. With typical dc–dc converters, the switching frequency (usually below 1 MHz) is not high enough to allow rapid modulation of the supply voltage for many RF amplifier communication purposes.

In this paper, we present a high-efficiency power-amplifier topology for use in a portable microwave communications system. Here, a boost dc–dc converter is used to provide the supply voltage to a MESFET power amplifier. The overall amplifier configuration is shown in Fig. 4. By sensing the RF envelope to be amplified, and providing a dynamically adjusted $V_{\rm DD}$ to the amplifier by means of the dc–dc converter, overall system efficiency may be increased. By using a boost converter operating at 10 MHz, two advantages are obtainable over

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