

Adaptive Power Management of Linear RF Power Amplifiers in Mobile Handsets – An Integrated System Design Approach

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Abstract— Energy-efficient, linear RF power amplifiers (PAs) are critical for achieving longer battery life in state-of-the-art radio transceivers because typically they determine and dominate the power consumption of the system. In this paper, an adaptive power management scheme using a novel dual-mode, noninverting, buck-boost converter targeted for code-division-multiple-access (CDMA) RF PA is presented. The control scheme dynamically adjusts the PA supply voltage using a noninverting buck-boost converter, and bias current as a function of the transmitter's output power thereby reducing the quiescent power loss and improving the system efficiency. The use of a dual-mode converter enables the PA system to operate with high efficiency over a wide loading range, which translates to an improvement in battery life. This paper also presents several alternate control strategies that simplify the buck-boost converter accuracy requirements and transmitter gain adjustment circuit design, which directly translates to a reduction in the system's design complexity thereby saving silicon and PCB real estate. A comparative evaluation of the control methods considering the average efficiency of the system reveals that a three-step and an approximate continuous 1-dB power control schemes result in comparable efficiency enhancement with respect to the accurate continuous control method while offering simpler solutions.

Index Terms—CDMA portable applications, dynamic supplies, battery life, buck-boost dc-dc converter

I. INTRODUCTION

The impressive growth and use of radio-frequency (RF) hand-held devices with increasing functional densities (e.g., voice, video, and data) has resulted in a wide-spread demand for efficient power-saving techniques to increase battery life. Consequently, energy-efficient linear RF power amplifiers (PAs) are key components in mobile, battery-operated systems with wireless connectivity, e.g., cellular phones, personal digital assistants (PDAs) because they account for a significant portion of the total power consumption of such systems. In addition to battery life improvement, the PA efficiency at power back-off mode is critical to ensure lower heat dissipation due to the quiescent power loss, which impacts the thermal characteristic and reliability of the system.

With longer battery life becoming a key design goal in every portable handset, dedicated power supplies for point-of-load applications are being proliferated in next generation wireless systems [1]. While state-of-the-art radio transmitters are being designed in low cost CMOS process, the PA is still fabricated in a specialized process e.g., GaAs, InP, etc. due to the availability of high quality factor passive components used in matching networks, and the transistor exhibiting higher efficiency and linearity. Furthermore, the PA is usually operated with a higher supply voltage, of course limited by the process technology, enabling the transmitter to deliver its peak power with a larger voltage swing and a lower current, thereby minimizing power loss in the current flowing path and subsequently achieving a higher peak-power efficiency. In state-of-the-art CDMA power management systems as many as eleven different power supplies are used to dynamically optimize the operation of the circuit building blocks and thereby save power [2]. It is therefore perfectly logical for a system already having a dedicated power supply to incorporate additional intelligence to improve the efficiency. A comparative evaluation of state-of-the-art schemes for efficiency enhancement of linear PAs [3]-[6] and linearity improvement for nonlinear PAs [7]-[9] are offered in [10], where a RF PA scheme with a dynamically adaptive buck-boost supply is also experimentally demonstrated for code-division-multiple-access (CDMA) applications. The PA efficiency is improved by dynamically adjusting the supply voltage and bias current as a function of its transmitted power, thereby minimizing the quiescent power loss. The buck-boost conversion capability enables the system to utilize the entire battery voltage profile and operate at its peak performance even with a close-to fully discharged battery.

In this paper, the use of a new dual-mode, buck-boost converter is proposed for the power management scheme exploiting the supply voltage variation profile of the PA. By operating the converter in pulse width modulation (PWM) mode during heavy loading conditions and pulse frequency modulation (PFM) during light loads, a high efficiency over wide loading range is achieved, which is critical to improve the battery life. Section II describes an overview of the proposed power management system for the CDMA PA. In Section III, system design considerations for the buck-boost converter are described highlighting the PA system specification. A number of alternate control strategies are presented in this section. In Section IV, average efficiency results for various control schemes are presented and discussions on efficiency complexity trade-off are offered. The paper is concluded in Section V.

II. PROPOSED PA POWER MANAGEMENT SCHEME

A simplified block level schematic of the power management scheme is presented in Figure 1(a). Spectrally-efficient non-constant envelope modulation schemes with inherent power control mechanism, e.g., CDMA, have control loops in the system whereby the transmitter output power information is known to the digital signal processor (DSP), which is adjusted up/down by 1-dB in each 1.25 msec/666 μ sec for CDMA/WCDMA [11] as required by the base-station. The power management architecture

operates with the processor sending a control signal via a digital to analog converter (DAC) to the control unit, which ultimately adjusts the supply voltage using a noninverting buck-boost converter, and bias current for the RF power transistor. A simplified graphical representation of the mechanism is offered in Figure 1(b).

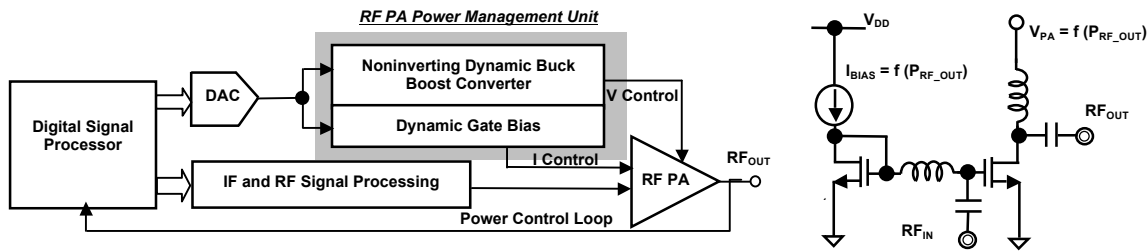


Fig. 1. (a) Simplified block diagram of representation of the RF transmitter and PA power management unit, (b) PA schematic with dynamic bias.

Variation of the bias current and supply voltage of the PA, however, changes the transistor's transconductance resulting in a variable gain PA as a function of its output power. In a practical implementation, the PA gain is adjusted with the other components in the signal transmission chain, e.g., drivers and variable gain amplifiers (VGAs) to achieve the desired output power dynamic range. A look-up table based open-loop approach can be adopted to implement such a system, where for a given RF output power, corresponding input power and control signals are stored in the DSP's memory based on the experimentally predetermined gain characteristic of the PA. Along with the VGAs, the PA is dynamically programmed to achieve the transmitter's output power variation. However, like any other open-loops scheme, this scheme suffers from time dependent performance drifts resulting in a degraded accuracy. An advanced approach would require an automatic calibration procedure using a closed-loop feedback system like the Cartesian feedback predistortion system [12], where during the start-up the parameters in the look-up table are updated. The accuracy of the system is significantly improved, which however obtained with added complexity and thereby increased cost.

III. SYSTEM DESIGN CONSIDERATIONS

The simplified schematic of a non-inverting, synchronous buck-boost converter suitable for wide-range of supply voltage with dynamic output voltage capability is shown in Figure-2(a). The critical design requirements of the converter are: (a) to maintain the desired output voltage accuracy (steady state, ripple and transient voltage), (b) ability to respond to the control-signal change by 1-dB as requested by the base-station, and (c) maximizing its power efficiency over the entire output voltage range. The output ripple in the supply voltage is responsible for both in-band (error vector magnitude) and out-of-band spectral regrowth (adjacent channel power rejection) depending on the switching frequency. On the other hand, a finite delay in the tracking the control signal by the converter's output results in unwanted clipping of the signal ultimately translating to a out-of-band spectral regrowth. The accuracy and transient response trade-off is critical for the PA system to operate within the in-band and out-of-band linearity specifications required by the wireless standard. The PA specifications and resulting constraints are exploited to optimize the converter operation, the details of which are offered in the following subsections.

(a) Dual-mode operation: Using a simplified model, the output power transmitted to the load is given by V^2/R , where R is the load seen by the transistor, and V is the voltage swing at the transistor's drain node. As the output power decreases, the system acts in such a way that the output voltage and bias current are reduced proportionately. A supply voltage range of 5 – 0.5 V translates to an output power variation from 27 – 7 dBm, yielding a power control range of 20 dB, below which the PA supply and bias current are kept unchanged. Figure 2(b) conceptually illustrates the two regions (A and B) of operation. Therefore, the converter is operated in a two separate modes: (a) one with high output power capability and fast transient response, and (b) the second mode with low power capability without the need to respond to 1-dB control steps. A pulse-width modulation (PWM) control is suitable for the high power mode because of its higher accuracy and better stability. A constant on time pulse-frequency modulation (PFM) scheme is adopted for the light load conditions because of its higher efficiency owing to a lower switching frequency and minimal quiescent current use. The converter can be operated with only PWM mode throughout the loading range; however, switching losses generally dominate during low loading conditions yielding a poor efficiency and thereby a shorter battery life.

(b) Buck/Buck-Boost/Boost operation in PWM: In the PWM mode of operation a conventional buck-boost converter [10], all the four switches are functional resulting in unnecessary switching losses. Considering the output voltage requirement of 0.5 – 5 V, from a Li-ion battery supply, 2.7 – 4.2 V, it is evident that the converter can be operated in either buck mode or boost mode where only two of the four switches are functional. However, for stability considerations there must be some region of overlap between two regions for the converter to ensure smooth operation of the converter. By using a modified control strategy [13], [14] the converter is adaptively operated to maximize the converter efficiency.

(c) Performance trade-offs in a buck-boost converter: For a buck-boost converter operating in boost mode, the control loop is compensated to achieve a unity-gain bandwidth before the right-half plane (RHP) zero, which is inversely proportional to the converter's power inductor value. Increasing the bandwidth of the converter requires pushing-out the RHP zero by choosing a smaller inductor, which for a given switching frequency increases the ripple current thereby requiring larger output capacitor to meet the output voltage ripple specification. A larger output capacitor requires more energy to be transferred from the input supply to change its terminal voltage from one step to the other, which translates to an increase in number of switching cycles and thereby longer control-to-output transient response time. Moreover, the steady state output voltage accuracy of the converter affected by

the error amplifier's input offset in control loop. Especially in a vanilla CMOS process, realization of a low offset amplifier requires complex offset cancellation schemes.

(d) Alternate Control Strategies: Considering the circuit complexities, e.g. look-up table based open-loop or closed-loop gain adjustment requirement, steady state accuracy and transient response trade-offs in a buck-boost converter, control schemes alternate to the continuous tracking of supply voltage and current are offered. One way to control the system is to introduce a systematic offset at the converter's output voltage such that at any given time the PA supply voltage is 1-dB higher than the desired voltage to achieve acceptable linearity. This method simplifies transient response requirement of the converter, however still requires a calibration scheme similar to an exact continuous control mechanism. Alternatively, a two- or three-step approach is considered where the power management system adjusts the supply voltage and current in discrete steps. These approaches greatly simplify the calibration and transient response requirements of the power converter and associated control circuitry. Figure 2(b) conceptually illustrates these alternate control schemes with respect to the accurate continuous control method.

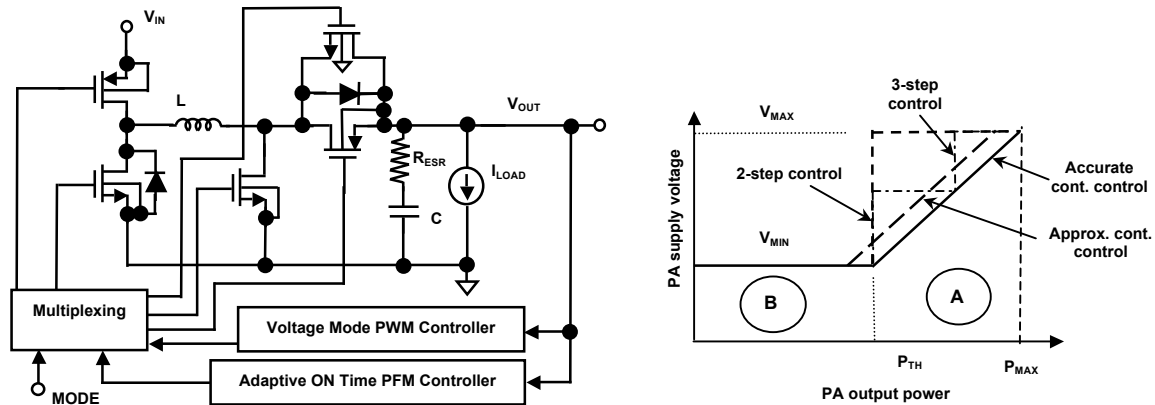


Fig. 2. (a) Simplified schematic of dual-mode noninverting synchronous buck-boost converter, (b) PA supply voltage variation profile with transmitter output power for alternate control schemes (A: Controllable voltage, B: Constant voltage).

IV. EFFICIENCY RESULTS AND DISCUSSIONS

A dual-mode noninverting buck-boost converter is designed and currently being fabricated using AMI's 0.5- μm CMOS process through MOSIS, the details of which can be found in [15]. The power converter's simulated efficiency curves for a resistive load of 10 Ω used for the PA system efficiency calculation are given in Figure 3. In the low power PFM mode, simulated efficiency result of 80 % is used for the system efficiency computation. Although peak-power efficiency (drain efficiency or power-added efficiency) is widely used to report the PA's figure-of-merit, in battery powered portable systems the output power probability distribution should be considered to estimate average efficiency (η_{avg}) of the system, which is the true indication of its ability to transform battery energy into useful transmitter power. To estimate the average efficiency improvement, input power profiles of the dynamic-supply PA control schemes (presented in Figure 4) are multiplied with the output power probability density function [10] to generate the weighted input power curves for the system (Figure 5). The output voltage of the PA is adjusted from 5 V to 0.5 V with the change in output power from 27 dB to 7 dBm, below which the supply voltage is kept constant at 0.5 V. Similarly, the PA bias current is changed from a maximum of 350 mA to 35 mA, for the output power range.

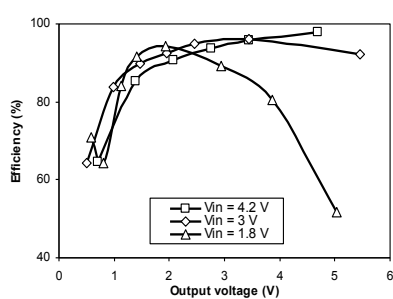


Fig. 3. Simulated efficiency characteristics of the buck-boost converter in PWM mode.

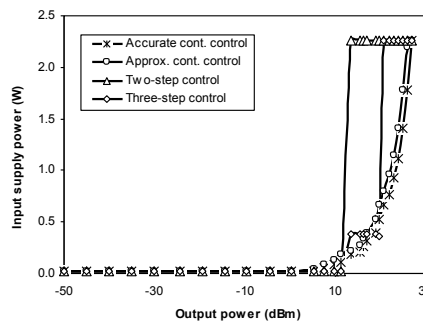


Fig. 4. Input power variation for different control schemes for an input supply of 3 V.

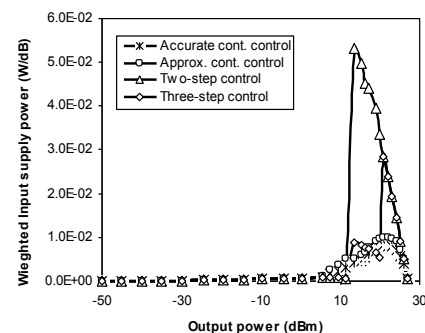


Fig. 5. Weighted input power variation for different control schemes for an input supply of 3 V.

The area saving under the weighted input power curves represents a reduction in average input power for the various control schemes which ultimately yields a higher average efficiency for a given output power probability distribution characteristic. Average efficiency results and a summary of circuit complexity with accuracy requirement of the system are given in Table I. Operating the system in accurate continuous 1-dB control scheme using a dual-mode buck-boost converter (15.75 %) yields an

average efficiency enhancement of more than 15 % compared to using a single mode converter (13.62 %). Similar improvement is expected for the alternate control strategies described in this paper. By controlling the system with a systematic offset comparable increase in efficiency can be obtained with respect to accurate control while having relatively simple design requirements to implement in an IC environment. A three-step approach offers attractive alternative to both the accurate and exact control scheme with a simple calibration scheme while achieving reasonable average efficiency.

Table I. Implications of the control strategies on the average efficiency and system complexity of the PA.

Conv. Mode	Scheme	η_{avg}	Calibration	Conv. Tran. Resp.	Conv. Output Accuracy
N/A	Fixed supply and bias	1.23 %	N/A	N/A	N/A
PWM	Accurate continuous control	13.62 %	Complex	Fast	Accurate
Dual-Mode PWM/PFM	Accurate continuous control	15.75 %	Complex	Fast	Accurate
	Approx. continuous control	12.36 %	Complex	Moderate	Moderate
	2 discrete step control	3.7 %	Simple	Moderate	Moderate
	3 discrete step control	10.06 %	Simple	Moderate	Moderate

V. CONCLUSIONS

In this paper, the characteristic of the PA supply voltage change with the transmitter's output power variation is exploited to introduce the use of a novel dual-mode, buck-boost converter for the power management scheme of an RF PA. Operating the converter with PWM mode at peak loads and PFM at light loads offers a unique opportunity to improve the system efficiency over a wide loading range, which is critical to improve battery life. Considering the circuit complexity, especially due to the gain adjustment (calibration) needs and accuracy requirement of the dynamically adaptive converter, alternate control strategies are offered. Using the simulated efficiency results of a dual-mode converter, the overall system efficiency of various control schemes are computed and compared. It is also demonstrated that by employing a converter with just enough speed and operating at one level higher than the required supply voltage for the PA, the RF performance of the system can be met while comparable improvement in battery life. Further simplification of the system can be achieved with a three-step control scheme with reasonable efficiency enhancement. With energy efficient linear RF PAs becoming a key requirement in feature-laden handheld devices having high speed data connectivity, adaptive power management schemes with a dynamically buck-boost converter offer an unique possibility to enhance efficiency, not to mention its inherent capability to be functional over a wider supply voltage range.

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